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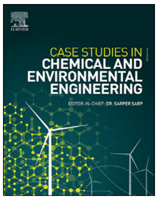

Membrane bioreactor for wastewater treatment: A review

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ABSTRACT

Due to the growth in the human population globally, it is noted that various industries have also grown. The need for an excess supply of water and the generation of high effluent quality upon proper treatment technologies has become a necessity. These two crucial needs can be achieved with the aid of membrane bioreactor (MBR) that has been proven to be effective in removing organic and inorganic matters as a biological unit for wastewater treatment. MBR plants are created by integrating the biological process with membrane filtration which possesses numerous benefits if compared with conventional methods such as activated sludge; MBR is widely used for municipal and industrial wastewater treatment. This review addresses basic concepts of MBRs plants and subsequently provides information on the recent developments of each part related to MBR plants. The characteristics of the bioreactor treatment process is discussed in detail, and then a comprehensive review of the membrane separation process is examined. The fouling phenomena as a main obstacle to widespread MBRs plant is presented in detail with recent fouling mitigation methods. The efforts of a number of novel MBR processes are summarized. In order to tackle the existing limitation of MBRs to be practical on a larger scale, the existing challenges and future research efforts are proposed.

List of abbreviations

AFBR	Anaerobic Fluidized Bed Bioreactor
AFM	Atomic Force Microscope
AFMBR	Anaerobic Fluidized Membrane Bioreactor
AnMBR	Anaerobic Membrane Bioreactor
APAC	Asia Pacific
BCC	Business Communication Company
CA	Cellulose Acetate
CAGR	Compound Annual Growth Rate
CAS	Conventional Activated Sludge
COD	Chemical Oxygen Demand
CSTR	Completely Stirred Tank Reactor
DOM	Dissolved Organic Matter
EPS	Extracellular Polymeric Substance
FESEM	Field Emission Scanning Electron Microscope
GHG	Greenhouse Gas
HRT	Hydraulic Residence Time
MBR	Membrane Bioreactor
MF	Microfiltration
MFC-MBR	Membrane Bioreactor integrated with Microbial Fuel Cell
MLSS	Mixed Liquor Suspended Solid
MPBR	Membrane Photobioreactor
MSCS	Melt Spinning and Cold Stretching
NF	Nanofiltration
NIPS	Non solvent Induced Phase Separation
OLR	Organic Loading Rate
PAC	Powdered Activated Carbon

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PSF	Polysulfone
PTFE	Polytetrafluoroethylene
PVDF	Polyvinylidenedifluoride
SCOD	Soluble Chemical Oxygen Demand
SMP	Soluble Microbial Products
SPM	Scanning Probe Microscope
SRT	Solid Retention Time
TIPS	Thermal Induced Phase Separation
TMP	Transmembrane pressure
TSS	Total Suspended Solid
UASB	Up-flow Anaerobic Sludge Blanket
UF	Ultrafiltration
VFA	Volatile Fatty Acid
VSS	Volatile Suspended Solid
WAS	Waste Activated Sludge

1. Introduction

Due to growth in population, the number of industries has exponentially increased. This result in either severe environmental challenges or huge demand for water supply. According to the current status of water resources, it is utmost importance to utilize novel solutions to improve water cycle management in public and industrial areas. Additionally, implementation of the novel sustainable techniques in water cycle are required to consider the true value of water. With this in mind, recovery of the wastewater can be considered as a highly valuable resource which can be accomplished with the aid advanced technologies [1]. One of the alternative technologies for wastewater treatment is the use of membrane biological reactor. It is a combination of biological process with membrane filtration that is called Membrane Bioreactor (MBR). In this case, the degradation of biomass is occurred inside the bioreactor tank, while separation of treated wastewater form microorganisms is completed in a membrane module. Over the last two decades, MBR attracts lots of attention due to its potential to produce high quality effluent and currently considered as a mature technology to treat wastewater [2]. It was reported that 22.4% of Compound Annual Growth Rate (CAGR) was expected for the MBR market [3]. Recent BCC (Business Communication Company) report showed that the market size of MBR to be 3.0 billion USD in 2019 and is expected, at a CAGR of 7%, to reach 4.2 billion UDS by 2024. Worldwide, APAC (Asia-Pacific i.e., one segment of MBR market if it is categorized based on the region. It is considered to have a highest MBR market growth in the world. Fig. 1 summarizes the MBR market growth by region during the period 2017-2024 [4].

1.1. A glance at the history of MBR

In 1969, Smith et al. was the first one who introduced the MBR technology through Dorr-Oliver research program. The aim was to treat sewage produced from a manufacture plant (i.e., Sandy Hook, Connecticut, United State) for 6 months with high equality effluent. Ultrafiltration membrane was installed instead of sedimentation tank outside the bioreactor tank to separate treated water and activated sludge. Although this configuration generated a very high-quality effluent, it's widespread was restricted due to the high energy cost and membrane fouling associated with it at that time [5].

