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Review

Innovative Solutions for Palm Oil Mill Effluent Treatment: A Membrane Technology Perspective

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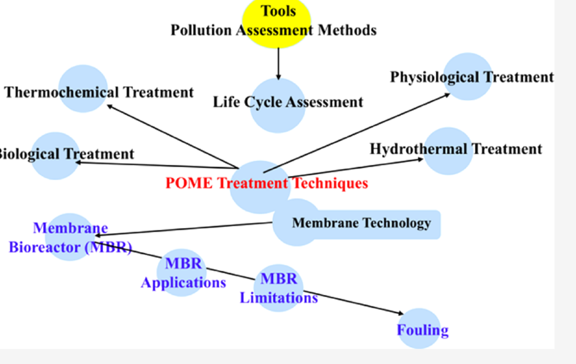
ABSTRACT: Palm oil mill effluent (POME) presents significant environmental challenges in palm oil-producing countries due to its complex composition and high organic content. Membrane technology has emerged as a viable treatment option that offers efficient separation processes. This review examines various POME treatment methods with an emphasis on membrane bioreactor (MBR) applications. MBRs, including aerobic, anaerobic, and hybrid configurations, have demonstrated effectiveness in pollutant reduction, with a key emphasis on fouling minimization. Despite their advantages, membrane fouling remains a major limitation, leading to reduced performance and increased maintenance costs. This review critically evaluates factors influencing fouling and explores sustainable mitigation strategies. Furthermore, life cycle analysis (LCA) is highlighted as a vital tool for evaluating the environmental impact of POME treatment. Various chemical and biological pollution assessment methods used in existing risk evaluations are also discussed. The main objective of the insights offered is to improve knowledge of the opportunities and limitations related to using membrane technology for the efficient and sustainable treatment of POME. This review encourages the continuous development of novel membrane-based solutions, promoting environmental sustainability and improved wastewater management in the palm oil industry by addressing key challenges and developments.



1. INTRODUCTION

A significant quantity of wastewater that is detrimental to the environment is produced as a byproduct during the production of palm oil. It is a dense, brownish liquid made mostly of water with 0.7% oils, 4% suspended particles, originating from fruit debris.[1] Palm oil mill effluent (POME) is a nutrient-rich material that has a dark color due to the presence of carotene (8 mg/L), pectin (3400 mg/L), tannin, phenolic compounds (5800 mg/L), and lignin (4700 mg/L). It has high levels of organic pollutants, suspended solids, oil, and nutrients, rendering it inappropriate for direct discharge into the environment.[1] Furthermore, Table 1 lists significant concentrations of amino acids, carbohydrates, free organic acids, and inorganic minerals in POME. The amount and concentration of pollutants contained in POME influence whether it is classified as high-strength or low-strength wastewater. Significant amounts of total solids (TS), total suspended solids (TSS), ammonia, inorganic nutrients, chemical oxygen demand (COD), and biochemical oxygen demand (BOD) are indicative with high-strength POME.[2] According to this, high-strength POME exhibits a lower biodegradability index (BI), shown by a lower BOD/COD ratio. This is likely due to the high concentration of hazardous components, including nitrogenous compounds and organic pollutants like COD.[3] Consequently, there is a significant risk to the environment when high-intensity POME is discharged directly without appropriate treatment.

Organic matter with a high BOD/COD ratio is deemed to be easily biodegradable, indicating that the organic pollutants can undergo biological breakdown. Consequently, it can be classified as a low strength. Conversely, a low BOD/COD ratio shows the presence of toxic substances that inhibit biodegradation, classifying such wastewater as high strength.[4]

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Table 1. General Properties of Raw POME[a][1,2,6,7]

Parameters	Concentration Range	Current Discharge Limit
Chemical oxygen demand (COD)	15 000–100 000	-
Biochemical oxygen demand (BOD)	10 250–43 750	100
Color	Brown	-
Total suspended solids (TSS)	5000–54 000	400
Oil and grease	130–18 000	50
Temperature	80–90 °C	45
pH	Acidic, 3.4–5.2	5–9
Oil and grease	4000–5000	-
Total volatile solids	10 000 to 50 000	-
Ammoniacal nitrogen (NH_3–N)	25–35	-
Total nitrogen (T.N.)	180–800	200
Pectin	3400	-
Lignin	4700	-
Carotene	8	-
Phenolic	5800	
Phosphorus (P)	120–140	-
Potassium (K)	2200–3000	-
Magnesium (Mg)	600–700	-
Calcium (Ca)	400–500	-
Boron (B)	7–8	-
Iron (Fe)	150–200	-
Manganese (Mn)	8.139	-
Copper (Cu)	3–4	-
Zinc (Zn)	25–30	-

[a]With the exception of pH and temperature, all values were given in mg L^{-1}.

Looking at the data in Table 1, BI ratio for the considered POME samples falls within the range of 0.36 to 0.617.[1,5] A POME sample with a BI of 0.617 is more prone to biological decomposition due to its high level of biodegradable substances such as BOD, whereas a BI of 0.36 suggests a prevalence of nonbiodegradable components. Consequently, wastewater exhibiting a low BI ratio might require supplementary treatments alongside bioremediation. This clearly underscores the significant role of BI in the decision-making process and the development of appropriate treatment approaches for the specific quality of water. The fundamental properties of untreated POME are detailed in Table 1 below.

As seen in Figure 1, POME is produced by the crude palm oil (CPO) clarification, hydrocyclone separation, vacuum drying, and sterilization of fresh fruit, respectively.[7] Sterilization is the first step in the extraction of palm oil. It involves heating fresh fruit bunches (FFB) in an autoclave to 140 °C for 75 to 90 min. This procedure deactivates enzymatic activity and tenderizes the oil palm fruits, yielding a coagulated viscous solution termed sterilizer condensate and sterilized fruit bunches (SFBs). At this stage, it generates 36% of the total POME.[2] Following this, SFBs undergo stripping, pressing, and clarification, contributing to 60% of the total POME.[7] The crude palm oil is subsequently purified and vacuum-dried, accounting for 4% of the total POME production.[8] Several industrial processes are involved in the processing of palm oil, which results in massive production of waste. This waste is commonly termed palm oil mill sludge (POMS) and palm oil mill effluent (POME). POMS comprises empty fruit bunches, trunks, leaves, and fibers.

Palm oil mills, especially in major producing countries such as Indonesia and Malaysia, generate significant amounts of wastewater, around 3 billion pounds annually. Table 2 illustrates the quantity of palm oil produced in various countries. Between 1995 and 2015, annual palm oil production increased 4-fold, and there are expectations for it to quadruple once more by 2050.[10] This significant growth in palm oil production has severe environmental repercussions, as it predominantly involves cultivation in tropical rainforests. This practice has led to extensive and unregulated deforestation, causing damage to the habitats of numerous endangered species, such as the orangutan, Sumatran tiger, and Sumatran rhinoceros.[11] Based on the data from the US Department of Agriculture (USDA) for the years 2022–2023, global palm oil production is estimated to reach 77.22 million

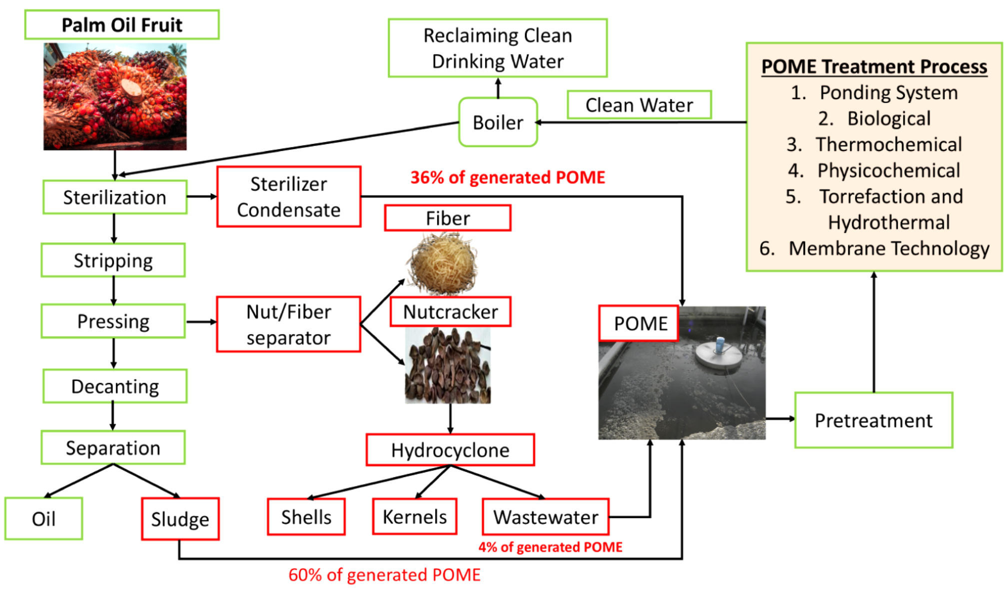

Figure 1. Systematic process flow diagram for palm oil production and proposed processes for POME treatment. Reproduced with permission from Ref. 9. *Copyright [2023] [Elsevier].*

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Table 2. World Palm Oil Production for the Years 2019 and 2022[10,11]

Country	Production (Million metric tons) (2019)	Percentage of World Production (2022)	Production (Million metric tons) (2022)
Indonesia	42.50	58	45.5
Malaysia	19	26	18.80
Thailand	2.80	4	3.26
Colombia	1.53	2	1.84
Nigeria	1.02	1	1.4
Guatemala	0.85	1	0.91
Honduras	0.58	1	0.60
Papua New Guinea	0.55	1	0.65
Brazil	0.54	1	0.57
Cote d'Ivoire	0.52	1	0.60
Ecuador	-	-	0.47
Cameroon	-	-	0.46
Congo (Kinshasa)	-	-	0.30
Ghana	-	-	0.30
India	-	-	0.29
Peru	-	-	0.28
Costa Rica	-	-	0.27
Mexico	-	-	0.23
Philippines	-	-	0.10
Sierra Leone	-	-	0.075
Benin	-	-	0.07
Angola	-	-	0.055
Dominican Republic	-	-	0.053
Guinea	-	-	0.050
Liberia	-	-	0.045
Senegal	-	-	0.014
Togo	-	-	0.0090
Venezuela	-	-	0.0080

metric tons. In the previous year, 2021/2022, palm oil production amounted to 73.83 million tons. The estimated production of 77.22 million tons for the current year represents an increase of 3.39 million tons, which is approximately a 4.59% growth in palm oil production worldwide.

