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Review

Treatment of Palm Oil Mill Effluent Using Membrane Bioreactor: Novel Processes and Their Major Drawbacks

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Abstract: Over the years, different types of alternative technologies have been developed and used for palm oil mill effluent (POME) treatment. Specifically, membrane bioreactor (MBR) has been employed to relegate pollutants contained in POME under different operating conditions, and the technology was found to be promising. The major challenge impeding the wider application of this technology is membrane fouling, which usually attracts high operating energy and running cost. In this regard, novel methods of mitigating membrane fouling through the treatment processes have been developed. Therefore, this review article specifically focuses on the recent treatment processes of POME using MBR, with particular emphasis on innovative processes conditions such as aerobic, anaerobic, and hybrid processing as well as their performance in relation to fouling minimization. Furthermore, the effects of sonication and thermophilic and mesophilic conditions on membrane blockage were critically reviewed. The types of foulants and fouling mechanism as influenced by different operating conditions were also analyzed censoriously.

Keywords: POME; membrane bioreactor; treatment processes; hybrid conditions; sonication; foulants and fouling mechanism

1. Introduction

The industrial processing of oil palm involves a series of operations and these normally amounted to the immense generation of waste. The waste generated from palm oil processing have been broadly categorized into palm oil mill sludge (POMS) and liquid waste [1]. The POMS include the empty bunches, trunk, leaves, decanter cake, and mesocarps fibre. POMS constitutes about 70% of the total weight of the processed fresh fruit bunches [2]. While the liquid waste which is also called palm oil mill effluent (POME) is generated during crude palm oil (CPO) clarification, fresh fruit bunch (FFB) sterilization, and hydro-cyclone separation of a mixture of the shell and kernel [3]. Usually, sterilization is the first process, and it involves heating the FFB to a temperature of 140 °C for a specified time, ranging from 75 to 90 min in the autoclave machine to form a coagulated gummy solution called mucilage. At this stage, about 36% palm oil mill effluent (POME) is generated [4]. Afterward, the mucilage is conveyed for stripping, pressing and clarification processes where about 60% of the total POME produced was generated [2,5]. The produced crude palm is further purified and dried using hydro-cyclone separation and vacuum drying process respectively [2], and studies have shown that only 4% of the total POME is generated at this stage [6,7].

Quantitatively, reports have shown that 1 ton of crude palm oil requires 5–7.5 tons of water, over 50% of which ends up as POME [5]. This mammoth rate of POME generation has posed a considerable lethal to the environmental safety which resulted in the significant concern of the researchers over the years [7]. Intensive researches and innovations on POME treatment methods and technologies have been recorded globally. Since 1990, biological methods of treatment have been prominent among the palm oil millers, particularly in Malaysia [8]. This is due to the simplicity, cost-effective, and less requirement of technical know-how [9,10]. Many reports have substantiated the inefficiencies of the method such as prolonged treatment duration, large operational footprint, high tendencies of underground water contamination and emission of unpleasant odour gases such as sulphur dioxide (SO_2) and methane (CH_4) [3,11–13]. In addition, the treated effluent using this method have always failed to meet discharge standard limits of Malaysia, and it repeatedly needs periodic maintenance to discharge the accumulated sludge at the bottom of the pond [14]. Therefore, the inefficiencies of these methods couple with the stringency of the discharge standard necessitate alternative technologies [15].

Recently, membrane technologies have demonstrated potentials for POME treatment [16–21]. The membrane technology provides a higher quality of water and resources recovery, shorter period of treatment processes, requires a smaller area or footprints, and emits less odour [22]. However, this technology has a serious drawback—the susceptibility to fouling [23–26]. Fouling is the resulted challenge from the gradual accumulation of the colloids and particulates on the membrane pores walls and surface [27]. The narrowed pores and clouded membrane surface increased the hydraulic resistance, thereby intensifying the driving pressure required to conduct the liquid through the membrane. This effect usually attracts excessive operational energy and higher running cost which portrayed the treatment method unprofitable for industrial applications [28].

However, several attempts have been made to mitigate the problems of membrane fouling by using different types of approaches such as aeration, anaerobic process, novel combination of anaerobic-aerobic (hybrid) process, as well as the use of adsorbents, alternating filtration-relaxation during operation, and application of sonication and mesophilic and thermophilic conditions [19,29,30]. More recently, there have been quite a number of review articles on MBRs, such as the reports of Rana et al. [31], Coutte et al. [32], and Ohimain and Izah [33]. They have attempted to account for the contemporary application of MBR for wastewater treatment. Essentially, the reports pay emphasis on the types of MBR system, configurations and operating parameters such as temperature, organic loading rate and pH. Conversely, the review articles did not highlight the detailed effect of the treatments approaches on POME in relation to the membrane fouling which had been the major drawback of the technology. Besides, MBR technology is an evolving method for treating POME, as such an up-to-date review with a good comparison of different process conditions on the performance becomes indispensable. In view of this highlight, the major focus of this paper is to provide a holistic review on the recent processes for POME treatment with the main intention of understanding the effect of POME physicochemical properties as well as treatments processes such as aeration, anaerobic, integrated (hybrid) process (aerobic-anaerobic-anoxic), sonication, and temperature (thermophilic and mesophilic conditions). Also, the different types of the associated foulants and fouling mechanism were critically reviewed. The availability of such up-to-date information on novel treatment approaches will furnish a better thoughtfulness to redesign the existing MBR, thus improving its overall performance and reducing the propensity to fouling.

2. Physicochemical Properties and Biodegradability Index of POME

The POME generated during palm oil extraction is dark brownish in colour, viscous in nature, and also contains a high amount of water and suspended solids [34]. Mohammed and Chong [35] reported that the brownish colour is due to the high content of organic matter such as carotene (8 ppm), pectin (3400 ppm), tannin, phenolic (5800 ppm), and lignin (4700 ppm). Also, other reports have established that raw POME contains a considerable amount of carbohydrates, amino acids, free organic acids with pH ranging from 4.0–5.0 along with organic pollutants, fibres, and some inorganic nutrients such as iron, copper, potassium, magnesium, nitrogen, chromium, and cadmium [31,34]. Wang et al. [20] reported that chemical oxygen demand (COD) and biological oxygen demand (BOD) level in POME ranged from 15,000 to 100,000 mg/L and 10,250–43,730 mg/L, respectively. Accordingly, the presence of such a high concentration of organic pollutant (POME) in waterways could make it inhabitable for the aquatic lives [36,37].

POME may be characterized as high strength or low strength wastewater, depending on the number and concentration of contaminants confined. High strength POME holds a large amount of COD, total solids (TS), total suspended solids (TSS), ammonia, and inorganic nutrients as mentioned earlier [38]. This denotes that high strength POME has low biodegradability index (BI) as the constituted organic pollutants are predominantly COD and other toxic substances, such as the nitrogenous compound [39,40]. Therefore, discharging without proper treatment is hazardous to the environment. Concise information on the physicochemical properties and *BI* of various POME reported by different researchers is presented in Table 1.

First, *BI* is the ratio of BOD to COD elements contained in a given POME sample [37,41]. It measures the strength and treatments strain requirements [42,43]. The ratio of biodegradable elements (BOD) to non-biodegradable elements (COD) is a good index to measure the strength of wastewater and it also shows the degree of readiness to decompose biologically. This implies that POME with high BOD/COD ratio is considered readily biodegradable, that is, the organic pollutants can easily deteriorate biologically, and as such, it can be categorized as low strength. On the other hand, low BOD/COD ratio contains toxic substances which are inhibitors to biodegradation, such type of wastewater is measured high strength [43–46]. From Table 1, the BI ratio of the POME considered is in the range 0.36 to 0.617 [46–49]. POME with 0.617 of BI is more readily decomposed because of the high content of biodegradable substances such as BOD, while 0.36 *BI* indicates the prevalence of non-biodegradables.

In a more wider scope, if the *BI* ratio is less than 0.5, there is a need for additional physical and/or chemical treatments [43,50]. Hence, any wastewater with low *BI* ratio may require supplementary treatments to the bioremediation, such as membrane technology, use of adsorbent or dissolved air flotation [39,47]. This clearly shows the important application of *BI* in deciding and development of suitable treatments approach for a particular wastewater. The availability of information on *BI* and physicochemical properties of POME could serve as design information to develop MBR that is less susceptible to technical challenges such as membrane fouling [48].

Table 1. Published information on physicochemical properties and biodegradability index (BI) of palm oil mill effluent (POME).

Parameters												**Reference**
BOD	**COD**	***BI***	**pH**	**T (°C)**	**TS**	**TSS**	**TVS**	**TN**	**Oil/Fat**	**NH_3-N**	**TP**	
27,000	51,000	0.5294	4.2	-	40,000	18,000	34,000	750	6000	-	-	[51]
30,000	50,000	0.6000	4.5	-	16,495	59,350	-	1820	-	-	-	[17]
32,500	64,500	0.5039	4.65	88	-	-	-	41	1950	-	-	[14]
34,950 ± 1450	70,500 ± 917	0.4957	4.72	-	51,880 ± 300	26,547 ± 3043	43,260 ± 140	1620 ± 26	-	-	-	[52]
40,000	65,000	0.6154	4.5	55.5	45,000	20,000	26,300	890	1500	90	950	[53]
25,000	50,000	0.5000	4.7	85	40,500	18,000	34,000	750	4000	-	180	[54]
27,000	75,000	0.3600	4.3	-	100,000	50,000	80,000	-	-	-	-	[46]
30,000 ± 10,391	70,000 ± 7612	0.4286	4.75	-	-	28,900 ± 3065	-	980 ± 50	10,540 ± 1000	-	608 ± 81	[55]
24,500	49,100	0.4989	4.1	-	-	18,000	2600	600	5300	-	-	[48]
45,357	73,498	0.6171	4.5	-	56,279	32,005.5	41,650	760	6670.5	69	-	[49]
-	4500	-	5.6	-	4300	8200	4000	500	-	200	-	[56]
25,000	50,000	0.5000	4.7	85	40,500	18,000	34,000	75,000	-	3500	-	[2]

Units: The units of the parameters are in mg/L except for *BI*, pH and T (°C). Both *BI* and pH are unit-less. TVS is total volatile solid, TN is total nitrogen, NH_3-N is ammonia-nitrogen, and TP is total phosphorous.

3. Membrane Bioreactor (MBR) Application for POME Treatment

In the last few years, intensive studies have been reported on the use of MBR for POME treatments [12,40,56–60]. Principally, the MBR treatment processes constitute membrane-filtration and bio-decomposition of organic substance present in the mixed liquor to form a more innocuous product, such as carbon dioxide (CO_2) and water [61]. During the filtration process, the membrane retains the microbial flocs and any particles whose size is greater than the pores diameters within the concentrate and produce filtrate with more inoffensive substances [62]. This ensures the suitability of the MBR system to keep hold of the activated sludge in the reactor.

The treatment processes of MBR only requires small footprints because the aerated membrane filtration performs double functions as the secondary and tertiary clarifier, unlike the conventional treatment method that involves separate sludge and sedimentation tanks [63]. It has shorter hydraulic retention time, handles a higher organic loading rate, and generates less sludge [64–66]. Furthermore, MBR technology is flexible and can be integrated with another type of wastewater treatment system to improve the quality of effluent [67,68], but in doing this, special considerations must be given to the pore size, as it is very critical factor in the separation process (selectivity), driving force requirements as well as the fouling susceptibility [69]. The commonly used membranes are classified based on their pore sizes and they include; Microfiltration (MF), Ultrafiltration (UF), Nano-filtration (NF), and reverse osmotic (RO) [48].

3.1. Membrane in MBR System

The applications of the membrane for filtration process in MBR entail the physical estrangement of the suspensions into concentrates and permeate at a certain range of pressure [61,70]. This implies that a membrane acts as a discerning barrier based on the molecular weight of the constituted substances. The solutes with a molecular weight smaller than the pore sizes will be able to navigate through the membrane as permeate, while the larger molecules are retained as the concentrates [71]. Usually, membranes are fabricated and devised into modules to make it applicable for wastewater treatment. The membrane fabrication and their implementation into modules have been comprehensively reported in a previous study [72]. More importantly, the reports anonymously confirmed that the membrane pore sizes and stability are determined by the constituting materials used for the fabrication, the concentration, and method of fabrication. However, the targeted applications, treatment conditions, and the characteristic of the feed are also important factors that determine the suitability of membrane pore size for a specific application [22]. In view of this note, it can be deduced that pores sizes play a major role in terms of applications, the kinetic ability of mass transportation through the membrane, and the trans-membrane pressure (TMP) requirement [73–77]. The TMP provides the required force to conduct the substances of smaller sizes through the membrane pores [61,70]. During filtration, the TMP together with the pore sizes and membrane construction materials directly influence the overall selectivity and productivity performance of the membrane during treatment [71]. Therefore, the range of pore sizes, molecular weight cut-off (MWCO), and required transmembrane pressure can be used to define the types of the membrane and their suitable applications [77]. Based on this, researchers have classified membranes into MF, UF, NF, and RO [39,78].

3.1.1. Types of Membrane

The contaminants with size range 0.08–2 µm and 100–500 kDa of MWCO can be separated using an MF membrane [79]. This shows that MF is most suitable for separating suspended particles, and it requires lower TMP (7–100 kPa) compared to a UF membrane. The UF membrane is mostly applied at a pressure 70–700 kPa to separate contaminants with size range 0.005–2 µm and 20–150 kDa of MWCO [80,81]. Studies have shown that a UF membrane is suitable for the separation of protein and carbohydrate [82,83]. It has also demonstrated good performance in the separation of virus and macro-nutrients from wastewater [84]. NF and RO membranes require much higher pressure to permeate through the membrane. The tighter pore sizes elevate the hydraulic resistance and adhesive forces; thus, higher pressure (850–7000 kPa) is required to overcome the drag forces [84]. The NF membrane is suitable for separation of contaminants smaller than 0.002 μm, while RO is usually used for desalination and/or removal of dissolved constituents [85]. RO has a very good rejection efficiency but requires exorbitant operational energy, and it takes much longer to finish filtration [86]. This drawback may be attributed to the narrow pore sizes of the membrane [87,88].

