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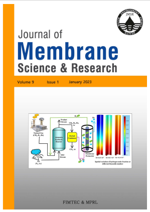

Review Paper

Membrane Bioreactor (MBR) as a Reliable Technology for Wastewater Treatment: Review

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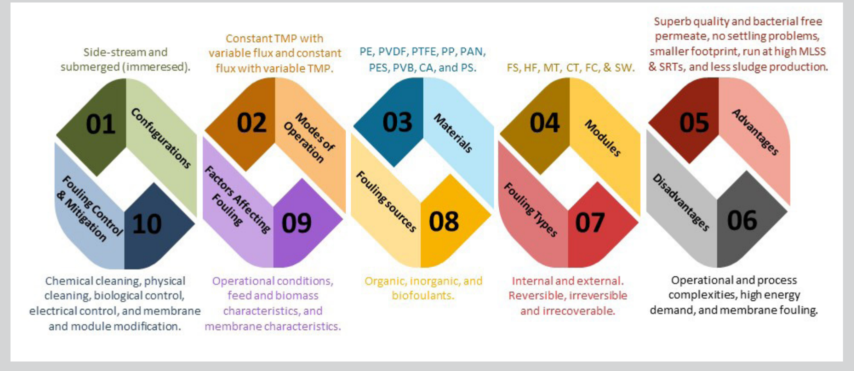
Highlights

- Up-to-date and comprehensive coverage for MBR technology for wastewater treatment.
- Constructing of systematic historical referenced-based record of literature.
- Presenting the newest progress and development to understand and minimize MBR fouling.

Graphical abstract



Abstract

Effluents from municipal wastewater treatment plants become a major contributor to water contamination. Higher quality effluent and the need for wastewater reuse are the key reasons for developing technologies towards improved wastewater treatment (WWT). Membrane bioreactor (MBR), a modern method for municipal wastewater treatment, combines membrane separation and biological treatment. In this article, an overview of MBR, its advantages and disadvantages, configurations, modes of operations, materials, and modules were presented. Membrane fouling issue was covered with a focus on types, sources and forms of fouling. Factors affecting fouling including operational conditions, feed, biomass and membrane characteristics were comprehensively discussed based on the latest research results. The article furtherly highlights recent experimental work conducted to mitigate and control fouling which include chemical cleaning, physical cleaning, biological control, electrical control and membranes and module modification. Challenges and future perspectives for MBR industry were also presented. The article concluded that despite having high capital and operation costs, the widespread of MBR is continuing and is expected to increase year by year, but fouling is the most significant hinder of its large-scale application for WWT. Fouling control, minimization or prevention is a hot research point that still needs further investigation and development.

Contents

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1. Introduction

Activated sludge (AS) has tremendous merit in treating polluted wastewater as well as sewage. It is a reliable, economical, and robust technology that contributes to our lives daily. Owing to this technology, we are living in a cleaner and safer water environment, although world populations are steadily growing and are concentrated in big cities. Nevertheless, the demand for a cleaner water environment has increased to protect aquatic life, and effluent standards are getting more stringent. The concern regarding environmental pollution, the anticipation of tough global waste discharge regulations, and the need for reusing wastewater are the key reasons for developing technologies towards improved wastewater purification [1, 2].

Applying WWT technologies aims to achieve the highest levels of water quality needed for a certain industry or by the environment. However, effluents from municipal wastewater (MWW) treatment plants generally do not comply with the national standard for effluent quality [3]. Many wastewater treatment plants (WWTPs) working with AS are inefficient enough to comply with the standards of wastewater reuse. So, it is important to treat the wastewater properly to overcome the above-mentioned problems as well as to comply with treated wastewater reuse standards [4, 5]. Wastewater including MWW, once treated properly, is a probable source that could be utilized as clean water supply to deal with the problem of water shortage. Of the modern methods that can be utilized for MWW treatment is membrane technology [6]. Membrane bioreactor (MBR) is a WWT technique combining both membrane separation and biological treatment. Although MBR technology did not come into the spotlight when it was first introduced by Smith and coworkers in the late 1960s, it has been playing a remarkable role in WWT and wastewater reuse since the mid-1990s. Stringent regulations on effluent discharge, demands for wastewater reuse, and the reduction of membrane capital costs are regarded as the main drivers for today's widespread use of this technology worldwide[1]. Membrane technology is vastly utilized in different treatment and reuse applications. In the recent years, membrane process was acknowledged as one of the preferable treatment methods for both domestic and industrial wastewaters [7-9].

Many advantages are associated with MBR which enabled it to be a better alternative as compared with AS. Removal of all suspended solids (SS) and the majority of dissolved matter inside the bioreactor will lead to superb permeate quality that is able to meet stringent discharge standards and provide the opportunity to direct wastewater reuse, particularly in regions of water shortage [4, 10]. The possibility of detaining bacteria will also result in a sterilized effluent, eliminate excessive use of disinfectants and the accompanying hazard related to disinfections by-products. The total separation of SS and control of sludge retention time and hydraulic retention times are possible in MBRs, this will facilitate controlling the optimum bacterial population and will result in flexible operation. Dispense of the secondary sedimentation tank, which is considered a natural elector for settling organisms, will enable sensitive, slow-growing nitrifying bacteria to develop and stay within the system even at short SRT. However, membranes retain the biomass and inhibit escaping extracellular enzymes and soluble oxidants, hence generating more active biological environments that are able to degrade wider ranges of carbon sources. The MBR also overcomes process difficulties and issues accompanied by settling, which is generally the most annoying part of WWT. The possibility to operate the MBR at a very long SRT without facing the problem of settling enables obtaining a higher concentration of biomass within the reactor. Therefore, stronger wastewater can be treated, and less biomass yield is achieved. This will also result in a compact system as compared to conventional systems and will significantly reduce plant footprint rendering it suitable for wastewater reuse applications. Soluble matter of high molecular weight, which can't easily be degraded in conventional systems, is removed in the MBR. Additionally, MBR is capable of handling variations in nutrient concentration because of extensive biological adaptation and retention of decayed biomass [10]. CAS cannot be operated at a high concentration of MLSS (Max. 5000 mg/L), this is because of the settling conditions in the final sedimentation tanks. However, MBRs can be run at high MLSS concentrations, resulting in less waste sludge because of bacterial degradation [11, 12]. This will also result in a smaller bioreactor footprint required to treat wastewater to a certain level (i.e., more compact), or a higher quality of treated water is obtained from the same volume of bioreactor compared to a CAS process. In MBR processes, theoretically, there is no maximum concentration of MLSS in a bioreactor, although 8, 000 – 12, 000 mg/L MLSS are regarded as optimal levels. Microorganisms tend to degrade themselves in bioreactors, MBR processes will produce less waste-activated sludge (WAS) and, therefore, reduce the cost associated with WAS removal [1]. Operating MBRs at longer SRTs is preferable because longer SRT reduces sludge production and this leads to lower sludge wastage [13].

For all the advantages, MBR also has disadvantages mainly related to the membranes. Membrane installments result in more operational and process complexities. These complexities are mostly associated with membrane maintenance and cleaning [14]. Membrane installment also requires additional capital cost, although the price of membranes has dramatically reduced over the last 20 years [1]. The high cost of membrane units and the high energy needed for developing a pressure gradient can also be added to the MBR drawbacks [15]. MBR tends to foul with time, this requires different operational strategies and techniques to minimize MBR fouling tendency [1]. Also, concentration polarization and other MBR fouling issues can result in a recurrent cleaning process, which will affect the operation and need clean water and chemicals [15]. In addition, antifouling strategies like aeration in immersed MBRs and recirculation of MLSS in side-stream MBR require additional operational costs. Sometimes the electrical consumption for MBR operation is greater than twice that of CAS. MBR also produces more bioreactor foams, a nuisance during operation [1]. Another drawback is the problem of disposing of the produced waste-activated sludge. Moreover, operating MBRs at long SRT results in inorganic matter accumulation in the bioreactor. When its concentrations become high, they may adversely affect the microbial populations or even the MBR structure [15]. Nevertheless, when no compromise is to be made in terms of effluent quality, the application of MBRs remains a potent choice for treating complex wastes in achieving disposal standards [10].

In accordance with the popularity of MBR technology, researchers and wastewater professionals are in continuous need of knowledge about the principles and applications of the technology. As MBR technology has great importance in WWT, it is important to have an updated review of MBR operation, fouling phenomenon, and fouling control and mitigation techniques. This paper will provide a broad thorough and systematic presentation of the comprehensive aspects of MBR. It will also provide a new-looking angle into MBR technology where general or partial perspectives do not trace and cover historically, and will follow a comprehensive and systematic approach that reflects the value and significance of MBR technology.

Nevertheless, up-to-date and comprehensive reviews on MBR technology including principles, applications, operations, fouling phenomenon, and its mitigation and control measures are difficult to find; only a few MBR publications cover all the previous topics. It is worth mentioning that this article is directed towards presenting MBR technology adopted for WWT; it presents a comprehensive summary of MBR technology and its basic terms, MBR configurations and modes of operation, MBR comparison with CAS, MBR materials and modules, fouling of MBR and factors affecting fooling. On the other hand, state-of-the-art methods of fouling control and mitigation in MBRs are presented. As well, some of the latest developments, future perspectives, emerging research, and studies focusing on MBR fouling minimization are also highlighted. This review was conducted comprehensively based on systematic historical order including the latest progress achieved by numerous researchers supported by results-based data and information.

2. Membrane bioreactor (MBR) technology

2.1 Definition of terms

- **Flux:** The water flow throughout a specified membrane surface area is known as the flux, and is calculated from:

$$Flux\ (\frac{L}{m^2,h}) = \frac{Permeate\ Flow\ (\frac{L}{h})}{Membrane\ Surface\ Area\ (m^2)} \tag{1}$$

- **Transmembrane pressure (TMP):** To generate flow throughout the membrane, water must have a pressure drop. The pressure drop means that there should be two pressure points, the static pressure when there is no permeate flow and the dynamic pressure with permeate flow. These two pressure points can be used to calculate TMP:

TMP = static pressure – dynamic pressure

- **Permeability:** If the flux is divided by the TMP, the specific flow rate throughout a specific surface area for a particular pressure drop can be got [16]. This is the membrane permeability and is calculated from the:

$$Permeability\ \left(\frac{L}{m^2,h,bar}\right)=\frac{Flux\ \left(\frac{L}{m^2,h}\right)}{Transmembrane\ \ Pressure\ (bar)} \qquad (2)$$

- **Critical flux:** It is a key operational factor in the MBR, and it was proposed that immersed MBR systems should be operated at subcritical flux to reduce fouling [17]. The critical flux is the maximum initial flux that the TMP value stays stable during MBR operation [12, 18].

2.2 MBR systems

The MBR is a generic term referring to the synergetic coupling of conventional biological WWT and membrane filtration. From a technical angle, the principle is the same as that of a conventional WWTP, except for separating the AS and effluent. In MBR systems, the separation isn't achieved by sedimentation in a final clarifier, however, it can be done by porous membranes with 0.05 - 0.1 µm pore diameters via membrane filtration [16, 20]. The bioreactor in an MBR system has the same role as the aeration reactor of any AS system in which wastewater is treated by microbial activity. As presented in Fig. 1; membranes utilized in MBR systems have pore diameters that are small enough to separate AS flocs, bacteria, and even viruses. Therefore, MBR produces very high-quality treated water containing almost no detectable suspended solids (SS). The treated water quality is equivalent to tertiary WWT (i.e., the combination of AS and deep filtration). In addition, membrane filtration in MBR processes eliminates gravity sedimentation tanks, which leads to a smaller footprint as compared to CAS processes [1].

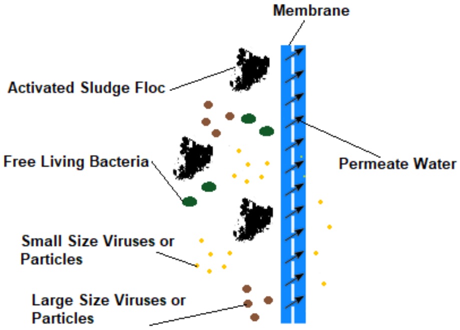


Fig. 1. Schematic presentation of the filtration of MBR.

Considering the ever-increasing pollutant load and the varying wastewater characteristics, conventional technologies are getting inadequate to meet the stringent standards [10]. MBR technology has gained in popularity as a method for MWW treatment to meet such stringent discharge standards. Capable of producing high-quality effluent, the membrane units in these systems are almost always coupled with aerobic reactors. Since almost all bacteria can be kept inside the reactor, MBR can provide sustainable and high-quality treated wastewater. Another advantage the MBR has; it can operate at high solids retention time (SRT), which is useful for micro-organisms characterized by slow growth [21]. The potential for MBR operation at very long SRT without having settling obstacles gives the chance to have higher biomass concentration in the bioreactor. Therefore, treating stronger wastewater can be attained, and lower sludge yield is obtained. This will lead to a more compact system as compared to conventional systems and dramatically reduce plant footprint, hence making MBR preferable for water recycling usages. The MBR has also the capability to retain soluble compounds of high molecular weight, these compounds cannot be easily biodegraded in conventional systems. Thus, the provided residence time for such compounds is lengthened and the possibility of their oxidation is enhanced. In addition, MBR can deal with any changes in nutrient concentrations caused by overall biological acclimation and retention of decayed biomass [10]. Therefore, biodegradation of refractory organic matter takes place even under shorter hydraulic retention times (HRT) [21]. MBR has also many advantages including better biological activity control, fast start-ups of the reactors, and higher organic load rates. MBR also overcomes operational obstacles and challenges accompanying the settling process [10, 16, 22, 23].

Using MBR systems for WWT does not always necessarily mean producing stable high-quality effluent. Obtaining effluent of high quality is not easy to obtain once the optimal conditions for the microorganism's function are not attained. This is because the treatment of wastewater pollutants, including organic and particulate biodegradable matters, inorganic nutrients, and non-settleable colloids, depends mainly on the microorganisms' activity in bioreactors in MBR plants. In addition to that, the characteristics of microbiological floc, including size and microorganisms' filamentous content, are affected by the bioreactor operational conditions, and they influence the membrane fouling properties. Therefore, it is extremely important to optimize the operation of bioreactors in MBR plants to achieve the intended goals of WWT [14].

MBR systems are considered reliable alternatives for WWT that can produce effluents of excellent quality. They have proved their efficiency in removing organic, inorganic, and biological constituents from wastewater [16]. The removal efficiency of chemical oxygen demand (COD) was reported to vary from 90 % to 99 % for domestic, municipal, and synthetic wastewater and from 63 % and 99 % for industrial wastewater. Out of the overall COD removal efficiency of MBRs, the bioreactor contributed 80-90 % COD removal efficiency mainly due to biological degradation and the membrane contributed 10-20 % COD removal due to rejection, plugging, and adsorption properties [24, 25]. The degradation in a bioreactor at high biomass concentration resulted in high COD removal. Several other factors responsible for COD removal are HRT, SRT, Organic loading rate (OLR), and membrane separation phenomena [10]. Earlier, only 65 % of SS removal was possible utilizing AS process [18]. Addition of membrane unit in CAS by replacing secondary clarifier improves SS removal efficiency up to 100 % [26-28].

Membranes used for water and wastewater applications include micro-filtration (MF), ultra-filtration (UF), nano-filtration (NF), and reverse Osmosis (RO). Generally, MF is appropriate for removing suspended solids, protozoa, and bacteria. UF is needed to remove viruses and organic macro-molecules down to a size of approximately 20 nm. Organic matter that has a smaller size and multivalent ions can be detained by NF, but RO is used to remove all species of dissolved matter [4, 5, 29]. Fig. 2 outlines an overview of membrane separation processes. The produced effluent per unit membrane area (flux) ranging from 0.05 to 10 m/d ($m^3/m^2/d$) is highly dependent on both membrane material and configuration. At the temperature of 20 C°, the inner skin membranes have flux values from 0.5 to 2.0 m/d, the outer skin membranes have flux values that range from 0.2 to 0.6 m/d. The applied TMP Values range from 0.02 to 0.5 MPa for inner skin membranes and from -0.01 to -0.08 MPa for the outer skin membranes.