The extraction process for CPO involves adding water, resulting in substantial wastewater stored in ponds. Around 5 to 7.5 tonnes of water is required to produce 1 tonne of CPO, with more than 50% of this water being transformed into POME.[1] This huge POME generation has established a great concern for environmental safety and protection.[12] POME poses significant challenges owing to its large volume and disposal issues. Directly releasing POME onto land leads to soil clogging, waterlogging, and vegetation destruction. Meanwhile, discharging it into waterways depletes water and causes aquatic pollution, turning rivers brown with an unpleasant smell. The discharge adversely affects aquatic life and depletes water sources for domestic use and fishing in local communities. Hence, effective POME treatment techniques are crucial. Certainly, discussing the available treatment methods for POME and their acceptance in the industry along with their performance is crucial in understanding how to address this environmental challenge effectively. Various biological, physical, and pharmacological approaches have been recommended over the last 20 years for the treatment of POME, but only a limited number have garnered acceptance within the industry. Therefore, many researchers are intensively working on POME treatment technologies globally. The advantages and disadvantages for POME treatment methods are summarized in Table 3. Generally, biological methods have been used for POME treatment in Malaysia due to their simplicity, economic advantages, and less technical requirements.[2] In Malaysia, the ponding system of biological treatment is the traditional method of treating POME.[11] This biological process is not enough to cope with the huge production of POME.[7] Numerous researchers have validated the inefficiency of the mentioned method, citing drawbacks such as extended treatment times, significant operational complexities, and a heightened risk of contamination of groundwater, accompanied by the release of unpleasant odorous gases.[13] Aerated lagoon system,[2] conventional anaerobic digester,[6] anaerobic contact process,[6] upflow anaerobic sludge blanket (UASB) reactor,[14] close tank digester,[15] trickling filter,[2] aerobic lagoon system,[6] aerobic rotating biological contactor,[16] and evaporation process[14] are among the other biological treatment methods that numerous researchers have proposed. The newest option is integrated anaerobic−aerobic bioreactor system (IAAB), which has demonstrated encouraging outcomes by dramatically lowering BOD and COD in just 115 days.[17]

The process of membrane separation is recognized as a low-cost, straightforward, and eco-friendly approach with significant potential for the treatment of POME.[22] It delivers superior water quality in a shorter treatment duration and demands relatively a reduced space for the process.[23] Due to the growing environmental regulations and sustainability concerns, membrane technology has been explored as an alternative because it offers higher pollutant removal efficiency, significant water recovery, and a smaller footprint. The capacity of membranes to remove contaminants from POME selectively with a small chemical input offers an appealing approach. Membrane technologies such as microfiltration (MF), ultrafiltration (UF), and nanofiltration (NF) are extensively used for the treatment of POME as they can separate suspended particles, oils, and organic chemicals. Due to its ability to efficiently reduce COD, BOD, and TSS levels and facilitate water reuse, ultrafiltration and nanofiltration are used widely. Research has shown that ultrafiltration is useful in lowering the amount of oil and suspended particles in POME,[31] although fouling remains an issue. Similarly, UF membranes were found to be highly effective in lowering organic pollutants by Aryanti et al.[21] However, membrane fouling, which increases operating costs and shortens membrane lifespan, is again a common issue. Furthermore, recent developments in membrane materials, such as the development of fouling-resistant membranes using nanomaterials and surface modification methods, have demonstrated the potential for fouling mitigation. More resilient, scalable membrane systems that can tolerate the challenging circumstances of POME treatment are still required, even with current advancements. To improve membrane performance, Tang et al.[32] have investigated fouling control techniques such as chemical cleaning and backwashing. Meanwhile, Yunanto et al.[33] focused on the application of ceramic membranes, which offer better fouling resistance compared to polymeric ones but are generally more expensive.

The membrane bioreactors (MBRs) are a major advancement over traditional biological treatment techniques. MBR systems remove suspended particles and organic contaminants more effectively by combining membrane filtration with biological degradation. The primary benefit of MBR systems

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Table 3. Advantages and Disadvantages of the Various POME Treatment Methods

Treatment method	Advantages	Disadvantages	Reference(s)
Biological treatment	Capable of processing an extensive amount of solids	Large amount of land is required to build different ponds	[18,19]
	Inexpensive treatment process	Extended retention periods	
	Reduces greenhouse gas emissions	Complex controlling parameters	
	Generates more biogas		
Electrocoagulation	Fast colloidal settling time	High energy usage causes high operating costs	[20,21]
	The equipment is simple to operate and set up	Specific pH dependence for appropriate production of coagulants	
	Low carbon and environmentally friendly		
Coagulation and flocculation	Easy setup and minimal operational energy requirement	Requires follow-up treatment for the removal of sludge	[1,8],22
	Low floc settling time	Demanding precise dosing with frequent monitoring	
Fenton oxidation	Decomposition products are nontoxic	Production of an intensely acidic atmosphere	23
	The chemical addition process is simple and user-friendly	High acquisition costs for chemicals	
	High COD removal efficiency	Excessive use of oxidizing agents	
		Limited pH range	
Utilizing land or ponding methods	Low maintenance costs, energy economy, reliability of the system, simple design	Ponding method is limited by the long hydraulic retention time (HRT) and the requirement for a large pond size	23
	The optimal approach to handling high-strength wastewater	Fails to attain complete decolorization	
	During the hydrolysis process, complex polymers disintegrate into their constituent monomers	Requires a large area	
		Significant environmental problems due to the production of methane gas	
Physicochemical treatment	90% color removal within 23 min	High chemical usage	[19,24]
	Efficiency in pollutant removal	Sludge generation	
	Quick processing time	Higher operational costs	
	Less space required		
	Flexibility in process control		
Thermochemical treatment	More sustainable due to energy recovery	Potential for incomplete conversion	[22,25]
	Efficient pollutant reduction	Emission of harmful gases	
	Easier and less expensive waste management due to less sludge volume	Operational complexity	
	Produces valuable byproducts, such as biochar and syngas	High capital and operational costs	
	Less space requirement	High energy requirement	
Membrane technology	High removal of nitrogen, suspended solids, turbidity, and color	Require membrane periodic cleaning and maintenance	[26,27]
	Utilizing treated water as boiler feedwater	Effective pretreatment is often required to remove large particles	
	Low initial investment costs, low energy consumption, and minimal space requirements	Membrane fouling leads to reduced production	
		A significant amount of water is required for a continuous process	
Membrane bioreactor	Produces high-quality effluent with low pollutant levels	High initial cost	[28−30]
	Compact design	Membrane fouling	
	Minimizes excess sludge, lowering disposal costs	High energy requirement	
	Effective under varying conditions with less operator intervention	High maintenance cost	

is their capacity to sustain larger biomass concentrations, which leads to a more thorough breakdown of organic matter and a reduction in the formation of sludge.[34] They are renowned for their capacity to generate a high-quality effluent with lower COD and BOD levels. Numerous research works have investigated the use of MBR systems in treating POME. When compared to traditional treatment methods, Abdulsalam et al.[35] showed that MBR systems significantly improved effluent quality in terms of COD, BOD, and TSS elimination. Similar results have been reported by Zhang et al.,[36] indicating the effectiveness of MBR systems in treating POME with low environmental impact. The major advantage of MBR systems is their compact design, which allows for lower footprints compared to conventional treatment facilities. Nevertheless, because of POME's high organic load, MBR systems are vulnerable to fouling, just like other membrane processes. According to Drews,[37] the deposition of organic materials on the membrane surface is the main cause of fouling in MBRs treating POME, requiring frequent cleaning cycles. Thus, further research is required to mitigate fouling, such as the use of advanced cleaning methods and antifouling membrane coatings. Using hybrid MBR systems, which combine membrane filtration with additional treatment methods, such as adsorption, photocatalysis, and advanced oxidation processes (AOPs), is one viable strategy. Research conducted by Yee et al.[38] and Saputera et al.[39] showed that hybrid MBR systems could improve overall treatment efficiency while reducing membrane fouling.

While MBR systems and membrane technology have demonstrated much promise for treating POME, there are still a few important areas that need to be innovated to reach their full potential. Membrane fouling is one of the most important issues and continues to be a major barrier to the broad use of these technologies. The development of

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antifouling membranes that include different nanomaterials has demonstrated potential in lowering fouling in POME treatment systems. Therefore, the investigation of hybrid MBR systems as innovative solutions for dealing with membrane fouling and energy consumption in POME treatment reflects the novelty of this review. These advancements offer significant potential to improve the cost-effectiveness, sustainability, and efficiency of POME treatment processes, addressing the growing demand for eco-friendly technologies in the palm oil industry. In summary, this work lays the foundation for future breakthroughs in POME treatment employing membrane mechanisms by synthesizing current advances and novel concepts.

2. REVIEW METHODOLOGY

By utilizing databases like Scopus, ScienceDirect, Web of Science, and Google Scholar, we obtained updated information by focussing on research published in the past 10 years. Most of the references were taken from recent review papers and journal articles. Information from book chapters, journal articles, and reviews is among the publication categories incorporated into this review, and keywords frequently used in the search for articles include "POME treatment", "Membrane bioreactor", and "membrane fouling". The methodology and results sections of each publication was assessed carefully to learn more about the innovative approaches towards POME treatment. The publications that were assessed were categorized based on the treatment involved; whether it was based upon biological, membrane bioreactor, or membrane processes, as these keywords are commonly used by researchers.

3. TECHNIQUES FOR TREATING PALM OIL MILL EFFLUENT (POME)

In the past 20 years, a variety of alternatives, including chemical, physical, and biological treatments, have been identified, but only a few have gained acceptance in the industries.[40] Recently, there has been a concerted effort to explore cost-effective treatment approaches, prompting the examination of numerous unconventional and budget-friendly methods, including the use of microorganisms.[41] Only the most successful POME treatment methods are selected for more thorough discussions.

3.1. Utilizing Land or Ponding Methods. The utilization of land or ponding methods is widespread in effluent treatment. Its affordability, minimal maintenance costs, energy efficiency, system dependability, and simple design are the reasons behind this decision.[3] Nevertheless, the long HRT and the requirement for a huge pond size constrain antiquated ponding technology. The untreated POME that is removed from the oil-trapping pond is transported to the acidification pond during this procedure, where it is kept for 6 days. The POME is then transferred into a cooling pond and held there for a further 7 days.[42,43] It serves to lower the POME temperature and stabilize the pH level. Through anaerobic decomposition, anaerobic treatment ponds have been recognized as the most effective way to handle high-strength wastewater.[31] Complex polymers, including proteins, carbohydrates, and lipids, are broken down into their individual monomers during the hydrolysis process. Thermotolerant microbes facilitate the conversion of these compounds into sugars, amino acids, and fatty acids.[19] Acetic acid, propionic acid, butyric acid, valeric acid, and small quantities of nonvolatile fatty acids and lactic acid are produced during the fermentation of carbon-containing monomers which takes place during the acidogenesis process.[45] Long-chain volatile fatty acids from acidogenesis are further reduced by acetogenesis to H_2 and CO_2. Afterward, hydrogenotropic methanogens use H_2 and CO_2, while acetoclastic methanogens use acetic acid and CO_2 to produce methane gas, which is the final byproduct of biogas production. Anaerobically treated POME exhibits an alkaline transition following the breakdown of volatile and long-chain fatty acids. This is attributed to the partial decomposition of lignin into phenolic compounds, which gives the POME a blackish-brown color.[3] Four ponding series make up the anaerobic treatment process, and their combined HRT ranges from 54 to 60 days. After that, the anaerobically treated POME is subjected to an extra round of treatment in three sets of aeration ponds equipped with floating aerators. This procedure takes about 20 days, after which the POME is discharged into facultative ponds.[12] These three ponding series are essential to further reduce the amount of organic matter in the wastewater prior to its release into the river system. This is consistent with the 1974 Environmental Quality Act (EQA), which delineates regulations governing the release of treated effluent from crude palm oil processing.[46,47] Sedimentation takes place in the last polishing pond stage. It lasts for around 2 days and helps to separate suspended microorganisms from the aerobically treated POME. The anaerobic ponding method has performed remarkably well in the treatment of POME by effectively reducing the high-level organic properties present in the effluent.[11,42] This treatment system, unfortunately, could not achieve complete decolorization.[3] The open ponding system also necessitates significant land space, concurrently causing notable environmental issues due to the production of methane gas, contributing to the depletion of ozone layer.[41]

3.2. Biological Treatment. Despite the widespread use of the ponding system for treating POME on an industrial scale, the substantial land area requirement (30−45 acres) and prolonged HRT of 100−160 days present economic challenges.[1] As a result, there is an urgent need for the development of cost-effective methods that make use of available materials more efficiently in industrial settings. The difficulties posed by these challenges have sparked research interest in alternative production techniques aimed at partially replacing the outdated open ponding system. Some potential alternatives or improvements to the open ponding system for POME treatment could include:

i. Bioreactors: Implementing bioreactors can provide a controlled environment for the treatment of POME, allowing for more efficient use of space and shorter retention times.[48]

ii. Constructed Wetlands: Natural or artificial wetlands can be designed to treat POME effectively. They are known for their ability to remove pollutants through biological and physical processes.[49]

iii. Anaerobic Digestion: Utilizing anaerobic digestion processes can help in reducing the treatment time and space requirements. This process can also produce biogas as a byproduct, which can be further utilized for energy generation.[43]

iv. Advanced Oxidation Processes (AOPs): AOPs involve the use of chemical, physical, and biological processes to

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break down and remove pollutants from POME. This might reduce the need for extensive land areas.[7]

v. Membrane Bioreactors (MBRs): MBRs integrate membrane filtration and biological treatment, resulting in a more compact system that requires less space compared to open ponding.[50]

vi. Innovative Material Use: Research might focus on finding economical materials used for POME treatment, reducing the cost of the system.[51]

vii. Process Optimization: Improved engineering and process optimization can also contribute to reducing the land area and HRT required for POME treatment.[52]

3.3. Physicochemical Treatment. POME has a complex mixture of organic matter, suspended solids, and oil and grease, making it challenging to treat. Physicochemical treatment methods play a vital role in mitigating the environmental impact of POME and facilitating its safe disposal or reuse.