However, in most practical situations, MF and UF are applied for pretreatment prior to the application of NF and RO. This practice is an operational measure to reduce the contaminants load in the wastewater, thus alleviating fouling rate in the membrane. Figure 1 shows the summary of the distinctions between the types of membranes commonly used. From this figure, it is obvious that MF and UF have a larger pore sizes compared to the NF and RO. This suggest that lower TMP is required to drive permeate through the membranes (MF and UF). However, the NF and RO reject wider size range of contaminants, and also they are suitable for the removal of organic molecules and ions in wastewater filtration. More so, NF membranes incline to navigate monovalent ions such as the K^+, Li^+, Na^+, but retained most of the divalent (Ca^{2+}, Mg^{2+}, Fe^{2+}) and trivalent ions (Fe^{3+}). Reports have also shown that the mono- and divalent ions rejection performance of NF is between 35–85% [89–92] and 65–90% [90], respectively. The RO membrane has higher monovalent ions rejection efficiency in the range between 90 to 99% [91]. Overall, the high selectivity performance of the NF and RO have been attributed to the smaller pore sizes of the membranes [93].

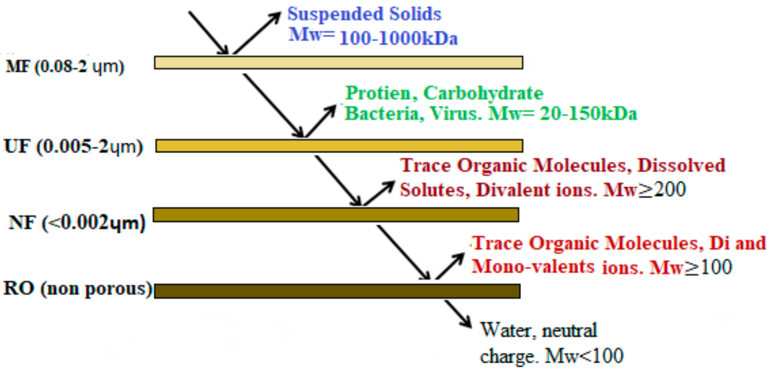


Figure 1. Contaminants rejection by the different type of membrane based on molecular weight.

Nevertheless, it is important to strike a balance between the selectivity and productivity performance indices; this will prevent compromise of any of the indices. In view of this, it is undesirable that RO and NF require higher TMP, and they have also been attributed with lower productivity and more susceptible to fouling compare to MF and UF membranes [47]. All these defects have been featured to the narrow pore sizes in the RO and NF which often elevate hydraulic resistance of the membrane [93]. This suggests that it is logical to apply the RO/NF for filtration after using MF and/or UF to pretreat the feed. Ultimately, this procedure will significantly reduce the overall pore blockage and fouling challenges [47].

Irrespective of the type of membrane, the two methods often used to operate membrane in a typical MBR system include cross-flow and dead-end operations [40]. Cross-flow operation allows parallel passage of concentrated feed (POME) to the surface of the membrane (see Figure 2a). Interestingly, this mode of operation averts further deposition of foulants on the membrane surface, thus constant permeability or flux is maintained for a longer period during filtration operation. The cross flow may be configured inside-out or outside-in [94,95]. However, outside-in is preferred in the cylindrical configuration, more especially when dealing with feed that contain high amount of suspended solid. This is because outside-in cross filtration ensures minimal loss of the tangential velocity and accessibility to the fouled surface of the membrane [95]. Figure 2b depicts dead-end filtration. Unlike in the cross-flow operation, filtration takes place at right-angle to the surface of the membrane [96]. Report has shown that the tendency for membrane surface polarization to occur in dead-end filtration is high due to the persisting interaction with the feed [97]. The particulates and other foulants such colloids, EPS and SMP, easily tack onto the pore walls to initiate fouling. This defect in dead-end filtration justifies the usual batch process recommended, which ultimately obviates frequent fouling, diminishing critical flux and declination in selectivity [97]. This implies that, in a practical MBR application, the important membrane performance and functionality indices under variable processing conditions include the critical flux, TMP, and selectivity factors [40,61].

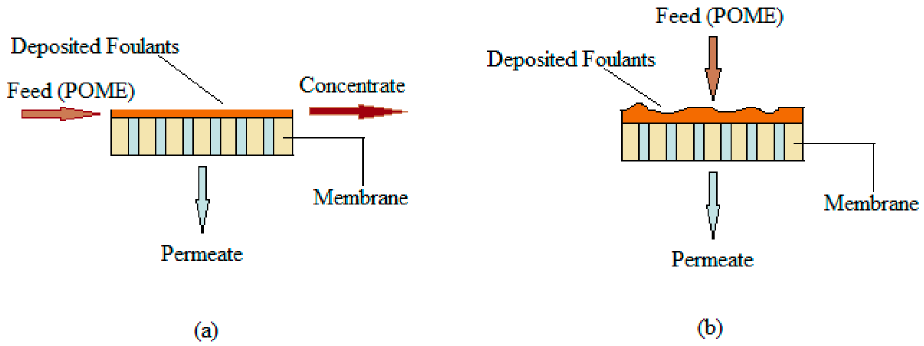


Figure 2. Schematic of membrane operation (**a**) cross-flow and (**b**) dead-end filtration.

3.1.2. Membrane Performance Indices

Critical flux (J_c) is a performance indicator quantifying the productivity of the membrane under operation [98]. The flux rate is relatively steady up to the critical flux rate and it has been said that within this stage of filtration, the fouling rate is negligible [40,99]. However, further increase in flux above the critical range influence fouling, due to the rapid formation of cake layer that usually occur under this condition [100]. At a flux above critical rate, the mass transportation of foulants towards the membrane surface is high and this eventually cause membrane polarization [39,100]. Though there is not one standard procedure to determine the critical flux, this might be due to the complexity and persistence fluctuations in the results of the experiment, which definitely pose difficulty in data analysis and report. One of the most practical and widely used procedures is the flux step technique, and it involves determination of flux, permeability and fouling rate using Equations (1)–(3), respectively [40,99]. Essentially, at a varied flux, the initial TMP_i after the first jump due to the increase in flux at time t_i, and the final pressure (TMP_f) after time t_f of filtration are measured in this technique. According to Le-Clech et al. [100] and Mutamim et al. [40]; the interception of the flux (P_{av}), permeability (K) and fouling rate ($\frac{dP}{dt}$) on the plot gives the critical flux.

$$Fouling\ rate,\ \frac{dP}{dt} = \frac{TMP_f^n - TMP_i^n}{t_f^n - t_i^n} \tag{1}$$

$$Average\ TMP,\ P_{av} = \frac{TMP_f^n + TMP_i^n}{2} \tag{2}$$

$$Membrane\ Permeability,\ K = \frac{J}{P_{av}} \tag{3}$$

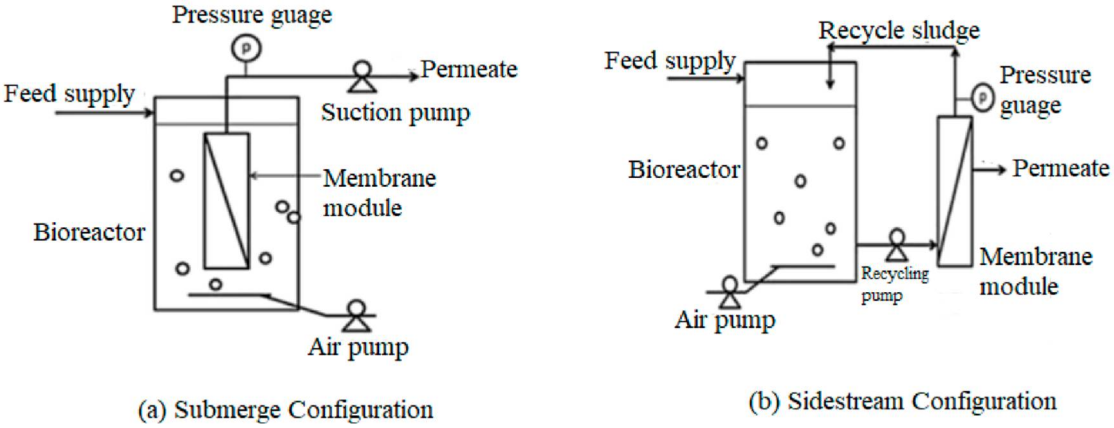
Membrane selectivity ratio (α_i) is another important performance indicator and it determines the capability of any given membrane to distinct wastewater into concentrates and permeates [101] Dutta et al. [102] reported that selectivity ratio of membrane has correlation with capacity to transmit variable constituent to different level. They further reported that pH of the feed, ionic strength, nature of the solute, membrane properties, permeate flux and hydrodynamic conditions are the major factors that determine membrane selectivity. Practically, α_i depend majorly on the molecular weight and they varied proportionately to one another [81]. Also, Sert et al. [103] reported that wastewater with multivalent as well as monovalent co-ions are usually retained as a result of their surface electrical charges, particularly when RO membrane is used for the treatment. However, some of the monovalent could navigate through to balance up the disparity in the charges on the both surface of the membrane [103–105]. Vaughn et al. [106] used Equation (4) to measure α_i, and they considered the specie concentration before membrane filtration as C_{ib} and specie concentration contained in the permeate flux as C_{ip}

$$\alpha_i = \frac{C_{ib} - C_{ip}}{C_{ib}} \tag{4}$$

Besides the types of membrane, the system configurations along with the wastewater characteristics are other important factors that could influence the performance of MBR [106,107].

3.2. MBR Configurations

Irrespective of the process treatments, the MBR is usually utilized in two types of configurations; the submerged (sub-) and side-stream (ss-) configuration [31,76,108–110], as depicted in Figure 3a,b, respectively. Basically, submerge configuration consist of immersion of the membrane module(s) inside the reactor and this allows direct interaction with activated sludge, while the side-stream configuration has its membrane placed outside the reactor and usually, it requires adequate cross flow velocity because of the need for recycling of activated sludge [111,112].



(a) Submerge Configuration
(b) Sidestream Configuration

Figure 3. Schematic of Membrane Bioreactor (MBR) configurations (**a**) submerged, (**b**) side-stream [90].

3.2.1. Submerged Configuration (sub-MBR)

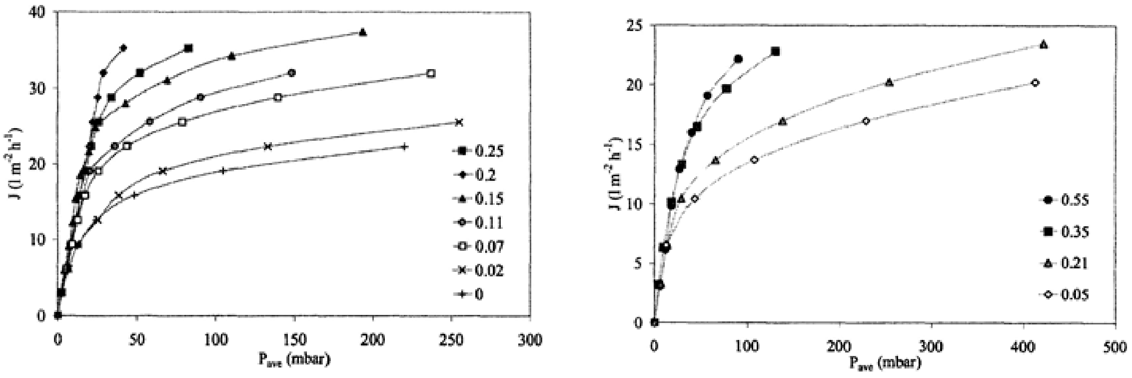
Submerged configuration involves dipping of membrane module(s) into the wastewater. This type of configuration allows direct dealings between the membrane and microbial activities. The interactions of the membrane and the microbes are greatly influenced by several factors such as the treatment processes, characteristics of the feed, and the membrane properties. However, during the filtration process, the microbial flocs and all other substances larger than the pore sizes are retained within the concentrates [63]. The sub-MBR is normally operated at lower flux and pressure with an adequate supply of coarse aeration to meet the oxygen requirements of the biomass and to mitigate the rate of cake layer formation on the membrane surface [74,113]. This condition of operation could considerably reduce the operational energy and the overall cost of MBR treatment application [114,115]. The membrane modules of this type of configuration are often taken out of the reactor when there is a need for chemical and/or mechanical cleaning [116]. This makes the submerge configuration less flexible in terms of fouling control, unlike the side-stream configuration that the membrane module is placed externally.

3.2.2. Side-stream Configuration (ss-MBR)

Side-stream configuration has long found industrial applications for wastewater treatment before the submerged configuration [110]. The external placement of the membrane module ensures easy operational assessment. However, it requires an additional pump for the recycling of the sludge and also to maintain the required cross-flow velocity (CFV) for a specified permeate flux [110,117]. The magnitude of CFV is a key factor that determines the rate of suspended solid deposition on the membrane. The tangential CFV must be high enough to minimize the rate of biomass settling in both membrane pores and surface [117]. In doing this, the resulting effect must be carefully considered. This is because, at a certain range of trans-membrane pressure (TMP) and permeates flux, the membrane became more prone to fouling [114]. Studies have shown that at elevated TMP and flux, the membrane could easily polarize and the tendency for bio-flocs disintegration is high. This habitually resulted in excessive operational energy requirements [118–120]. The findings of the previous studies on MBR configurations are summarized in Table 2.

3.2.3. Effect of MBR Configuration

The effects of configurations on MBR performance under different treatment processes have been reported by several researchers [63,111,116,121,122]. Le-Clech et al. [111] reported the hydraulic performance of submerged and side-stream configuration under selected operational parameters on a hybrid MBR. Essentially, they claimed that fouling susceptibility was less pronounced in the submerged configuration at a varied air flow velocity. As shown in Figure 4a, the steep increase in Flux was observed under gradual upsurge of TMP. However, a sudden increase in the TMP was noticed at a further increase in the critical flux. This indicates that the membrane has started fouling which may degenerate if the filtration continues under this condition [122]. Conversely, the operation of side-stream MBR at varied CFV confirmed that the membrane is more prone to fouling, as represented in Figure 4b. This could be due to the high operational TMP and CFV [123]. Based on this findings, It can be deduced that at equivalent conditions of operations (such as TMP, flux), the submerged configuration sustains less operating energy and is less prone to fouling compare to side-stream configuration [63,111].



(**a**) (**b**)

Figure 4. Flux J vs. average pressure P_{ave} at (**a**) various air flow velocity in sub-MBR configuration (**b**) values cross-flow velocity (m/s) in ss-MBR configuration [111].

In another study, Gander et al. [121] strengthen that the rate of flux declination is more in the side-stream configuration under the same operating pressure. Also, Andrade et al. [120] investigated the effect of membrane configuration and reported that side-stream submerged MBR indicates a significant slow growth of the biomass. This might be due to the shearing process required by the sludge recirculation pump [123]. However, both configurations give excellent COD and colour removal.