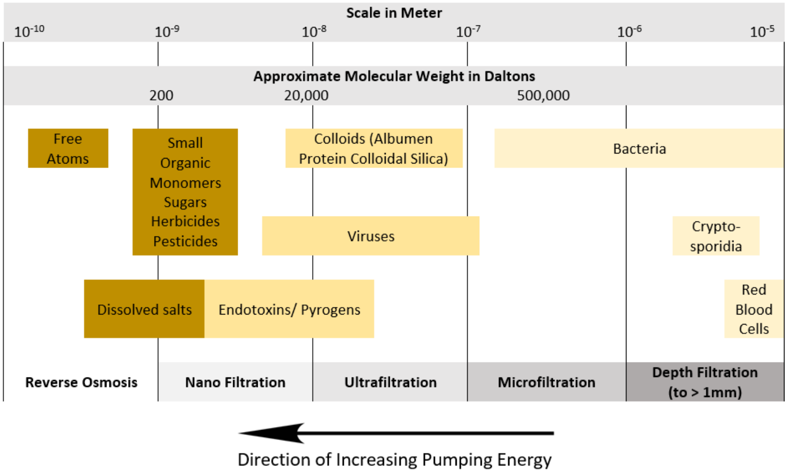


Fig. 2. Membrane separation processes overview.

3. MBR configurations

The membrane bioreactor is mainly composed of two parts, the biological unit which aims to degrade the organic matter, and the membrane unit which is for responsibly separating the effluent from the mixed liquor [16]. Two MBR generations are available; the submerged MBR system and the side-stream system as shown in Fig. 3. Here is a brief description of each type.

3.1 Side-stream MBR

The first type of MBR system (side-stream) is composed of an external membrane operated by cross-flow, which was installed outside the AS reactor. Both inner and outer skin membranes can be utilized in this system. The cross-flow precept, accompanied by high flow velocity, was utilized to avoid solids' accumulation on the membrane's surface, which is termed cake-layer formation. The cross-flow operation requires a great energy amount to overcome the sludge velocity across the membrane surface to keep both the high cross-flow velocity needed to clean the membrane and the needed pressure drop needed for permeation. Due to its high energy demand, this type was considered a not-viable application for treating MWW. Moreover, using a pump for recirculating the cross-flow requires high pressure, and excessive shear was assumed to negatively affect the size of the floc and stability inside the system [16, 19, 30]. Most pressurized membrane modules are cylindrical and can have either flat sheet or hollow fiber-type membranes. Pressurized modules have to endure higher hydraulic pressure and accommodate thousands of membrane fibers to satisfy larger effective membrane areas, and the cylindrical shape is the most adequate [14]. In such MBRs configuration, the crossflow velocities range from 1.2 to 1.8 m/s with 150 - 185 kPa to reduce fouling and to maintain a stable flux (13.6 to 23.4 L/m^2/h). The effluent quality was typically lower than 5 mg/L BOD and achieved 100% removal of coliform bacteria for 90% of the operational time [1].

Flat sheet membranes are wound tightly with spaces of proper thickness to secure the source and permeate water channels inside. Inside-to out-type hollow fiber membrane modules have as many orientation choices as spiral wound ones, but outside to in-type hollow fiber membrane modules have to be installed vertically to avoid unfilled water channels. The biggest advantage of pressurized membrane modules is higher permeate water flux rates. Unlike drinking water treatment membranes, MBR membranes endure high concentrations of biomass (5, 000 to 15, 000 mg/L) higher operating pressures, and flux, all of which accelerate membrane fouling. Pressurized membranes cannot be scrubbed by aeration during permeation, so they tend to foul more quickly. To solve this problem, they are operated at higher cross flows instead of aeration, but higher cross flows result in too much energy loss from overdesigned crossflow pumps that have 5-15 times higher flow capacity than that of the permeate flow. At least in MBR, pressurized membrane modules have problems that need to be solved to guarantee higher permeate water flux at high influent water flux rates [14].

3.2 Submerged MBR

An outstanding development for MBR has achieved the immersion of the outer skin membrane that took place inside the aeration basin. To obtain the required permeate, the system used lower pressure as compared to external installations in pressure tubes and the need for high over pressure, such type was known as submerged MBR (SMBR). Energy requirements were dramatically lowered. The applied pressure utilized for extracting the permeate was substantially less than that needed for cross-flow permeation. Moreover, an important part of the cross-flow system, the recirculation pump, was unavailable in the SMBR systems. Therefore, the choice between submerged and side-stream aerobic MBR systems becomes stable, in favor of submerged MBR [19, 30, 31]. Air diffusers are generally located directly below the membrane module to achieve aeration, and mixing and to enhance scouring for the filtration surface [16].

In general, submerged membranes are directly installed in the source water tank. In MBR systems the modules are located in the bioreactor or a separated membrane tank right after the bioreactor. Even in the latter case, the membrane tank is filled with biomass. Submerged setups can reduce the footprint and the need for an extra source water tank. The membranes are exposed to source water and can move freely. This setup is easy to maintain and experiences less fouling because of extra aeration provided by aerators installed below the modules. The energy of the suction pump producing permeated water is lower than that of a pressurizing pump at the same permeability given constant temperature. The only disadvantage of submerged membrane modules is a narrow permeate flux range. They are operated at 70% flux compared to pressurized membrane modules. In MBR systems, permeate flux is generally in the range of 10-40 LMH at 20 ºC [14].

Unlike flat sheet membranes, hollow fiber membrane modules have orientations. Vertically oriented membrane modules show less accumulation tendency for AS flocs on the membrane surface. However, a part of the system footprint has to be left available for an aeration channel because they have the permeate water channels at the bottom that hinder the air bubbles from the aerators. Horizontally-oriented ones have the permeate water channels on both sides, so they do not consume any footprint for membrane installation; thus, they show higher packing densities than vertically oriented ones. However, horizontally oriented modules have a higher fouling potential and may experience an easy accumulation of foulants or AS flocs [14].

4. Modes of MBR operation

The MBR can be operated in two operating modes they are, constant TMP with variable flux and constant flux (L/m^2 h) with variable TMP. The latter is preferred because it is able to easily handle variations in influent hydraulic loadings [32]. Fig. 4 shows the typical pattern of MBR performance according to the operation mode. Naturally, the lines in Fig. 4 are exactly opposite because TMP and flux reciprocate each other [14].

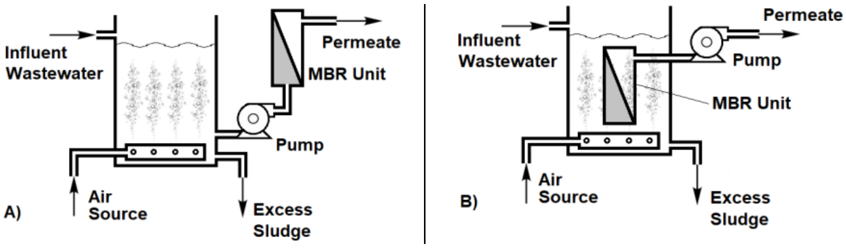
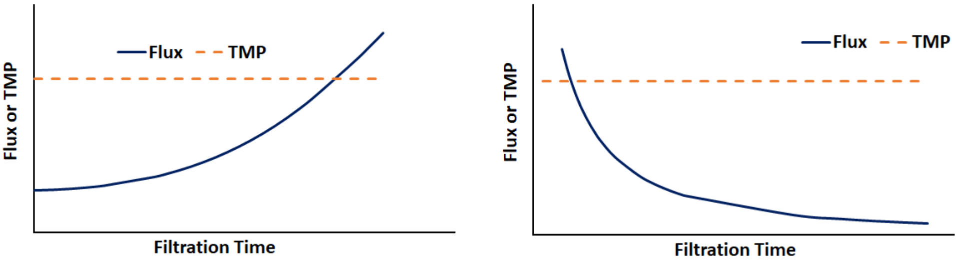


Fig. 3. (a) Side stream MBR system and (b) submerged MBR system.



(a) Constant Flux Operational Mode

(b) Constant Pressure Operational Mode

Fig. 4. Operational modes of MBR.

5. Comparison between conventional activated sludge (CAS) and MBRs

CAS processes mainly consist of a bioreactor treating wastewater using activated sludge (i.e., active microorganisms) and a secondary clarifier for separating the treated wastewater from the mixture of activated sludge (plus some SS originating from non-biomass) and treated water. Sedimentation tanks are not perfect in settling all of the activated sludge. A lighter fraction of activated sludge is washed away with the treated effluent. Typically, the SS concentration of the supernatant from the sedimentation tank is about 5 mg/L even for well-functioning secondary clarifiers [1]. However, in MBR processes, all AS is separated from the effluent via membranes because the membranes' pore size (<0.1 µm) is smaller than the AS particles [33], as shown in Fig. 5. This results in almost no detectable concentration of SS in the treated effluent, although dissolved matters can pass through the membrane pores. This means that MBR processes produce a higher-quality effluent than CAS processes. The higher effluent quality is primarily due to the near-perfect removal of SS by membrane filtration. Although CAS processes result in 5 mg/L SS even for a well-operated secondary clarifier, MBR processes can reject most SS in a bioreactor by membrane filtration (SS < 0.2 mg/L). If we acknowledge that organic matters, nitrogen, and phosphorus are components of SS, it is no wonder that the quality of treated wastewater using MBR is better than that of CAS. Therefore, tertiary treatments such as sand filters and micro-filters for removing SS can be eliminated from MBR systems [1].

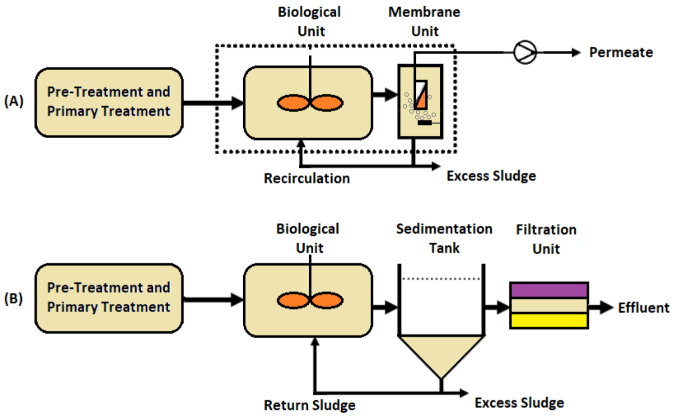


Fig. 5. Configuration of: (A) Submerged MBR system, (B) CAS System

Both CAS processes and MBR processes utilize the metabolic power of microorganisms in bioreactors for treating wastewater. Therefore, the rate of WWT is basically proportional to the concentration of active biomass in the bioreactor. However, in CAS processes it is not possible to increase the concentration of activated sludge greater than a certain level due to the limitations of secondary clarifiers. Clarifiers are operated according to the settling properties of activated sludge governed by gravity and interactions between activated sludge particles [1]. Table 1 outlines a comparison summary between MBR and CAS in terms of operational and performance parameters and effluent characteristics.

SRT is a significant operational parameter for a bioreactor that controls the treated water quality and MLSS concentration of the bioreactor. SRT is the average amount of time a solid spends in a bioreactor. It is determined by dividing the total MLSS mass in a bioreactor over the WAS removal rate (MLSS concentration × bioreactor volume) ÷ (WAS concentration × flow rate). Generally, increasing SRT will increase the WWT efficiency and will decrease the concentration of substrate. Longer SRT operation of MBR systems (usually > 20 days) compared with CAS systems (usually 5–15 days) contributes to the effluent of high quality in MBR systems. In many CAS cases, SRT is controlled by modulating the WAS rate in the sedimentation tank. However, the concentration of WAS is not stable depending on the settling characteristics of the AS in the secondary clarifier, which makes it difficult to precisely control the SRT. In MBR, WAS is got directly from the bioreactor (MLSS concentration= WAS concentration). SRT is thus calculated as bioreactor volume over wastage flow rate, which provides a simpler and more precise way to modulate SRT [1].

6. Membrane bioreactor materials and modules

Membrane materials used for MBR processes are categorized into polymeric and ceramic materials. Although polymeric materials have been commonly used to fabricate membranes, membranes made of ceramic materials have started to gain attention due to their durability and chemical resistance. Diverse polymer materials including polyethylene (PE), polyvinylidene difluoride (PVDF), polytetrafluoroethylene (PTFE), polypropylene (PP), polyacrylonitrile (PAN), polyethersulfone (PES), polyvinyl butyral (PVB), cellulose acetate (CA), and polysulfone (PS) have all been used to fabricate membranes. Among them, PVDF is the most popular. The development of enhanced mechanical-structured PVDF membranes has made it possible to overcome the brittleness of membranes of which WWT practitioners often complain. The prolonged lifetime of PVDF membranes has led to widespread installations of MBR plants worldwide [1, 34].

Table 1
A comparison summary between MBR and CAS

Parameter Type	Parameter	MBR	CAS	Reference
Operating Parameters	DO (mg/L)	2 – 5	2.7 – 7.9	[35]
	MLSS (mg/L)	2500 – 15000	1000 – 1600	[35]
		15000 – 25000	3000 – 5000	[36]
		10000 – 12000	3000 – 5000	[37]
		10000	3000	[38]
	SRT (d)	8.2 – 16.8	3.4 – 8.9	[35]
		26	15 – 18	[37]
		15	15	[38]
	HRT (h)	0.5 – 4.5	5.2 – 7.9	[35]
		18	18	[37]
		3.6 – 6.5	12 - 23	[38]
	pH	7.0 – 7.8	7.3 – 7.8	[36]
	VLR (kg/m^3/day)	8.6 – 12.9	0.75 – 1	[36]
		0.91 – 1.24	0.6 – 0.9	[37]
Performance Parameters (%)	COD Removal	97	82	[36]
		94.82 ± 2.07	92.7 ±/5.18	[39]
		97.1	85.6	[40]
	Oil Remove	99.9	82	[36]
	Ammonia Removal	98.34 ± 2.01	97 ± 3.21	[39]
		94.6	42.9	[40]
	SS Removal	100	63.6	[40]
Effluent Characteristics (mg/L)	Effluent Turbidity	0.44	15	[40]
	BOD	0.3 – 2.8	0.15 – 2.1	[40]
	COD	7.2 – 22.4	0.2 – 15.4	[40]
	SS	0.2 – 2.1	0.5 – 3.5	[40]
	TN	3.8 – 17.1	5.1 – 10.2	[40]
	TP	0.06 – 1.4	0.01 – 0.2	[40]

Currently, six main membrane configurations are available, they have different practical pros and cons as outlined in Figure 6. These configurations are classified according to either planar or cylindrical geometries and include Plate and Frame/Flat Sheet (FS), Hollow Fiber (HF), Multi Tubular (MT), Capillary Tube (CT), Pleated Filter Cartridge (FC), and Spiral Wound (SW). MBR systems must promote turbulence, cleaning, or, ideally, both. Turbulence is promoted through the passage of feed water and air/water mixtures along the membrane surface to aid in passing the permeate through it. This crossflow operation is vastly applied in various membrane processes, and its efficiency increases with increasing membrane interstitial distance (membrane separation) [30].

FS and HF types, the predominant configurations worldwide, are generally utilized for the submerged MBR configuration, while the MT type is exclusively used in side stream MBR configuration. All types of membranes are packaged into modules for application in MBR. Membrane modules were developed to intensify their packing density because more highly packed membrane modules are better in terms of saving footprint. Packing density is mainly increased by increasing the number of stacks (or decks) for FS membrane modules and by packing (or potting) membrane fibers more closely together or by lengthening the membrane fibers for HF membranes [1, 41]. Fig. 7 shows HF, FS, and MT membrane bioreactor samples.

The most important advantage of hollow fiber MBRs over flat sheet MBRs is the membrane cleaning times. Hence, less chemical consumption and shorter maintenance times are experienced [42]. HF membranes have a full back-pulse ability for fouling control, scouring by air is also utilized for the same purpose [43] and their fibers are suitable for backwashing [42]. On the other hand, FS membranes can experience fast clogging and are unable to be back-pulsed. Air scouring can be used to control FS membrane fouling [43]. As backwashing characteristics were not good in FS membranes, backwashing cannot be done completely, therefore, they must be taken out of the pool for washing [42].

7. Membrane fouling

Despite the outstanding progress of MBR technology, MBRs do not escape from fouling which hinders their application tremendously. Fouling is the major hurdle accompanying the universal and full-scale application of membrane processes for WWT and is still a major scientific and practical concern. Fouling reduces the membrane permeability, limits flux, and decreases the membrane's lifespan, hence raising the investment cost and the running expenses of the system. Therefore, most research on MBR concentrates on investigating the mechanism of fouling and controlling/ minimizing its occurrence [4, 47-57].