Physicochemical treatment involves the use of physical and chemical processes to separate, break down, or transform the contaminants in POME. Some of the key physicochemical treatment methods for POME include:

i. Coagulation and Flocculation: This is a highly effective technology for removing suspended solids.[53] Remarkable results were achieved in decolorizing POME with over 90% color removal within 23 min,[54] using a combination of dual coagulants, ferric chloride, and anionic polyacrylamide.[55] Coagulants primarily consist of chemical compounds due to their ease of handling, cost-effectiveness, and excellent removal efficiency for wastewater treatment applications. Coagulants such as alum and ferric chloride are added to POME to neutralize the charge on the suspended particles. This causes them to clump together into larger flocs, which can be easily separated through sedimentation or flotation. In another study, mango pits were used as coagulant, and fly ash as adsorbent.[56] This approach achieved removal rates of 89% for COD and 96% for TSS in just 1 h. Combining it with additional treatment techniques could further enhance the efficacy of POME treatment. However, it is important to note that a notable challenge postflocculation treatment is the accumulation of substantial sludge, posing an additional concern.

ii. Chemical Precipitation: Precipitation is used to remove phosphorus and heavy metals from POME. Chemicals like lime and magnesium oxide are added to form insoluble precipitates that can be separated from the liquid phase.[57]

iii. Dissolved Air Flotation: It is an effective method for removing suspended solids, oil, and grease from POME. Air is dissolved in the wastewater, and as it rises, it carries the contaminants to the surface for removal.[6]

iv. Adsorption: Activated carbon (AC) and other adsorbents can be used to remove organic pollutants from POME by adsorption onto their surfaces. This method is effective in reducing color and odor in POME.[58]

v. Membrane Filtration: Reverse osmosis and ultrafiltration are two membrane technologies that effectively remove dissolved salts, organic debris, and suspended particulates from POME, resulting in high-quality treated water.[59]

vi. Ozonation: Ozone, being a potent oxidizing agent, has the capability to decompose complex organic compounds present in POME. It is particularly effective in reducing the COD of POME.[60]

vii. Electrocoagulation: This method involves passing an electric current through POME, which induces the coagulation of suspended particles. It is an eco-friendly alternative to conventional coagulation methods.[61]

viii. Electrochemical Chemical Treatment: Electrolysis and electrocoagulation techniques have been proven to be highly efficient for the elimination of contaminants from various industrial wastewater streams.[62] Electrocoagulation is regarded as a potent wastewater treatment approach, involving a sequence of processes including coagulation, precipitation, and flotation. With the hydrolysis process, this method uses iron or aluminum anodes to produce iron or aluminum hydroxide flocs. The effectiveness of electrocoagulation for POME treatment has been explored in the context of decolorization during the polishing phase.[63] Notably, the use of an aluminum electrode resulted in nearly 100% color removal in POME decolorization, achieved within a 65-min operation.

ix. Ultrasonic Cavitation: This technology, in conjunction with the utilization of hydrogen peroxide (H_2O_2), has been employed for POME treatment.[50] Cavitation is the phenomenon characterized by the creation, expansion, and subsequent collapse of microbubbles within a particular liquid. There are several types of cavitation, including particle, hydrodynamic, optical, and acoustic cavitation. This technology has been widely used to breakdown textile dyes,[2] degradation of chemical pollutants, and treatment of industrial wastewater.[64]

x. Photocatalytic Reactions: Photocatalytic reactions have been proven to be highly effective in breaking down organic compounds.[16] TiO_2 is the most widely used photocatalyst due to its outstanding performance, high chemical stability, low cost, and low toxicity. Heterogeneous photocatalytic systems using TiO_2 as the photocatalyst have demonstrated excellent performance in degrading organic pollutants, particularly in the case of POME.[65] During a particular study, a significant reduction of 78% in COD was attained, commencing from a starting value of 168 mg/L within a settling pond for POME.[36] Additionally, using 0.83 g/L of a 20% weight Cu/TiO_2 loading resulted in the effective breakdown of organic molecules within a 7-h chemical reaction period.[66] While photocatalytic systems have many benefits, they also have certain drawbacks, such as restricted light penetration during the process and challenges in separating the catalyst. Various modifications have been suggested to overcome these problems, such as the use of a double-cylindrical shell photoreactor,[67] a cylindrical column photoreactor,[68] and the addition of ZSM-5 zeolite support doped with Fe^{3+} and Ni^{2+}.[69]

xi. Neutralization: POME is often highly acidic. Neutralization with lime or other alkaline substances can help raise the pH, making it more amenable to biological treatment and reducing the corrosive nature of the effluent.[70]

3.4. Thermochemical Treatment. Thermochemical treatment methods offer a promising solution to transform this

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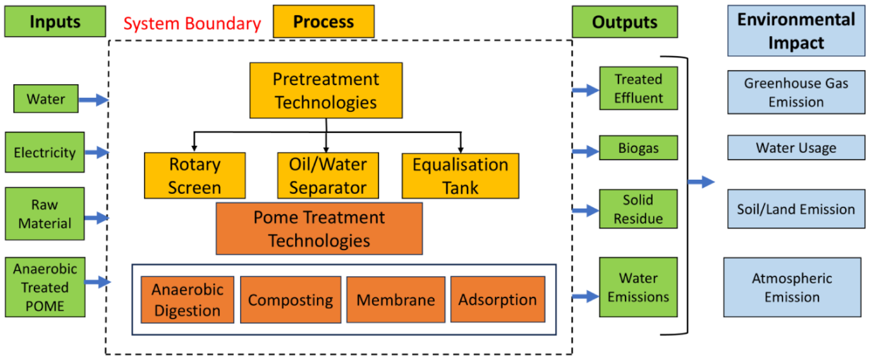

Figure 2. Evaluation of the environmental impact for POME treatment methods utilizing the LCA methodology. Reproduced with permission from Ref. 78. Copyright [2011] [Elsevier].

waste into a valuable resource while mitigating its environmental impact. The traditional method of anaerobic ponding has been the primary means of POME disposal, but it is associated with various environmental issues, including greenhouse gas emissions and odorous compounds.

Some potential thermochemical treatment processes include:

i. Incineration: Incineration is the most effective ways to treat POME thermally. It is a controlled combustion of POME to generate energy and reduce the volume of waste. This method not only minimizes the environmental impact of POME but can also produce useful energy in the form of steam or electricity.[62]

ii. Pyrolysis: Pyrolysis is a process that breaks down the organic matters in POME at high temperatures in the absence of oxygen. This method can produce biochar, bio-oil, and syngas, which have various applications, including soil conditioning and biofuel production.[71]

iii. Gasification: Gasification is another thermochemical treatment option that converts POME into synthetic gas or syngas,[14] which can be used for power generation or as a feedstock for chemical production.[7]

3.5. Torrefaction and Hydrothermal Treatment.

POME is a significant environmental concern in regions where palm oil production is prevalent. It is a byproduct known for its high organic content, which makes it a challenging waste to manage. In recent years, innovative approaches like torrefaction and hydrothermal treatment have emerged as promising solutions to address the issues associated with POME disposal.[72] Torrefaction is a thermal treatment process that involves heating biomass without oxygen to extract moisture and volatile substances. Torrefied biomass, a more stable and energy-dense product, is the end result of this process.[73] The torrefaction of POME can significantly reduce its volume and make it easier to handle. The torrefied POME can be used as a renewable energy source, as it has higher calorific value than raw POME. It can also be utilized in various industrial applications, including cofiring in power plants or as a sustainable biofuel. However, hydrothermal treatment involves the conversion of organic materials under high-temperature and high-pressure conditions in the presence of water. This process can effectively break down the complex organic compounds in POME into simpler, more manageable components.[73] Hydrothermal treatment of POME can produce biogas, bio-oil, and solid biochar. The biogas can be used for electricity generation or as a clean fuel, while the bio-oil can serve as a renewable feedstock for various chemical and biofuel production processes. The solid biochar can be employed as a soil conditioner to increase soil fertility and carbon sequestration.

Both torrefaction and hydrothermal treatment offer several environmental and economic benefits. They help reduce the environmental impact of POME disposal by transforming it into valuable resources. These technologies also provide an opportunity for palm oil producers to diversify their revenue streams by generating income from the sale of torrefied POME, biogas, bio-oil, and biochar. Additionally, the implementation of these technologies aligns with sustainability goals and reduces the carbon footprint of the palm oil industry. Torrefaction and hydrothermal treatment methods face challenges related to technology scalability, cost-effectiveness, and regulatory compliance.[63] Moreover, the acceptance and integration of these technologies within the palm oil industry require careful planning and investment. Torrefaction and heat treatment are set to become essential in the sustainable management of POME because of the growing need for sustainable practices and adherence to circular economy concepts.

4. LIFE CYCLE ASSESSMENT OF POME

A life cycle analysis (LCA) of POME treatment is a comprehensive assessment that examines the environmental, social, and economic impacts of the entire lifecycle of POME, from its generation in palm oil mills to its treatment and disposal.[71,74] This analysis considers the energy, water, and resource inputs associated with POME production, as well as the emissions and waste generated at various stages.[75] By conducting an LCA, we can gain insights into the environmental sustainability of POME management practices and identify opportunities for improvement. Monitoring of variables including BOD, COD, and CO_2 emissions allows for a quantitative assessment of the extent of environmental effects when using the designated POME treatment procedures.[76] Over the past five decades, there has been growing global awareness regarding the importance of safeguarding the environment, with a specific emphasis on preserving water resources. Addressing this concern, the European Commission Council Directive has articulated the goal of wastewater treatment as shielding the environment from the detrimental impacts associated with the release of urban and industrial wastewater.[77] Nevertheless, it is noteworthy that pollutants present in wastewater may, to a certain extent, be translocated to the air, manifested as emissions of

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greenhouse gases (GHGs).[41] Similarly, the disposal of sludge resulting from wastewater treatment can introduce pollutants into the soil, potentially leading to negative impacts on the environment and human health.[78] A simple description of the environmental assessment impact for the LCA methodology is shown in Figure 2.

Utilizing environmental assessment tools offers reliable information on environmental impacts, aiding decision-making for the sustainable operation of a process system. The impact of POME treatment methods can currently be evaluated using a variety of instruments, such as the LCA method, economic and energy analysis (EEA), environmental impact assessment (EIA) approach, and net environmental benefit analysis (NEBA).[79] Within the LCA framework, the environmental impacts of individual treatment processes are evaluated comprehensively, spanning from the extraction of raw materials to the final disposal of materials. This approach, often referred to as ″cradle to grave,″ aims to establish environmentally acceptable technologies for future development.[80]

Researchers and industry experts are very interested in using LCA to assess sustainability and environmental effects during the selection of POME treatment procedures. Aziz and Hanafiah[77] underscored the significance of harnessing biogas through the anaerobic digestion of POME to produce sustainable energy products and implement an effective waste management strategy. Anyaoha and Zhang[81] pointed out that POME plays a substantial role in methane emissions during the palm oil refining process, with efficient reduction of GHG emissions. In contrast to the phases of plantation, palm oil mill, and transportation, Nasution et al.[41] reported that emissions from open ponds involving EFB and POME account for 77% of the total global warming potential (GWP) in a worst-case scenario during the LCA. An LCA focusing on the utilization of EFB in power plants revealed that it contributes to over 60% of the total GWP.[81] Additionally, combining LCA with economic evaluation can result in a thorough analysis at the system level, strengthening the validity of evaluating sustainable operations. However, LCA also has several drawbacks and constraints, particularly in terms of data quality and the selection of methodologies. Therefore, more research is needed to provide direction to aspiring LCA specialists on the appropriate data requirements and impact assessment techniques for technologies that deal with POME treatment.[81] To address these limitations comprehensively, thorough evaluations are necessary, encompassing diverse aspects of LCA applied to POME treatment. This approach aims to pinpoint the most noteworthy environmental concerns, while incorporating considerations of economic impacts.