As summarized in Table 2, it can be inferred that sub-MBR requires lower TMP (0.1–26 bars) compared to ss-MBR (0.6–46 bars) for effective permeate filtration. Jefferson et al. [122] reported that a steady permeate flux (of 7.9 L/m^{2}h) is obtained at lower TMP (0.1 bar) at a reasonable operational energy (4 kW/m^3) in the sub-MBR. In another similar study, Radjenovic et al. [64] confirmed that operating submerged configured MBR at low TMP (0.2–0.5 bar) ensure constant flux (20–50 L/m^{2}h) and lesser energy demand (0.3–0.6 kW/m^3) compared to the ss-MBR configuration (4.12 kW/m^3). The two studies validate that the observed steady permeate flux in the sub-MBR is an indication that the membrane is less prone to fouling at the operating condition. This report is in a similar trend with other studies [113,124], as summarized in Table 2. On the other hand, Wang et al. [26] reported a flux of 25 L/m^{2}h at a relatively higher TMP of 30 bars with a cross flow velocity of 0.3 m/s. It was observed that the vulnerability to fouling becomes more frequent due to the elevated TMP and permeability flux.

Likewise, some of the previous studies on ss-MBR are contained in Table 2. From this Table, ss-MBR requires higher TMP but gives more permeability flux compare to the sub-MBR. For instance, from the report of Radjenovic et al. [64], about 50 to 100 L/m^{2}h of permeability flux were obtained at TMP of 4 bars. This is also in accordance to the work of Yin et al [125]: they confirmed that as the TMP varied to 300 psi, the permeate flux increased from 39 to 59 L/m^{2}h. However, the major defects attributed to these operating conditions were the excessive energy demand (12 kW/m^3) for aeration and the lofty fouling susceptibility [121]. Equally, studies conducted by Le-Clech et al. [108], Morrow et al. [113], Xiao et al. [126], and Abdurahman et al. [127] reported comparable results, as presented in Table 2.

Table 2. Published data on the effect of configurations on MBR.

MBR-Configuration	Parameters						Reference
	TMP bar	Permeate L/m^{2}h	CFV m/s	Air flow m/s	EDP, kW/m^3	EDA, kW/m^3	
sub-MBR	0.1	7.9	0.5	NA	4	4	[122]
sub-MBR	0.13	8	-	NA	0.14	0.0055	[124]
sub-MBR	26	26	0.25	0.25	-	-	[108]
sub-MBR	0.2–0.5	20–50		0.8696	0.3–0.6	-	[64]
sub-MBR	30	25	0.3	20	-	-	[26]
ss-MBR	4	50–100	-	-	-	4–12	[124]
ss-MBR	46	16	0.35	0.35	-	-	[108]
ss-MBR	2	175	3	-	9.9	2.8	[113]
ss-MBR	0.6	115	3	-	-	-	[126]
ss-MBR	2	10–30	1–1.1	-	-	-	[127]

Notes: EDP = energy demand for permeate, EDA = energy demand for aeration, NA = not available.

Based on these reports, SS-configuration requires higher TMP, though it may give more flux at a time. However, these conditions of operation expose the membrane to rapid fouling [64]. Also, the higher energy demand (0.045–140 kW/m^3) in the ss-MBR configuration is another considerable factor which could make it undesirable for industrial applications. Furthermore, this indicates that sub-MBR configuration is more cost effective in application than ss-MBR configuration due to its sustainable running cost [113,123]. However, the initial cost of procuring submerged configuration may be higher, as a result of its larger surface area and volume [128]. Since, in the most application of membrane, low energy cost, low TMP and minimal fouling rate are encouraged [121]. Therefore, the high operational energy requirement of the side-stream must be vindicated based on the purpose of applications.

3.3. Treatments Process Using MBR

As reported above, the type of MBR configurations could greatly influence the treatment processes along with operational parameters. The effect of different processes conditions such as aerobic, anaerobic, anaerobic-aerobic, or combinations (hybrid), sonication and thermal application on the performance of MBR have been investigated and reported in the previous studies. In the MBR system, aeration may be required not just for biomass degradation but also for fouling control [62,103]. Particularly, at the initial stage of the treatment, deposition of colloids on membrane surface is less at higher aeration intensity but it may increase the fouling rate after a certain period of operation [129]. This pragmatic effect may be attributed to the high shearing force provided by the scouring air which eventually deflocculates the aggregates hence generating more particles (colloids) of smaller sizes. As the aggregates agglomerate to form bigger sizes, the intensity of scouring air becomes critical due to its effect its stability and degeneration. This could lead to the generation of more colloids or particles with smaller sizes, and this plays a key role in initiating pore blockage and gel layer formation [10,130]. This shows that optimal aeration is essential because of its strong correlation with fouling mechanism [131]. In another word, the performance of MBR under limited aeration paved another important investigation which has been considered extensively under anaerobic treatment conditions.

The anaerobic process involves degradation of biomass by microorganisms in oxygen-lacking conditions [32,132,133]. It requires less energy, suitable for treatment of high strength wastewater, efficient removal of organic pollutants, produces little amount of sludge and support resources recovery usually in the form of biogas and bio-fertilizer [134]. This implies an efficient microbial activity is the key indicator of the optimal anaerobic process in an ideal MBR [132,135]. It has been reported that the performance of bacteria in the anaerobic process is influenced by environmental conditions such as temperature, pH and nutrients availability [136]. Particularly, methanogen bacteria is very sensitive to pH and is best performed at a neutral value, while pH value less than 7 is more suitable for both acidogenosis and acetogenesis activities at a temperature ranged between 35–40 °C [137–139]. Anaerobic processes have been applied in MBR with different configurations, both the sidestream and submerged. Anaerobic MBR generally exhibits longer start-up and recovery time, low pathogen and nutrients removal [140,141]. This is because, under the anaerobic process, the bacteria require an extended time to acclimatize to the new environment (MBR) and also to get stabilized in terms of decomposition performance [30,142]. At the stabilized stage, adequate numbers of bacteria are available to perform the anaerobic decomposition more efficiently, especially if the environment is conducive for the bacteria [2,143–145]. Thus, the rate of membrane fouling is considerably relegated at this condition [143].

In an effort to improves the limitations of both aerobic and anaerobic processes, studies have shown that better performance could be achieved by hybridizing the two processes (anaerobic-aerobic) [13,28,37,146]. The combination of an anaerobic-aerobic treatment approach integrates the benefits of both processes and thus ensures adequate bio-decomposition, a higher rate of degradations, more biogas/bio-fertilizer recovery, efficient nitrification and denitrification processes [37,147,148]. Essentially, at acclimatized state, the anaerobic bacteria significantly reduced the pollutants such as COD, BOD and TSS [149], while the aerobic treatment is much suitable for the removal of toxic gases such as ammonia [8,150,151]. In addition, at the aerobic treatment, further deterioration of the remnants COD and BOD is possible to obtain better permeates [38]. Based on these reports, it can be deduced that hybrid treatment processes improve inclusive performance consistency.

Table 3 shows the summary of the recent different processes applied using MBR for POME treatment. Based on Table 3, it is obvious that selections of treatment processes have significant effects on the performance indices, particularly on the rate of membrane fouling and pollutants removal [20,55,152–154].

3.3.1. Aerobic Processes in MBR (*AerMBR*)

Aerobic process in MBR involves the combined application of microorganisms in an oxygen environment and membrane technology for POME treatment [38,155]. Aeration is a required factor for aerobic bacteria to facilitate stabilization of organic pollutants such as COD and BOD, which eventually decomposed through the metabolic activity to release CO_2 [156,157]. In MBR, the injected air is not just to meet up with dissolved oxygen (DO) demand by the bacteria but also to provide shearing forces required to scour the accumulated foulants on the membrane [158]. Technically, the air supplied must be adequate to sustain both bacteria oxygen demand and requisites shearing forces [110,159,160]. It is noteworthy that bacteria are prolific in nature; this indicates that in no-time the available oxygen could be depleted. Thus, this obliges the need for supplementary aeration to meet up with the ever-increasing oxygen demand and imbalance in the F/M ratio [161,162]. In a balanced aerobic MBR system, a certain amount of activated sludge is predetermined to maintained the food –microorganism (F/M) ratio to ensure equilibrium in aeration depletion-replenishment, by so, the problem of bulking or sudden increase in aeration is curtailed and this allows optimal biodegradation [78,163]. Normally, the rates of oxygen consumption by the active biomass as well as the required scouring air are one of the critical factors considered in the design of MBR [63].

In contrast, studies have shown that excess scouring air encourages the fouling mechanism in the membrane [124,164–166]. This is because as the activated sludge prolong, smaller organic aggregates get agglomerated to form bigger bio-flocs which may easily crumble by the scouring air. This resulted in the generation of more bio foulants, colloids and particulates with a range of smaller sizes [114,164,165,167]. Eventually, the disintegrated flocs settle on the membrane to initiate pores blockage as well as the formation of the dense cake layer, thus increase in hydraulic resistance [168,169]. This implies that providing optimal aeration is indispensable to derive the best performance and application of MBR at industrial scale.

Researches have shown that mixed Liquor suspended solid (MLSS) of POME have a strong influence on the characteristics of activated sludge and membrane fouling rate. At an increasing MLSS concentration, the oxygen transfer efficiency (OTE) through the mixed liquor decreases by 400% [10,170,171]. This is because of the high F/M ratio which invariably encourages sludge bulking and an increase in the viscosity [65,172]. The increase in viscosity is not suitable for hydraulic conductivity within mixed liquor because of the excessive drag resistance which may amount to a noticeable decrease in mass and oxygen transfer [98,169]. Therefore, more turbulent aeration with stronger forces may be required to overcome the hydraulic resistance and to ensure proper mixing of the activated sludge [172]. Conversely, reports have shown that depleted oxygen after biological degradation in activated sludge improves the bio-flocculation and sedimentation process of the flocs [173,174]. This is because of the declination in oxygen gradient across the biofilm, and this normally leads to the formation of a layer devoid of oxygen in the interior. Thus, stability in flocs for effective biodegradation is promoted [39].

In an attempt to improve OTE and general performance of MBR, different techniques such as mechanical agitator and adsorbents were combined with the *AerMBR* and evaluated. It has been reported that mechanical agitator improves OTE by promoting the contact between the bacteria and substrate, and this immediate effective biodegradation process [158,175]. Also, Deoawan et al. [109] reported that agitation advances mass transfer within the mixed liquor and thereby stabilizing the environmental conditions for the bacterial activities. In addition, pulverization of the activated sludge ensures even distribution of DO, nutrients, as well as the microorganism [176]. This shows that agitations contribute immensely to the excellent removal of pollutants (99.9%), though most often further operational energy is required and so the additional cost of operation is incurred [105,128,129].

Also, combinations of the adsorbent with MBR operated under aeration have also received substantial attention recently. Mostly, a good adsorbent is characterized by small volume, large surface area (500–3000 m^2) and dense micro-pores [177–179]. The dense micro-porosity of the surface area is the key factor required to perform the removal of pollutants through adsorption process [179]. As a result of these special features, the applications of adsorbents for POME decolourization and polishing have received a lot of attention. On a general overview, adsorbents have recorded a credible performance in decolourization of POME with removal efficiency ranging from 80 to 99.9% and also improves the membrane fouling condition under optimal process conditions [180,181]. Yuniarto et al. [18] operated a submerged *AerMBR* under aeration condition comparing the treatment with and without adsorbents. They reported that at an optimal dosage (4 g/L) of activated carbon (AC) a significant improvement both in flux (42 LMH, LMH = Litre per meter per hour) and COD removal efficiency (98.5%) was observed, while the operation without AC presents lesser performance. Also, a similar report by Guo et al. [180], they applied adsorbent in a submerged MBR operated under aeration condition. The results confirm the improvement in fouling reduction and removal performance of the organic pollutants, as reported previously. This could be due to considerable deterioration of pollutants by the adsorbent (AC) prior to the membrane filtration treatment. Hence, the adsorptive process as pretreatment reduces the number of contaminants present in mixed liquor and so relegate pores blockage initiation and the propensity of biofilm formation [18,47,180,181]. However, AC requires chemical treatment, such as the use of buffer solution to vary the pH level [182] for good adsorption during treatment, and this practices often lead to the formation of acidic or basic permeate [183] which is hazardous to the environment if discharged without further treatments.

In another report, the application of nanofiltration (NF) membrane under suitable aeration for POME decolourization has been proved promising [153]. However, the most serious drawback of this treatment process is the outrageous TMP required to conduct the filtrate through the pores [184]. As substantiated earlier, membrane filtration at high TMP exposed the membrane to more expeditious fouling [185], due to the prohibitive foulants polarization towards the membrane surface [4]. More recently, nanoparticles have been applied to the membrane to improve its antifouling properties and net energy consumption [152,153]. Ultimately, nanoparticles such as zinc iron oxide ($ZnFeO_4$) and Titanium dioxide (TiO_2) checks the fouling process by releasing hydroxyl and antimicrobial radicals on the interface between the activated sludge and membrane. The hydroxyl radicals adhered to the surface to improve the hydrophilic properties of the membrane. This, in turn, diminishes the hydraulic resistance and fouling susceptibility [152,153]. In addition, the antimicrobial radicals inhibit the organic foulants metabolic activities, thus, preventing initiation of fouling.

Tan et al. [152] prepared a composite UF membrane (PVDF) with $ZnFeO_4$ nanoparticle using blending additive technique. The study aimed at improving decolourization performance and fouling properties of the membrane under the aeration condition. They reported 70% colour removal and 40.14 LM under aeration condition. In addition, 0.5 wt % of nanoparticles ($ZnFeO_4$) loading significantly improves colour removal and permeability. At this loading (0.5 wt %), the membrane surface negativity is optimal and readily releases zinc ion which actively hampers the metabolic activities of the bio-foulants as well as colour removal. However, the major weakness at 0.5 wt % loading was the instability of the nanoparticle after a number of filtration cycles. This leads to the collapsing of the nanoparticles and eventually exposes the membrane to rapid fouling. From a similar study reported by Subramaniam et al. [21], a titanium oxide (TiO_2) was used as nanoparticle to produce composite UF membrane-titanium nano-tube (TNT). The target of the study was to decolourize POME under photo-catalytic conditions. The best colour removal of 67.3% efficiency was obtained at 0.5 wt % TNT loading. Principally, TNT nano-tube works similarly as $ZnFeO_4$, the released ions not only act like denaturant with strong efficacy against bio-foulants but also create hydration interface between the membrane and activated sludge. This prevents foulants accumulation and also improves the hydrophilic property of the membrane [186,187]. In contrast, TNT is expensive and it requires the presence of ultraviolet radiation for good performance [188].