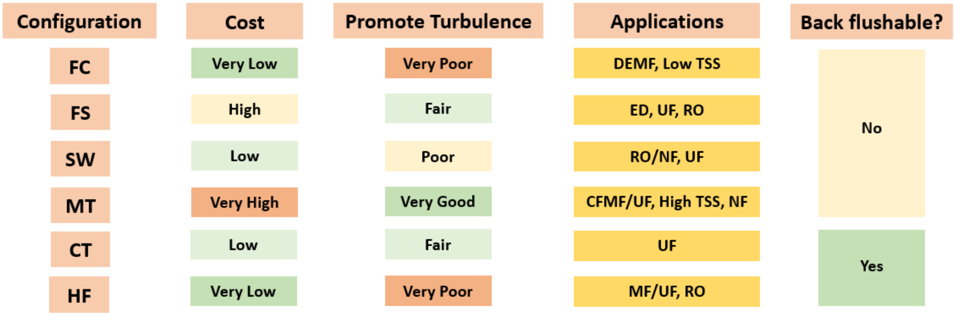
Fouling is a serious issue for MBR systems and it must be inhibited or mitigated so that its adverse effects can be minimized and production loss can be overcome [58]. Fouling is the phenomenon in which the performance of MBR is retracted due to the presence of different components in wastewater, which can gradually raise the membrane's resistance because they are adsorbed or deposited on the membrane surface, or entrapped in its pores [52, 59]. It is the most significant parameter to control for sustainable membrane operation, and it is tightly dependent on the source water quality and the membrane operation process [1].

7.1 Types of fouling

In MBR operation, TMP and flux are two operational parameters linked to each other. If operational conditions stay unchanged, to get more flux, TMP is to be increased. On the contrary, if TMP is changed, the flux will change accordingly [60, 61]. According to the operational mode (constant flux or constant pressure), fouling in membranes can be characterized by flux reduction or increase in TMP respectively. Constant pressure mode is represented by a quick flux decrease at the beginning of the operation, after that gradual decline takes place until reaching a steady state or a pseudo-steady state flux. TMP in the constant flux mode and flux in the constant pressure mode should be monitored along with operation run time to perceive fouling in MBR [14]. Fouling is too complex to completely understand, therefore, no single mechanism can describe fouling. Fouling in MBR can be classified into various types according to what the classifying criterion is applied to [1].

In general, fouling can be either external or internal. External fouling resulted from the accumulation of foulants on the outer surface of the membrane. Internal fouling is resulted from the adsorption of small particulates or macromolecules inside the membrane's internal pore structure. Such type of fouling will degrade the performance of the membrane even under dynamic conditions [62]. Fouling results in declining permeate flux hence shortening the time intervals required for the membrane replacement and/or cleaning; both requiring higher operational costs [52]. Thus, successful MBR operation depends on how to cope with membrane fouling, which is influenced by many factors [14].

From another angle, fouling can be reversible, irreversible, and irrecoverable. Reversible fouling takes place because of the external deposition of material and can be overcome by physical methods like backwashing or relaxation, irreversible fouling can only be cleaned by chemical methods with intense physical flushing and irrecoverable fouling can't be overcome and takes place over long periods [21, 50]. Furthermore, frequent chemical recovery cleaning reduces the life span of membranes because of increasing irrecoverable fouling and deterioration of the membrane material [1]. It was found in the literature that fouling in MBRs can be classified according to five criteria, these classifications and their descriptions are outlined in Fig. 8.



Configuration	Cost	Promote Turbulence	Applications	Back flushable?
FC	Very Low	Very Poor	DEMF, Low TSS	No
FS	High	Fair	ED, UF, RO	
SW	Low	Poor	RO/NF, UF	
MT	Very High	Very Good	CFMF/UF, High TSS, NF	
CT	Low	Fair	UF	Yes
HF	Very Low	Very Poor	MF/UF, RO	

Fig. 6 Membrane Configurations and Applications

Note: CFMF: Cross flow micro filtration, DEMF: Dead end micro filtration, ED: Electro dialysis, MF: Micro filtration, NF: Nano filtration, RO: Reverse osmosis, UF: Ultra filtration

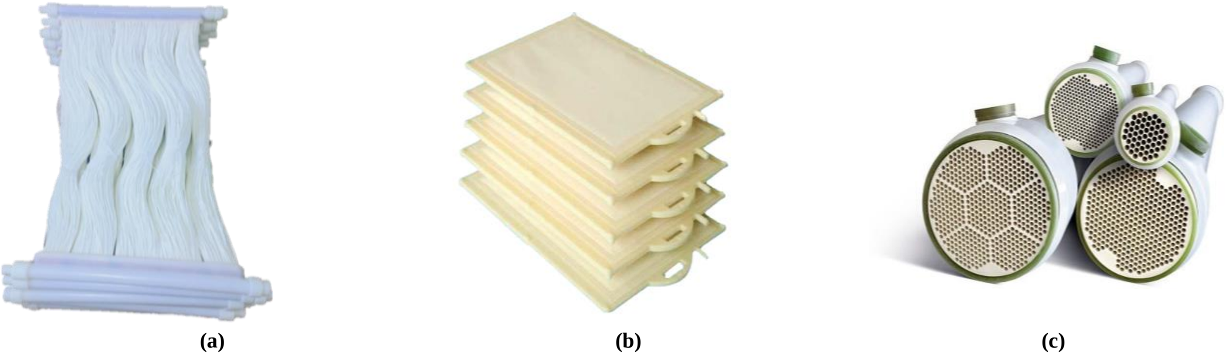
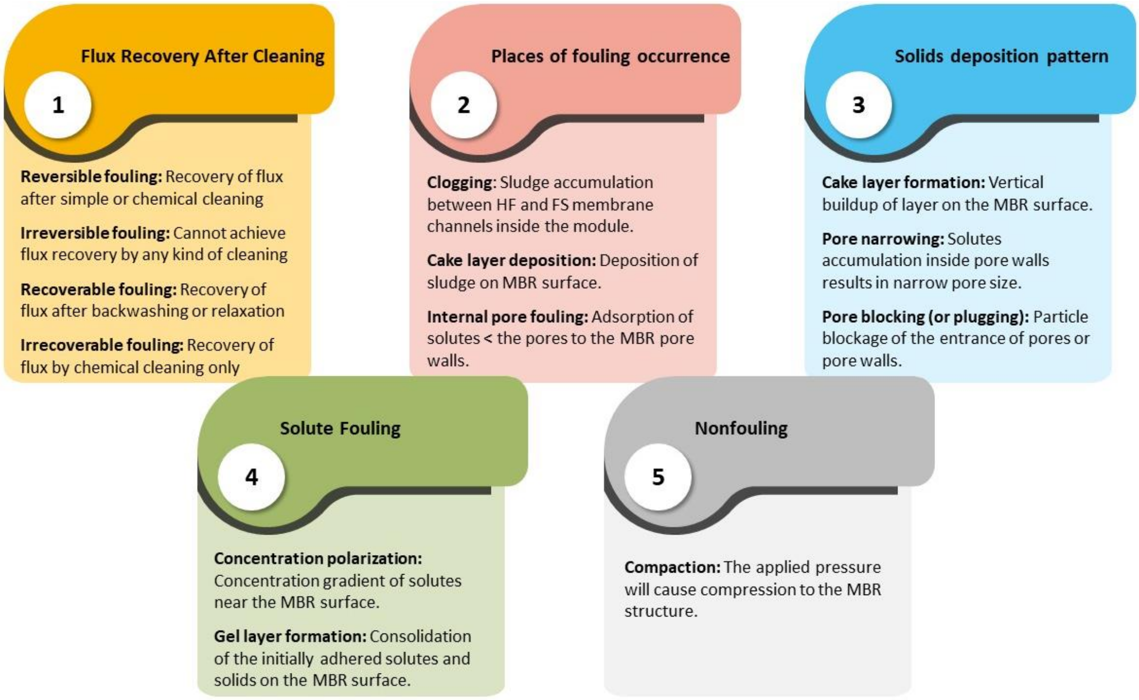


Fig. 7. MBR samples: (a) Hollow fiber [44], (b) Flat sheet [45], (c) Multiple tube [46]



Flux Recovery After Cleaning

Reversible fouling: Recovery of flux after simple or chemical cleaning

Irreversible fouling: Cannot achieve flux recovery by any kind of cleaning

Recoverable fouling: Recovery of flux after backwashing or relaxation

Irrecoverable fouling: Recovery of flux by chemical cleaning only

Places of fouling occurrence

Clogging: Sludge accumulation between HF and FS membrane channels inside the module.

Cake layer deposition: Deposition of sludge on MBR surface.

Internal pore fouling: Adsorption of solutes < the pores to the MBR pore walls.

Solids deposition pattern

Cake layer formation: Vertical buildup of layer on the MBR surface.

Pore narrowing: Solutes accumulation inside pore walls results in narrow pore size.

Pore blocking (or plugging): Particle blockage of the entrance of pores or pore walls.

Solute Fouling

Concentration polarization: Concentration gradient of solutes near the MBR surface.

Gel layer formation: Consolidation of the initially adhered solutes and solids on the MBR surface.

Nonfouling

Compaction: The applied pressure will cause compression to the MBR structure.

Fig. 8 Classifications of MBR fouling and their description

7.2 Sources of fouling (Foulants)

According to the foulant type deposited onto the membrane surface and its biological and chemical properties, foulants are grouped into organic foulants, inorganic foulants, and biofoulants. However, fouling usually happens in a complex manner, where the different types of fouling can't be distinctly identified. The attachment of organic matter to the membrane surface will result in organic fouling. Inorganic fouling (mineral scale) happens as a result of inorganic particle sedimentation, colloids, and crystallization of solids and salts initially existing in the feed-water in the membrane pores. Bio-fouling is caused by the adhesion and growth of viruses, bacteria, algae, and fungi on the surface of the membrane [63-68]. The following paragraphs give a short description of each type of fouling.

Organic Foulants: They include bio-polymers which accumulation on the membrane will result in their permeability decrease. Such foulants are available in bacterial products, which are collectively named extracellular polymeric substances (EPS). Compared to larger particles size, for example, the sludge floc, cleaning organic foulants from the membrane surface is not easy [69]. In an experimental investigation of fouling at different operating conditions using a lab scale immersed hollow fiber MBR modules, it was found that bio-polymers are significant foulants and have an important effect on fouling. The experiment also revealed that the fouling rate was dependent on bio-polymer concentrations in the mixed liquor [70]. Research revealed that the MBR system includes a variety of free organic solutes known as biopolymer clusters (BPCs), [71], such solutes differ from bacterial flocks and are characterized by large sizes as compared to soluble microbial products (SMPs) [72, 73]. Because of their larger size, BPCs are captured in MBRs and hence are absent from the permeate. The high area of MBR systems provides a suitable condition for forming and growing BPC; hence resulting in severe fouling [73].

Inorganic fouling: Inorganic foulants include inorganic matters, and biological precipitations of inorganic and organic compounds on the membrane surface or in its pores. These compounds may contain positively and negatively charged species that may precipitate on the membrane surface because of hydrolysis which will result in oxidation and variation in pH [53, 70, 74]. Moderate concentrations of metal ions, like Ca^{2+} (up to 280 mg/L), may have a positive role in mitigating and reducing biofouling [75]. The two main mechanisms playing a crucial role when inorganic fouling in MBRs is developed are crystallization and particulate fouling. In crystallization, the ion's precipitation takes place on the MBR surface, but particulate fouling takes place due to colloids, available in the solution, deposition on the MBR surface [76]. To overcome this fouling, chemical cleaning methods are generally applied as they are more efficient than physical methods [49].

Biofoulants: The attachment, growth, and biological activity of bacteria and flocks will result in biofouling [49], which is a major troublesome matter in membrane operation [77]. Firstly, one bacterial cell might adhere to the surface of MBR or within its pores, later on, the cell will multiply into clusters, resulting in bio-cake formation, and permeability decline. Bacteria and their metabolic products enhance biofouling [78].

7.3 Forms of fouling

Fouling takes place in multiple forms, pore-clogging, gel formation, and, cake formation. Pore clogging results from the membrane micro pores blocking [79] and is largely dependent on the particle size and the membrane pore size [80]. In general, it happens quickly in the early stage of membrane operation because the membrane surface is free from depositions and the incoming particulates may directly interact with the membrane pores. Pore blockage increases the flux through the unclogged pores and also the mass transfer rate that may or may not enhance the internal fouling if the flow rate is maintained constant [80]. The attachment of particles inside the pores is enhanced by slimy materials in the mixed liquor [79].

Gel formation is resulted due to the consolidation of a layer including a high concentration of macromolecules immediately close to the membrane surface resulting from concentration polarization [81-84]. The transition from concentration polarization to fouling happens when the force of attraction exceeds the force of electrostatic repulsion [85]. The flux at which the gelation happens denotes the ''limiting flux'', which represents the highest stationary permeate flux that the system can yield [86]. Furthermore, cake formation resulted from the uninterrupted deposition of bacterial clusters, bio-polymers, and inorganic matter, which create a bio-cake onto the membrane [79]. Cake formation is the stage through which particles accumulate gradually on the external membrane surface, resulting in further resistance to the permeate flux. This is usually known as a fouling cake formation and the additional resistance is referred to a cake resistance. A cake layer may contain various types of solutes that include inert or active colloids. Forming an initial cake layer of inert colloids adjacent to the membrane surface inhibits the direct interaction between the membrane surface and further foulants. The inert cake layer behaves as a pre-filter, that filtrates those materials characterized by a high fouling tendency [87], this phenomenon is known as a 'filter aid' [88]. Additionally, active foulants may reach the membrane surface first and bridge inert depositions to it [89, 90]. This results in a more adhesive cake and therefore fouling turns irreversible. Occasionally, 'over-clogging' may happen when smaller macromolecules get into and occupy the interstices of a cake formed by particles with the same structure, resulting in a higher hydraulic resistance [87, 91]. The morphology of the fouling cake controls the flux reduction, while the interaction between the membrane surface and the cake layer determines the fouling reversibility [90]. There is no united statement describing the membrane fouling mechanism, however, fouling in MBR is schematically outlined in Fig. 9.

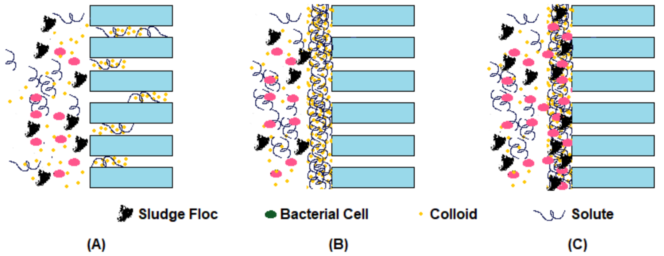


Fig. 9. Presentation of MBR fouling: (A) Pore clogging, (B) Gel layer formation, and (C) Cake layer formation.

8. Factors affecting fouling in MBR

Membrane technology includes complicated interactions among membrane surfaces, operational conditions, and wastewater being treated. Membrane fouling – regardless of its type – is a complex process that is affected by lots of factors [80, 92-95]. Despite the difficulty to define a single rule about membrane fouling in MBR, many groups of factors influence the fouling formation rate, they are membrane characteristics, operational conditions, and feed and biomass properties. Under such groups there are many factors as outlined in Fig. 10. The interaction between these factors will result in multiple effects on MBR fouling. Understanding the fouling phenomenon is very important to apply a proper strategy to reduce, mitigate and overcome its consequences. The following sections provide a short description of the main parameters affecting MBR fouling.

8.1 Operational conditions

8.1.1 Mode of operation

When MBR is operated at constant permeate flux, the sudden increase in TMP indicates that fouling starts to develop. The critical flux is a numeric value above which solids attachment to the membrane surface becomes visible; its determination should be done in the constant permeate flux mode. The sustainable flux, generally less than the critical flux, will provide a reasonable TMP increase. When the operational flux is more than the sustainable flux, MBR fouling rate is not sustainable from economic and environmental points of view [96, 97]. Therefore, it is preferable to run MBR at the sustainable flux rather than the critical flux [86] or at fluxes that will develop an appropriate incremental rise in TMP, hence, chemical cleaning is not necessary [98]. In summary, operating a certain MBR at a flux lower than the critical value will prevent immoderate biomass deposition on the membrane surface [49, 99, 100].