4.1. Key Steps for LCA Assessment.

LCA encompasses several essential stages to thoroughly assess the environmental impacts of a product or process across its entire life cycle. The essential steps in conducting an LCA for POME treatment typically include:

i. Defining the aim and scope[77]

Clearly define the LCA purpose and its boundaries.

Specify the system being studied and the functional unit of analysis.

ii. Life cycle inventory (LCI)[81]

List all the materials and other inputs and outputs, along with their quantities (emissions, trash, etc.)

Collect data on resource extraction, manufacturing, transportation, use, and end-of-life processes.

iii. Life cycle impact assessment (LCIA)[40]

Evaluate the possible environmental impacts of the identified inputs and outputs.

Utilize impact categories (GHG, water consumption) to quantify and evaluate the effects.

iv. Interpretation[82]

Evaluate and interpret the results of the LCI and impact assessment.

Identify the key contributors to environmental impacts and assess their significance.

v. Improvement assessment[79]

Explore opportunities to reduce environmental impacts.

Consider alternative materials, processes, or technologies that could enhance sustainability.

vi. Reporting[82]

Communicate the findings and results of LCA in a transparent and understandable manner.

Ensure that the report adheres to established LCA standards and guidelines.

vii. Peer review[76]

Subject the LCA study to peer review for validation and to enhance the credibility of the results.

Address any feedback or concerns raised during the review process.

viii. Iterative analysis[77]

Consider conducting multiple iterations of the LCA as new data become available or as changes occur in the system being studied.

Ensure that the LCA remains up to date and relevant over time.

5. POLLUTION ASSESSMENT METHODS FOR POME

Pollution assessment methods include measurements of key parameters, such as COD, BOD, TSS, and various toxic compounds. Additionally, microbial and toxicity analyses are used to assess the potential harm POME may cause to aquatic ecosystems.[19] The goal is to measure and comprehend the ecological hazards and pollution levels linked to POME to support the development of efficient management and treatment plans that will mitigate the effects on the environment.

5.1. Chemical-Based Monitoring.

Chemical-based monitoring refers to a method of environmental assessment and analysis that relies on the use of various chemical compounds and indicators to measure and quantify specific parameters or substances in a given environment.[83] This approach is commonly used in fields such as water quality assessment, air pollution monitoring, and soil analysis. For example, chemical-based monitoring in water quality may involve measuring parameters like pH, dissolved oxygen, heavy metal concentrations, or nutrient levels to assess the health and safety of aquatic ecosystems.[62] These methods play a crucial role in understanding and managing environmental conditions and pollution levels by providing accurate and quantitative data for decision-making and regulatory purposes. This section clarifies the preliminary monitoring and subsequent detection of pollutants in POME with the aim of controlling environmental pollution. The main difficulty involves the sensitivity and selectivity required for the detection of toxins within POME.[84] Consequently, chemical methodologies, with a particular emphasis on analytical chemistry, may play a pivotal role in quantifying the amounts of pollutants. In analytical chemistry, on-site analysis may not be one of the most effective approaches. On the other hand, electroanalytical methods can enable instantaneous analytical evaluations, which are more appropriate for addressing environmental issues.[52]

5.1.1. Chemically Modified Electrodes Composed of Cellulose and Hydroxyapatite. Electroanalytical methods leverage electrochemical sensors to effectively monitor pollutants in POME, offering advantages such as high strength, high detectability with smaller analysis time, and simplicity of process.[8] Nonetheless, the toxic nature of the electrode materials can lead to alterations during analysis. To mitigate this issue, substituting conventional electrodes with plant-based cellulose materials can help counteract toxicity through attachment with different metal ions. Chemical modification increases the adsorption capacity of these plant-based cellulose materials compared to their unmodified equivalents. Apart from cellulose, hydroxyapatite (HAp) has also been employed to enhance ion exchange capacities, which qualifies it as a material for ions associated with heavy metal detection. It also offers an efficient way to remove heavy metals from POME by combining the hydrophilic groups of cellulose with the sorption capabilities of HAp. Therefore, the constructed electrodes using cellulose and HAp demonstrated effectiveness in the analysis of POME. The growing use of plant-based materials in electrodes adheres to green chemistry principles and promotes sustainability, addressing environmental issues in analytical chemistry.[22]

5.2. Monitoring Using Biological Indicators. Analyzing real-time samples within a natural ecosystem has shown that using biological species for monitoring is more effective than using chemical approaches.[85] This approach offers heightened responsiveness, as these biological entities naturally respond to changes in their living environment, serving as vital indicators of ecological impacts stemming from variations in environmental parameters. Numerous biological species, including *Daphnia magna*, *Chlorella* sp, *Scenedesmus* sp, Chromatiaceae, and Alcaligenaceae, have been used in this category to evaluate the type and amount of contaminants present in POME. Additionally, they have the capacity to track the activity and nucleic acid ratios of bacterial cells.[85−87] These techniques have consistently yielded satisfactory results, paving the way for the potential involvement of fish species in a future whole effluent toxicity (WET) test utilizing POME discharge as the testing material.

5.2.1. Whole Effluent Toxicity (WET). WET test is a novel technique developed by the U.S. Environmental Protection Agency (USEPA) in 1991 to assess the presence of hazardous materials in biological species found in wastewater discharge.[57] This method represents a significant advancement in environmental monitoring, providing a comprehensive approach to evaluating the potential ecological impact of effluent discharges on aquatic life. WET is a pivotal concept in environmental management and regulation, primarily focused on assessing the overall ecological impact of wastewater discharges.[83] It involves subjecting the entire effluent, which is the liquid waste produced by industrial, municipal, or agricultural activities, to rigorous toxicity testing with the use of aquatic organisms, such as fish, invertebrates, or algae. The goal of WET testing is to evaluate the cumulative toxicity of the effluent, accounting for the potential harm it may cause to aquatic ecosystems. This holistic approach ensures that not only individual chemical components but also the synergistic effects of the entire mixture are considered, providing a more comprehensive assessment of the effluent's environmental impact. WET testing plays a crucial role in the development of environmental regulations, helping to establish and enforce limits on pollutant discharges to safeguard aquatic environments and their inhabitants. While chemical methods are valuable tools for analyzing POME to detect pollutants, they may not provide a comprehensive assessment. In this context, the WET test emerges as a vital tool, helping to mitigate the ongoing discharge of wastewater and toxic substances, with far-reaching implications for effective environmental management.[16] However, it is important to note that the emphasis on the WET test can sometimes shift the focus away from identifying the root causes of pollution, which remains a critical aspect of the analysis. This dynamic underscores the multifaceted nature of pollution control and the importance of a balanced approach in addressing environmental challenges.[1]

5.2.2. Toxicity Identification Evaluation (TIE). This cutting-edge approach, which was also developed by USEPA, combines chemical and biological evaluations to analyze harmful chemicals in wastewater.[1] This approach involves subjecting materials to a series of controlled physical and chemical transformations, and the presence of toxicants is found by monitoring the responses of test organisms. The TIE test allows for the isolation and identification of the specific toxicants responsible for the adverse effects. A range of freshwater aquatic organisms can be utilized in this process, with commonly employed organisms including fish bioassays, macroinvertebrate survival tests, bacterial assessments, and algal growth assays. This set of aquatic tests is instrumental in detecting short-term toxicity to evaluate water quality. There are three separate phases for the TIE test: Characterizing the sources of toxicants, such as suspended solids (SS) and organic chemicals, is the focus of Phase I. The goal of Phase II is to identify toxins that might prevent organisms such as *Daphnia magna* from growing. Phase III, the last stage, validates the existence of toxicants that show low degrees of toxicity toward *Daphnia magna*.[1] A minimal level of toxicants detected in effluents can pose significant challenges for aquatic ecosystems,[57] making the TIE test a valuable tool for identifying various wastewater sources, such as landfill leachate.[88]

5.2.3. Toxicity Assessment Using Microalgae. The organic and inorganic materials in POME have positive as well as negative effects on the variety of tiny algae called microalgae, which are important for a process called phytoremediation.[27] Aquatic plants can react with various harmful substances and can be used in tests to check their impact. Furthermore, microalgae are excellent indicators of the toxins in POME, helping us to understand how the environment is changing in a short time. To replicate natural environmental conditions, a variety of algae species are used in the microalgae-based toxicity assessment.[89] The high concentration of acetic acid in POME encourages microalgae growth, leading to higher levels of microalgae. On the other hand, other organic compounds like butyric acid, which are present in lower concentrations, have been observed to stimulate microalgae growth at low levels and inhibit it at higher levels. Additionally, the presence of copper, oil, and grease in POME can hinder the growth of microalgae by affecting their ability to undergo division, access nutrients, and receive air. Studies conducted have suggested that POME can influence the response of microbial cells to organic compounds, both in the short and long term, thereby

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either promoting growth or inhibiting it, depending on the specific compounds present.[1]

5.2.4. Biocatalytic Protocol. A biocatalytic protocol presents an innovative approach for assessing pollution in POME. By harnessing the power of biological catalysts, such as enzymes, this method offers a sustainable and efficient means of monitoring pollution levels in POME.[90] Enzymes are highly selective and sensitive, making them ideal for the detection and quantification of specific pollutants in this complex wastewater. This eco-friendly technique not only enhances our understanding of environmental impact but also aligns with the broader objective of sustainable and responsible industrial practices within the palm oil sector.[91]

5.2.5. Assessment Employing Bacterial Indicators. Microbes, particularly bacterial communities, are increasingly utilized to pinpoint contamination stemming from POME. Bacteria are preferred indicators due to their propensity to cease reproduction when exposed to POME-related toxicants. Sharuddin et al.[85] stated the fact that Chromatiaceae and Alcaligenaceae are found downstream rather than upstream indicates the final discharge point of POME. Redundancy analysis adds more evidence that bacterial species are endangered by POME-induced environmental changes. The higher concentrations of BOD, COD, temperature, and TOC in POME have a negative effect on bacterial cells by raising the concentrations of viable and total cells, which cause oxygen depletion. The constituents present in POME pose a threat to the nucleic acid ratios within the bacterial cells. A concentrated presence of these toxicants heightens the risk of nucleic acid transformation.[85−87] Bacteria undergo a transition from low to high nucleic acid (HNA) content, which causes dormant cells to become active and depart from their initial low nucleic acid (LNA) levels.

5.2.6. Innovative Evaluation Utilizing Various Fishes. Assessing pollution in POME is crucial for environmental protection and sustainability. A novel approach to this assessment involves the utilization of various fish species as bioindicators. These fish are highly sensitive to water quality changes and can reflect the health of aquatic ecosystems affected by the POME discharge. By studying the physiological, biochemical, and histological responses of the fish, researchers can gain valuable insights into the extent and impact of pollution. This innovative method not only aids in better understanding the ecological consequences of POME pollution but also contributes to the development of more effective mitigation strategies, promoting responsible palm oil industry practices and safeguarding aquatic environments.[89]

The evaluation of heavy metal presence in effluent can also be accomplished through Fish Embryo Toxicity (FET) test, using fish species such as *Danio rerio*. Heavy metals are known to hinder the development of fish embryos, with tests capable of detecting metals, such as copper, zinc, and iron. Exposing these fish species to POME under controlled laboratory conditions not only addresses the environmental concerns but also sheds light on their ecological traits, including reproductive performance.[92] Nevertheless, it is worth noting that real-time monitoring of native fish species has yet to be explored in research endeavors.

6. MEMBRANE TECHNOLOGY FOR POME TREATMENT

Membrane technology is one of the most promising and effective solutions for POME treatment. Membrane processes are generally more energy-efficient compared to traditional POME treatment methods like ponding systems.[23,55] They require less space and can be operated continuously. Different membrane processes according to the size of their pores are used to treat POME, such as reverse osmosis (RO), microfiltration (MF), ultrafiltration (UF), and nanofiltration (NF).[93−95] Each of these processes offers varying degrees of filtration and separation capabilities. POME contains suspended solids, organic matter, and other contaminants; therefore, effective pretreatment is often required to remove large particles and protect the membranes from fouling.[96] Coagulation and flocculation are common pretreatment methods. In POME, bigger molecules and suspended particles are separated using MF and UF. These are effective at removing particulate matter and some oil components. NF membranes can remove smaller molecules, including color and some dissolved organic compounds. They are useful for improving the clarity of treated POME. Meanwhile, RO is the most advanced membrane technology and can effectively eliminate a variety of pollutants, such as dissolved salts and organic substances. It is often employed for producing high-quality water from POME. Membrane technology helps to reduce the environmental impact of POME by treating it effectively, preventing the discharge of untreated effluent into water bodies, and minimizing soil and water pollution.[96−98] It can lead to cost savings in the long run by reducing the need for land and pond construction and improving the efficiency of the palm oil production process. It offers numerous advantages in terms of environmental sustainability, compliance with regulations, and resource recovery while also addressing some technical challenges associated with POME treatment.