An attempt on the use of microbial fuel cell (MFC), and *AerMBR* to remove colour from POME under alternate aeration and anoxic conditions have been reported [189]. In this study, they concluded that decolourization was only significant at the anoxic condition and that MFC only favours the formation of biofilm which assists organic pollutants deterioration. This suggests that MFC used in this experiment can only decolourize POME under anoxic conditions and also the rapid deterioration of the pollutants was as a result of the dense microbes population contained in the activated sludge [190].

Collectively, the summary of the *AerMBR* treatments processes is presented in Table 3. *AerMBR* could provide high-quality POME treatment with 98.9% COD removal and 95.2% colour deterioration at a shorter hydraulic retention time [2,155]. Based on these indices, the combined use of adsorbent (AC) and *AerMBR* is more applicable. However, considering other factors such as fouling control and flux recovery, the combination of composite nanoparticle and *AerMBR* is most appropriate at 0.5 wt % loading of nanoparticle [21,154]. More so, the practical approach to reducing operational cost and downtime using *AerMBR* for POME treatment can be based on efficient fouling management. This could be archived by integration of adsorbents as pretreatment and composite nanoparticle-membrane into the MBR system. Primarily, the adsorbent component reduces the concentration of the contaminants in POME at a controlled pH level prior to the filtration process. The membrane filtration further purifies the effluent by removing all the remnants of the contaminants. This combination could provide several advantages such as high efficiency of organic removal, colour treatments, steady permeability flux and less fouling susceptibility [10,56,183,187].

3.3.2. Anaerobic Processes in MBR (*AnMBR*)

Decomposition of organic substances in the absence of oxygen involves a series of processes such as hydrolysis, acidogenesis, acetogenesis and methanogenesis processes [190]. In the anaerobic process, the carbonated POME are degraded to soluble derivatives by hydrolysis process, then acidogenic and methanogens bacteria further decomposed it into a simpler and soluble compound in the form of acetic acids, ammonia (NH_3), hydrogen gas, carbon dioxide (CO_2), methane (CH_4) and some quantity of hydrogen sulphide (H_2S) [190]. These processes are significantly influenced by the environmental factors, particularly, pH level and temperature [191,192]. It has been known that at neutral pH value the methanogens decomposition activity improves [65], which is normally indicated by the significant increase in methane generation at a suitable temperature between 35–40 °C [193,194], while pH values less than 7 are more suitable for the hydrolysis, acidogenesis and acetogenesis [195,196]. This implies that optimal control of the environmental conditions improves anaerobic activities.

Recently, Abdurahman et al. [196] and Abdurahman and Azhari [197] both gave similar reports that higher biomass concentration (MLSS and MLVSS) yield more methane (CH_4) ranging between 0.58–0.87 L/g COD-d with COD removal efficiency between 94.8–98.4% using *AnMBR* system. The improvement in CH_4 production and efficient removal of COD were attributed to the adequate balancing of F/M ratio at the ranged biomass (MLSS and MLVSS) concentration and this condition accelerates the anaerobic biodegradation of the organic pollutants [6,139,153]. Therefore, biomass (MLSS) concentrations have strong influences on kinetic properties of the activated sludge and also determine the magnitude of its growth yield coefficient (GYC) [191]. Mostly, the rapid increase in GYC is as a result of the availability of favourable conditions such as pH, temperature and nutrients (as mentioned earlier) [165]. These conditions ensure optimal biodegradation and prolific multiplication of the bacteria required for the anaerobic treatment. In contrast, the tendency of membrane fouling at concentrated MLSS is high during anaerobic treatment. This is because, at a limited scouring air, the SMP easily adhered onto the pore walls to initiate blockage which may eventually develop into biofilm [198–200]. However, the intermittent filtration-relaxation could minimize the SMP deposition in the pores [171].

According to Annop et al. [201], prolonged filtration-relaxation under anaerobic condition expedites the formation of biofilm on the membrane. This is because of the massive transportations of foulants towards the membrane surface, and this often resulted in high polarization [174,202,203]. This is in line with the report of the study conducted at high flux (35 $Lm^{-2}h^{-1}$) with a specified aeration demand (0.25 Nm^3/m^2h) by [117]. According to this study, in a longer-term operation, a significant increase in fouling rate was observed due to the polarization effect [117]. In a different study, solid retention time (SRT) pose a strong influence on the rate of biofilm formation as a result of the protracted polarization of biomass and persisting interaction on the membrane surface [204]. At a longer SRT, the soluble microbial product (SMP) concentration is high which easily got accumulated onto membrane pore walls to initiate blockage [98,203–205]. In addition, longer retention of activated sludge encourages shifting of microorganism growing rate to endogenous phase and this may lower the F/M ratio. This resulted in a higher oxygen demand [63] and the rapid production of bio-fouling material commonly known as extracellular polymeric substances (EPS) [98,130,141].

Faisal et al. [61] attempted reducing the rate of bio-fouling by incorporating a dissolved air flotation (DAF) system with *AnMBR*. They observed a reduction in the membrane fouling rate and the overall organic pollutants removal efficiency improves significantly in the range between 94–99.9%. They attributed the improvement in the performance to the DAF applied for pretreatment prior to the membrane filtration. In addition, considerable deterioration of suspended solids (87.5% removal) was noticed after the pretreatment. This inferred that fewer foulants are contained within the mixed liquor after the DAF pre-treatment, hence enhancement in the filtration rate and minimal vulnerability to fouling were achieved [15,61].

In recap, *AnMBR* processes for POME treatment were summarized in Table 3. From Table 3, the results pointed out that the *AnMBR* treatment system is suitable for high strength POME with MLSS concentration ranging from 11,760 to 20,800 mg/L. Also, it remains the most appropriate treatment method for COD removal (with an efficiency ranging from 98 to 99.9%) and resources recovery/utilization, such as biogas and bio-fertilizer [39]. However, the membrane is more susceptible to fouling under an anaerobic condition at high MLSS concentration. This is because as the activated sludge aged (SRT), the viscosity increases and the foulants such as particulates, EPS and SMP easily get polarized on the membrane to form cake layer [206,207]. However, some of the noticeable approach used to mitigate fouling in *AnMBR* system includes BAF [62] and intermittent frequent filtration-relaxation [201] which have presented some improvement in terms of steady filtration and pollutants removals, particularly the COD and TSS.

3.3.3. Hybrid (Integrated) Processes in MBR (*HybMBR*)

Hybrid processes encompass a systematic combination of the anaerobic, anoxic and aerobic process to improve treatment efficiencies [46,54,160]. Hybrid MBR (*HybMBR*) provide a platform for anaerobically treated wastewater to undergo aerobic treatment, and this gives the possibility for chains processes such as biodegradation, de-chlorination, nitrification, denitrification as well as filtration process which usually takes place at the membrane section [38].

The structural configurations of *HybMBR* have to be compatible to ensure sequential and efficient accomplishment of the several treatment processes, as mentioned above. Also, a report has shown that the integrated processes in single footprint guaranteed *HybMBR* suitability for treating high strength POME with a reduced modus, and this could lower the cost and treatment time [55,56,139,207–210]. Efficient performance of *HybMBR* could be influenced by the physicochemical properties of POME, sequential arrangement of the processes (anaerobic-anoxic-aerobic) and operational parameters such as MLSS concentration, activated carbon, temperature, solid retention time (SRT) and hydraulic retention time (HRT) [38]. The application of *HybMBR* for POME treatments under variable operating factors is summarized in Table 3.

MLSS concentration is considered one of the most important factors that influence the MBR performance, particularly, the membrane fouling susceptibility. Damayanti et al. [207] investigated the effect of membrane fouling in *HybMBR* under varied MLSS concentration from 5 to 20 g/L [130]. They observed that the relationship between the TMP and flux change is steeper at higher MLSS concentration compare to lower concentration, as depicted in Figure 5. From Figure 5, at 5 g/L MLSS concentration; rise in TMP under the progressive increase in flux is insignificant until at a critical point where a sharp increase in TMP was observed. Similarly, Ahmad et al. [208] reported the effect of varied MLSS concentration (4–8 g/L) on the performance of hybrid MBR. At the initial stage of the study, the fouling rate was constant with 0.08 gradients, but a sudden decrease in filtration volume was observed at further increase in flux beyond the critical value (16 LMH). Collectively, it can be construed that operating MBR at higher flux, influence more foulants (SMP, EPS and colloids) generation and transportation towards the membrane surface [209]. Consequently, the generated foulants could easily commence fouling mechanism through pore blockage and gel formation [48]. Damayanti et al. [56]

investigated the effect of several bio-absorbents (activated carbon, zeolite and moringa oelfera) under varied MLSS concentration. They deduced that increasing biomass (MLSS) to higher concentration could cause a reduction in permeability by 400% [207]. Furthermore, they reported that, at the optimal dosage, the powdered activated carbon (PAC) present the best treatment performance, with 85% contaminants removal efficiency during the pretreatment [57]. The improvement in fouling problem is as a result of the adsorbents pretreatment which substantially reduced the foulants contents by adsorption process [210]. A modified *HybMBR* with a sedimentation compartment has been reported to perform remarkably in term of fouling control as well as removal of contaminants such as total phosphorus and nitrogen with average 94, 87, and 85% efficiency, respectively [211]. They further reported that as the temperature varied from 27 °C to 13 °C, the swift increase in TMP was observed when the flux is maintained at a constant rate. This could be due to the temperature effect on the viscosity of the activated sludge. As the temperature decreases, the shearing force within the sludge increases due to the higher hydraulic resistance and viscosity [212]. Similarly, the mixed liquor became denser and sticky at a lower temperature, and thus has an antagonistic effect on the entire oxygen transfer efficiency [213]. Whereas, at a higher temperature the foulants gain more kinetic energy with relatively low hydraulic resistance due to the considerable decrease in viscosity. More so, the accumulated foulants can easily get sheared or dislodged by lighter scoring air at the higher temperature (27 °C). This implies that operating the *HybMBR* in such condition could favour the overall performance in terms of TMP, critical flux, and fouling propensity [110,213].

The recap of *HybMBR* performance under different operational conditions (such as MLSS, organic loading rate {OLR}, AC and temperature) were presented in Table 3. It is obvious that increasing MLSS and OLR concentration could decrease the flux filtration rate drastically [207]. This effect has been attributed to the high density of foulants generated from concentrated biomass which easily initiate pores blockage in the membrane. Based on this, it can be deduced that biomass concentrations (MLSS) have a strong correlation with the number of foulants generated during biodegradation [214]. The biodegraded biomass contains extracellular polymeric substance (EPS) and carbohydrate, which are the major biofilm and organic foulants [58,65].

In terms of performance indices, *HybMBR* is suitable for POME with high concentration MLSS (5000 to 20,000 mg/L) [207] and capable of deteriorating COD by 94 to 97% efficiency. Also, it has a high possibility of flux recovery of the fouled membrane with 91 to 95.3% [15,47]. Therefore, the combined adsorbent and the *HybMBR* system could easily achieve the aforementioned performance indices. Studies have shown that temperature has a strong influence on kinetic properties and biological activities of the biomass in *HybMBR* [130,215]. At lower temperature, the rate of particles and colloids gyration is low, thereby higher shearing force is required to scour the accumulated foulants on the membrane [70,216] and vice versa. Consequently, this could drastically increase the operating energy, and running cost [121,217].

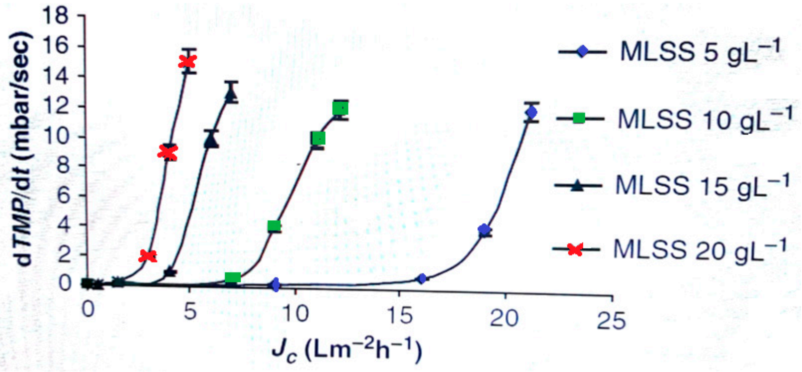


Figure 5. Influence of MLSS concentration on TMP and J of an MBR system during operation [207].

3.3.4. Sonication Processes in MBR (*SonMBR*)

This is one of the most recent concepts employed in the MBR treatment process for POME. Mainly, ultrasonic MBR (*SonMBR*) involves the use of sonication to facilitate the decomposition of organic matter in POME [218]. The intensity and duration of sonication have a strong effect on the rate of contaminants disintegration [219,220]. At higher biomass concentration, higher intensity and longer sonication duration are required to provide sufficient particles collision, cavitation process, as well as effective mass transfer within the mixed liquor [194,195].

Several types of research have proved this technology efficient, particularly, in the aspect of bio-resources recovery from POME under anaerobic conditions. Shafie et al. [218] investigated the effect of ultrasonic on the performance of an anaerobic MBR at varied sonication duration. They reported a 105% increase in the CH_4 yield under sonication. In addition, about 98.75% deterioration in the organic pollutants was also observed. They attributed the significant improvement in the performance to the sonication applied during the treatment. This denotes that the prolong sonication not only improves CH_4 yield but also advance the kinetic properties of the microbial activities. Thus, faster degradation of organic matter in the activated sludge could be enhanced through sonication, and this presents another simple and clean method of preventing membrane fouling [219].

Furthermore, a combination of microwave and sonication present a novel means of disintegrating organic matter in activated sludge. Lately, studies have shown that increasing the ratio of soluble chemical oxygen demand (SCOD) to total chemical oxygen demand (TCOD) (SCOD/TCOD) and *BI* is best achieved through a combination of microwave and sonication [219,220]. From their results, a higher yield of CH_4 (44 mL) at a short period (10 min) of sonication was obtained. They further confirm that the net operational energy was relatively low, though it has a strong correlation with MLSS concentration, sonication intensity/frequency, sonication duration, the volume of the POME treated at a time, as well as the targeted treatment qualities [98,221]. The study reported by Abdurrahman and Azhari [197] validated the above statement. According to the report, POME with a high concentration of MLSS (13,800–22,600 mg/L) requires prolonged sonication at a relatively high intensity. Under sonication condition, shorter SRT and longer HRT (8.6 days) are the most favourable operating parameters for the maximum yield of CH_4. This shows that SRT has no significant effect on the degradation of biomass under ideal sonication conditions after stabilization [222]. They concluded that POME with higher biomass concentration (MLSS) produces more biogas with an average increment of 44% compared to the lower concentration [197].