8.1.2 Rate of aeration

The rate of aeration (m/h), which is one of the key design parameters for submerged MBRs, is the ratio of the supplied airflow rate (m^3/h) to the membrane area (m^2) [1]. Aeration has two roles in MBRs as it provides oxygen for bacteria and displaces the cake layer from the membrane surface. Oxygen provided through aeration will facilitate the biodegradation process and biomass cell synthesis [101]. Research showed that an increase in the aeration rate in MBR will lead to reduced membrane Fouling [102, 103]. In research to study the effect of aeration rate on fouling in a lab scale immersed MBR, Yigit et al. 2008 [104] found that increasing the aeration rate will positively control fouling in MBRs. The level of this positive influence was extraordinarily decreased when MLSS was increased. This is attributed to elevated viscosity due to the high MLSS concentrations.

Even though higher aeration rates can reduce membrane fouling via the scouring action, they also influence microbial characteristics. Aeration of high intensity was accompanied by breaking the sludge flocs and producing SMPs [49]. Furthermore, higher aeration rates require more energy and hence will lead to an increase in operational costs [105, 106]. Therefore, an optimum aeration intensity is needed to achieve the balance between these issues. It was outlined that moving far from the critical aeration intensity will increase fouling in MBR because big flocks will be broken by the action of shear [107].

8.1.3 Sludge retention time (SRT)

SRT is a significant factor influencing fouling in MBRs [34]. A large number of researches indicated that increasing SRT resulted in decreasing the EPS concentration as the biomass stayed longer in the bioreactor and decreasing SRT increased the EPS amount [108-111]. High SRTs produced a starvation condition in the bioreactor, thus generating a suitable condition to produce fewer EPS, generate less sludge, and enhance nitrification [30, 69]. Excessively high SRT isn't preferable as it may increase membrane fouling because of MLSS accumulation and raising sludge viscosity [110]. Extremely high SRTs cause high biomass concentration leading to a lower efficacy of the aeration process [112]. The impact of altering SRT on membrane fouling is attributed to the corresponding microbial characteristic variations. In an experimental investigation to study the influence of SRT on MBR fouling, Van den Broeck et al. 2012 [112] noted less fouling rates at SRTs of 30 and 50 days as compared to 10 days. It was reported that MBRs' operation at more than 50 days will increase fouling [34]. Likewise, operating MBRs at very short SRTs (≈ 2 days) will extremely increase fouling [98]. This is due to the elevated EPS (bound and soluble) concentrations at short SRTs [49]. Extremely short SRT also led to a reduced MBR performance because of the small biomass concentration [113].

8.1.4 Hydraulic retention time (HRT)

As the HRT of a biological reactor such as an activated sludge basin decreases, the possibility of washout increases. Therefore, it is important to maintain a proper HRT [1]. HRT indirectly affects membrane fouling because it influences the sludge characteristics. Most research findings show that decreasing HRT will increase fouling rates in MBRs [114, 115] this is because of increasing sludge viscosity and EPS concentration [49]. Decreasing HRT will stimulate releasing EPS from bacterial cells, will result in excess growth of filamentous bacteria, and thus will result in forming of irregular large flocs. Moreover, decreasing HRT will result in increasing MLSS concentration and sludge viscosity which are the dominant parameters influencing the hydrodynamic conditions of MBRs [77, 114]. Isma et al. 2014 [116] studied the effect of changing HRT and SRT on MBR fouling using SRTs of 4, 15, and 30 days at HRTs of 4, 8, and 12 h, respectively. They concluded that SRT of 30 days and HRT of 12 h will reduce MBR fouling and slow the jumps in TMP. Likewise, research on the influence of bacterial activity and fouling tendency in immersed anaerobic MBRs operated at HRTs of 14, 16, and 20 days revealed that lowering the HRT from 20 to 14 days caused more EPS production, and thus extreme fouling [117]. Therefore, HRT indirectly influences membrane fouling by changing the microbial characteristics [1].

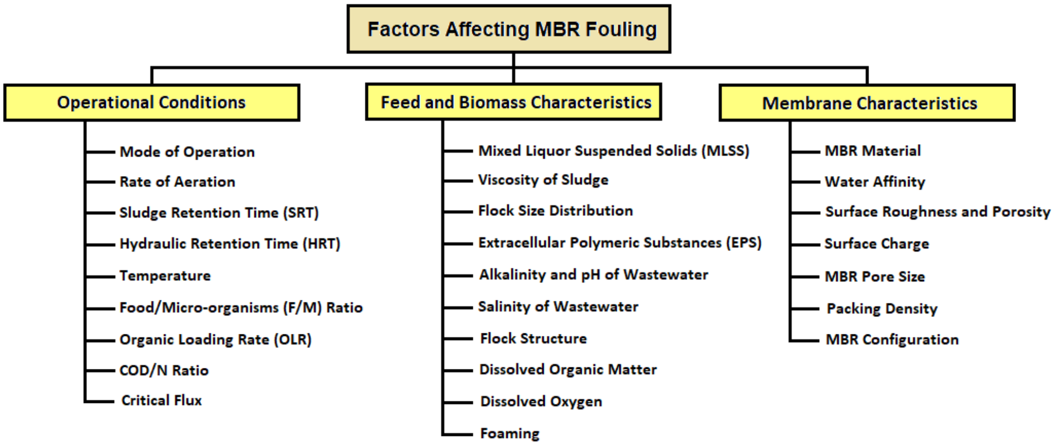


Fig. 10. Factors affecting MBR fouling

8.1.5 Temperature

Temperature affects fouling by changing the characteristics of MLSS and influencing the rate of biodegradation. It was found that lowering the operational temperatures will allow bacteria to produce more EPS [118]. Very low temperature is accompanied by an intense presence of filamentous bacteria that release more SMPs [77], thus a higher tendency to fouling. De-flocculation, diffusivity, biodegradation, and adsorption in MBR were denoted to be temperature-dependent [50]. In general, four phenomena have been put forward to illustrate how the lower temperature in MBRs will increase membrane fouling: (a) increased viscosity that leads to lower shear stress produced by aeration; (b) intensified de-flocculation that leads to lower biomass floc size and release of EPS; (c) lowered back transport velocity, and (d) less organic matter biodegradation [119]. Sudden temperature variations were found to result in unprompted production of SMPs, deterioration of the biomass, and increase fouling rates [120]. De-flocculation of sludge flocs was found to happen after a temperature elevation from 30 to 45 degrees which will also raise both turbidity and SMPs concentration [121]. To control such issues, running the MBR at ambient temperatures and averting abrupt temperature variations are recommended. If low temperatures can't be avoided, aeration should be intensified to control the elevated viscosity.

8.1.6 Food/micro-organisms (F/M) ratio

To investigate the impact of F/M on fouling in MBRs Kimura et al. 2005 [47] studied fouling in three similar lab-scale MBRs by changing operational conditions. The study revealed that there is a correlation between high F/M and high, therefore F/M affects the nature of foulants. Likewise, Trussell et al. 2006 [122] concluded that membrane fouling rate in MBRs increased with increasing F/M ratio. High F/M ratios can result in elevating EPS amounts because of high bacterial substrate utilization [113]. It was also revealed that reducing the F/M ratio will result in reducing the EPS concentration [123], hence it is preferable to run MBRs at lower F/M ratios.

8.1.7 Organic loading rate (OLR)

OLR, a significant operational factor, is greatly influencing the biological processes in WWTPs [124]. Zhang et al. 2010 [125] studied the impact of both variable and constant OLR on fouling in two similar lab-scale immersed MBRs run for 162 days at an SRT of 30 days. In the beginning, fouling in the MBR fed with variable OLR was more noticeable than that fed with constant OLR. However, when the MBRs are progressively stabilized, fouling propensity was notably reversed with lower fouling noticed for variable OLR influent. In other research, Johir et al. 2012 [126] studied the influence of OLR on fouling in MBRs run at 6 OLRs that range from 0.5 to 3.0 kg COD/m^3 day at constant HRT and SRT of 8 h and 40 days, respectively. Results of their research stated that higher fouling rates were noticed at higher OLRs (2.75–3 .0 kg COD/m^3 day).

8.1.8 Chemical oxygen demand / nitrogen (COD/N) ratio

The COD/N ratio is a significant parameter for micro-organisms' growth and it plays an important role in removing nutrients [127]. It was also reported that this important parameter is well correlated with fouling in MBRs. As reported in the literature, there is a contradiction regarding the COD/N impact on fouling. Feng et al. 2012 [128] investigated the influence of COD/N on fouling using two similar immersed MBRs run simultaneously at COD/N of 10: 1 and 5: 1, respectively. They found that operating the MBR at COD/N of 10: 1 obviously lowered the rate of fouling. Likewise, Hao et al. 2016 [129] studied the influence of COD/N on fouling in MBRs run at 3 COD/N values; 100: 5, 100: 2.5, and 100: 1.8 for one year. Results of the study stated that COD/N of 100: 5 caused an improvement in MBR performance and lengthened the operational time before membrane cleaning as compared to a COD/N value of 100: 1.8. Han et al. 2015 [130] studied membrane filtration performance with COD/N values of 9.9 and 5.5. They revealed that fouling will be more at higher COD/N ratios since increasing COD/N resulted in an increased production of humic acids. Gasmi et al. 2015 [131] also noticed less fouling rate at COD/N ratios of 1.5 and 203. Yang et al. 2014 [132] found that COD/N of 3.5 broadly enhanced control of membrane fouling simply by aeration and back flushing strategy.

8.1.9 Critical flux

The basic idea of critical flux was widespread in all areas of membrane processes including MBR application. If the initial operational flux in MBR starts as low as possible, the fouling rate could be hindered. There are many protocols suggested to obtain the critical flux but no single protocol has been accepted. A popular method is the flux step technique, to gradually raise the flux for a specified duration as long as each flux step results in a stable TMP. Critical flux is determined when the TMP increases with time. TMP increase is an indication of higher permeation resistance resulting from a growing cake formation and internal fouling. TMP depends on many factors including MLSS, membrane materials, and system hydrodynamics [1].

8.2 Feed and biomass characteristics

8.2.1 Mixed liquor suspended solids (MLSS)

The MLSS includes bacterial flocs, EPS, colloidal matter, and micro and macro solutes. MBRs are usually run at higher concentrations of MLSS as compared to ASP. However, the higher MLSS concentration in MBR systems, if other microbiological factors are unchanged, tends to accelerate membrane fouling because of higher concentrations of suspended solids [133]. This is because of the thick (dense) cake layer that is formed when the biomass concentration is greater. However, this hypothesis is only true under very limited conditions as the MLSS concentration could be responsible for membrane Fouling [1]. Research results also revealed as the MLSS concentration is increased, the membrane permeability decreases [103]. There are many studies contradicting that fouling in MBR membranes is always a function of MLSS concentration [1].

Although SS concentrations may intuitively appear to give a sensible indication of fouling tendency, the relationships between the concentration of MLSS and fouling occurrence are indeed complicated. Once the other characteristics of the biomass are not considered, the effect of MLSS increase on membrane permeability can be negative [134, 135], positive [136, 137], or insignificant [138, 139]. Wu and Huang [140] stated that MBR operation at MLSS concentrations > 10 g/L will largely raise the viscosity, which, in turn, influenced the filterability; MLSS had almost no effect on the filterability when it is lower than 10 g/L. Yigit et al. 2008 [104] studied the effect of biomass concentration and operational conditions on fouling in immersed MBRs and revealed that polysaccharides concentrations and protein fractions of EPS increased when the MLSS concentrations were increased. Their investigation also concluded that increasing MLSS caused a remarkable increase in fouling rate at each flux tested. Such results indicated that increasing MLSS concentration will increase membrane fouling. Likewise, in the case of dominant filamentous bacterial presence in the MLSS, the filamentous bulking occurrence is high. Filamentous bulking can greatly enhance SMPs production which in turn ultimately increases membrane fouling [111].

In literature, articles about the MLSS influence on membrane fouling in MBR systems are inconsistent up to the moment. Rosenberger et al. 2005 [141] found that membrane fouling is reduced as MLSS concentrations increased until 15000 mg/L while the trend reversed at concentration exceeded 15000 mg/L. This can be linked to the remarkable changes in sludge rheology. Therefore, no concrete correlations between MLSS concentration and fouling in MBRs are available, indicating that MLSS alone gives a tacky indication of biofouling tendency [30].

8.2.2 Viscosity of sludge

AS MBRs have the ability to deal with wastewaters of high MLSS, the TSS will be very high; resulting in larger values of viscosity [142]. Higher values of viscosity in MBR systems may hinder the transfer of oxygen, resulting in higher energy demand for aeration. As with a conventional ASP, the viscosity of biomass is strongly correlated with its concentration and enhances fouling [30]. Trussell et al. 2007 [103] stated that a viscosity increase will result in a decline in membrane permeability. Basically, MLSS has a critical concentration, under this value, the viscosity of sludge tends to be low and will increase gradually with increasing MLSS concentration [98]. MBR operation at concentrations higher than the critical MLSS leads to the exponential increase of viscosity with MLSS concentration [143]. According to the operational conditions, the critical MLSS values were found to be in the range of 10 to 17 g/L [98]. At high MLSS viscosities, the membrane fouling rate in MBRs will increase.

8.2.3 Flock size distribution

Among the different parameters influencing membrane fouling in MBRs, the most dominant one is presumably floc size [1]. Micro-organisms have the tendency to accumulate and formulate flocs in the system. The size of these flocs helps the separation of liquid and solids available at the influent wastewater from MLSS. As found in the literature there was a wide range of floc sizes in MBR systems starting from 5 to 240 μm [25, 98]. Recently, Shen et al. 2015 [144] studied the influence of floc size on fouling in immersed MBRs utilized to treat synthetic wastewater. Results of their research, which had sludge floc > 1 μm, stated that decreasing the floc size will largely increase the attractive specific interaction energy [144]. This means that the adhesion capability of smaller flocs to the membrane is increased, thus further fouling takes place. From a practical angle, it can be stated that as the floc size increases, the preferable it is for fouling mitigation. Therefore, the focus of the current research is directed toward increasing the floc size by aerobic granulation [145-149], and the addition of activated carbon or zeolite. The increase in floc size enhances filtration by fouling reduction [150, 151].

8.2.4 Extracellular polymeric substances (EPS)

EPS is the waste released by bacteria as a result of microbial metabolites, cell lysis, or un-metabolized constituents present in wastewater [50], they largely influence the physiochemical characteristics of microbial aggregates like surface charge, structure, settling characteristics (parameters basically measured as an indicator for EPS quantity), flocculation and adsorption capacity [152]. EPS mainly contains proteins, polysaccharides, humic acids, nucleic acids, lipids, and uronic acids [111, 153, 154]. From the fouling perspective and when using hydrophilic membranes, proteins show hydrophobic nature while polysaccharides are naturally hydrophilic hence indicating that polysaccharides proportion have more fouling tendency as compared to protein proportion [104, 155]. The existence of both hydrophilic and hydrophobic species in EPS is a sign of their amphoteric nature. As the hydrophilic proportion causes membrane fouling higher than the hydrophobic proportion, the fraction of hydrophobic to hydrophilic constituents has a significant role in fouling development [156]. Therefore, the proportion of proteins to polysaccharides in EPS controls fouling in MBR systems [101]. There are two types of EPS; bound and soluble (also known as SMPs) [154]. SMPs are the organic matter produced within solution due to substrate utilization and endogenous decay [69, 157]. SMPs produced due to substrate utilization are known as substrate utilization-associated products (UAP) and those produced due to endogenous decay are known as biomass-associated products (BAP) [158]. On the other hand, bound EPS is characterized by adhesion to sludge flocs and includes loosely bound EPS (LB-EPS) and tightly bound EPS (TB-EPS) [159]. SMPs and bound EPS are assumed to be the main MBRs' foulants [49, 53, 160, 161] as they have many interactions with the remaining other types of foulants [154]. Biomass aggregation can take place through a partnership between bound EPS and SMPs, resulting in a highly hydrated gel matrix [101, 161]. Such products behave as a "glue" keeping the microbial aggregates together.

It was found that SMPs' contribution to fouling is more than colloids in MBR systems [140]. Neither bound EPS nor MLSS is the main fouling contributor when being compared with SMPs [153]. The influence of SMPs on fouling in MBR systems relies on their concentrations, operational mode, and the material of MBR [34]. This indicates that controlling the concentration of SMPs in MBR systems is an important factor in dealing with fouling. Research indicated that increasing SRT will decrease SMPs concentration, and higher concentrations of SMPs are noticed at lower concentrations of DO [49]. Different from bound EPS, SMPs more easily get inside the space of sludge flocs and the pores of the membrane; thus more fouling occurs.