6.1. Types of Membrane. The identification of membrane types and their appropriate applications can be achieved by considering factors, such as pore size and the required membrane pressure.[9] Researchers have categorized membranes into four distinct groups: MF, UF, NF, and RO.[99] The effectiveness in separating contaminants of different sizes and molecular weight cutoff (MWCO) relies on the specific membrane filtration method used, whether it is MF or UF. MF membranes are well-suited for separating contaminants with a size range of 0.08−2 μm and MWCO of 100−500 kDa, and they typically operate at lower transmembrane pressure (TMP) levels ranging from 7 to 100 kPa contrasted with UF membranes.[100] However, UF membranes are commonly used under higher pressures, typically ranging from 70 to 700 kPa, and are effective in separating contaminants with a size range of 0.005−2 μm and MWCO of 20−150 kDa.[101] Multiple studies have confirmed the suitability of UF membranes for separating substances like proteins and carbohydrates,[102] and they have shown excellent performance in separating macronutrients and viruses from wastewater.[6]

NF and RO membranes demand significantly higher pressures to enable the passage of substances through them. Reduced pore sizes lead to elevated hydraulic resistance and greater adhesive forces, necessitating the application of higher pressures, typically ranging from 850 to 7000 kPa, to counteract the opposing drag forces, as noted by Karim et al.[102] NF membranes are well-suited for the removal of pollutants smaller than 0.002 μm. Conversely, desalination and dissolved components are the main applications for RO membranes.[103] RO membranes offer excellent rejection efficiency but come with the drawback of consuming a substantial amount of operational energy and requiring a

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longer filtration time.[67] This limitation is often attributed to the membrane's narrow pore sizes.[46]

In many practical situations, MF and UF serve as preliminary steps before applying RO and NF. It is used to reduce the contaminants in wastewater, which, in turn, mitigates the fouling rate experienced by the membrane. Figure 3 provides a concise overview of the key distinctions among the commonly used membrane types. MF and UF membranes have pores larger than those of NF and RO membranes. As a result, this implies that a smaller TMP is required to enable the passage of chemicals across UF and MF membranes. In contrast, NF and RO membranes exhibit the capability of rejecting a broader range of contaminants and are particularly well-suited for the removal of organic substances. Additionally, NF membranes selectively allow the passage of monovalent ions such as K^{1+}, Li^{1+}, and Na^{1+}, while retaining a significant portion of divalent ions (Ca^{2+}, Mg^{2+}, Fe^{2+}) and trivalent ions (Fe^{3+}). NF membranes exhibit mono and divalent ion rejection performance within the ranges of 35–85% and 65–90%,[104] respectively. On the other hand, RO membranes show a greater rejection efficiency for monovalent ions, usually between 90 and 99%.[105] Generally, RO membranes show a greater rejection efficiency for monovalent ions, usually between 90 and 99%.[27]

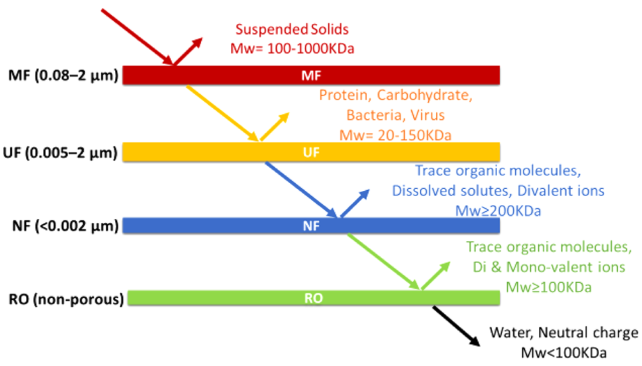

Figure 3. Rejection of contaminants by various types of membranes based on their molecular weight. Reproduced with permission from Ref. 105. Copyright [2025] [Elsevier].

Nonetheless, it is crucial to find a delicate balance between selectivity and productivity performance metrics to avoid compromising either of them. Therefore, it is worth noting that RO and NF membranes, due to their narrower pore sizes, require higher TMP. Moreover, they display reduced productivity and heightened susceptibility to fouling when compared to MF and UF membranes.[106] These limitations stem from the elevated hydraulic resistance created by the narrow pores in the RO and NF membranes. Therefore, it makes sense to utilize MF and UF as feed pretreatment steps before using RO/NF membranes for filtration. This sequential process can substantially reduce the overall issues related to pore blockage and fouling.[107]

6.2. Challenges of Membrane-Based Treatment.

Membrane technology is essential for lowering pollutant levels and purifying and concentrating a wide variety of fluids, including chemical, pharmaceutical, as well as wastewater.[93] However, several elements, such as power cost and consumption, labor, materials, maintenance, scale prevention, membrane lifespan, and substitution, affect operational expenses. The primary barrier hindering the adoption of membrane technology is the sudden decrease in the permeate flow rate due to membrane fouling. This issue poses substantial challenges for technologies like RO, NF, UF, and MF.[95]

Fouling is a critical aspect that must be considered in membrane-related processes. When dealing with high-strength wastewater containing a substantial concentration of contaminants, it often results in significant obstruction or clogging of the membrane.[44] Numerous causes contribute to this blockage, such as the membrane's inherent characteristics, the presence of biomass, and the specific operating conditions. Figure 4 illustrates various factors that influence membrane fouling in the context of membrane separation technology.

Membrane fouling can happen in one of two ways: either the system is operating at constant pressure and the flux decreases or the TMP increases to maintain a specified flux. There are two primary types of fouling: reversible and irreversible. Both backwashable and non-backwashable fouling are categorized as reversible fouling, caused by the development of a cake layer or concentration polarization of components at the rejection surface of the membrane.[108] Physical cleaning techniques, such as hydrodynamic scouring (surface washing) or backwashing,

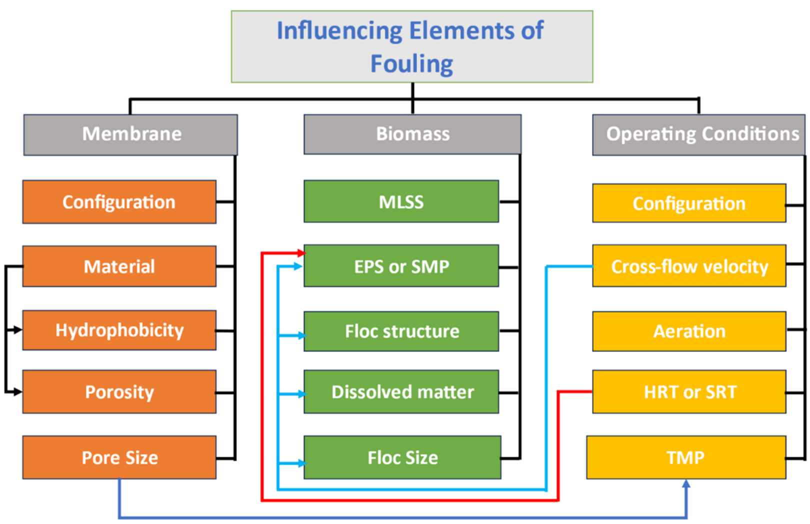

Figure 4. Factors influencing membrane fouling during the membrane separation process.

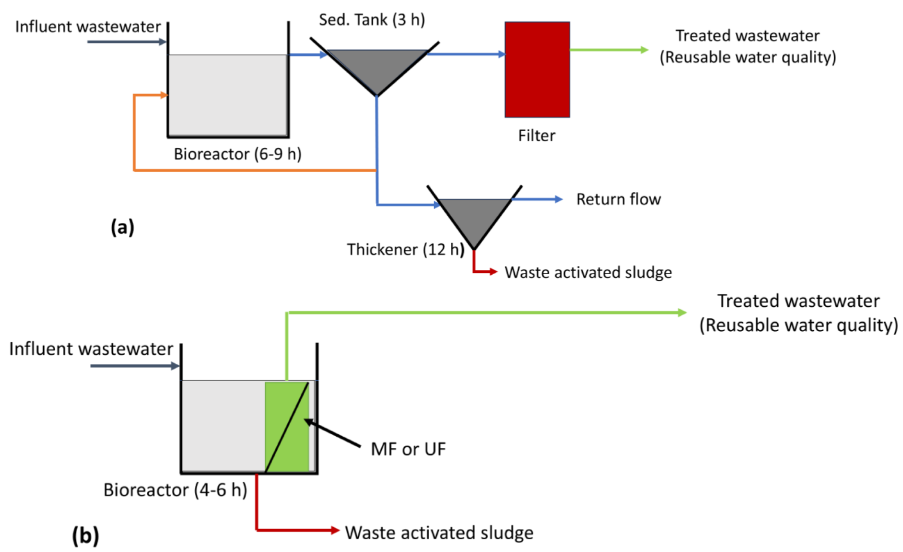

Figure 5. Comparison between CAS and MBR processes: (a) CAS system and (b) MBR system.

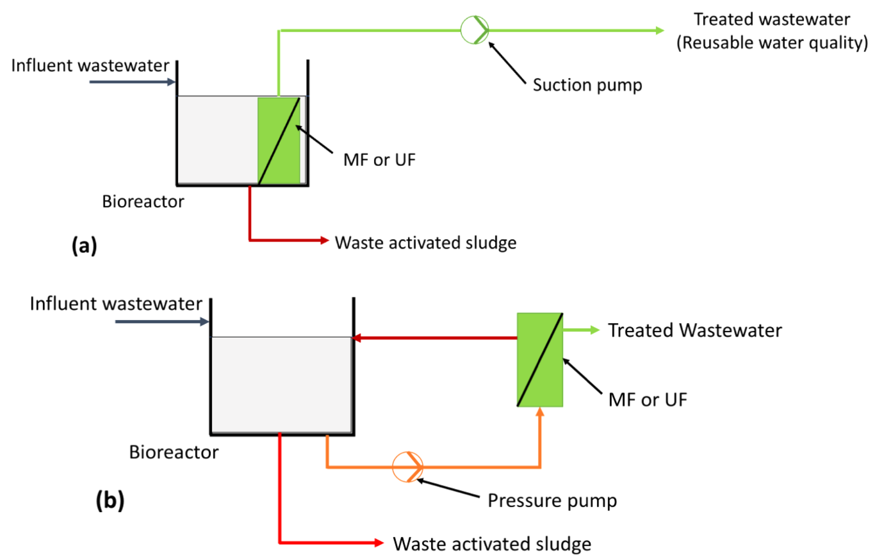

Figure 6. Illustration of MBR configurations: (a) Submerged and (b) Side stream.

can be used to address backwashable reversible fouling. Nevertheless, chemical cleaning is necessary for non-backwashable reversible fouling.[109] Transmembrane flux is permanently reduced because of irreversible fouling, which is caused by chemisorption and pore plugging, and is not reversible by hydrodynamic or chemical means. The membranes require extensive chemical cleaning or replacement, as there is no viable means to recover their performance.

Membrane fouling occurs due to complex physical and chemical interactions among various fouling components in the feed and the membrane surface.[110] Transport of substances can result in the adherence or absorption of particles on the surfaces and pores of the membrane. Previous studies have demonstrated the influence of several factors, including feedwater composition, temperature, mode of operation, hydrodynamic conditions, concentration of the primary components, and water chemistry parameters, on membrane fouling and foulant qualities. The presence of dissolved organic compounds, tiny particles, colloids, less soluble salts, and biological matter in raw water sources can all lead to membrane fouling. Numerous mechanisms contribute to the fouling process; however, six main mechanisms have been identified by recent studies: (i) pore clogging; (ii) cake formation; (iii) concentration polarization; (iv) organic adsorption; (v) inorganic precipitation; and (vi) biological fouling.