Equally, Abdurahman et al. [222] reported that a combination of ultrasonic and sonic-thermal in MBR system accelerates the degradation process. Integrated ultrasonic and sonic-thermal was operated at a 37 Hz frequency with a varied temperature of 45, 55, 65, and 75 °C. They observed an increase in biomass disintegration and weight reduction with an average of 39.05%, and the best performance was obtained at the highest temperature of 75 °C. Similarly, Leano et al. [223] reported that ultrasonic pretreatment accelerates bio-hydrogen production from POME. The sonication duration and ultrasonic dose (0.91, 143, and 195 J/mL) were varied to different levels. The best performance was obtained at the highest ultrasound dose (195 J/mL) with 0.7 mmol H_2/g COD of bio-H_2 yield and 65% COD removal. Taha and Ibrahim [224] investigated the effect of sonication intensity at a varied pH (2–4) and time (3–10 min). They concluded that longer sonication time presents better COD removal in a short period of time. Manickam et al. [225] examined the effect of combined ultrasonic bath and hexagonal ultrasonic reactor. The experiment was conducted at a varied frequency of 28, 40, and 70 kHz, and they concluded that the combined effect presents consistent COD degradation. They further added that applying only ultrasonic at 37 kHz frequency give final COD fluctuating between 45,000 and 60,000 mg/L. Based on these reports, it will not be wrong to conclude that under optimal sonication intensity and duration, a higher yield of biogas, and better organic degradation (COD removal) is realizable [226–228].

3.3.5. A Thermophilic and Mesophilic Condition in MBR (*TheMBR*)

Temperature is one of the notable factors that influence the biodegradation process in MBR [157]. The level of its effect may depend on the intensity and duration of exposure [65]. The temperature process in MBR for POME treatment is mostly considered under two conditions: thermophilic and mesophilic [195,229]. Actually, the temperature has a direct effect on the viscosity of mixed liquor which could significantly influence the overall mass transportation [213,217]. This implies that high permeate volume is more visible under thermophilic condition because of the lesser hydraulic resistance [195]. In addition, thermophilic is more suitable for a higher range of organic loading rate [230]. Mass transfer efficiency is higher at this condition and this feature can be attributed to the high kinetic energy attained by the activated sludge. Thus, better contact between the bacteria and substrate is promoted [229]. However, the thermophilic condition could cause the formation of fatty acid which may considerably reduce the pH value of the activated sludge [146]. The acidic pH range could hamper methanogenesis process, in consequence, protracting the biodegradation [231]. Therefore, the rate of biogas (CH_4) production may significantly reduce because of the inactive methanogen bacteria at such low pH [44]. In addition, at a prolonging thermophilic condition, the flocs can easily disintegrate to form small particles sizes with varied ranges [232]. Subsequently, the generated particles easily initiate pore blockage, then afterwards develops into a dense cake layer on the membrane surface [232]. In this manner, it can be said that the mesophilic condition is more favourable to the physiological process of the microbes [208]. This is because at a higher temperature (> 55 °C) the metabolism of the microorganism is negatively denatured, thereby, retarding the rate of microbial activities [191,232]. Based on this note, efforts have been vetted by researchers to identify the optimal effects of temperature on MBR.

Ma et al. [212] investigate the effect of temperature on fouling rate with the presence of microbial in MBR. They reported that temperature has an effect on the accumulation rate of polymeric and carbohydrate substance, also on the microbial prolificacy. As the temperature increases from 8.7 °C to 19.7 °C, the biomass concentration (28.1 mg/g-MLSS) significantly reduced to 2.2 mg/g-MLSS. This suggests that the thermophilic bacteria are more active as temperature increases (19.7 °C); for this reason, they multiply rapidly to dominate and decompose the organic matter [209]. However, the high rate of decomposition under thermophilic conditions may cause generation of more particulates with an extensive range of smaller sizes. This could contribute immensely to the fouling initiation as well as in the formation of the biofilm matrix [233–235]. In another study reported by Tee et al. [214], the optimal removal efficiency of COD was obtained at mesophilic condition (35 °C) but the bacteria growth rate was observed slower. They concluded that the growth rate of microbial and decay are directly proportional to one another but lost their proportionality at some critical temperature limits (>55 °C) [236]. Choorit et al. [236] reported that temperature could increase the rate of biogas generation by 33.33% but often expose the membrane to higher fouling propensity [237]. This finding is actually in line with the report of Abeynayaka and Visvanathan [228]. Under thermophilic conditions, lower sludge accumulation and higher COD removal efficiency were archived but frequent fouling was observed. The author attributed this effect to the excessively generated foulants under the operating condition.

In overall, the combination of mesophilic conditions (32–45 °C) and microbial fuel cells (MFC) could improve the permeability flux and reduce the fouling rate [146]. This is because of the strong correlation that exists between several factors such as operating temperature, granulation stability, the sludge viscosity as well as biodegradation process [48,157,238,239]. Particularly, the bio-granular could lose its stability at elevated temperature. This is because, at a higher temperature, the death rate of the biomass increases, and the large bio-flocs disintegrate to generate more colloids and smaller particulates [36,240,241] This stress the importance of applying suitable temperature during MBR treatment.

Table 3. Summary of the published processes for POME treatments using membrane bioreactors.

Treatment Configuration/Process	Primary Procedure	Operating Conditions	Major Results and Contaminants Removal	Critical Findings and Effect of Treatment Process on Membrane Fouling	References
AerMBR (Pure Oxygen)	OTE under pure oxygen treatment at varied MLSS and HRT was investigated	MLSS = 4071 to 11,192 mg/L, HRT = 12–18 h; AF = 141 L/h, DO = 2 mg O_2/L	HRT 18 h, varying MLSS from 4300–10,275 mg/L: Alpha aeration-factor decrease from 0.6115 to 0.1223; while at HRT 12 h and MLSS of 4017 to 11,192 mg/L; it decreases from 0.2787 to 0.0221	MLSS strongly influence OTE; OTE increased by 400% as MLSS decreased with increase in HRT.	[167]
AerMBR + Agitation	Effects of aeration and agitation on POME treatment were investigated.	pH = 5–9; three tanks = T^a, T^s and T^{as}	61.2 and 58.9% removal efficiency for BOD and COD respectively after 6 d; UF membrane improved the treatment with the overall performance of 99.9% at pH 7.39	Integrated bioremediation and ultrafiltration membrane improves the total treatment performance to 99.9%. also, the bio pre-treatment reduces fouling propensity	[154]
AerMBR + Nano-composite-membrane	The composite UF-PVDF-ZIO was evaluated with aim of deteriorating colour and fouling rate.	ZIO = 0.0, 0.5, 1.0, 1.5 and 2.0 wt %.	Best colour removal and permeability was 80.5% and 50.18 LMH respectively at 0.5 wt % of ZIO dosage	ZIO nanoparticle improves colour removal, permeability; reduce the fouling rate but collapse after 4 cycles. M2.0 retain it throughout	[152]
				Also, ZIO oxidises to release antimicrobial and hydrophilic radicals. This makes it a good antifouling material	[152,240,241]
				ZIO reduces fouling	[152]
AerMBR + Microbial	The experiment investigates the correlation between the microbial community and MBR performance for POME treatment under alternating conditions.	Aeration period = 40 d, non-aeration period = 10 d; sample collection interval = 25 d, 50 d and 75 d	Aerobic conditions favour microbial as follows: Proteobacteria (19–23%), ODI (11–15%), Chloroflexi (11–13%). While; in the Non-aerobic condition: ODI (20%), proteobacteria (18%) and plantomycetes (16%) were visible	Protein was the main constituent of ESP. Taxonomic profile on the day 75 is similar to day 25. Proteobacteria survives in both conditions but ODI dominates under no aeration condition.	[141,152]
				ESP constitutes the major component of the accumulated biofilm	[242]
AerMBR + TNT nanoparticle PVDF	Composite PVDF-TNT was fabricated with variable TNT amount and evaluated under varied POME concentration with aim of decolourization	TNT load = 0–1 wt %; POME concentrations = 100, 75 and 50% with DF: 1, 2, 3	At PVDF-TNT 0.5; colour removal = 67.3%. but 5.7% flux reduction was observed after 5 cycles of filtrations	TNT improve the colour removal, also, it is a good antimicrobial material. Hence, capable of mitigating membrane fouling.	[21]
				However, TNT could be exorbitantly expensive compared to other antimicrobial nanoparticles	[243]
AerMBR + Adsorbent (AC + Zeolite)	Performances of 2 different adsorbents were compared with SubMBR evaluated without adsorbent same conditions.	Dosage: AC = 2, 4 g/L; Zeolite = 2 g/L; SRT = 70 d	Total of COD removal with adsorbents ranged from 97.5–98.5% and without was 95.2%, colour reduced to 16–26 Pt-Co while without adsorbent was 80 Pt-Co and improve flux to 42 LMH	Adsorbent improve flux, TMP, and reduce SMP deposition, COD and colour significantly	[18]
				The improvement in flux indicates that the membrane is less prone to fouling due to the significant reduction in contaminants	[185]

Table 3. *Cont.*

Treatment Configuration/Process	Primary Procedure	Operating Conditions	Major Results and Contaminants Removal	Critical Findings and Effect of Treatment Process on Membrane Fouling	References
AerMBR + AC	The performances of SubMBR with and without adsorbent were compared.	SRT = 20 d; HRT = 3.1 h; MLSS = 1.25 g/L; PAC dosage = 5 g/L; Backwash at F-R = 1 h per 1 min with 30 L/m^{2}h	With PAC, COD removal = 100%, DOC removal = 99% requires 7.5 kPa But without; COD removal = 94% and DOC = 95%. Requires 20 kPa to obtained the maximum flux of 20 L/m^2	PAC lowered the operating TMP, improves organic matter removal and mitigate fouling rate	[180]
AerMBR	effect of SRT and HRT on membrane fouling was studied under 10 min-4 min intermittent operation	SRT = 30, 15, 4 d; HRT= 12, 8, 4 h; pH = 7.2 ± 0.1; DO = 2.0 mg/L; flux = 4 L/m^2/h; Temp. = 25 to 35 °C	17 µm cake layer observed after 4 d of SRT and 12 h HRT; COD removal = 93%, TSS = 98%, NH$_3$-N = 80% and PO$_4$ = 30%	SRT influence organic matter removal. But equal removal of TSS at all SRT, higher HRT with shorter SRT induced faster fouling	[244]
AerMBR	Fouling behaviour was studied in three separate Submerged MBR: A,B,C under varied aeration intensity as 150, 400 and 800 L/h respectively at constant TMP.	HRT= 10–12 h; MLSS = 6000 mg/L; SRT = 30 d; Aeration:= 150, 400 and 800 L/h; DO= 3.21, 4.76 and 6.5 mg/L; TMP = 3.97 kPa	permeate of A and C, decline after 10 h operation; B reach a steady value after 100 h. Sludge bulking observed at 2.0 mg/L DO	Low DO causes sludge bulking because of the overgrowth of filamentous bacteria.	[131]
				Fouling rate decrease with an increase in aeration at the initial stage but breaks flocs to smaller sizes after sometimes hence more formation of colloids and higher fouling.	[245]
AnMBR	Kinetic coefficient of the POME was studied.	MLSS = 11,760–20,800 mg/L, MLVSS = 8938–17,680 mg/L, OLR = 1–11 kg COD/m^3-d, HRT = 600.4 to 6.8 d	GYC and SGR was 0.67 g vss/g COD, and 0.24 d^{-1} respectively. COD removal efficiency varied from 96.6 to 98.4% while the CH$_4$ yield varied between 0.25 to 0.87 L/g	Biomass concentration has a significant influence on CH$_4$ production. Concentrated biomass yield more CH4 but the membrane is more prone to fouling	[196]
AnMBR	Kinetic coefficient was investigated under anaerobic condition and the result was compared with kinetic equation models	MLSS = 8220 to 15,400 mg/L, MLVSS = 6329 to 13,244 mg/L, OLR = 2–13 kg COD/m^3-d, HRT = 400.6 to 5.7 d	COD removal efficiency varied between 94.8 to 96.5%; GYC was 0.62 g vss/g COD and SD was 0.21 d^{-1}	The treatment process deteriorates COD significantly, varying MLSS concentration influences CH$_4$ yield	[222]
AnMBR	Effect of intermittent Filtration-Relaxation (F-R) and membrane fouling under anaerobic conditions were investigated	F-R: L$_1$ = 240 s–30 s; L$_2$= 480 s–30 s; L$_3$ = 720 s–30 s and L$_4$ = 960 s–30 s	Protein and carbohydrate dominates and L$_1$ gives the least fouling rate with 50% lower in Hydraulic Resistance	More Frequent F-R reduced prevents fouling by 50%. SMP and EPS contributes to fouling mechanism	[201]
AnMBR	Under a specified range of TMP (125–130 mbar), the influence of SRT on membrane fouling under double stage anaerobic conditions was studied.	SRT = 15, 30 and 60 d; Flux = 2.41 L/m^2-h; TMP = 125–130 mbar	Foulants deposited for SRT = 15, 30 and 60 d was 34.28–16.81; 64.1–26.07 and 84.19–37.18 mg/g vss respectively	The longer the SRT, the denser the biofilm hence the more the severity of the fouling	[204]
AnMBR +	Effect of Baffled Aeration Flotation (BAF) system on *AnMBR* performance was studied.	Number of BAF = 5; HRT = 3, 4 and 5 d; AFR = 11, 8 and 5 L/min	At optimal condition of 5 d HRT and 11 L/min aeration: BAF system gives 35.5, 86.4, 57.7, 57.3, 59.7 and 52.6% removal of while the overall system gives 97, 93.9, 99.8, 94.5, 96.1 and 99.9% respectively	BAF system improves the performance of the *AnMBR* in terms of contaminants removal and reduces the fouling rate	[61]