8.2.5 Alkalinity and pH of wastewater

Alkalinity and pH have a significant influence on the biodegradability of organic matter. With respect to MBR, these two parameters influence the fouling rate. It was found that lower values of pH caused an adsorption increase of MBR-originated EPS at the membrane [162], and the maximum EPS flocculation propensity took place at pH 4.8 [163]. Zhang et al. 2014 [164] stated that a repulsive energy barrier is present between the membrane surface and sludge flocs; such barrier will decrease as pH decreases thus facilitating the foulants' attachment to the membrane. Similarly, Sanguanpak et al. 2015 [165] observed more significant fouling at a pH of 5.5 because of more EPS formation in the MBR system. All such researches agreed that decreasing MLSS pH will increase the fouling rate in MBR. Inside the bioreactor, nitrification produces acid that could reduce the pH [166]. To maintain an ideal range of pH in the bioreactor, alkalinity is needed in the influent to neutralize the hydrogen ion produced through nitrification. If low alkalinity is available in the influent, it should be accounted for by providing additional alkalinity.

Since inorganic fouling takes place due to both chemical and biological precipitations, pH should be observed because it will influence chemical precipitation. It was outlined that a pH of 8 to 9 will enhance $CaCO_3$ formation [49]. However, moderate quantities of calcium precipitate can facilitate controlling biofouling because of EPS binding and bridging (thus, improved bio-flocculation). Arabi and Nakhla [75] concluded that a calcium concentration of 280 mg/L enhanced membrane permeability, but a high concentration, for example, 830 mg/L caused serious inorganic membrane fouling.

8.2.6 Salinity of wastewater

Salinity was found to negatively impact biological processes. In MBR systems, it was proved that salts in MLSS resulted in chemical precipitation and electrostatic attraction towards the membrane surface [167]. Reid et al. 2006 [168] investigated the effect of high salinity on AS properties and membrane permeability in an immersed MBR. Results of their study concluded that when salinity is high it will largely influence the physical and biochemical characteristics of AS by raising the concentrations of bound EPS and SMPs, thus increasing fouling [168]. Likewise, Jang et al. 2013 [169] studied the effect of salinity on fouling in MBR systems with high salt concentrations and found that high salts concentration speed up membrane fouling by increasing the pore blocking. This indicated that the high salinity has changed the biomass properties which finally enhanced membrane fouling. Di Bella et al. 2013 [170] found that the MBR system showed high biomass respirational activities and high removal efficiencies at ordinary salinity levels. On the other hand, when salinity increased, respiration rates decreased, and fouling increased due to the deterioration of high EPS concentrations.

Moreover, the ionic constituents in influent also play a role in floc formation. It was found that floc structure and strength are highly dependent on the ionic constituents and their concentrations [171]. High concentrations of multivalent cations, Mg^{2+} and Ca^{2+}, enhance the formation of strong and compact flocs [172, 173]. This can be attributed to the divalent bridging model where Ca^{2+} and other divalent ions bridge the EPS negatively charged locations, hence forming a matrix of EPS and single cells. Furthermore, monovalent cations could reduce floc strength [174]. Therefore, the existence of multivalent positively charged ions in relation to monovalent ones, despite the high salinity, tends to assist forming strong bio-flocs which would enhance membrane filtration.

8.2.7 Flocs structure

The structure of activated sludge flocs depends mostly on the physicochemical characteristics of biomass, nutrient balance, and feed characteristics. The floc structure of AS can be categorized into three types based on the balance of floc-forming and filamentous bacteria (ideal normal flocs, pinpoint, and bulking). Comparing the aggregate size distributions of ASP and MBR sludge showed a significant variation in terms of the average particle size (160 and 240 µm, respectively) [175]. The MBR sludge had a bimodal distribution (5-20 and 240 µm), a high concentration of colloids, and particles, and free bacteria resulted from their perfect detention by the membrane. The MBR flocs up to 100 µm were partially characterized; floc diameters ranging from 10 to 40 µm were observed with an average size of 25 µm [176]. Despite increasing the mean floc size marginally from 5.2 to 6.6 µm for SRTs increasing from 20 to 60 days, the floc size distribution obtained for three MBRs run at different SRTs was identical [177]. Because of the large size of flocs in comparison to membrane pore size, pore-clogging by the flocs themselves will not probably happen. To a certain degree, the drag force and shear-induced diffusion also prevent flocs deposition onto the membrane surface. However, they are contributors to fouling by producing EPS and also have a direct effect on membrane channel clogging [30].

According to the studies of Chang et al. 1999, the order of fouling propensity was found to be normal sludge < pinpoint sludge < bulking sludge. They explained that the key parameters governing cake resistance were the shape, the size of the AS flocs, and the porosity of the cake layer accumulating onto the membrane surface [160]. However, Wu and Huang, 2009 reported that the zeta potential and SVI do not affect membrane filterability [140]. Contradictory results are often found in literature dealing with membrane fouling in MBRs just like the two previously mentioned studies. This is attributed to the oversimplification of microbial conditions [1].

8.2.8 Dissolved organic matter (DOM)

DOM present in the aeration basin of MBR plants includes unmetabolized feed constituents and metabolites produced during biological reactions such as SMPs and free EPSs. In terms of membrane fouling, they cannot be distinguished from each other based on the chemical structure. DOM in aeration basins significantly influences membrane fouling. They affect both internal and external fouling, the latter being enhanced by concentration polarization. DOM can be adsorbed to the pores' surfaces and walls, which results in inner membrane fouling rather than cake layer formation. This generally occurs at the initial stage of the filtration process. However, DOM can be adsorbed in the interstices of the cake layers during their free paths to the membrane. This will consolidate the cake layer, which can lead to severe fouling. The sludge flocs are the basic building units of the cake layer on the membrane surface. Soluble matter including DOM can fill the interstices of the building blocks present in the cake layer, causing dense cake layers' formation. DOM acts as glue and consolidates the cake layer [1].

8.2.9 Dissolved oxygen (DO)

DO concentration within the bioreactor is governed by aeration that supplies oxygen to bacteria and controls membrane fouling. DO influences MBR fouling through the biofilm structure, SMP concentration, and floc size distribution [178]. Higher levels of DO commonly result in improved filterability, as demonstrated in filter cakes of less specific resistance because of bigger particles [179]. Aeration rate, according to Ji and Zhou [102] can directly affect the amount and content of SMP, EPS and total polymeric substances in the biological flocs as well as the ratio of protein/carbohydrate accumulated onto the membrane surface. The influence of oxygen deficiency resulting in a reduction of the cell surface hydrophobicity was identified as a possible source of fouling in MBRs [180]. The impacts of decreasing DO may result in filamentous growth that leads to dispersion of sludge flocs and colloids in the MLSS, this will exponentially launch the TMP and membrane fouling respectively [181]. On the other hand, suspended air does not appear to be an important factor for MBR membrane fouling [182].

8.2.10 Foaming

Foaming in AS WWTPs resulted due to long SRTs, warm temperatures, low F/M ratios, high MLSS concentrations, oil and grease, and detergents in the feed water. Plenty of actinomycetes like Nocardia or Microthrix are generally linked to foam appearance in AS WWTPs and were found in full-scale MBR plants subjected to mutable OLRs. However, foam in MBR systems was noticed in the lack of actinomycetes. The foaming level was found to be linked to the concentrations of protein EPS [30]. Foaming sludge also appears to yield lower membrane permeability, due to the higher hydrophobicity of foaming AS [183]. Foaming hence gives an indication of sludge fouling tendency [30].

8.3 Membrane characteristics

Important parameters of membrane design include configuration (geometry and flow direction), surface properties (pore size and material, surface charge, hydrophobicity, porosity, pore tortuosity and shape, and crystallinity), and the separation between the membranes. Commercially available MBR materials have pore sizes falling in the coarse UF to fine MF regions, as experience shows that this range provides adequate separation and suitable fouling control under proper operational conditions. In practice, organic membrane materials are mainly polymers characterized by: (a) physically and chemically strong enough to hold out against the applied pressure, (b) easily improved to give hydrophilic surfaces, making them much reluctant to fouling, (c) easily attached to a substrate to provide the required mechanical integrity, and (d) produced at reasonable costs [30].

8.3.1 MBR material

Membranes used in MBRs are mostly polymeric materials that have inherent limitations to cope with extreme conditions. Particularly, polymeric membranes are very vulnerable to wide ranges of pH values and oxidizing agents when chemical cleaning is made like Cleaning In Place (CIP) [1]. The fouling propensity of a membrane is affected by the material it is comprised of. Membranes are classified into three types according to the material they are made of: ceramic, polymeric, and composite membranes. Due to their outstanding chemical resistance, integrity, inert nature, and easy cleaning, ceramic membranes provide good filtration performance and low operational costs [34, 184, 185]. They show superior hydraulic, thermal, and chemical resistance compared to polymeric materials [1], they are also highly hydrophilic [69], rendering them more resistant to fouling. But, they are not economically feasible for usage in MBR applications because that have high fabrication cost and fragile nature [184]. Polymeric membranes are the most suitable membranes type found in the market. They are characterized by suitable physical and chemical resistance but are typically hydrophobic [69]. Due to their hydrophobicity, they are prone to foul quickly, however they are now broadly utilized because it is easy to fabricate their pore sizes. Composite membranes are those made up from two or more materials that integrate the strength of the constituting materials in the final product. The active surface is usually made of one material, while the support layer is made of another [34]. To reduce fouling in composite membrane systems, hydrophobic membranes are generally covered with hydrophilic polymers [186].

Inorganic materials such as alumina (Al_2O_3), zirconia (ZrO_2), silicon carbide (SiC), and titanium oxide (TiO_2) have been developed for membrane separation and are used today in food and dairy industries. The application of inorganic membranes to MBRs has been limited due to their cost and module manipulation limitations. Most inorganic membrane modules have the geometry of tubular monoliths, resulting in much lower packing densities than hollow fiber bundles with the same volume. If this difficulty is overcome, applications of inorganic membranes to MBR would be widespread because simple and powerful cleaning options using chemicals under severe conditions such as high/low pH, high temperature, and strong oxidizing agents can be applied to control membrane fouling [1].

8.3.2 Water affinity

Water affinity is a membrane material characteristic that influences MBR fouling [32]. Hydrophilic membranes usually yield higher fluxes than hydrophobic membranes. Since hydrophobic membranes interact more strongly with the feed solution’s components than hydrophilic ones do, fouling is more likely to occur in hydrophobic membranes, and this is called “hydrophobic interaction” [1]. Because of the hydrophobic interactions taking place among the membrane material, microbial cells, and solutes; fouling is much significant in hydrophobic membranes than hydrophilic ones [98]. A comparison conducted between two UF membranes of identical properties outlined that the influence of membrane hydrophobicity in aerobic MBRs showed more solute rejection, more fouling, and greater cake resistance for the hydrophobic membrane [187]. Furthermore, hydrophobic materials tend to adsorb hydrophobic species in wastewaters; hence, causing fouling. To achieve the balance, composite membranes are generated by adding a slime layer of hydrophilic material on hydrophobic membranes to integrate the strength of the latter with the low fouling tendency of the former [32]. As found in literature, variations in membrane hydrophobicity are generally associated with different membrane modifications like pore size and morphology, making the correlation between membrane hydrophobicity and fouling harder to determine [30]. It has also been suggested that membranes with more hydrophilicity are much susceptible to foulants deposition characterized by hydrophilic nature, therefore the most hydrophilic membranes were also the most porous, which could also increase fouling [188].

8.3.3 Surface roughness and porosity

Roughness and porosity of the membrane have been suggested as potential causes of getting different fouling behaviors [30]. Fouling in MBRs is somehow affected by the surface roughness of the membrane material. Membranes characterized by regular surfaces are less likely to foul than MBRs with irregular surfaces [32]. According to some research results, membranes that have more surface roughness foul more quickly [167]. This is due to the fact that surface roughness of the membrane will provide valleys for the colloids in the influent to deposit on [189], resulting in the blockage of the valleys hence increasing the fouling intensity for rough membranes [190]. However, a research aimed to study the influence of surface roughness on fouling in MBRs revealed that membranes of higher projections on their external surfaces showed more antifouling properties, with a permeability recovery after backwashing following similar pattern [191]. Although rough surfaces may enhance fouling tendency, rougher ones with protruding projections can capture foulants in their valleys while remain operating as normal.

Fang and Shi studied fouling tendency of four MF membranes with nominal pore size ranging from 0.20 to 0.22 µm operated in parallel. The track etched membrane, with its compact structure and small but uniform cylindrical pores, gave the least resistance because of its high surface iso-porosity while the remaining three ones were more prone to pore fouling because of their highly porous network [188]. On the other hand, comparing two microporous membranes prepared by stretching showed that fouling was affected by pore aspect ratio (length/width). While the two membranes had similar average pore size and permeate, lower fouling was noticed with the membrane of the higher pore aspect ratio [192]. Research on anaerobic MBR systems revealed that surface roughness of the membrane will promote membrane fouling [193].

8.3.4 Surface charge

Membrane surface charge is another significant characteristic linked to membrane fouling especially if the feed water contains charged particles [32]. This property has a significant role that determines the permeability of charged ions in nano-filtration or reverse osmosis systems, this can be related to the rejection mechanism that is substantially correlated with the static charge interaction between the transported solute and the membrane [1]. According to research findings, the majority of membrane materials are normally negatively charged [32]. This is due in part attributed to the colloidal particles deposition onto the surface of the membrane [189]. When certain cations such as Ca^{2+} and Al^{3+} present in the mixed liquor which will react with the negatively charged membrane surface, inorganic fouling will occur [186]. Despite the fact that flocs in MBRs are slightly negatively charged particles, the charge interaction between the membrane and flocs isn’t sufficiently strong to control the pressured convection to the membrane [1].

8.3.5 Pore size

In general, membranes used in WWT are classified into two main categories: porous and non-porous membranes. The porous category includes microfiltration (MF), ultrafiltration (UF), and loose end nano-filtration (NF) membranes. They usually employ straining, sieving, or size exclusion to achieve solids separation [68]. Furthermore, non-porous membranes (dense NF and reverse osmosis (RO)) separate particles by exploiting the difference in diffusivity or solubility between the solvent and the solute in the membranes [194]. Since the separation mechanism needed in MBR systems is sieving, MF and UF membranes are commonly utilized [69], hence permitting full physical bacterial retention and virtually all SS in the biological reactor [98].

The influence of pore size on fouling intercorrelates with the feed water properties, particularly the particle size distribution of the AS suspension. This resulted in contradicting patterns found in literature, with no clear reported relationship between pore size and hydraulic performance. This is due partly to the complicated and variable nature of the biological suspensions in MBRs and the comparatively big pore size distribution of the used membranes, as well as operational factors including system hydrodynamics and test duration. A direct comparison between MF and UF membranes at a CFV of 0.1 m/s revealed that a MF membrane has approximately twice the hydraulic resistance of a UF membrane. Interestingly, the DOC rejection of both membranes was the same after two hours of operation, demonstrating that the dynamic membrane layer formed on the membrane surface has provided the perm-selectivity rather than the membrane substrate itself [1, 30, 101, 137, 195].

Larger pore sizes don’t always result in higher flux rates due to internal fouling (i.e., the flux produced from smaller pore sizes can be higher than that from larger pore sizes). This is because that the pore’s size and the particles in the feed are similar. If the average pore size is the same as the size of the particles, pore plugging (or clogging) is likely to occur, which will fatally reduce the permeate flux. The typical lower size range of activated sludge suspension particles is sub-micrometer (i.e., nearly close to the pore size of conventional microfiltration membranes). Therefore, ultrafiltration membranes that have smaller pore sizes than microfiltration membranes are often used in MBRs [1]. Pore blocking mechanisms tend to increase as membrane pore size increases [32]. This can be explained as; fine particles are easy to get into the membrane pores and become trapped inside them, leading to pore blocking [112]. For the case of smaller pores, larger particles will quickly generate external layer on the membrane and attract the smaller ones. Air scouring caused by cross flow filtration can simply expel the layer created on the surface of the membrane [186].

8.3.6 Packing density

An important design parameter of hollow fiber membrane modules in MBRs is the packing density, which is the membrane surface area per unit cross-sectional area of the module header (m^2/m^2) or the membrane surface area per module volume (m^2/m^3). High packing densities decrease the number of membrane modules and/or the footprint of the module in the aeration tank of the MBR. However, over-packed modules can badly affect the mass transfer efficacy within the fiber bundles, resulting in a decreased design flux [1].