7. MEMBRANE BIOREACTOR (MBR): OVERVIEW AND CONFIGURATIONS

There has been a notable emphasis on employing MBR for the treatment of POME, as documented in various studies.[104−108] An MBR is a state-of-the-art wastewater treatment solution that combines membrane filtration with biological treatment processes.[112,114] This technology has found applications in treating different types of industrial wastewater, including POME. Essentially, MBR treatment consists of membrane filtration operations, together with the biodegradation of organic materials found in the mixed liquid. It yields environmentally sustainable end products, including CO_2 and H_2O.[84,116] During the filtration stage, the membrane retains

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microbial flocs and particles larger than the pore diameters, resulting in a filtrate with fewer hazardous chemicals.[19] This ensures that activated sludge can be kept in the reactor by the MBR system. In contrast to conventional treatment approaches employing distinct sludge and sedimentation tanks, the MBR treatment processes have a smaller footprint because aerated membrane filtration serves dual roles as the secondary and tertiary clarifier.[117,118] The MBR system boasts a shorter HRT, can manage higher organic loading rates, and produces a lower amount of sludge.[119] To further enhance the effluent quality, MBR technology is flexible and may be effectively incorporated with various treatment facilities.[25] The advantages of using MBR for POME treatment include: (i) Efficient solid−liquid separation, (ii) Reduced footprint, (iii) High-quality effluent, (iv) Operational flexibility, and (v) Reduced sludge production.

Despite these advantages, challenges, such as pore size, driving force requirements, operational costs, and fouling susceptibility need to be addressed in MBR applications.[22] Continuous research and development aim to improve the efficiency and cost-effectiveness of MBR systems for POME treatment, contributing to sustainable and environmentally friendly practices in the palm oil industry.

7.1. Principles of MBR. MBR wastewater treatment technology integrates membrane separation with a bioreactor. A bioreactor in an MBR system performs a role similar to that of the aerated tank in any activated sludge process, treating wastewater by means of the activity of microorganisms. Porous membranes with 0.05−0.1 μm diameters are utilized in an MBR process to separate treated water and microorganisms, as opposed to using gravity to separate them.[19] The membranes employed in MBR typically have pore diameters small enough to reject large-sized viruses or particles, free-living bacteria, and activated sludge flocs. Hence, MBR yields exceptionally high-quality treated water with minimal or almost undetectable suspended solids. Additionally, MBR processes use membrane filtering instead of gravity sedimentation tanks, which results in a smaller footprint compared to traditional activated sludge systems (CAS).[120] The comparison between MBR and CAS is shown in Figure 5a,b.

7.2. Configurations in MBR. The MBR is commonly used in two configurations: the side-stream and submerged designs,[119] as illustrated in Figure 6a,b, respectively. Direct contact with activated sludge is made possible by the membrane module's immersion within the reactor in the submerged mode. However, because activated sludge recycling is required, the side-stream configuration places the membrane outside the reactor, usually requiring a sufficiently high cross-flow velocity.[84]

7.2.1. Submerged Configuration. By submerging the membrane modules in the wastewater, the submerged configuration allows the membrane module to directly engage with microbial activity. The nature of this interaction is significantly influenced by various factors, including treatment processes, feed characteristics, and membrane properties.[121] Submerged MBRs typically operate at lower flux and pressure, accompanied by ample coarse aeration to satisfy biomass oxygen requirements and reduce the growth of cake layers on the membrane surface.[108] This state of operation can substantially reduce energy consumption and the cost of treatment.[122] However, it is important to note the inherent inflexibility in fouling control with a submerged configuration. In this setup, membrane modules need to be taken out from the reactor for chemical and mechanical cleaning.,[3] In contrast, the membrane module is externally positioned in the side-stream design.

7.2.2. Side-Stream Configuration. Prior to the emergence of the submerged design, this configuration had a long history of industrial usage in wastewater treatment.[108] The membrane modules placed outside make it simple to conduct an operational assessment. However, in order to recycle sludge and maintain the required cross-flow velocity (CFV) to reach a specific permeate flux, an additional pump is needed.[7] The rate at which suspended solids deposit on the membrane is largely dependent on the magnitude of the CFV. In order to decrease the rate of biomass settling on membrane pores and surfaces, the tangential CFV must be high enough.[22] Nonetheless, critical analysis is necessary since the membrane becomes more susceptible to fouling within a particular range of TMP and permeate flux.[108] Research reveals that the membrane is prone to polarization at high TMP and flux, and there is a heightened risk of biofloc disintegration. This tendency often results in increased operational energy requirements.[123]

8. APPLICATION OF MEMBRANE BIOREACTORS (MBR) FOR THE TREATMENT OF POME

Extensive research on the application of MBR for POME treatments has been reported.[39−41] The primary aspects of the MBR treatment processes are membrane filtration and the biodecomposition of organic materials found in the mixed liquor to produce water and carbon dioxide (CO_2). The membrane retains the microbiological flocs and particles larger than the concentrate's pore diameters throughout the filtration process, resulting in a filtrate that contains less harmless chemicals. Additionally, MBR technology is adaptable and can be combined with other wastewater treatment systems to enhance effluent quality. Several MBR treatment processes for the treatment of POME are discussed in the following subsections.

8.1. Aerobic Treatment Methods. The MBR's aerobic method uses membrane technology to treat POME while also simultaneously using microorganisms in an oxygen-rich environment.[25,124] To make it possible for aerobic bacteria to flourish and help break down and stabilize organic pollutants, such as COD and BOD, aeration is essential. These pollutants are ultimately broken down through metabolic activity, leading to the release of CO_2.[125] In the context of MBR, the injected air helps to both provide the shearing forces necessary to remove accumulated foulants on the membrane and to meet the dissolved oxygen (DO) demand of the bacteria.[126] It is essential that the supplied air is sufficient to fulfill both the oxygen demand of bacteria and the necessary shearing forces.[127] It is important to note that bacteria are highly prolific, suggesting that available oxygen can be depleted rapidly. A specified amount of activated sludge is retained in a well-balanced aerobic MBR system to regulate the F/M ratio, thereby maintaining a balance between aeration depletion and replenishment. This approach helps mitigate issues such as bulking or sudden increases in aeration, allowing for optimal biodegradation.[25] Generally, important variables like the active biomass's rates of oxygen consumption and the required scouring air are taken into consideration while designing MBRs.[125]

On the other hand, studies suggest that excessive scouring air may encourage the membrane's fouling process.[34] This happens when the activated sludge lingers; larger bioflocs are formed when smaller organic aggregates join, and the scouring air may cause them to break apart readily. More biofoulants, colloids, and particles of different sizes are produced as a result.[128] When the broken flocs eventually settle on the membrane, holes become blocked and a thick layer of cake forms, which raises the hydraulic resistance.[115] This emphasizes how vital it is to provide ideal aeration to maximize MBR's efficacy and applicability on an industrial scale.

Recently, there has been significant interest in the combination of adsorbents with a membrane in the MBR operating under aeration. The characteristics of an efficient adsorbent usually include a small volume, a large surface area (between 500 and 3000 m^2), and densely packed micropores.[129] The intense microporosity of the surface area plays a critical role in the adsorption process' ability to effectively remove pollutants. Due to these unique characteristics, the use of adsorbents for the decolorization and polishing of POME has garnered considerable attention. In a broad perspective, adsorbents have demonstrated commendable performance in POME decolorization, achieving removal efficiencies between 80% and 99.9%. Furthermore, under optimal process conditions, they contribute to improving membrane fouling conditions.[130,131] Yuniarto et al.[132] conducted experiments using submerged aerobic MBR under aeration conditions, comparing treatments with and without adsorbents. Their results showed that a significant improvement in flux (42 liters per meter per hour, LMH) and COD elimination efficiency (98.5%) was observed at an ideal dosage of 4 g/L of AC. On the other hand, the experiments without activated carbon (AC) performed worse. The adsorbent (AC) significantly degrades contaminants prior to the membrane filtration treatment. Therefore, when employed as a pretreatment, the adsorptive process reduces the amount of impurities in the product. This reduction helps prevent the initiation of pore blockage and minimizes the likelihood of biofilm formation.[133] Regretfully, this procedure frequently produces basic or acidic permeate,[134] which, if released untreated, may be hazardous to the environment.

In a separate study, the use of nanofiltration (NF) membranes with appropriate aeration for the decolorization of POME has shown promise.[68] But a major disadvantage of this treatment approach is the extraordinarily high TMP needed to get the filtrate through the membrane pores.[135] Due to the strong polarization of foulants toward the membrane surface, membrane filtration under high TMP exposes the membrane to quicker fouling.[136] Combining composite nanoparticles with an aerobic membrane bioreactor at a 0.5 wt % loading of nanoparticles is the ideal strategy, taking into account variables like fouling management and flux recovery.[137] Furthermore, a practical strategy for reducing operational costs and downtime in POME treatment using aerobic MBR revolves around effective fouling management. Adsorbents can be used as a pretreatment to achieve this target, and the MBR system can be integrated with a composite nanoparticle−membrane. Before the filtration stage, the adsorbent utilized in the process lowers the concentration of pollutants in the POME at a predetermined pH level. The residual impurities are subsequently removed by the membrane filtration, which improves the effluent's purity. Numerous benefits stem from this integrated approach: uniform permeability flux, color treatment, excellent organic removal efficiency, and decreased fouling susceptibility.[129]

8.2. Anaerobic Treatment Methods. In the absence of oxygen, organic matter breaks down into a series of steps, comprising acetogenesis, hydrolysis, acidogenesis, and methanogenesis processes.[19,138] Carbonated POME is hydrolyzed to produce soluble compounds during the anaerobic process. The compounds are then further broken down into simpler and soluble forms by acidic and methanogenic bacteria. Examples of such compounds include acetic acids, ammonia (NH_3), hydrogen gas, carbon dioxide (CO_2), methane (CH_4), and a small quantity of hydrogen sulfide (H_2S).[12] The pH level and temperature are two important environmental parameters that play significant roles in influencing these processes. In anaerobic treatment, there is a heightened likelihood of membrane fouling at concentrated mixed liquor suspended solids (MLSS). This is explained by the fact that soluble microbial products (SMP) easily stick to the pore walls in the presence of little scouring air, causing obstruction that may eventually lead to the formation of biofilms.[139] However, it has been demonstrated that using intermittent filtration-relaxation may reduce the amount of SMP that accumulates in the pores.[135]

Annop et al.[141] have observed in their research that prolonged filtration-relaxation under anaerobic conditions accelerates the formation of biofilm on the membrane.[140] This is attributed to the substantial transport of foulants toward the membrane surface, leading to elevated polarization.[136] The study showed that the polarization effect leads to a significant rise in fouling rate over a prolonged operating duration.[127] According to another investigation, the SRT has a major impact on how quickly biofilms form. This is due to the biomass's extended polarization and continual interaction on the membrane surface.[142] With an extended SRT, the concentration of SMP is high, leading to easy accumulation on membrane pore walls and the initiation of blockage.[143,144] Moreover, a lengthier retention of activated sludge promotes a shift in the microorganism growth rate to the endogenous phase, potentially reducing the food-to-microorganism ratio. Higher oxygen demand is the outcome[4] and biofouling material, often referred to as extracellular polymeric substances (EPS), is produced quickly.[34,145]

To mitigate the rate of biofouling, an anaerobic MBR and a dissolved air flotation (DAF) system were investigated by Faisal et al.[146] They noticed a significant drop in the rate of membrane fouling, accompanied by a significant improvement in the overall removal efficiency of organic pollutants within the range of 94−99.9%. The improved performance was due to the application of DAF as a pretreatment step before membrane filtration. Additionally, there was a substantial decrease in suspended solids with a removal efficiency of 87.5%, following the pretreatment. Various approaches have been employed to address fouling in the anaerobic MBR systems. These include biological aerated filters (BAF)[147] and the implementation of intermittent and frequent filtration-relaxation processes.[127] These strategies have shown improvements in terms of maintaining stable filtration and enhancing the removal of pollutants, particularly, TSS and COD.