Table 3. *Cont.*

Treatment Configuration/Process	Primary Procedure	Operating Conditions	Major Results and Contaminants Removal	Critical Findings and Effect of Treatment Process on Membrane Fouling	References
HybMBR (+PAC)	Effect of PAC particle sizes: fine = M_f; medium = M_m; coarse = M_c, on POME treatment were studied and compared with treatment without PAC under anaerobic	MLSS = 8050 mg/L; MLVSS = 6850 mg/L; SRT = 30 d; HRT = 6 d PAC dosage: Mb = 0; M_c = 5 g/L; M_m = 5 g/L; M_f = 5 g/L; Temp.= 45 °C; OLR= 7658 ± 408 mg COD/L-d	Without PAC: removal efficiency are COD: 64.90 ± 1.46%; protein: 2407 ± 230 mg/L; polysaccharide: 71 ± 1.827 mg/L. With PAC: Mf present the best performance with 78.53 ± 0.66% COD removal; protein: 1647 ± 175 mg/L; M_c: least COD removal with 72.99 ± 1.47% and protein: 2075 ± 305 mg/L	The Fine PAC (M_f) presents better COD removal of 90.55 ± 0.21 than medium PAC (M_m), particle size influence adsorption performance, biogas yield and reduce fouling rate	[246]
				This shows that PAC of fine particles sizes present more active sites for COD adsorption	[26]
HybMBR	POME was pre-treated using hybrid anaerobic and aerobic process-then polished with membrane techniques. The treatment lasted for a period of a year	Anaerobic HRT = 9.8 d; Aerobic HRT = 48 h; DO = 3.5 mg/L	55.6% of the waste oil in raw POME was recovered at anaerobic treatment; aerobic treatment degenerate BOD_3 level to less than 20 mg/L	Deterioration of COD is more significant during anaerobic treatment, while the aerobic process is more suitable for BOD removal.	[69]
				Also, the hybrid system is suitable for resource recovery, such as biogas	[140]
HybMBR	The *HybMBR* was acclimatized for 45 days with 4 different samples at a varied MLSS to observe the fouling rate on the membrane.	MLSS = 5–20 g/L; HRT = 11, 7 and 8 h; SRT: 70 days, 120 rpm; flux: 11 L/m^2-h	As varied from MLSS from 5 to 20 g/L, the flux reduced down to 400%. However, 97% denitrification and nitrification was obtained at 20 g/L MLSS	MLSS concentration strongly influences fouling.	[207]
				But, higher MLSS concentration promotes NH_4-N and nitrogen substance removal in MBR	[162,207]
HybMBR (+adsorbent)	The *HybMBR* was Evaluated under different adsorbent and varied dosage but same SRT.	Dosage: AC = 4 g, Zeolite = 8 g, Moringa Oliefera = 12 g and SRT = 30 days	Adsorbent: 58, 48 and 42% removal of SMP was observed by AC, Zeolite and MO respectively.	Adsorbents reduce SMP significantly. At optimal operating conditions, AC gives better performance.	[56]
			At an optimal dosage of AC; 70 and 85% SMP removal efficiency and fouling reduction were archived respectively	The improvement in performance was attributed to the availability of the active sites to adsorb the SMP	[56,247,248]
HybMBR	TMP and flux was continuously monitored for a complete season under varied temperature to investigate the membrane fouling characteristics	SRT= 20 days, HRT = 17 h, Temp. = 27 to 13 °C	At summer the TMP was 25 kPa with 10 L/m^2-h permeability flux while at winter the TMP was 60 kPa at 10 L/m^2-h.	This study revealed that temperature influences the organic concentration of the supernatant, filtration resistance, viscosity and humic substance.	[210]
				Higher temperature disintegrates the flocs aggregates, thereby increasing the concentration of the foulants of smaller sizes.	[141,214]
HybMBR	Effect of biomass concentration on POME treatment and membrane fouling with fitted controllable recycling device and agitator at the anoxic and anaerobic condition	MLSS = 4000–8000 mg/L, OLR = 1.77 to 1.87 kg COD/m^3, steady inflow = 108 m^3/d, flux = 15 L/m^{2}h	The removal efficiency of COD, SS, TN and TP was 94, 98, 83 and 64% respectively	Both Protein and carbohydrate contribute to the fouling.	[58]
				The hybrid system deteriorates the organic pollutants significantly	[226]

Table 3. *Cont.*

Treatment Configuration/Process	Primary Procedure	Operating Conditions	Major Results and Contaminants Removal	Critical Findings and Effect of Treatment Process on Membrane Fouling	References
HybMBR	Each sections of the hybrid system was subjected to different operating conditions. Also, the MLSS concentration was varied with the aim of investigating the fouling effect	Anaerobic: HRT = 12 h, pH = 5.5 to 6.5, DO = 0-0.1 mg/L Anoxic: HRT = 6 h, pH = 7.2–8.5, DO= 0.3–0.6 mg/L Aerobic: HRT = 4 h, pH=7–7.5, DO= 6–8 mg/L. MLSS = 4–8 g/L	94, 98, 83 and 64% for COD, SS, TN and TP removal efficiency respectively. At 12 LMH flux, permeability increased to 70 LMH.	Initially, the filtration rate was steady, then, diminished abruptly after the critical flux 16 LMH.	[208]
				This was due to the fouling which often causes TMP jump.	[65,108]
HybMBR	An integrated Biological-composite membrane system was acclimatized at room temperature. The anaerobic and aerobic section takes about 111 and 10 days respectively, for complete acclimation	Influent COD: 4331 to 35,000 mg/L, UF membrane TMP = 200,000 Pa; RO membrane TMP = 1,300,000 Pa Temperature = 25 °C, OLR = 10 kg COD/m^3-d	Anaerobic deterioration of COD = 93%, While, 22% of COD was removed in aerobic. UF membrane removes SS and turbidity with a total of 99.288% efficiency the RO membrane removed all the remnants contaminants with 100% efficiency.	Anaerobic performed excellently in terms of COD removal. UF membrane is suitable for removing SS and turbidity.	[15]
				RO remove all the contaminants including the colour but it requires high TMP.	[249,250]
				The setup mitigate fouling rate and also improved membrane flux recovery (between 91.7 to 95.3%)	[15]
HybMBR	POME passes through the integrated system for treatment and recourse recovery (biogas and bio fertilizer)	Screening operation, biological treatment, reclamation operation, biogas generation, sludge disposal system	About 94% of COD removal was achieved during anaerobic treatment; improvement in the COD removal of 97% was observed after Nano air flotation treatment.	Zero discharge from POME was achieved; SS, residual oil, NH_4-N, toxic material and colour were removed in the aeration section. In overall, less fouling was observed using the integrated system	[47]
			BOD is less than 20 mg/L after the final treatment with 80% consistency		
SonMBR	Effect of sonication on MBR was studying for different sonication durations: 2 h and 1 h	Acclimatization period = 2 days, pH = 6.8 to 7.8, pressure = 2 bar	COD removal efficiency for 2 h and 1 h sonication was 98.75 and 97.71% respectively; more CH_4 yield was obtained at 2 h sonication	Sonication improves organic matter removal, CH_4 production rate and mitigating fouling. This implies that the biomass degradation is more at longer sonication duration	[218]
SonMBR	The study was conducted to investigate the effect of sonication on the kinetic coefficient of POME prepared in three samples: S^c, S^p and S^r	Sonication time = 3 h, at constant MLSS concentration	Specific Growth Rate in S^c, S^p and S^r was 0.0115, 0.279 and 0.3550 kg VSS/kg COD respectively. 87.5% and 85% COD removal were observed with and without sonication respectively	The higher growth rate was observed in reacted sample S^r under sonication with improved COD removal. This implies that the microbes are more active in the reacted sample under the applied sonication	[218,219]
SonMBR anaerobic	Effect of sonication in anaerobic degradation and CH_4 production was investigated	MLSS = 13,800 to 22,600 mg/L; MLVSS = 10,400 to 17,350 mg/L; OLR = 1–15 kg COD/m^3-d; SRT = 15.8–300 d; HRT = 500.8 to 8.6 days; pH = 2 to 12; pressure = 2–4 bars	COD removal were between 92.8–98.3%; Growth Yield Coefficient = 0.73 g VSS/g COD, SMD rate= 0.28 d^{-1}, CH_4 yield= 0.27–0.62 L/g COD-d	Maximum yield of CH_4 (0.7 L/g COD/d) was obtained at highest biomass concentration (22,600 mg/L) and highest HRT	[197]
				While the least yield was obtained at the lowest MLSS concentration.	[188,196]
				Also, SRT has an insignificant effect on CH_4 production rate	[188]

Table 3. *Cont.*

Treatment Configuration/Process	Primary Procedure	Operating Conditions	Major Results and Contaminants Removal	Critical Findings and Effect of Treatment Process on Membrane Fouling	References
SonMBR + Microwave	The effect of combined microwave and sonication process on organic degradation and CH_4 production rate was investigated	Temp. = 32–37 °C; TVS = 32–34 g/L; ^{M}F = 2450 Hz; ^{I}T = 3 to 15 min; ^{U}F: = 18 Hz; intensity = 0.2 to 0.5 WmL^{-1}; ^{S}T = 1–30 min; HRT = 15–2 d	At optimal microwave and 11 min sonication duration, the SCOD/TCOD and BOD/SCOD ratio increased to 0.77 and 0.95 respectively. Also, about 44 mL of CH_4 obtained	SCOD/TCOD ratio and BI increase significantly under sonication and microwave process. The higher CH_4 yield obtained under sonication	[219,251]
Son MBR	The combined ultrasonic and sono-thermal was applied in an MBR system for pre-treating the POME at a varied temperature and time.	Temperature = 45, 55, 65 and 75 °C. Ultrasonic frequency = 37 Hz, sonication time = 1–6 h	39.05% increment in degradation was observed when ultrasonic-sono-thermal pretreatment were applied Also, after the pretreatment, the average particles size 321.94 µm reduced to 79.16 µm	The ultrasonic and sono-thermal pretreatment promotes degradation and is more rapid at elevated temperature (75 °C)	[222]
SonMBR	Application of ultrasonic pretreatment to accelerate bio-hydrogen production.	Ultrasound dose = 0,91, 143 and 195 J/mL; pH = 7;	Average COD removal = 65% Bio-H_2 yield = 0.7 mmol H_2/g COD In overall, 38 and 20% increment in bio-H_2 yield and COD removal, respectively were obtained.	The ultrasonic improve the overall performance of the reactor significantly. The best performance was obtained at the highest ultrasound dose (195 J/mL)	[223]
SonMBR	The application of nano zero valent ions to treat POME was accelerated by applying ultrasound.	pH = 2–4; sonication intensity = 10–50%; sonication time = 3–10 min	At 50% intensity, COD was deteriorated by 80% within 2 h	Significant improvement in COD removal was observed when ultrasound was applied.	[16]
TherMBR + MFC	Effect of temperature and microbial in MBR was investigated under intermittent operation and variation in TMP was monitored	Temp. = 8.7–19.7 °C; F-R = 10–2 min; HRT = 4.9 h; SRT = 40 d, TMP = 60 kPa	As temperature increases from 8.7 to 19.7 °C, the MLSS of SMP reduces from 28.1 to 2.2 mg/g. also, Proteobactaria, bacteriodestes, nitrospira, firmicutes and acidobacteria dominate with 41–51.8%, 6.7–22.2%, 8.9–15.1%, 4.32–10% and 2.2–7.0% respectively	Increase in temperature decreases SMP. Lower temperature is more suitable for *Proteobacteria*, while the higher temperature is capable of activating some bacteria such as Zoogloea from a dormant state.	[224]
TherMBR + MFC	The effect of temperature and MFC in an MBR was investigated. R1, R2, and R3 were run under mesophilic while R4 was under thermophilic.	Sample: reactor R1, reactor R2, reactor R3, reactor R4; SRT = 30 d; PAC = 5 g/L dosage; Temp.= 35, 45 and 55 °C	R3 shows the best removal of COD and polysaccharide with 95.6 ± 0.3% and 73.01% respectively, under the mesophilic condition. While R4 under thermophilic present COD removal with 79.23 ± 9.36%. Also, highest MLVSS was obtained in R1 with 38,133±1804 mg/L while least was observed in R3 with 16,467 ± 3239 mg/L	Best performance as obtained at mesophilic conditions. This indicates that mesophilic conditions are more suitable for biodegradation.	[212]
				Fouling rate is higher at the mesophilic condition.	[31,195,252]
TherMBR	The Effect of varied temperature on MBR performance was investigated. The MBR system was incorporated with PAC	PAC dosage = 50 g/L, Temperature = 10–20 °C	At 10 °C, Start-up time = 9 days; Complete nitrification was attained after 10 days. NH3-N removal = 90% at both 10 and 20 °C	Lower temperature (10 °C) cause delay in the start-up of the system, nitrification process. The membrane is less susceptible to fouling at this temperature	[234]

Notes: AF = air flow rate, T^{a} = aeration tank, T^{s} = stirring tank, T^{as} = aeration + stirring tank, ZIO = zinc iron oxide, F-R = frequency-relaxation, $L_{1,2,3}$ = duration for F-R, BAF = baffled aeration flotation, M_f = fine size, M_m = medium size and M_c = coarse size, S^{c} = control sample, S^{p} = permeate sample, S^{r}= reacted sample, $R_{1,2,3,4}$ = reactors.

4. MBR Major Drawbacks

The most challenging limitation of the MBR treatment method is the membrane fouling which often resulted from the accumulation of foulant(s) such as bio-flocs, colloids, and particulates [65,242,253,254]. Membrane fouling could cause gross deterioration of the system performance in terms of filtration and operational energy utilization, as highlighted earlier. Therefore, the need to control the fouling is indispensable and this justified the previous studies reported on this critical area [67,110,161,255–258]. The efforts devoted by the researchers have yielded some improvements such as membrane fouling control strategies and filtration. However, the level of achievement is still under development and economically unsustainable for industrial application [243–245], particularly in the oil palm processing.

Regardless of the type of operation, mass transportation and frequent interaction of contaminants with the membrane modules is unavoidable. Primarily, MBR is operated either at stable TMP while flux is varied or vice versa [100]. This implies that the TMP and flux have strong correlations with the fouling mechanism. From Figure 6, at the initial stage of the filtration process, as the flux increases at a steady d(TMP)/dt rate, the fouling rate (blue curve) is almost constant [206]. However, the maximum permeability was attained at a critical flux of 12 LMH, in which further increase yielded a steep declination of permeability and a sharp increase in membrane fouling (red line). The sharp increase in fouling indicates a sudden jump in TMP [208]. This effect is initiated by the intense flux and by the biomass concentration, wastewater chemistry (such as divalent cations concentration, ionic strength, and pH), membrane surface morphology, membrane surface charge, membrane molecular weight-cut-off, and hydraulic and operating conditions [167,233,245].