8.3.7 Membrane configuration

As already presented earlier, the submerged process configurations are generally preferred to the pumped side-stream configurations for medium to large-scale domestic WWT [30, 196-198]. This is basically related to the aeration effect, which controls fouling through the generated shear.

Table 2 summarizes all the previously discussed factors affecting fouling in MBR systems.

9. Fouling control / mitigation

Membrane cleaning is an important operation and maintenance (OM) routine in MBR plants, if it isn’t the case the overall plant seriously suffers and could be shut down eventually. Therefore, membrane cleaning precedes other routines. Setting up the cleaning strategy during the plant design stages should be considered a key step for the design of MBR plants [1]. Over decades, control and preventive fouling strategies are extensively studied to extend the lifespan of membrane modules with maintaining the maximum effluent flux service capacity [199]. Despite a period longer than a decade of substantial progress in the development of fouling mitigation strategies, many physical and cleaning methods are still requiring development to reduce membrane fouling [200]. The unavoidable fouling necessitates an additional installation footprint to compensate for the declined permeate [201]. Several trials have been made to deeply investigate fouling issues. Practically, it could be applicable to inhibit fouling before its occurrence by employing different techniques [80].

Table 2
Summary of the impacts of different parameters on fouling of MBR

Factor Type	Factors	Impacts on MBR Fouling
Operational Conditions	Mode of Operation	When MBR is operated at constant permeate flux, fouling is noticed by TMP increase, while when operating MBR at constant TMP, fouling is noticed by flux decline.
	Rate of Aeration	Aeration tends to reduce Fouling in MBR but will increase its operational cost.
	Sludge Retention Time (SRT)	Generally, increasing SRT will reduce fouling in MBRs. SRTs < 2 days and > 50 days will cause severe MBR fouling.
	Hydraulic Retention Time (HRT)	Decreasing HRT will increase fouling in MBRs.
	Temperature	Lowering the temperature will increase the fouling tendency in MBRs. Sudden temperature variations will enhance fouling.
	Food/Micro-organisms (F/M) Ratio	High F/M will increase fouling in MBRs.
	Organic Loading Rate (OLR)	Higher OLR will result in higher fouling in MBRs.
	Chemical Oxygen Demand / Nitrogen (COD/N) Ratio	There is a contradiction in the impact of COD/N on MBR fouling.
	Critical Flux	Running the MBR below the critical flux will reduce fouling, and vice versa.
Feed and Biomass Characteristics	Mixed Liquor Suspended Solids (MLSS)	Depending on MLSS alone to study MBR fouling is misleading.
	Viscosity of Sludge	At high MLSS viscosities, the membrane fouling rate in MBRs will increase.
	Flock Size Distribution	Increasing floc size enhances filtration by fouling reduction
	Extracellular Polymeric Substances (EPS)	The existence of hydrophilic and hydrophobic species in EPS means that they have an amphoteric influence on fouling
	Alkalinity and pH of Wastewater	Lower pH values will increase MBR fouling. Very high will result in severe inorganic fouling.
	Salinity of Wastewater	Higher salinity wastewater will increase the fouling tendency in MBRs.
	Flocs Structure	Order of fouling propensity: bulking sludge > pinpoint sludge > normal sludge.
	Dissolved Organic Matter (DOM)	Increasing DOM will enhance fouling in MBRs.
	Dissolved Oxygen (DO)	Higher DO concentrations will enhance fouling reduction.
	Foaming	Foaming sludge appears to increase MBR fouling.
Membrane Characteristics	MBR Material	Order of antifouling resistance: ceramic MBRs > composite MBRs > polymeric MBRs.
	Water Affinity	MBR fouling is much more significant in hydrophobic membranes than in hydrophilic ones.
	Surface Roughness and Porosity	Homogenous MBR surfaces are less likely to foul as compared to that irregular surfaces. MBRs with protruding projections have antifouling properties. MBRs with higher pore aspect ratios have a lower fouling tendency.
	Surface Charge	Since the MBR’s surface is negatively charged, positively charged ions in the influent result in inorganic fouling.
	Pore Size	Fouling can’t be linked to pore size alone; influent composition and membrane material will influence the relation between MBR fouling and pore size.
	Packing Density	Higher packing density will result in reduced MBR flux.
	Membrane configuration	Submerged MBRs are preferred to side-stream MBRs because of more fouling control.

Fouling in MBRs can’t be precluded and one of the major indicators of the successful performance of MBR systems is determined by the efficiency of the fouling control, without affecting the permeate quality. Different physical cleaning methods are currently used in several pilots and full-scale membrane filtration systems around the world [57]. Many approaches to control fouling have been investigated and applied to laboratory and/or MBR plants so numerous cleaning options have been reported. All of the methods reported can be divided into two groups: membrane cleaning and fouling prevention. Membrane cleanings refer to the process normally done after the development of fouling, while fouling prevention refers to all precautions taken to prevent fouling. This classification is based on how to set up a fouling control strategy. A more familiar method of classifying fouling control is through chemical, physical, biological, electrical, and membrane and module development. This classification considers the characteristic nature of cleaning materials or protocols [1]. From an operating standpoint, fouling can be regulated and reduced by applying different methods including aeration, relaxation, backwashing, and chemical cleaning. Even though such methods can’t completely eliminate the fouling problem, effective measurements and control systems can be applied to improve the membranes’ filtration performance [57]. Some of the common fouling control/mitigation techniques are outlined in Fig. 11, and they will be briefly described in the following sections.

9.1 Chemical cleaning

Membrane cleanings using a variety of chemicals have been broadly applied for a long time due to their immediate and excellent capabilities of restoring deteriorated filtration performance. In spite of the merits, chemical cleanings have inherent disadvantages. First of all, chemical cleanings always accompany secondary contamination. The added chemicals themselves or conjugated with foulants increase the amount of waste. These waste pollutants should be treated further or disposed of after chemical cleaning. The regulations on waste chemicals have become stringent for environmental protection so treatment and disposal costs have increased. Moreover, safety concerns about chemicals related to their transportation, storage, preparation, and uses have increased nowadays, leading to increasing OM and safety costs [1].

Notwithstanding the safety concerns, chemical cleanings for fouling control are still used as a primary tool to restore membrane permeability in MBR. That is, the convenience of using chemicals still outweighs the inherent and unavoidable problems as well as the environmental burden. It is well known that the reversible fouling resulting from cake layer deposition of sludge flocs can be partly avoided by subcritical flux operation and overcome by air scouring. However, the irrecoverable fouling resulted from adsorption and/or physicochemical bonding/interaction between the internal pores’ walls and foulants can’t be managed by simple subcritical flux operation or other physical cleanings. This is the main cause why periodical chemical cleanings are currently practiced in MBR plants [1]. Chemical cleaning reagents used for fouling control in MBR are categorized into many groups as follows:

- Oxidizing agents: Sodium hypochlorite (NaOCl), ozone (O_3), and hydrogen peroxide (H_2O_2).
- Acids and bases: Inorganic and organic acids can serve as cleanings agents. Acids including sulfuric and citric acid dissolve inorganic precipitated foulants and scales. Bases can also be used to remove organic foulants.
- Enzymes: Enzymes aiming at specific organic foulants such as proteins and polysaccharides can also be used for cleaning. They are not used alone but are formulated with other reagents.
- Chelating agents: Chelating reagents such as ethylene diamine tetraacetic acids (EDTA) can be used as ligand material for complexing inorganic foulants. Chelating agents are not used for fouling control in MBR because of pH adjustment requirements and possible interferences by cations present in the wastewater. Cost is another factor preventing the use of chelating agents.
- Detergents (or surfactants): They are also used for cleaning organic foulants by emulsification.
- Coagulants: Ferric chloride and aluminum sulfate (alum) [1]

9.1.1 Activated carbon

The addition of powdered activated carbon (PAC) directly to a membrane tank is often tried to control membrane fouling in MBRs. The membrane permeability of the PAC-added MBR is obviously enhanced compared with the non-PAC-added MBR [1]. The addition of PAC results in a decrease not only in the compressibility of sludge flocs but also in the EPSs content inside the microbial flocs. This increases the cake layer porosity and hence improves the membrane flux [202]. PAC addition mitigates membrane fouling and also enhances the biodegradation of recalcitrants or slowly biodegradable compounds [203].

9.1.2 Chemical pretreatment and additives

Chemical pretreatment is considered mandatory to improve the membrane permeability for drinking water treatment. Potential foulants are removed by chemical precipitation prior to the main membrane filtration processes. However, it has not been often tried in MBR applications for wastewater treatment. In special cases, for example, piggery wastewater including a high concentration of suspended solids coagulation prior to MBR is reported [204]. Instead of pretreatment by coagulation, in situ EC techniques are combined with MBR. Electrolytic polymers have been found to effectively mitigate fouling. Several electrolytes improving membrane permeability in MBR are commercialized and available in the market. For example, some commercial cationic polyelectrolytes can improve filterability up to 150% with doses of several hundreds of ppm. The addition of these chemicals makes the cake layer porous and induces a reduction in soluble EPS. Furthermore, soluble constituents in the bulk solution, which are potential foulants, are captured inside sludge flocs during flocculation. However, the MBR market does not use these chemicals frequently due to the lack of a long-term evaluation as well as cost [1].

9.2 Physical cleaning

9.2.1 Preliminary treatment

Classic screens of about 0.6 cm rating are ordinarily not sufficient for MBRs because they are comparatively coarse. They tend to increase the clogging risk of the membrane channels, especially by hair in MWW, which aggregates and clogs the membrane interstices and aeration ports [30]. One of the notorious troubles in submerged MBRs is the entanglements of hairs with the membrane fibers, which results in the entire system shutdown. Therefore, debris such as grit, particulates, hair, and plastic materials should be removed before the main membrane reactor in MBR. Proper selection of the preliminary treatments should be considered more importantly at the design stage of MBR than for conventional wastewater treatment systems [1].

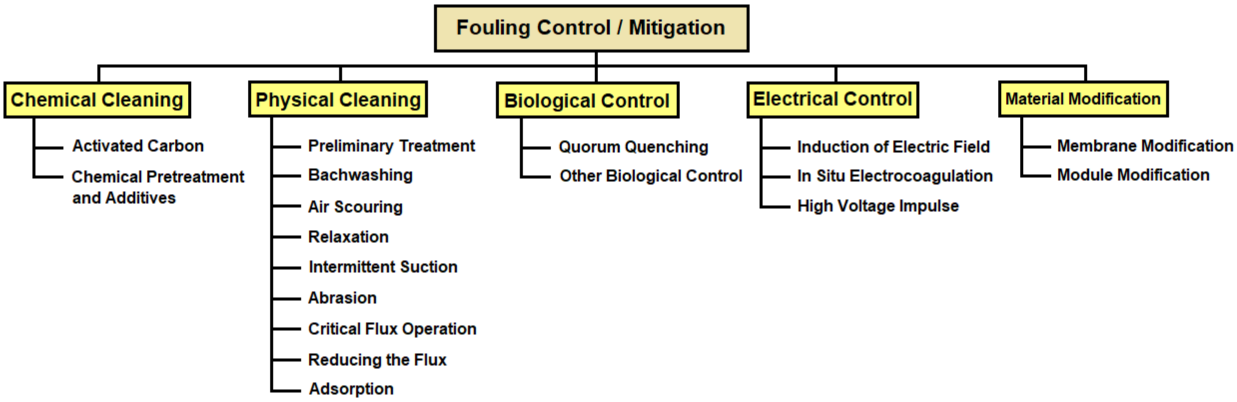


Fig. 11. Fouling control and mitigation techniques

HF membranes have a propensity for aggregating hair and collecting other debris at the surface of the membrane element. Hair may then become entangled with the filaments and are not notably controlled by back flushing. FS membrane clogging happens when debris deposits on the edges of the channels and into their entrances. If aeration does not succeed to scour such depositions, sludge accumulation will occur over the blockage, hence increasing the impacted excluded area. Fibers collected in the aeration system may alter the flow regime and air volume hence lowering the scouring level. As scouring decreases, membrane fouling will increase; therefore, aerators are usually designed to hinder clogging and/ or to facilitate periodical membrane flushing using water. As HF membranes are more prone to clogging and may cause more severe impacts; screens of 0.8 to 1.5 mm openings are commonly used in such systems. FS membranes are somewhat more tolerant of clogging, despite lacking the ability to backflush them, screen openings of 2–3 mm are commonly suitable for such MBRs configuration [30].

9.2.2 Backwashing (Back-flushing)

Backwashing is a very common method applied to control fouling in membrane filtration systems [205]. It is simply the reversal of permeate flow back throughout the membrane [30]. The same principle of backwashing for conventional media filtration (sand and/or anthracite filtration), a reverse direction of water flow removes the foulants from the filter media, and can also be applied to membrane separation. Membrane backwashing is the most frequently used means to keep a steady flow in membrane filtration processes due to its simplicity and controllability. Therefore, backwashing was considered a basic tool for fouling control in most MBR plants. Basically, backwashing is carried out with permeate or pure water, air, and other mediums that can remove fouling. Occasionally, the addition of chemicals to the backwashing solution can be done to increase the efficiency of cleaning, which is called chemically enhanced backwashing [57] [1]. Air can also be applied to influence backwashing or to improve backflush with water [206]. While air backwashing is surely efficient, anecdotal evidence suggests that it can result in partial drying out of some membranes, which can then result in embrittlement and so problems of membrane integrity [30]. The backwashing frequency and pressure applied (maximum pressure is usually given by the membrane manufacturer) depend on the membranes and module design [1].

Periodic repeating of backwashing in MBR could result in severe damage to the membrane structure. In particular, asymmetric membranes constructed by the skin and supporting layers have relatively weaker structures than the microporous membranes, so they should be backwashed cautiously. That is, periodic backwashing can cause the disintegration of membranes and/or modules so the lifetime of membranes should be considered first before backwashing [1].

Implementation of backwashing as a fouling control mechanism can only be succeeded if factors influencing its application, including the intensity of backwashing flux, the instantaneous flux, permeate to backwash ratio, and the type of backwashing agent used are taken into consideration. Scheduling an optimized backwashing pattern is commonly set by trial and error, and is also depending on the operators' experience [57]. The frequency of backwashing can be classified into two types, namely (a) less frequent with a longer backwash and (b) a frequent backwash with a shorter backwash period [53]. Generally, intensive experimental work is conducted to get the optimum filtration flux [207]. Applying a backwashing mechanism was found to be more efficient than aeration, however, this mechanism was more efficient when integrated with an aeration fouling control technique [208]. The backwashing facilities in MBR plants should include valves, pipes, and pressure gauges for the air and/or water. Moreover, backwash pumps and backwash water storage tanks are needed. The generated backwashing wastewaters normally return to the aeration tank unless chemicals are used for the backwashing [1].

9.2.3 Air scouring (Coarse aeration)

Among the MBR cleaning processes, aeration is the most efficient because of the very effective scrubbing between two different phases (liquid and gas) [1]. Airflow through aeration is a commonly adopted strategy implemented to control fouling in MBR systems [209]. The aeration process is utilized to control external fouling and to decrease the cake layer deposition on the membrane surface [62]. The polarized layer concentration generated close to the membrane can be disturbed by the aeration process, and a correlation between the intensity of aeration airflow and the fluxation flow rate has been established [210, 211].

Most submerged MBRs employ coarse aeration as a fundamental tool for fouling control. The basic idea is that coarse aeration in a membrane tank accomplishes dual goals: (1) air transfer to cells for microbial growth and metabolism (2) and aeration for fouling control. Excessive and extensive coarse aeration onto the membrane surfaces has been practiced commonly to shake the submerged MBRs mechanically and remove sludge cakes from the membrane surfaces. However, coarse aeration consumes large amounts of energy for air blowing. Depending on MBR sites, aeration consumes about 49% - 64% of the total energy required for MBR plant operation [212, 213]. Optimizing aeration, including aeration rate, bubble size, and mode of aeration, is of major significance for controlling fouling and decreasing energy usage. Particularly, membrane aeration in FS MBR systems is much greater than that in HF MBR systems [214]. Research conducted on air bubble systems showed better control of membrane fouling, however, this technique has a threshold flow rate beyond which foulants can't be removed efficiently [215]. Flux can be improved using a dual-phase airflow, and too high air flows don't have any importance regarding flux recovery [216].