8.3. Hybrid Treatment Methods. To improve treatment efficiency, hybrid procedures systematically combine aerobic, anoxic, and anaerobic processes.[139] It provides an avenue for wastewater that has undergone anaerobic treatment to undergo subsequent aerobic treatment. This permits a series of activities that normally take place at the membrane section, such as biodegradation, dechlorination, nitrification, denitrification,

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and filtration.[27] The physicochemical characteristics of POME, the anaerobic−anoxic−aerobic process sequence, and operational factors like temperature, SRT, HRT, AC consumption, and MLSS concentration all affect how well a hybrid MBR performs.[139] MLSS concentration is recognized as a critical factor influencing MBR performance, particularly the susceptibility of membrane fouling. The effects of fouling of the membrane in hybrid MBR were investigated by Eniola et al.[148] at MLSS concentrations ranging from 5 to 20 g/L. Their results showed that, in comparison to lower concentrations of MLSS, the link between TMP and flux change is more evident at higher concentrations. Hybrid approaches underscore the versatility of MBRs in achieving improved treatment efficiency, water quality, and resource recovery across diverse wastewater scenarios.

8.4. Sonication Treatment Methods. The ultrasonic MBR represents one of the latest techniques adopted in the MBR treatment of POME. Essentially, this approach utilizes sonication to aid in the breakdown of organic matter within POME.[129] The rate of contaminant disintegration is significantly influenced by both the intensity and duration of sonication.[149] When dealing with higher biomass concentrations, it becomes necessary to employ increased intensity and prolonged sonication durations to ensure the collision of particles facilitates the cavitation process and stimulates efficient mass transfer in the mixed liquor.[136] Numerous research works have demonstrated the efficacy of this approach, particularly when it comes to the anaerobic recovery of bioresources from POME. Research on the effects of ultrasonics on anaerobic MBR performance at different sonication durations was done by Shafie et al.[149] Under sonication, they found a startling 105% rise in CH_4 yield and a significant 98.75% decrease in organic contaminants. This notable enhancement in performance was attributed to the application of sonication during the treatment. This suggests that extended sonication enhances the kinetic characteristics of the microbial activity in addition to increasing CH_4 output. Consequently, sonication can be used to promote faster decomposition of organic matter in the activated sludge, providing an easy and sustainable way to stop membrane fouling.[150]

According to Abdurahman et al.[151] adding ultrasonic and sonic−thermal techniques to an MBR system speeds up the degradation process. They noted significant improvement in biomass disintegration and weight loss, averaging 39.05%. The best performance was achieved at a highest temperature of 75 °C. Based on these results, one may reasonably conclude that it is possible to achieve enhanced organic degradation (COD elimination) and a larger biogas yield under ideal sonication intensity and duration.[14]

8.5. MBR Operation under Thermophilic and Mesophilic Conditions. The biodegradation process in MBR is significantly influenced by temperature.[118] The duration and intensity of exposure may determine the extent of the influence.[152] Two conditions are usually considered when investigating the temperature dynamics in MBRs for POME treatment: thermophilic and mesophilic.[111,153] Notably, mixed liquor's viscosity is directly influenced by temperature, and this has a big impact on mass transfer.[89] Consequently, a higher permeate quantity is more evident under thermophilic conditions due to reduced hydraulic resistance.[108] In thermophilic conditions, the activated sludge's increased kinetic energy promotes better bacterial−substrate interaction, which, in turn, increases mass transfer efficiency.[154] It is important to note that thermophilic conditions can result in the production of fatty acids, which could significantly lower the pH of the activated sludge.[121] This acidic pH range has the potential to delay the methanogenesis process, thereby prolonging biodegradation.[113,155] Consequently, the production rate of biogas (CH_4) may experience a significant reduction due to the inactivity of methanogen bacteria at low acidic pH.[155] In addition, flocs readily break down into tiny particles with a wide range of sizes in prolonged thermophilic conditions.[156] These produced particles may lead to pore obstruction, which will ultimately result in the formation of a thick layer of cake on the membrane surface.[111]

The effect of temperature on fouling rates in MBR with microbial elements was studied by Ma et al.[157] They found that the biomass concentration significantly decreased (from 28.1 mg/g-MLSS to 2.2 mg/g-MLSS) when the temperature increased from 8.7 to 19.7 °C. This suggests that when the temperature rises to 19.7 °C, thermophilic bacteria become more active, which causes organic materials to decompose, grow, and attain dominance quickly.[158] However, more particles with a wider range of smaller sizes may be produced because of the increased breakdown rate under thermophilic conditions. Consequently, this may have a major impact on the initiation of fouling and the development of the biofilm matrix.[159]

9. LIMITATIONS OF MBRS IN POME TREATMENT

The most difficult limitation of the MBR treatment process is membrane fouling, which is frequently caused by the buildup of foulants, such as bioflocs, colloids, and particles.[18] As previously mentioned, membrane fouling may result in a significant decline in the system's filtration and operational energy consumption. Controlling fouling is therefore essential, which supports the findings of earlier research on this crucial topic.[129] Researcher efforts have led to some advancements, including improved filtration techniques and methods for controlling membrane fouling. However, the degree of accomplishment is still in its infancy and not feasible for industrial use,[115] especially in oil palm processing. A notable disadvantage of using MBRs is that it shortens the membrane's lifespan and performance, which increases maintenance and operating expenses. Membrane fouling in MBRs is caused by sludge flocs, colloids, solutes, and suspended particles (microorganisms and cell debris). These impurities build up inside the pores and on the membrane's surface, blocking the holes and reducing the membrane's permeability. Because the suspended particles and active microorganisms in MLSS are diverse and difficult to control, membrane fouling is a predicted problem in MBR applications. Reducing membrane fouling in MBRs has been a major focus of extensive research to enhance the technology's wider application.

Membrane fouling in MBRs exhibits various modes, such as pore narrowing, pore clogging, and cake formation. Foulants hinder membrane micropores, leading to pore clogging, a process influenced by both particle size and membrane pore dimensions.[48] Adhesive components in the solution are easily connected to the pores. On the other hand, the creation of a layer known as "biocake" on the membrane is the result of the ongoing buildup of inorganic materials, biopolymers, and bacterial clusters.[160] This biocake layer contributes to increased resistance in membrane filtration. A schematic

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illustration of these complex processes is given by Figure 7, which shows the mechanisms of membrane fouling in MBRs.

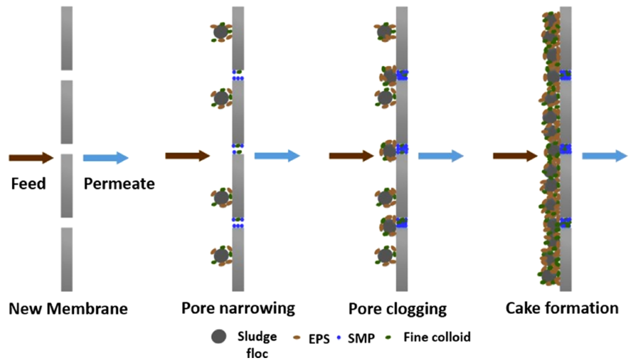

Figure 7. Mechanisms of membrane fouling in MBRs. Adapted with permission from Ref. 160. *Copyright [2018] [Elsevier].*

Practically, membrane fouling affects MBR functioning in two different ways: it decreases permeate flux under constant TMP conditions and increases the TMP under constant permeate flux conditions. A sudden increase in TMP, known as a ″TMP jump,″ when operating at a steady flux is the indication of severe membrane fouling. Three steps are involved in a TMP jump.[161] Stage 1 involves initial ″conditioning″ fouling, which occurs due to the blocking of pores and the adsorption of solutes; Stage 2 involves a gradual increase in TMP due to biofilm formation and additional pore blocking, and the third stage is characterized by an abrupt and fast increase in the TMP rise rate.[162] Stage 3 is considered to be the result of severe membrane fouling, which is caused by consecutive pore closure and variations in local flux that exceed critical values, accelerating particle deposition and causing abrupt changes in the cake layer's structure.[121] Consequently, reducing TMP jumps through changes in sludge properties (MLSS, floc size, EPS concentration, and apparent viscosity) or operational flux reduction is an essential goal of fouling control.[163]

9.1. Classification of Fouling Agents Using MBR for POME Treatment. The formation of membrane layers and pore obstruction are caused by four types of foulants: particulate, inorganic, microbial, and organic.[101] The biological, chemical, and physical characteristics of the foulants serve as the basis for this classification. Moreover, previous studies have shown a strong relationship between fouling rates and suspended-solute material, debris, and microbial/organic product concentrations.[87]

9.1.1. Organic Foulants. Organic foulant is frequently described as a complex microbial product (MP), particularly, when decomposer bacteria break down EPS during their metabolic processes, a biopolymer is created.[59,164] Moreover, it has been documented that the presence of these foulants is also influenced by the organic elements' breakdown in the mixed liquor.[123] EPS constitutes the predominant factor among the constituents that induce membrane fouling during POME treatment, contributing on average 52% of the total foulants.[165] EPS is a significant component of deposited foulants and is crucial for the creation of biofloc aggregates. It also affects the mixed liquor's zeta potential and the bioflocs' adsorption properties. EPS is composed of a variety of organic macromolecules, including humic acid, proteins, lipids, polysaccharides, nucleic acids, and fulvic compounds.[164] The main constituents of EPS foulants include polysaccharides, proteins, and humic materials, each exhibiting a range of hydroaffinities that determine how susceptible they are to fouling.

Furthermore, EPS is commonly divided into soluble EPS (s-EPS) and bound EPS (b-EPS). Specifically, b-EPS is important because it promotes biomass aggregation and stability by releasing a gel-like material that binds bioflocs together and helps them agglomerate. The slow adherence of bioflocs causes a gel to form; this gel can then become a cake layer.[59] Furthermore, in the MBR, b-EPS is crucial for the biological stability of microbial aggregates.[166] This demonstrates that b-EPS affects surface charge, mixed liquor viscosity, and the system's capacity to flocculate sludge in addition to improving microbial aggregation.[158] As a result, it can be claimed that b-EPS is essential for regulating the development and stability of bioflocculation.[123] This suggests that b-EPS can be easily adsorbed onto the surface to form a gel-like substance, irrespective of the type of membrane used.[56] Soluble EPS (s-EPS) is a term that mostly refers to organic components found in activated sludge, including byproducts from bacteria and the decomposition of biomass.[165]

9.1.2. Microbial or Biofoulant. Microbial fouling is commonly referred to as biofouling and is often considered a significant issue following organic fouling.[70] Essentially, biofouling involves the adhesion of bacterial microcolonies onto the membrane surface, engaging in various life activities such as growth, reproduction, and metabolic processes. Initially, a solitary bacterial cell may adhere to the membrane's surface or penetrate its holes. The cell eventually replicates to form a cluster of cells that develops into a biocake, which eventually results in decreased permeability. Fouling is caused by microorganisms and biofoulants, and the byproducts of their metabolism.[167] The two-step process of membrane biofouling starts with early bacterial adhesion to the membrane surface and proceeds with bacterial proliferation.[168] EPS is released by the biofilm's metabolic activity.[169] EPS acts as a bioadhesive substance that promotes the development of the biofilm matrix on the membrane surface.[56] Bacterial cells and EPS are the main parts of the biofilm. Research suggests that more than 70% of the microbial aggregates and complex organic materials in biofilm are made up of EPS.[66] Additionally, reports show that EPS contains polar charge groups, encompassing both aromatic and aliphatic components.[170] Prior studies have verified that EPS is complex, including both hydrophilic and hydrophobic functional groups.[101] This intricacy implies that EPS might be used to promote microbial aggregation formation and sludge stability, which would improve the total biodegradation of POME.[101,123]

9.1.3. Inorganic Foulants. Inorganic fouling, also referred to as ″mineral scale″ to distinguish it from biofouling and organic fouling, originates from nonorganic sources. This category of foulants is typically classified into anions (CO_3^{-2}, SO_4^{-2}, F^-, OH^-) and cations (Al^{3+}, Ca^{2+}, Fe^{3+}, Mg^{2+}).[168,171] Soluble salts such as calcium phosphate, calcium carbonate, barium sulfate, and silicon oxide contribute to the formation of inorganic foulants. The main processes that produce inorganic foulants are oxidation and hydrolysis, which cause the ions to precipitate. Particulate fouling and crystallization are two important mechanisms in the context of inorganic membrane fouling in MBR.[152] Ions precipitate due to the collaborative processes of oxidation and hydrolysis during crystallization. Eventually, the resultant precipitates settle and cover the

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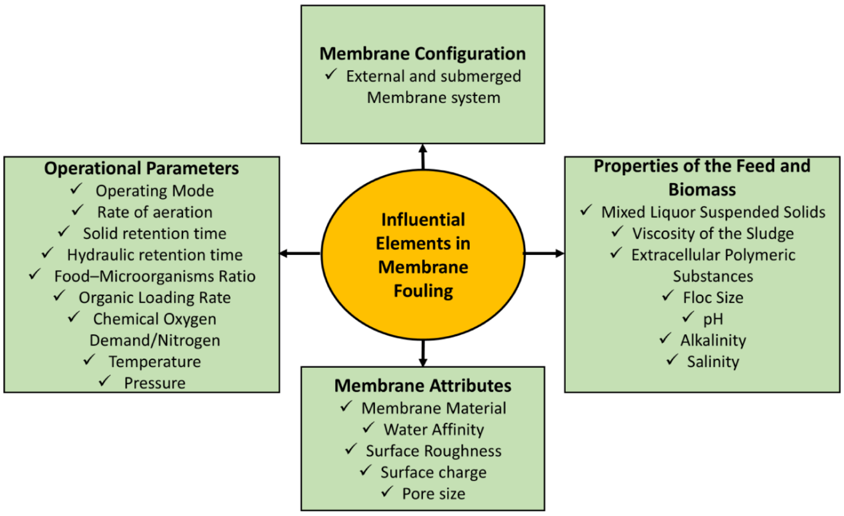

Figure 8. Key factors influencing membrane fouling in MBRs.