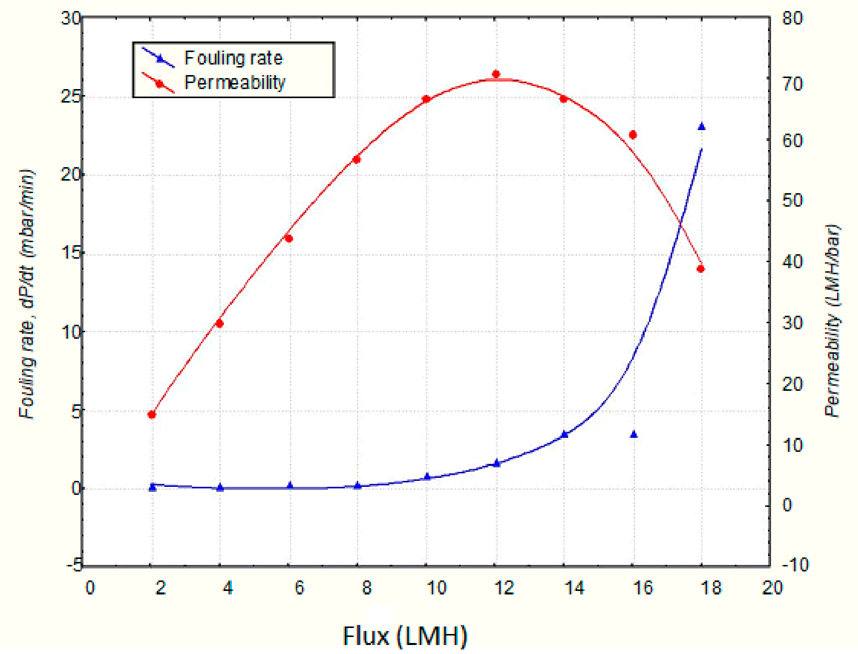


Figure 6. Relationship between the fouling rate and permeability during POME treatment using MBR [208].

The usually observed jump in TMP and a sharp drop in permeability-flux are of utmost concern. This condition is not suitable for profit-oriented industries due to the higher running cost required to maintain the dropped permeability-flux [15]. Therefore, it is essential to understand the nature and the different types of the foulants generated as well as the fouling mechanism during POME treatment using MBR. This could deeply succor both the industries and researchers to fathom the nature of the foulants and then espouse the most efficient and cost-effective measures to mitigate the problems of fouling. Considering the scope of this review paper, only the types of foulants as relates to POME and the detailed stages of the fouling mechanism were considered. This is because comprehensive reviews on the methods of fouling control such as the physical and chemical, as well as the novel application of composite nanoparticles have been reported previously [28,130,180,245].

4.1. Types of Foulants as Related to POME Treatment Using MBR

Foulants are the organic and inorganic substances that initiate pore blockage as well as layer formation on the membrane [247]. Foulants have been categorized into four groups: organic, microbial, inorganic and particulates foulants [248]. The classification was actually based on the biological, chemical and physical characteristics of the foulants. In addition, previous studies have shown that microbial/organic products, suspended-solute substances and debris concentrations have a strong correlation with fouling rate and also they determined the fractional contributions of each of the foulants [249,250].

4.1.1. Organic Foulants Generated during POME Treatment

Organic foulant is a biopolymer often describes as a complex microbial product (MP) [251,252] and it is generated through hydrolysis of extracellular polymeric substance (EPS) during the metabolic activity of the decomposer (bacteria). In addition, reports have also shown that the decaying of organic materials in the mixed liquor is another source of this foulants [253,254]. EPS is the major contributor to membrane fouling during POME treatment with an average composition of 52% of the total foulants [50]. Also, this is in accordance to the reports on the direct relationship that exists between the EPS contained in the mixed liquor with the fouling rate [255], specific flux [256], critical flux [128], and membrane filtration performance [257]. They all confirmed that EPS constitutes majorly in the deposited foulants. In addition to this, EPS plays a significant role in the bio-flocs aggregates formation, zeta potential properties of the mixed liquor and adsorption characteristics of the bio-flocs. This is because EPS encompasses a range of organic macromolecules which may include polysaccharides, proteins, lipids, humic acid, nucleic acids, and fulnic substances [258]. Though polysaccharides, proteins and humic materials are the key components of the EPS foulants, and they exhibit a different degree of hydro-affinity which determines the rate of fouling susceptibility. The polysaccharide is carbohydrate and is hydrophilic in nature, while the protein is less attracted to water due to its hydrophobic characteristic [254].

Furthermore, due to the several interactions with other types of foulants in the mixed liquor, EPS is normally classified into soluble-EPS (s-EPS) and bound-EPS (b-EPS) [254]. More interestingly, the b-EPS promote biomass aggregation and stability through agglomeration of bio-flocs by releasing a gel-like substance to resin them together. The gradual adhesion of the bio-floc resulted into formation of gel and this could later metamorphosis into cake layer [65,70]. More so, b-EPS exhibit a significant role in the biological stabilization and as well as the microbial aggregates in the MBR [254]. This shows that b-EPS not only promotes microbial aggregate but also influence the surface charge, mixed liquor viscosity and system sludge flocculation ability. Therefore, it can be said that b-EPS determine the formation or building of bio-flocculation and also define its stability [180]. One of the uniqueness of the b-EPS substance is the aptitude to demonstrate both hydrophilic and hydrophobic characteristics. This is possible because of the presence of both functional group charge which readily initiate deposition and adsorption on to unlike charged surface. Thus, this indicates that irrespective of the type of membrane used, b-EPS can easily get adsorbed on the surface to form a gel-like substance [259].

The soluble EPS (s-EPS) is also referred to as soluble microbial product (SMP) and they are mainly generated from organic based materials in activated sludge such as bacteria by-product and biomass decomposition [260]. This shows that they are biodegradable and a species form through the dissolution process of the b-EPS [51]. However, SMP is often considered into two major groups; biomass associated product (BAP) and utilization associated product (UAP) which are respectively generated from biomass deterioration and bacteria metabolism [254,260]. The macromolecular composition of the two SMP contains majorly protein, polysaccharide and humic acid just as the EPS [246] and this implies that they also contribute considerably to membrane fouling.

Nonetheless, the rate of fouling is not just influenced by EPS concentration but is as well depends on a number of factors which include membrane properties and operating conditions [246]. As already discussed above, operating conditions such as aeration, sonication, temperature, TMP and MLSS concentration, has a strong correlation with the bio-flocs formation, aggregate stability and fouling rate [16,207]. Similarly, a hydrophobic membrane with a rough surface is more susceptible to fouling due to the several cleavages that favour foulants deposition and the subsequent development of the biofilm matrix [50].

4.1.2. Microbial Foulants as Related to POME Treatment

Microbial foulant is commonly regarded as bio-foulant and is considered next to the organic foulant that usually causes serious fouling problem [186–188]. Fundamentally, bio-fouling involves sticking of bacteria micro-colonies by adhesion on the membrane surface to perform a complete living activity such as growing, reproduction as well as metabolic activity. After a certain period of time, bacteria micro-colonies multiply and develop into mature biofilms layers. The by-product released through the metabolic activity of the living layer (biofilm) generates extracellular polymeric substance (EPS) [261]. The secreted EPS is a bio-adhesive material, which normally serves as the glue that fosters the formation of biofilm matrix on the membrane surface [254,262]. This indicates that the major constituents of biofilm are the bacteria cells and the EPS. Ma et al [215] reported EPS is the major components of biofilm and it accounts for more than 70% of the complex organic matter and microbial aggregates. Besides, a report has also shown that EPS contain polar charge group which includes both the aromatic and aliphatic [254]. On the whole, EPS contains both the hydrophilic and hydrophobic functional group, as confirmed by previous studies [65,256]. Hence, the complex nature of EPS could be harnessed to improve the total biodegradation of POME through the microbial aggregate formation and sludge stabilization [263–272].

On the other hand, the presence of Lipopolysaccharides (LPS) on the bacteria cell wall plays a key role in the bio-fouling mechanism. Herzberg et al. [273] investigated the bio-fouling mechanism of *P. aeruginosa* under varied microbial fouling conditions. They confirmed that the rate of micro-colonies accumulation and bio-film development has a strong correlation with the secreted tacky substances (Lipopolysaccharides and EPS). They further added that the sticky substances promote auto-aggregation, and this ultimately immediate rapid growth and surface translocation of biofilm via twitching motility. Similarly, Ashhab et al. [274] reported that the secreted microbial substances not only influence film formation but also increase the viscosity of the mixed liquor. Consequently, this effect resulted in a significant increase in the overall hydraulic drag force [275,276]. However, measures and techniques to avert biofouling in MBR have been investigated under different conditions by several researchers. Kim et al. [277] uses a hybrid membrane modified using TiO_2. They reported that the hybrid polymeric membrane inhibits the biofouling by generating antimicrobial radicals under ultraviolent radiation. In addition, the reports of Subramaniam et al. [21] and Tan et al. [152] concur with this finding. Collectively, they confirmed that the photo-biocidal effect of the incorporated nanoparticles prevents bacterial aggregation along with biofilm formation. Moreover, studies have also shown that the counteraction of biofouling using nanoparticles also improves the hydrophilicity of the membrane [11,278]. The mutual activities are accomplished during the self-assembling of the incorporated nanoparticles, and this process resulted in the generation of hydroxyl radicals onto the membrane surface [10]. Hence, reduce the hydrophobicity of the polymeric membrane. More so, Zhu et al. [279] reported the state-of-the-art on the control of microbial fouling using different types of nanoparticles. Essentially, they pointed that nanoparticles such as fullerenes (C_{60}), Zinc based materials (ZIO-NM), silver-based particles (Ag-NM), grapheme oxide (GO-NM), and titanium dioxide (TiO_2-NM), exhibit a strong antimicrobial effect. The authors further reported that the anti-biofouling mechanism of these materials is centered on the ability to release radicals with strong efficacy against the bio-foulants. This verdict is in agreement with the previous studies reported earlier [21,156].

4.1.3. Inorganic Foulants Generated during POME Treatment

As the name implies, this type of foulant is not organically originated, and they are normally categorized into an anion (CO_3^{2-}, SO_4^{2-}, F^-, OH^-) and cations (Al^{3+}, Ca^{2+}, Fe^{3+}, Mg^{2+}) [157]. The inorganic foulant is produced from soluble salts such as calcium phosphate, calcium carbonate, barium sulphate as well as silicon oxide. Primarily, the generation of inorganic foulants occurs through oxidation and hydrolysis to precipitate the ions to form a scale on the membrane. Researchers have considered the mechanism of the inorganic fouling into two stages: crystallization and particulate fouling [65,70]. During the crystallization stage, the ions were precipitated by the synergistic process of the oxidation and hydrolysis. The precipitates eventually got settled to form a coat on the membrane surface. While in the case of particulate fouling, the colloidal ions generated from the bulk mixed liquor are transported by convective and finally got deposited [51].

It is noteworthy that higher TMP encourage generation and agglomeration of ions, which subsequently got attracted to the unlike charged membrane surface to form scales layer [279]. The deposited and precipitated scale stratum of ions on the surface and pore wall of the membrane increases both hydraulic resistance and TMP. Then, the fouling developed under this condition is fundamentally referred to as inorganic [161]. In a general view, other factors such as the shear rate (scouring aeration), system configurations, feed physicochemical properties and membrane characteristics (such as surface roughness) could as well immediate the mechanism [259,279].

Ayyavoo et al [278] reported that variable operating condition have correlation with inorganic fouling rate. The results of their studies explicate that the composition of Ca^{2+}, Mg^{2+} and Si^{2+} increases significantly as the aeration and TMP upsurges to a higher range (0.25–0.55 L/min and 15–35 psi respectively). In addition, the membrane fouling propensity increased by 400% at higher TMP and aeration. This suggests that as the operating conditions increases, the crystallization and particulate deposition of the colloidal matter prevails geometrically. As a result of this, it can be deduced that higher TMP and aeration could increase inorganic fouling [280,281]. Similarly, the effect of membrane surface geometry [258], filtration time [268], feed characteristics [153], and cross-flow velocity [108] on membrane fouling has been reported. Collectively, the findings pointed that the rate of fouling increases with the rough surface membrane, prolonging filtration time, higher organic loading rate and CFV. Furthermore, a higher range of CFV disintegrates the microbial flocs aggregate, thereby generating more colloids and particulates such as Ca^{2+} [65].

More interestingly, research has shown that moderate accumulation of Ca^{2+} ranging from 100 to 280 mg/L could mitigate organic fouling and bio-fouling. This is because the accumulated Ca^{2+} at this range has the ability to isolate and at the same time exert a binding effect on the organic foulants, and this could considerably hamper the metabolic activity of the bacteria colonies. However, excessive deposition of the ionic metal (Ca^{2+}) beyond this range (100–280 mg/L) could cause severe fouling by the formation of hard scale layer [254].

4.1.4. Particulate Foulants as Related to POME Treatment

Particulate foulant has a wide range of sizes which may be grouped into settling particulate (size greater than 100 μm), supra-colloidal particulates (size less than 100 μm) and colloidal particulates (size ranged between 0.001 and 1 μm) [50]. They exhibit similar features with inorganic foulants in terms of fouling mechanism but they are different in requisites of origination [282–284]. In another view, Asadollahi et al. [285] have reported that particulate foulants comprise of cellular fine debris with high molecular weight proficient of forming an agglomerated colloids and/or coagulated fine fibres from palm fruits.

Basically, the particulates with same diameter or slightly less than the size of the membrane pores can easily initiate blockage while those with larger dimension contribute majorly in cake layer formation [50]. The particulates are transported either by convection, inertial lift, gravitational effect, or a combination of some or all factors to initiate blockage [286]. However, the efficacy of the mass transportation depends on operating conditions, particulate sizes, cross flow velocity and bulk concentrations present in the mixed liquor. It was on this note researchers have classified pore blocking into standard, complete, and intermediate [287].

Standard pore blocking involves narrowing of the pores as a result of the deposition and adsorption of the particulate onto pores-walls. Intermediate pore blocking is the partial accumulation of foulants to bridge the opening, while the complete pore blocking involves a total seal of the pores as a result of the deposited particles [287]. The blockage forms a barrier such that any further drifted particles continue to accumulate on the primary glazed (blockage) and this could eventually degenerate into piles of particulates or layer. The cake layer set in an antagonistic relationship between TMP and filtration or flux rate due to the exponential increase in hydraulic resistance (drag force) [287,288]. In this condition, rapid accumulation of particles occurs which gradually develops into scale layer. Hence, deterioration of filtration rate prevails while the TMP increases rapidly. The jump in TMP nurtures fouling and also compacts the accumulated particulates and transforms the scales into a hard cake layer [288]. This implies that membrane fouling passes through stages; starting with pore blockage, the gel formation and compaction [278].