There should be some optimum range of air supplied, which is expressed by specific air demand (SAD). There are two SAD values: (1) SAD_m (per membrane area) whose units are N m^3/ (h m^2) and (2) SAD_p (per permeate volume) whose units are m^3 air/m^3 permeate. Most membrane cassettes have a SAD_m in the range of 0.3 - 0.8 N m^3/ (h m^2) and a SAD_p in the range of 10 - 90 m^3 air/m^3 permeate [1]. Intermittent aeration is supplied to the membrane modules in 20 or 40-s intervals of air on and off in order to reduce the energy cost for aeration in MBR [217].

Coarse aeration for fouling control inevitably introduces strong shear forces to the microbial flocs, so that the sludge flocs are apt to experience floc disintegration. Since membrane fouling is worsened by decreases in particle size arising from floc disintegration, segregation of the coarse aeration and fine bubbling for the cells is often tried: locating the coarse aeration diffusers just beneath the membrane module and locating the fine bubble aerator out of the module. Nevertheless, coarse aeration is still frequently practiced in MBR plants because it is easy to install and the dual goals are readily achieved by single aeration devices [1].

An example of effective use of air is the introduction of a two-phase (air + liquid) flow to MBR as shown in Fig. 12. Different flow regimes are formed according to the ratio of flow rates of air and liquid: bubble, slug, churn, annular, and mist flow. The flow regime changes from bubble to mist as the ratio increases. Among the various air-liquid multiphase flow patterns, the slug flow mode was found to be the most efficient one that enhances flux. The slug flow, air pockets formed in the shape of a slug, enhances mass transfer adjacent to the membrane surface and scours the cake layers, and thus, fouling is mitigated [1].

The introduction of slug flow in tubular membrane modules enhances the flux significantly (≈43%) in the MBR for domestic WWT [218]. It was reported that the slug flow exhibited better antifouling performance than free bubbling, and the slug flow prevented irreversible as well as reversible fouling. All of these results are attributed to the increased wall shear stress generated by the two-phase flow. However, the multiphase aeration remains incompletely understood because the flow in MBR is actually a three-phase flow consisting of solids (sludge flocs) + liquids + gas phase. The three-phase flow is more complex to model. Moreover, the solids, microbial flocs, are difficult to characterize because it changes with time. Due to this reason, "airlift" is the more widely accepted term describing the multiphase aeration in MBR, instead of two-phase MBR [1].

9.2.4 Relaxation

Relaxation takes place when the permeation process is stopped while scouring the membrane with air bubbles is still continuous [30]. It is a popular technique applied in immersed MBR processes for both HF and FS membranes [30, 219, 220]. This method can only be applied for the removal of reversible fouling. A longer relaxation period can assist fouling control and improve the permeate flux [221]. But, very long and highly frequent relaxations could result in critical fouling because of the relatively high instantaneous flux [222]. Therefore, optimizing the time of relaxation is considered to be critical for this method when dealing with fouling control. Many experiments on optimizing the relaxation process have been elaborated to control fouling occurrence [57].

MBR relaxation technique will encourage diffusive back transport of foulants far from the surface of the membrane under a concentration gradient, which is furthermore promoted by the shear generated by air scouring [107, 138]. An exhaustive study on TMP behavior through the relaxation process stated that, despite that the rate of fouling is commonly greater than for continuous filtration, membrane relaxation gives the opportunity to maintain filtration for longer durations before membrane cleaning is needed [223]. Despite what is reported by many researchers on the economical unfeasibility of operating large-scale MBR systems using relaxation as a fouling control method [138], relaxation is very popular in modern full-scale submerged MBR systems. Many studies conducted to assess the maintenance protocols of MBRs have suggested integrating relaxation with back-flushing to get optimum results [224, 225].

Research on the efficiency of relaxation for reversible and irreversible fouling was conducted by Zsirai et al. 2012 [226]. Rahimi et al. 2011 [227] conducted a comparison between the relaxation efficiency and backwashing process. As found in the literature, relaxation was comparable with backwashing in terms of TMP increase. However, relaxation didn't dive the intended results when attempting to maintain the permeability in the case of irreversible fouling. Wang et al. 2014 [53] conducted a review and found that many researchers had integrated relaxation backwashing to get more efficient cleaning results for membrane filtration. The researchers furtherly stated that it was necessary to consider the net permeate flux, and to optimize the relaxation time, because of losing some permeate through the relaxation period.

9.2.5 Intermittent suction

Since membrane separation is a pressure-driven process, abrupt pressure relaxation can cause a temporary back transport of permeates, which then assists cake layers to dislodge away from the membrane surfaces. Instant cessation of vacuum pressure in submerged MBR or stopping pressurization in side stream MBR was used vastly for fouling control in MBRs [1]. A sporadic suction (i.e., temporary cessation of suction) can provide an alternative tool for the suppression of fouling in MBR. This technique is called cyclic filtration because on and off suctions repeat periodically. Intermittent suction is economical for fouling prevention because suction energy can be saved during the off-suction periods. However, disadvantages originating from control complexity could compromise the merits of fouling prevention and energy savings. For example, installing a programmable logic controller (PLC) and solenoid valves to perform the on and off duties makes the system complicated and expensive. Although big progress in understanding particle deposition on membrane surfaces based on the force balance of particles has been accomplished, determining time intervals for on and off filtrations mainly depends on experimental data and not on theoretical analysis of hydrodynamics [1, 218].

9.2.6 Abrasion

The energy requirement during operating MBR systems is twice more than that of the CAS systems [228]. The greatest portion of the energy consumption in MBR systems results from aeration applied for fouling control [229, 230]. Aeration can sum up to 65% of the total energy consumption in MBR processes [231, 232]. Therefore, it is important to look for other fouling control strategies to reduce the energy demand during MBR operation. The utilization of scouring materials in MBR systems got high attention as an energy-effective technique to mitigate fouling. Mechanical cleaning using scouring materials became a hot research topic because it combines both the efficiency of membrane cleaning and lowering the energy demand [200].

To further improve the separation of foulants from the MBR surface, researchers focused on utilizing coarse material with air scouring to exist an efficient and uninterrupted membrane cleaning [186]. Free-moving materials in membrane tanks can rub the membrane surface, helping to dislodge cake layers of the membrane. They move freely to cake layers and then take them off by mechanical scouring, leading to increased membrane permeability. Soft sponge balls (or cubes) or hard plastic media have been used for the free-moving media causing abrasion. For the purpose of making biological activated carbon (BAC), granular activated carbon (GAC) is added to MBR. The BAC has dual duties: (1) the original duty of providing spaces for biomass attachment and growth and (2) moving carriers for abrasion [1].

The attached microorganisms show enhanced microbial performances due to the increased population on the carriers BAC, leading to better effluent water quality than the suspended growth microorganisms. Simultaneously, the BAC carriers move around the membrane tank and can work as abrasive particles, reducing membrane fouling. This system, an MBR-containing BAC, is often called a biofilm MBR. The use of moving carriers in MBR prevents a sudden rise of TMP by producing extra shear forces and minimizing the deposition of fine particles onto the membrane surface by scouring [1].

It was noticed that a remarkable reduction of the cake layer formation on the membrane can be achieved through the abrasion generated by introducing granular materials to the aeration tank of the MBR system. In addition to that, it was reported that using granular materials will result in a positive impact on the membrane permeability, provide higher flux enhancement (>20%), will not adversely influence the quality of the permeate, and conforms to the operational needs of biomass separation [233]. Some researchers stated that the introduction of granules into immersed MBRs can reduce membrane fouling because of their mechanical cleaning influence on the membrane surface [233-235].

9.2.7 Critical flux operation

The critical flux concept and subcritical flux operation in membrane separation processes were introduced To reduce membrane fouling [18]. Since this introduction, they have been applied to all kinds of membrane systems. The critical flux in MBR systems denotes the operating flux where no fouling occurs under the proper fouling control conditions. Even though MBR systems run under critical flux conditions, membrane fouling still obviously develops. If the strict meaning of critical flux – the flux where no fouling happens - is applied to MBR, a significantly lower flux would be identified as the critical flux. Therefore, the flux that endures severe and rapid fouling even with employing a proper fouling control strategy such as coarse aeration and periodic cleanings is regarded as the critical flux in MBR [1].

This kind of flux is often called sustainable flux to differentiate it from the strict definition of critical flux. Typical values of critical flux in MBR systems range from 10 to 40 LMH depending on the various factors affecting membrane fouling. Different methods to determine the critical flux have been proposed, however, no single protocol has been agreed upon to measure critical flux, making a comparison between the published data a challenging task [1].

9.2.8 Reducing the flux

Reduction of the flux usually results in fouling reduction, then it will clearly influence the capital cost because of the needed membrane area. However, a distinction between the operational flux and net flux as well as peak and average fluxes must be made. Basically, with respect to the operational flux of MBR, there are two modes of MBR operation, that will finally specify the cleaning requirements and hence the net flux:

- Sustainable permeability operation: In this mode, the conditions are selected to keep a stabilized operation (minimal or insignificant rise in TMP at constant flux) over an extended period (many weeks or months) with only reasonable remedial actions (such as relaxation), if any. All submerged FS and side-stream systems operate under such conditions, with MBRs continuously operated (without relaxation) between chemical cleaning processes.
- Intermittent operation: In this instance, the operational flux is more than that which can be sustained by the filtration cycle operating conditions, and, hence, intermittent remedial actions are utilized. These include relaxation complemented with backwashing and, generally, some kind of chemical cleaning process. All submerged HF MBRs are operated in this mode [30].

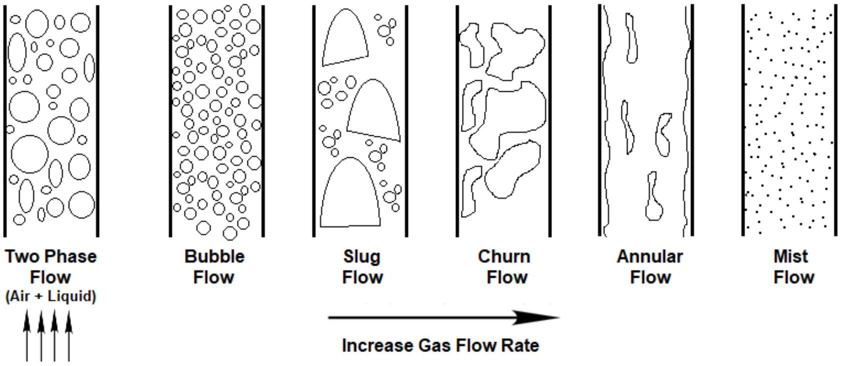


Fig. 12. (a) Two-phase flow in MBR (b) Flow regimes according to gas flow rate

9.2.9 Adsorption

Adding adsorbents to the biological treatment process tends to decrease organic compounds level. Adsorbent, for example, PAC, doses will produce biologically activated carbon (BAC) particles that adsorb and degrade soluble matters. In a comparative study between the side stream and submerged hybrid PAC-MBR, PAC was found to be efficient in lowering the levels of EPS and SMP [236]. Many studies conducted to investigate the influence of dosing MBR supernatant with PAC up to a concentration of 1 mg/L have demonstrated a decrease in membrane fouling, while other studies revealed that the optimum PAC concentration was 1.2 mg/L [237, 238]. Other researchers stated that dosing PAC into the bioreactor will influence the apparent viscosity of the biomass and the flock size distribution, hence resulting in a reduction of the cake resistance. On the contrary, when maintaining a PAC concentration of 5 mg/L in the bioreactor without wasting the sludge, no considerable performance improvement was obtained [223].

It was assumed that, in such cases, PAC was quickly saturated with organic matter and that fouling inhibition by PAC depends upon its regular dosing brought about by shorter SRT values.

Comparing the hydraulic performances of pre-flocculation and adding PAC was done based on experimental work performed with various system configurations of submerged HF membranes. Under the employed operational conditions, pre-flocculation showed more fouling reduction than that of adding PAC. However, using both techniques concurrently would provide the best enhancement of membrane permeability [239, 240].

9.3 Biological control

Biological fouling control has been developed recently thanks to the innovative developments in the fields of molecular biology over the last couple of decades. They show potential for MBRs to become abler to cope with membrane fouling than ever before. A representative biological fouling control development is quorum quenching technology [1].

9.3.1 Quorum quenching

The quorum sensing (QS) mechanism is quite well understood due to the progress in modern microbiology and molecular biology. QS is a method in which bacteria communicate by signal molecules called auto-inducers (AIs) released by bacteria themselves. QS is triggered when AI molecules exceed a critical threshold, after which point the AIs bind to receptors on the bacteria and make the whole bacteria population express certain kinds of genes together. Biofilm formation is a typical example of QS. When the micro-organisms attach to a surface, they maintain signaling to each other. Once they sense a quorum, genes are regulated and slimy exopolysaccharides are produced that "glue" the bacteria with each other [241].

The principal idea of the application of QS to fouling control in MBR is "quorum quenching". The microorganisms in the bio-cakes on membrane surfaces communicate together using AIs. Membrane fouling resulting from biofilm formation and deposition to membrane surfaces by microorganisms could be inhibited by the addition of AIs inhibitors. Based on this idea, signal-quenching bacteria were isolated and immobilized in free-moving beads keeping the bacteria in, but allowing the AIs to pass through. When it is placed near the membrane in MBR, the beads help to stop biofilm formation. The time to reach a TMP of 0.7 bar was extended 10 times compared with the control, indicating the fouling rate was greatly minimized because of using beads [242].

9.3.2 Other biological control

Other types of biological control techniques besides quorum quenching are:

- Nitric oxide to induce biofilm dispersal: The addition of low levels of nitric oxide causes the dispersal of biofilms, indicating that it can be used as a potential alternative for fouling control. However, it has not been investigated for fouling control in MBR, hence further studies are needed.
- Enzymatic disruption of EPSs: Since EPSs are mainly composed of proteins and polysaccharides, EPSs could be hydrolyzed to their building blocks by some specific enzymes such as protease and polysaccharides. If EPSs are readily degraded by enzyme addition, less membrane fouling would be anticipated. Several studies have indicated that this kind of enzyme cleaning showed better cleaning efficiency than alkaline cleaning. However, many limitations are still present in applying enzyme-cleaning techniques to MBR.
- Biofilm disruption by bacteriophages: The addition of bacteriophages reduces microbial attachment to membrane surfaces in MBR by disrupting biofilm formation, which is caused by the infection of host bacteria. However, further and wider studies on the characteristics of specific parasites between the bacteria and phages are needed to apply MBR.

Although further studies are needed for these recent applications, each biological approach looks like a promising alternative for fouling control in MBR. In particular, the quorum quenching techniques are still being developed in lab and field scale tests and they could arrive at mature stages soon [1].

9.4 Electrical control

Electricity has been used for conventional pressure-driven membrane filtration processes. Particularly, attention to fouling control using an electrical application in MBR has been paid extensively. The application of electricity to enhance membrane filtration performance is categorized into three groups: (1) Induction of electric field, (2) In situ EC, and (3) High-voltage impulse. The following sections include a brief description of each group.

9.4.1 Induction of electric field

An electric field applied across membranes can minimize the movement of charged particles to the membrane surface, leading to fouling mitigation. The mechanism is based on the electric negativity of particles. Suspended, fine, and colloidal particles have negative charges in an aqueous solution. The charged particles including AS sludge suspension moves from the membrane surface to electrodes if a direct current (DC) electric field is applied across the membrane, as shown in Fig. 13. Induction of a DC electric field facilitates migration of the charged particles on the membrane surface to the counter (+) electrode. This backward transport of the particles off the membrane can improve membrane fouling [1].

Recently, many studies on the electric field application to improve filtration performance in MBR have been reported. The introduction of minute electric fields from 0.036 to 0.073 V/cm to submerged MBR enhanced the permeate flux significantly [243]. The low electric fields improved microbial growth and activity and thus reduced EPS production, leading to retarded fouling. Moreover, applying an electric field to the MLSS has the potential to change the microbial activity and physicochemical characteristics of the sludge-like particle size, sludge volume index (SVI), and zeta potential. Many researchers emphasized that operating MBR with low electric fields can reduce inadvertent interferences with MBR performance while simultaneously decreasing energy costs [244].