Table 4. Influencing Factors on Fouling in Bioreactors (MBR)

Factors	Effects	Reference(s)
	Membrane Attributes	
Materials	Ceramic membranes are less likely to foul due to hydrophilic nature.	159,175
	Polymeric materials, predominantly hydrophobic, are more susceptible to fouling.	
Water affinity	Greater hydrophilicity is associated with a reduced tendency for membrane fouling, whereas increased hydrophobicity is closely linked to a higher tendency for fouling.	159,175
Surface roughness	Surface roughness tends to exacerbate fouling because it creates valleys where colloidal particles in wastewater may accumulate.	176
	Membranes with elevated projections on their surfaces demonstrate enhanced antifouling characteristics and improved permeability recovery after backflushing compared to those with smoother roughness.	
Surface charge	The colloidal particles on the membrane's surface cause it to become negatively charged, which eventually attracts cations (Al^{3+} and Ca^{2+}) and causes inorganic fouling.	172
Pore size	A larger pore size increases the potential of obstruction.	134
	Operating Parameters	
Operating mode	By using the cross-flow filtering mode, cake layers on the membrane surface are less likely to form.	177
Temperature	Reduced temperatures elevate the likelihood of membrane fouling, as bacteria release more extracellular polymeric substances (EPS), and filamentous bacteria numbers increase.	56
	Abrupt temperature fluctuations further intensify fouling rates through the spontaneous release of SMPs.	
Aeration	Elevating aeration rates leads to a decrease in membrane fouling.	28
Solid retention time (SRT)	High SRT diminishes EPS production, thereby reducing fouling.	178
	However, high SRTs can exacerbate membrane fouling because of MLSS buildup and enhanced sludge viscosity.	
Hydraulic retention time (HRT)	Lower HRT is associated with a higher membrane fouling rate.	133
	However, too high HRTs may cause foulants to build up.	
Food-to-microorganism (F/M) ratio	A high F/M ratio raises the membrane fouling rate, which causes the biomass to consume more food and produce more EPS.	65
Organic loading rate (OLR)	Membranes are more prone to fouling with an increase in OLR.	8
Chemical oxygen demand to nitrogen (COD/N)	Higher COD/N ratio diminishes the membrane fouling, enhances the performance, and increases the operating period before membrane cleaning.	134
	A low COD/N ratio causes a lower level of MLSS, reduced SMP production, and decreased levels of carbohydrates, proteins, and humic acids. Consequently, lower membrane fouling.	
	Properties of the Feed and Biomass	
Mixed liquor suspended solids (MLSS)	An elevated rate of membrane fouling is connected to the presence of MLSS.	56
Viscosity of sludge	Higher viscosity levels are linked with an increase in membrane fouling.	121
Extracellular polymeric substances (EPS)	Fouling is caused by high concentrations of EPS, both bound and soluble EPS.	68
Floc size	Membrane fouling is caused by a reduction in floc size.	123
pH	A lower pH causes membrane fouling.	110,179
Salinity	High salinity levels contribute to an increase in membrane fouling by altering biomass characteristics, such as the enhanced release of EPS and SMPs, as well as influencing floc size and zeta potential.	32

membrane surface. Meanwhile, particulate fouling is the process by which colloidal ions are transported from the bulk mixed liquid by convective processes and end up as deposits.[152] Since chemical cleaning usually outperforms physical cleaning in terms of effectiveness, it is the

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recommended technique for eliminating inorganic precipitation from the membrane surface.[172]

9.1.4. Particulate Foulants. Particulate fouling comprises a wide range of particle sizes, which are divided into three categories: colloidal particulates (sizes between 0.001 and 1 μm), supracolloidal particulates (sizes less than 100 μm), and settling particles (sizes greater than 100 μm).[162] However, in terms of fouling mechanisms, they are similar to inorganic foulants.[168] Larger particles have a major role in the creation of a cake layer, whereas particles with a diameter equal to or slightly smaller than the membrane pores are easily able to induce obstruction.[173] Particles are transported for blockage initiation by gravitational influences, inertial lift, convection, or a combination of these processes.[57] Operating parameters, particle sizes, cross-flow velocity, and bulk concentrations in the mixed liquid all influence the effectiveness of transportation. Based on these variables, researchers have divided pore blockage into three categories: standard, complete, and intermediate.[110] Standard pore blockage occurs when particles deposit and are adsorbed onto pore walls, causing the pores to constrict. Intermediate pore blocking entails the partial buildup of foulants, bridging the opening. Complete pore blocking causes the total closure of pores due to deposited particles.[19] Tijing et al.[174] confirmed that particulates with fine diameters frequently cause blockage. Most of the time, fouling of this kind is irreversible. Therefore, compared with larger foulants, tiny colloids or particles may pose more serious fouling difficulties.

9.2. Important Factors Influencing Membrane Fouling. In MBRs, membrane fouling is influenced by several factors, which can be categorized into three groups: the properties of the feed and biomass, operational parameters, and membrane attributes. Figure 8 illustrates the important variables that impact membrane fouling in MBRs.

Table 4 outlines the diverse features influencing fouling and their corresponding outcomes.

10. INNOVATIVE APPROACHES TO REDUCE MEMBRANE FOULING IN MBR SYSTEMS FOR THE TREATMENT OF POME

The wastewater generated during the production of palm oil, known as POME, is extremely hazardous and contains large quantities of oil, suspended particles, and organic debris. POME treatment has become essential, especially regarding growing environmental legislation and sustainability concerns.[152,180] Combining membrane filtration and biological degradation,[181] MBR system is one of the most efficient systems for treating POME.[66,182] Membrane fouling, however, continues to be a major problem that reduces MBR systems' effectiveness, durability, and operating sustainability.[183]

To reduce fouling in MBR systems utilized for POME treatment, emerging research has focused on understanding the fouling mechanisms. Below are some of the most innovative techniques.

10.1. Advanced Membrane Materials. To reduce the attachment of foulants such as organic matter, oil, and suspended particles, researchers are focusing on producing new membrane materials that are more resistant to fouling, such as hydrophilic membranes.[184] The fabrication of membranes with nanomaterials, such as carbon nanotubes, graphene oxide, and zeolitic imidazolate frameworks, is one of the latest advances. These substances increase the hydrophilicity and decrease pore clogging of membrane surfaces, enhancing their suitability for POME treatment.[185]

10.2. Surface Modification. Another possible approach is to modify the surface of current membranes. Techniques to lessen foulant adhesion on the membrane surface have been investigated, including plasma treatment, coating with antifouling polymers, and grafting with hydrophilic agents.[186] A hydration layer that repels organic pollutants can be generated by functionalizing membranes with polymers, such as zwitterionic or amphiphilic, thereby minimizing fouling.

10.3. Membrane Cleaning. To maintain the membrane's effectiveness and extend its lifespan, regular cleaning is necessary. Membrane performance frequently deteriorates over time due to conventional physical and chemical cleaning methods.[187] In response, researchers are exploring less harmful and more environmentally friendly cleaning techniques, such as electrochemical cleaning, which uses electrical charges to destabilize and remove foulants without destroying the membrane structure, and enzymatic cleaning, which employs enzymes to break down foulants.[188]

10.4. Dynamic Filtration. By disrupting foulant layers during their formation, dynamic filtration systems, including rotating disk filtration and vibrating membranes, have demonstrated potential in minimizing membrane fouling.[189] These techniques maintain a strong shear force, which prolongs the membrane life and improves flow by minimizing the buildup of particulates and organic materials on the membrane surface.

10.5. Control of Biofouling. In MBR systems, biofouling is a major problem caused by microbial colonies forming biofilms on the membrane surface, obstructing the flow. Quorum quenching (QQ) agents are a novel approach that limit biofilm development by disrupting the microbial communication.[190] Moreover, antimicrobial coatings and the integration of UV or ozone disinfection units in MBR units could minimize biofouling.[20]

10.6. Hybrid MBR Systems. Another efficient method to reduce fouling is to combine MBR technology with other innovative treatments, such as adsorption or coagulation—flocculation. Before membrane filtration, hybrid systems can pretreat POME to lower the load of substances that cause fouling. Incorporating powdered activated carbon (PAC) into the MBR system can adsorb organic compounds that would otherwise cause fouling, leading to cleaner membranes and more efficient operation.[61]

10.7. Optimization of Operating Conditions. To minimize fouling, it is essential to optimize operational parameters, such transmembrane pressure, sludge retention duration, and aeration intensity. Studies have indicated that establishing a balance between membrane filtration and the biological process by employing intermittent filtration and changing high- and low-flux cycles can greatly minimize fouling in MBR systems treating POME.[189]

11. CONCLUSION

The challenges in the treatment of POME using membrane technology are substantial, yet the potential benefits make it a crucial area of research and application. The review has highlighted the complex composition and high organic content of POME, emphasizing the environmental challenges posed by its discharge. Membrane bioreactor (MBR) technology is a game changer, outperforming many traditional treatment techniques in terms of sustainability and performance while

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showing up to 95% pollutant reduction efficiency. Key innovations include the adaptability of MBRs in handling a variety of operating conditions using anaerobic, aerobic, and hybrid techniques as well as their capacity to significantly reduce pollutants with suitable system design. Despite these developments, membrane fouling is still a major problem because fouling rates often lead to a 10−30% drop in membrane permeability over short operating periods, raising operating costs and decreasing efficiency. This review thoroughly examines the various types of fouling based on their chemical and biological characteristics, including particle foulants, organic foulants, inorganic foulants, and biofoulants. Additionally, it highlights cutting-edge mitigating strategies that have been shown to increase membrane lifespan by 30−50%, such as surface modification and dynamic cleaning processes. The review's unique contributions are found in its integration of various fouling mitigation techniques and its emphasis on the importance of life cycle analysis (LCA) in comprehensively evaluating the environmental effects of POME treatment methods. This study offers a thorough methodology for assessing environmental effects and performance indicators by combining LCA and fouling analysis, a combination that has not received enough attention in previous research. Additionally, new methods for assessing chemical and biological pollutants are covered in the review. These methods provide better risk assessment approaches for POME management. To summarize, this analysis highlights the revolutionary potential of membrane technology for treating POME and offers a way forward for more effective and sustainable methods in the palm oil sector. Future studies should focus on novel approaches to improve fouling resistance and pollutant removal efficiency, with the goal of reducing operating costs by at least 20−30% and extending membrane longevity. By incorporating membrane-based techniques, POME treatment may be redefined and the industry can become more environmentally and economically sustainable.

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