Li et al. [289] reported that the higher fractal pores in the membrane morphology encourage more hydraulic resistance. This elucidates that membrane morphology has a strong correlation with the rate of cake formation. Similarly, Tijing et al. [185] reported that higher TMP operating condition increases the rate of cake formation by 80%. Also, they confirmed that the particulates with fine sizes often initiates blockage and also perform a significant role in the subsequent fouling mechanisms. This type of fouling is usually irreversible in most cases, as substantiated in the previous studies [65,290]. This denotes that smaller colloids or particulates could pose more severe fouling challenges compare to the larger foulants.

4.2. The Mechanism in Membrane Fouling During POME Treatment

Fouling mechanism is the developmental stages of foulants accumulation on the membrane surface and pore walls. The nature of the foulants generated and the fouling mechanism have a significant correlation with the applied treatment processes and the feed characteristics, as discussed earlier. Based on Figure 7, the central functions of the MBR system includes biodegradation and filtration. It is obvious that feed (POME) characteristics, treatments processes and membrane properties influence the rate and types of foulants generated, as well as its deposition method [65,156,254]. Firstly, In the biodegradation, the feed (POME) characteristics (such as biomass concentration), HRT, SRT, aeration, F/M ratio, pH and/or temperature are key to expedite the process [291,292]. The condition must be ideal for the microbial to ensure swiftly decomposition of the biomass. This implies that selection of the treatment conditions is fundamental for optimal biodegradation and also it determines the resulted types of foulants as well as its properties. Membrane filtration is the second crucial function of the MBR system as depicted in Figure 7. At the filtration stage, the bio-degraded biomass or activated sludge interacts with the membrane under the influence of the applied driving force (TMP). During this process, the constituted foulants in the concentrate polarizes the membrane and the resulted fouling is strongly determined by the membrane properties, feed characteristics and operating conditions. This shows that all the three factors (membrane properties, feed characteristics and operating conditions) play a significant role in the membrane selectivity, productivity and fouling mechanism. Thus, the separation mechanism is a complicated phenomenon due to the complexity and antagonistic interactions of the several factors [70,292].

However, the fouling mechanism has been simplified into three stages; the build-up or the conditioning, the steady-growing and abrupt increase in TMP stage, (see Figure 7) [157,292]. From Figure 7, it is obvious that EPS (soluble and bound), bacteria colonies or cells, precipitated ions, and the colloids/particulates all contributes to the initiation of pores blockage, but the input of each of the foulants varies [108]. The steady fouling stage involves the formation of gel and scale layer on the membrane surface and pore walls. Consequentially, this usually amounted to the gradual increase in the operating TMP. In most cases, if the filtration continues at this condition, the gel or biofilm could degenerate into the cake layer, as illustrated in Figures 7 and 8c.

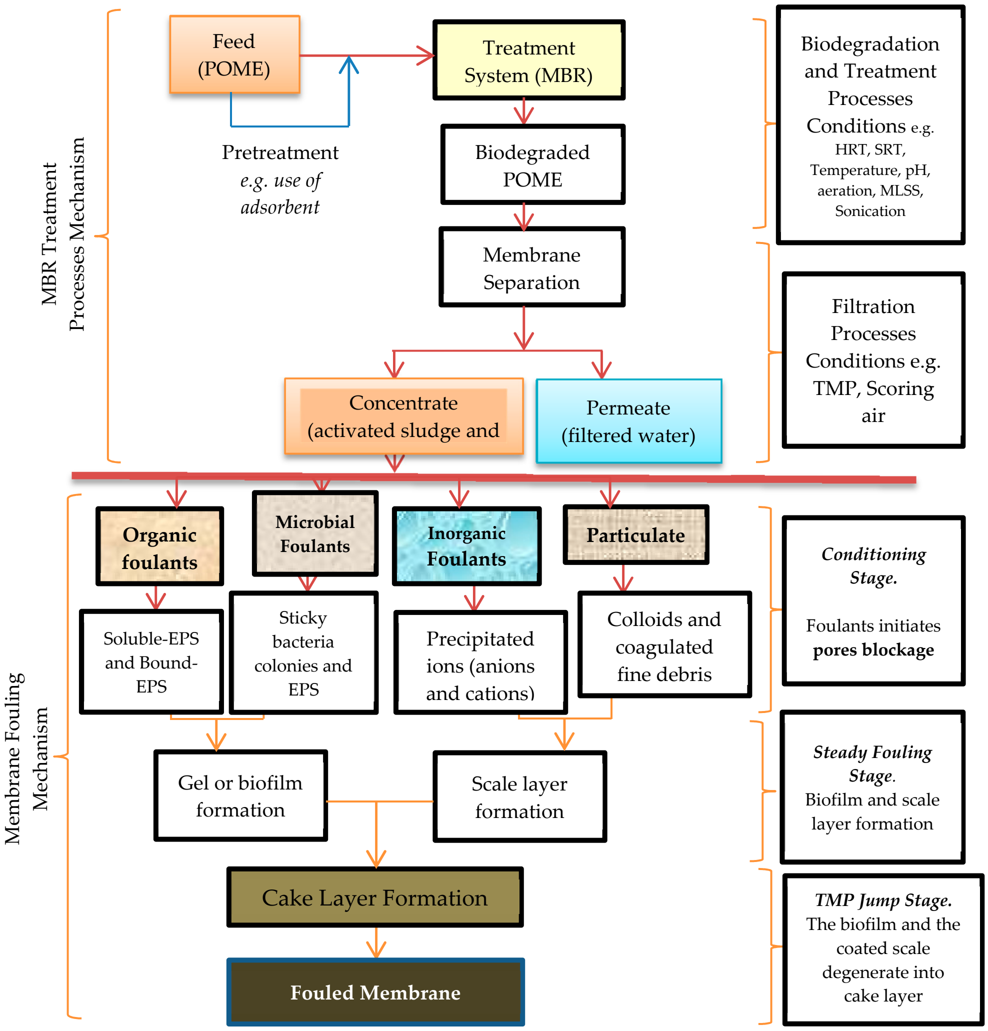


Figure 7. Flowchart showing MBR treatment process and membrane fouling mechanism.

4.2.1. Build-up (Conditioning) Fouling Stage

The initial conditioning stage is usually stemmed from the stream transportation and interaction of the particulates with membrane modules [50,264]. This resulted in the deposition and adsorption of the foulants onto the pore walls. As depicted in Figure 8a, the particulate of smaller sizes is transmitted into the pores by the driving force such as TMP, convections, shear-induced diffusion, gravitational influences as well as literal migrations [293]. The deposited particulates developed into the thin glaze, thereby creating a barrier capable of obstructing the hydraulic conductivity of the permeate flow. As filtration proceeds, additional particles or foulants will continue to accumulate on the initiated layer and ultimately degenerate into the next stage of fouling, as illustrated pictorially in Figure 8a. Furthermore, the hydrolysis and oxidation process during filtration as well as the by-products released by the microbial also contributes considerably to the initiation of pores blockage. This is because of the surface scale formed by the inorganic ions and the secreted bio-glue substance immediate particulate attachments onto the pore walls [70,108]. Nonetheless, the severity of the blocking stage of fouling can be quelled using back-washing, intermittent filtration operation and optimal scouring aeration [249].

4.2.2. Steady Fouling Stage

This stage is the continuation of the fouling mechanism of the initiated pore blockage through the deposited tacky substance, commonly known as soluble microbial products (SMP) [293,294]. The sticky surface condition of the membrane promotes attachment and swift accumulation of the colloids or particulates, bio-flocs and SMP to form a gel layer, and this could lead to a complete or intermediate pore blockage [48,293,294]. Figure 8b denotes the fouling mechanism at the steady stage, the TMP is observed rising gradually due to the growing films or gel layer on the membrane pores and surface. However, the rate of gel formation can be palliated by adopting good practicings such as frequent back-washing and intermittent filtration-relaxation operation [201,254]. On the contrary, poor control of fouling encourages the growth of bio-layer. The underneath of the accumulated bio-layer lacks oxygen and this could lead to the higher death rate of the bacteria, thereby secreting more EPS to further glue the matrix of the biofilm. This situation is more distinctive to the third stage of fouling, where the compacted and denser cake layer is predominant [294].

4.2.3. An Abrupt Increase in TMP Stage

All types of foulants contribute to this fouling stage, as clearly shown in Figure 8c. From Figure 8c, it can be observed that SMP was the major initiator of the pore blockage, while the colloids, EPS and particulates contribute majorly to the gel and hard-cake layer formation, respectively [130,295,296]. This stage of fouling is characterized by a sudden increase in the driving pressure, this effect is commonly referred to as “TMP jump”. The observed TMP jump is due to the pores blockage and the accumulated layer on the membrane surface which induced the exorbitant hydraulic resistance [61,77]. Therefore, diminishing in the filtration volume or permeability flux prevails at this condition due to the narrowed or blocked pores. This implies that TMP and the permeability flux are reciprocal to one another as the foulants gradually settled on the membrane. Essentially, it can be inferred that the sudden increase in TMP and flux waning are the most obvious indicators that can be used to confirm abrupt fouling stage in a typical MBR system. Furthermore, prolonging filtration at jumped TMP not only influence cake layer formation but also exerts a compacting force to harden the layer [248,294]. At such situation, there is a high tendency for the formation of irreversible fouling in the membrane [50,65].

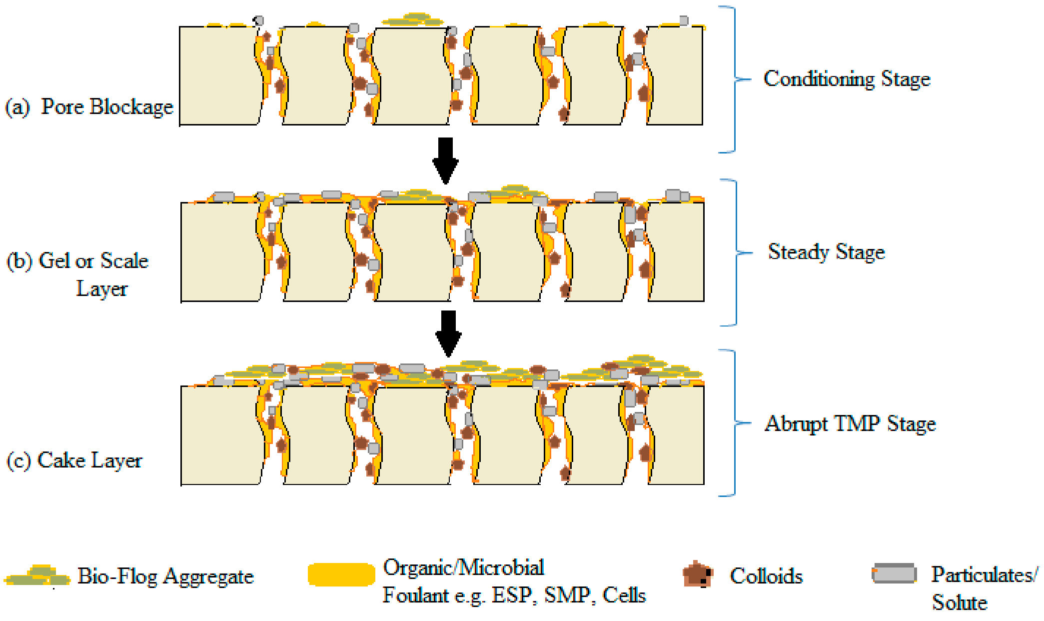


Figure 8. (**a**–**c**) Schematic showing mechanism of (**a**) conditioning stage, (**b**) steady stage, and (**c**) abrupt TMP stage.

5. Conclusions

Currently, MBR technology has gained substantial attention with high interest in its application for POME treatment. The technology presents a great potential in treating POME under optimal treatment conditions. Application of aeration (*AerMBR*) offers a sizable enhancement in performance of MBR in terms of organic pollutants elimination and fouling vindication, more especially at the initial stage of the treatment. It eliminates fouling through continuous scouring of the deposited contaminants. However, as the retention of activated sludge prolongs, the shearing force of the scouring air could pose a serious drawback on flocs stability and breakup to generate more foulants. This is the major challenge of the aeration process in MBR, and therefore there is a need for further investigation.

Comparably, *AnMBR* has demonstrated a propitious performance in deflation of contaminants in high strength POME, resources recovery and minimization of operating energy, but high foulants polarization on the membrane surface during filtration is still the major weakness of this treatment process. Attempts to improve on the weakness of aerobic and anaerobic process were made by combining the processes to the hybrid system (*HybMBR*), but the problem of membrane fouling is still demanding and discourages wider application of the membrane technology. Moreover, recent advances in the use of MBR suggested that activated carbon (AC), sonication (*SonMBR*), and temperature (*TheMBR*) could reduce the susceptibility of the membrane to fouling through relegation of the concentration of the contaminant during pretreatment.

It is worth mentioning that combination of AC with MBR is technically demanding because of the required chemical treatment of absorbent (AC) which often leads to the creation of acidic effluent. In addition, this may increase the treatment footprint and operational cost due to the further treatments required to neutralize the pH. Moreover, in the case of sonication and temperature, they have high tendencies of distorting granulation stability, which could increase the density of small particles sizes and colloids. Therefore, there is a need for further investigation to establish optimal magnitude and duration for sonication as well as temperature in treating POME putting MLSS concentration, organic loading rate and solid retention time (SRT) into cognizance. However, AC presents noticeable advantages of reducing the total contaminants erstwhile to MBR treatment and this could reduce the fouling tendencies and improve flux recovery (91.7 to 95.3%). This offers ample solution to the problem of fouling if AC process is optimally integrated with aeration-anoxic processes in MBR.

On this note, additional investigations are required to develop a sustainable integrated treatment system and its optimal operating conditions such as aeration, biomass concentration and temperature. The integrated system includes the ideal the pre-treatment process using AC prior to membrane filtration in a single and one-term aeration-anoxic MBR treatment system (AA-MBR). Furthermore, to be able to develop such a treatment system, a good understanding of the adsorption process, biomass-substrate contact, stabilization conditions, and the combine process of aeration-anoxic is essential. Indispensably, a combination of AC and AA-MBR system will lessen vulnerability to fouling during POME treatment due to the concerted effect of the integrated technology. The integrated technology (AC and AA-MBR) could also improve filtration performance, contaminants removal efficiency, and result in a significant reduction in overall treatment cost.

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