Akamatsu et al. 2010 [245] proposed intermittent electric field induction (on and off electric fields) to MBR systems, they kept the permeate flux as much as 3.5 times higher than the no-electric-field MBR case. Since they found no gas bubbles near the cathode, they concluded that the electrolysis of water did not occur, indicating that the higher flux was not owing to gases scouring sludge onto the membrane surface but to the electric field. They explained that the repulsion force between the membrane surface and the negatively charged AS particles prevents their adhesion to the membrane surface. However, they applied relatively high electric fields, 4–6 V/cm, compared to other researchers.

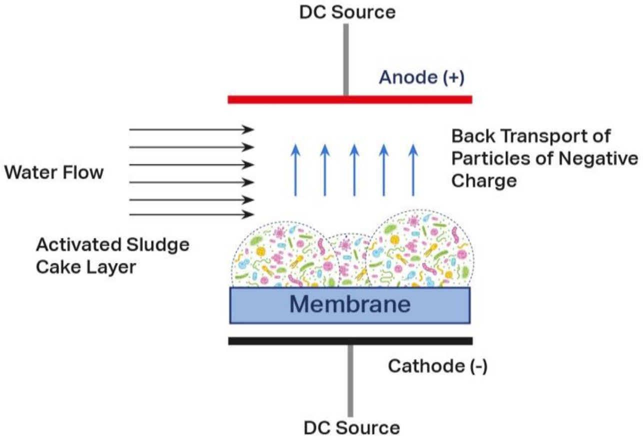


Fig. 13. Back transport of negatively charged particles by DC induction

Long-term studies on the effect of electric fields on microbial activity and other various physicochemical characteristics of biomass are needed. Chen et al. 2007 [246] applied much higher electric fields to a hollow fiber-submerged MBR. They found the flux enhancement was proportional to the electric field strength between 15 and 20 V/cm as the flux remained constant after 20 V/cm. However, they applied the electric fields for a very limited time within a day. The long-term effects of electric fields on the microbial activity should be investigated.

The advantages of membrane filterability gained by the electric field should overcome or at least compensate for the disadvantages caused by possible damage to microorganisms, which could lead to a decline in metabolism or wastewater biodegradation. Further investigations are needed for a wide application of the electric field to MBR plants. In addition, the energy consumption of electric field induction should be compared with conventional aeration for fouling control. Evaluation of the electric field in MBR and the conventional aerated MBR should be compared in terms of energy consumption and flux performance. Another unresolved issue is the lifetime of the electrodes. Since electrodes are very vulnerable to contamination and corrosion, they will likely require frequent cleanings and replacement. Since most studies currently being carried out in the laboratory for over a short time duration, long-term data about electrode contamination, corrosion, and cleaning are needed. Finally, the long-term impacts of electric fields on the microbial activity and physicochemical characteristics of microorganisms should be investigated [1].

9.4.2 In situ electrocoagulation (EC)

Particularly, the application of EC focusing on membrane fouling control in MBR has a growing research interest. The EC mechanism is based on in situ formation of cations at an anode such as aluminum (Al^{3+}) and ferric (Fe^{3+}) ions, which could work as coagulating agents in an aqueous solution to lower the electrical double layer of the negatively charged colloidal particles [1]. The mechanism of EC is similar to conventional coagulation. $Al^{3+}_{(aq)}$ ions are generated at the anode and dissolved into the bulk solution, whereas reduction occurs at the cathode generating hydrogen gas (H_2). Similar to alum, $Al_2(SO_4)_3\cdot 18H_2O$, the most frequently used coagulant in water treatment processes, the $Al^{3+}_{(aq)}$ ions react with water molecules to form various kinds of hydrolyzed aluminum ions as well as aluminum hydroxide, $Al(OH)_3$. Al^{3+} and the hydrolyzed aluminum ions coagulate the negatively charged colloidal matters via a charge-neutralization mechanism. The gelatin-like insoluble aluminum hydroxides, $Al(OH)_3$, work as coagulants by enmeshment of colloidal particles to their free-falling bodies in solution. It should be noted that huge amounts of inorganic and/or organic sludge are produced during EC-MBR. In general, metal hydroxides, $M(OH)_3$, are precipitated in bulk solution due to the dissolution of metal ions from the electrode. Moreover, any excess metal ion (Me^{2+} or Me^{3+}) has an opportunity to react with soluble phosphate ions (PO_4^{3-}) in bulk solution to form $Me_3(PO_4)_2$ (or $MePO_4$) precipitates. Enhanced phosphorus removal can be expected in EC-MBR because phosphorus is subjected to be precipitated by metal phosphate. For example, $FePO_{4\,(s)}$ in iron electrodes or $AlPO_{4\,(s)}$ in aluminum electrodes. This is one of the pros of the EC-MBR process [1].

9.4.3 High voltage impulse

The high voltage impulse (HVI) method, with a standard electric field strength of 20–80 kV/cm and nano-to-microsecond pulse duration, has been practiced to inactivate microorganisms. HVI has also been known as pulsed electric fields (PEFs) in the food industry and has been used for the non-thermal sterilization of foods. As shown in Fig. 14, bacterial cell membranes are damaged by HVI and thus torn and finally pin-holed (electroporation). This electroporation of cell membrane by HVI has been suggested as a basic mechanism of inactivating this micro-organism [1].

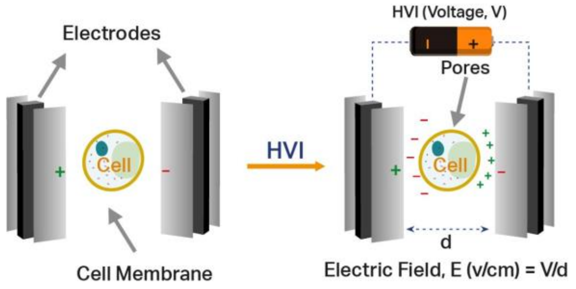


Fig. 14. Schematic presentation of electroporation of bacterial cell membrane by HVI

Kim et al. 2011 studied the disinfection of E-coli using HVI. They used square-wave pulses of 5-20 kV/cm of an electric field to inactivate the model microorganisms. They suggested disinfection kinetics and showed a possibility of membrane biofouling control by HVI [247]. The HVI technique was introduced by Lee and Chang to control fouling in MBRs. HVI was applied to mixed liquor of activated sludge instead of a model microorganism. Exponentially decayed waveform pulses for 10–20 kV/cm of electric field and 20–70 µs pulse durations were used. They reported that the flux recoveries after HVI induction were greater than those of the control at all times. They also found that increasing HVI contact time will decrease the MLSS concentration, while the concentrations of soluble COD, total nitrogen, total phosphorus, polysaccharide, and protein in the bulk solution increased, strongly indicating that the flocs and cells were destroyed by the HVI induction [248]. Such findings suggested that HVI induction resulted in sludge solubilization, which loosened the tightly deposited cake layer on the membrane surface, thus giving it the chance to be readily displaced from the membrane surface. HVI induction caused biofouling mitigation utilizing removing the solubilized bio-cake on the membrane surface. Even though the HVI application to MBR is still in its initial stage of research and development, this research supports the potential of using the HVI method to control fouling in MBR systems [1].

9.5 Membranes and module modification

9.5.1 Membranes modification

Physicochemical modification of membrane materials has been tried to improve the performances of membrane processes for a long time. Although surface morphology, structure, charge, and roughness of membranes are subject to be change, an improvement of surface hydrophilicity is a key factor to obtain a better flux and antifouling behavior. Surface modifications of hydrophobic to hydrophilic membranes are usually accomplished by coating or grafting a functional group on the ready membrane surface. Many studies dealing with membrane surface modification have focused on changes in hydrophilicity through versatile methods. Surface modification of PVDF, the most frequently used membrane material in MBR plants worldwide, is well-reviewed and documented [249]. Patterned morphology on membrane surfaces like a pyramid, prism, and embossing patterns, using a lithographic method, was developed recently [250]. Depositions of microbial cells on the patterned membranes were extremely reduced in comparison to that on the flat membranes in MBR. This was attributed to the hydraulic resistance of the apex of the patterned surface, which induced local turbulences. Contrary to the conventional methods of surface modification, researchers are focusing on the application of nanomaterials to improve the membrane properties thanks to the recent remarkable developments of nanotechnologies. Silver nanoparticles (nAg), titanium oxide (TiO_2) nanoparticles, carbon nanotube (CNT), and fullerene (C_{60}) could be potential candidates expected to show better performance when utilized to modify the membrane properties. This was attributed to a well-established fact that silver has bactericidal abilities [1].

Chae et al. 2009 [251] investigated the influence of fullerene C_{60} on the biofouling of microfiltration membranes with a model microorganism E. coli K12. They reported that C_{60} inhibited microbial respiratory activity and/or attachment to the membrane surface. They suggested that C_{60} might be useful as an antifouling agent to prevent membrane biofouling. Kwak et al. 2001 [252] fabricated hybrid organic/inorganic RO membranes composed of aromatic polyamide thin films underneath titanium dioxide (TiO_2) nano-sized particles. They found that the TiO_2 composite membrane showed improved water flux and photocatalytic bactericidal efficiency under UV illumination. Kim et al. 2012 [253] synthesized a thin-film nanocomposite membrane through an interfacial polymerization of a support layer containing multiwall carbon nanotubes (MWCNTs) and a thin-film layer containing nAg particles. They found that the membrane permeability of the composite membrane was enhanced in comparison to a non-CNT matrix through the diffusive tunnel effects of MWCNTs. The nAg particles in the thin-film layer enhanced membrane permeability and surface hydrophilicity, and provided the composite membrane with antibacterial and antifouling properties. Celik et al. 2011 [254] synthesized a blended membrane with MWCNTs and polyethersulfone (PES) by phase inversion. Increased hydrophilicity of the blended membrane led to more flux and slower fouling rate than intact PES membrane.

It has been known that TiO_2 shows a self-assembly behavior on the surface of polymeric membranes having functional groups such as carboxyl, sulfone, and ether. A self-assembled composite membrane can be made by bonding the sulfone group (or ether groups) in the membrane surface to Ti^{4+}; nanoparticles. It was reported that modification of a PES membrane by self-assembled TiO_2 nanoparticles enhanced the membrane hydrophilicity, suggesting it was a positive antifouling composite membrane. Although many studies have been made to get less fouling in MBR membranes using nanoparticles or nanotubes, more research work and development are still required [1].

9.5.2 Module modification

Optimization and modification of module configuration attempt to improve membrane performance. Particularly, fouling in membranes can be minimized by increasing turbulence near membrane surfaces via rotation of the membrane or spacer or using a helical membrane. Fig. 15 shows the structure of a vortex-generating membrane module (FMX, BKT Inc.). The vortex generators placed between membranes are driven by the center drive shaft. They create Karman vortices at the membrane interface without being in contact with the membranes, which maintains the foulants in suspension to be swept away by the bulk flow [1]. Kang et al. 2011 [255] used flat UF membranes equipped with rotating vortex generators for the filtration of anaerobic digestion sludge, which allows the membrane system to cope with high solid concentration feeds up to 5%. Helical-structured membrane systems proposed by Jie et al. 2012 [256] showed increased flux without increasing aeration intensity. The system consists of helical-supporting spacers and membranes. They explained that rotational flows near membrane surfaces were generated due to the helical structure. The enhanced wall shear stresses increased membrane permeability.

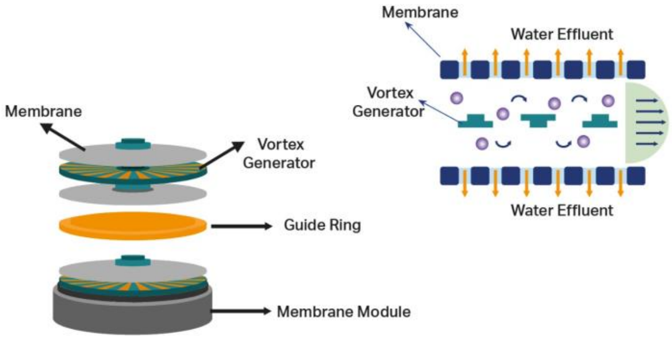


Fig.15. Schematic of the vortex generating membrane module

10. Challenges and future perspective

Despite the great efforts towards pushing the use of MBRs in WWT, their applications in WWT are still limited. Some bottlenecks should be addressed at a lab scale before moving toward large-scale applications. Below is a list of proposed research areas that could be investigated in future works to develop and improve the full application of MBRs:

- During the previous decades, researchers investigated different techniques to control and reduce fouling in MBRs and to improve their performance. Such investigations were limited to lab scale experiments and time constraints, therefore MBR fouling mitigation and energy provided for MBR operation still requires a further reduction for treatment processing need to be furtherly studied. Additionally, validation of lab-scale results should be tried on a large-scale system and in the long term [257].
- It is crucial to reduce the capital and operational costs of the MBR systems; this requires real and continuous efforts. Extending the lifespan of the MBR, minimizing depreciation cost, maintaining stable specific flux, and lowering the energy requirements need essential interests to ensure efficient, effective, and sustainable MBR systems [258, 259].
- To better control fouling in MBRs, the hydrodynamics of the system are to be optimal. Specifically, aeration techniques still need further improvement to achieve both biological requirements and enhanced scouring process. Chemical cleanings need to be thoroughly implemented to respond to the complex nature of fouling in MBRs. MLSS should be seasonally assessed to account for fouling tendency fluctuation, this will overcome flux decline in the long-term operation of MBRs [258].
- Increasing membrane hydrophilicity will provide better MBR performance and enhanced antifouling properties. Therefore, further experimental research is needed to produce membranes from blended materials to confirm their superiority in WWT applications [258].
- New MBR anti-fouling techniques should be researched and explored in addition to investigating optimal operational conditions. Besides the physical and chemical cleaning, extra work should be directed to modify membrane surface properties to enhance permeability and mitigate fouling [259].
- Since the influent wastewater is composed of different constituents, it is worth investigating the individual influence of such constituents on MBR parameters and properties; new insights for MBR modifications and improvements can be built on the results of these investigations [260].
- Impacts of different types of fouling and their control techniques on lab scale MBR performance must be studied in relation to duration, microbial activity, process stability, membrane improvement and sustainability, and environmental safety [260].
- Biofouling control strategies will certainly influence the microbial community and its diversity in the MBR. Hence, the effect of using these strategies on MBR performance still needs to be carefully investigated [261].
- Researchers should investigate the possibility of developing environmentally friendly cleaning methods for MBRs to minimize the effects of chemical cleaning on the MBR and the bacteria, for example, biological cleaning and ultrasonic cleaning [257].

11. Conclusions

The need for stringent effluent is the main driver of using MBR in wastewater treatment plants. Despite having high capital and operation costs, the widespread of MBR is continuing and is expected to increase year by year. Environmental legislation related to freshwater conservation and pollution reduction drove MBR development many decades ago. Governmental, institutional, and organizational incentives, have also encouraged installing MBRs in activated sludge wastewater treatment plants which results in producing higher quality effluent and at the same time utilizing a smaller footprint than conventional activated sludge systems. MBR configurations can be either submerged or side stream; submerged MBR is preferable because of its lower energy consumption. On the other hand, submerged MBRs can be operated at 70% permeate flux as compared to side stream MBRs. Two fabrications of submerged MBRs are used; hollow fiber and flat sheet, while side stream MBSs use multiple tube fabrications. Hollow fiber MBRs require longer periods between cleaning times as compared to flat sheets MBRs, they also consume fewer chemicals and have shorter maintenance times. MBRs can be run in two modes; constant permeate flux and constant transmembrane pressure with the first is preferable as it can deal well with variations of wastewater inflow.

Membrane fouling is the most significant hinder to MBR's large-scale application for WWT worldwide. Fouling in MBRs can take many forms, with the biofoulants and organic foulants being the main foulants of MBRs. Fouling control, minimization or prevention is a hot research point that still needs further investigation and development. Despite the huge research conducted on MBR fouling, there is no single statement describing the mechanism of membrane fouling and it is hard to have a generic rule about its development. This is because membrane fouling in MBRs is influenced by many strongly interconnected parameters including membrane characteristics, feed water properties and operational conditions. There is a wide space for controlling and minimizing fouling in MBRs, and researchers should take the cost of controlling / minimizing method, the impact on the biological nature of the mixed liquor, the impact on permeate and sludge quantity and quality, and effect on the membrane lifetime into consideration.

12. CRedit authorship contribution statement

L.I. Qrenawi: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Visualization, Original drafting, review and editing.

F.K.J. Rabah: Conceptualization, Data curation, Methodology, Supervision, Project Administration, Visualization, Original drafting, review and editing.

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14. Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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