To overcome the obstacle of previous configuration, in 1989, Yamamoto et al. [6] created an innovation configuration by placing the hollow fiber membrane in the activated sludge aeration tank. Instead of using pressurized pump installed outside to circulate the mixed liquor across membrane, suction pressure was applied into the bioreactor where the membrane immersed directly inside the aeration tank.

After the introduction of immersed configuration, number of studies have been applied to increase the application of MBR technology by providing high quality of permeate in large scale while reducing the capital cost since the mid-1990s. Parameters that have been investigated can be summarized as the shape of membrane module, the pore size distribution of membrane, operating condition to minimize the membrane fouling phenomena while finding new strategies to clean fouled membrane [7].

After 2008, the commercialization of MBR plants had decelerated due to the economic depression worldwide. Nevertheless, because of the necessity for a better water environment, MBR technology has a bright future to expand.

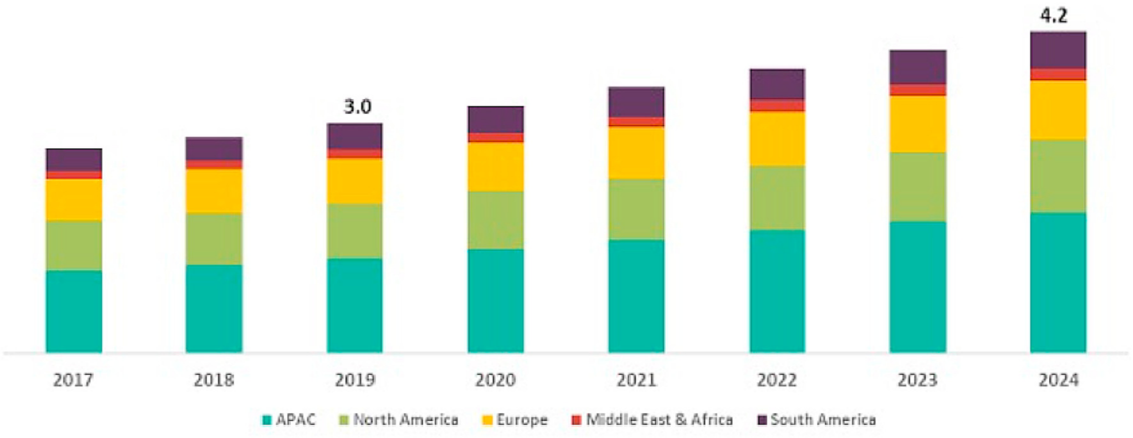

Fig. 1. MBR market by region (USD billion) [4].

1.2. Comparison between CAS and MBR

Conventional Activated Sludge (CAS) mainly consist of two steps. The first one involves aeration tank, in which wastewater is treated with the aid of active microorganisms (i.e., activated sludge). The treated water and the activated sludge are separated in the sedimentation tank, or secondary clarifier. Activated sludge cannot be completely separated in the sedimentation tank and usually lighter fraction is carried out with the treated effluent. However, in the case of using MBR, because of the existence membrane with different pore size, most of the activated sludge can be separated.

Advantages and disadvantages of MBR over CAS can be summarize in Table 1 [8] (see Table 2).

To this end, the main purpose of this review is to familiarize the reader with the basic concepts of MBR and subsequently provide information on the recent developments of each part pertaining to MBR plants such as fouling mitigation, which is a vital factor in terms of effecting the MBR performance. This review starts with fundamental of the biological wastewater treatment and membrane technology. Following sections highlight and discuss the fouling phenomena from the basic to the novel fouling mitigation strategies that are applied in the recent years. Subsequently, Novel configurations are also discussed, based on the recent literature on the subject for the purpose of clear understanding of the recent advances in MBRs. Finally, the challenges that need to be addressed to tackle the obstacles that prevent further development of the MBR technology, are outlined.

2. Biological wastewater treatment

Generally, the bioreactor operating conditions highly influence such characteristics of the microorganism as size, content of filamentous microorganisms, growth rate, etc. On the other hand, the activity of microorganisms can affect the performance of the MBR in two different ways; in the quality of the effluent and how much the MBR can treat the wastewater pollutant, and the fouling properties of the membranes. Hence, profound study of the principle of the biological wastewater treatment such as microbiology, metabolism of microorganism, microbial stoichiometry, and kinetics in bioreactor is necessary in order to determine the optimum operating conditions of the bioreactor and design characteristics of the MBR plants [9].

Table 1
Advantages and disadvantages of MBR compared to CAS [8].

Advantages	Disadvantages
• Smaller bioreactor size with omitting sedimentation tank resulting in smaller footprint.	• Fouling phenomena is a common problem of MBR which necessitates various operational strategies to reduce the fouling propensity of membrane regardless of the process and operational complexity of membrane installment.
• No limitations on the concentration of Mixed Liquor Suspended Solid (MLSS) in the MBR, thus the generation of Waste Activated Sludge (WAS) is reduced. (i.e., maximum concentration of MLSS in CAS is around 5000 mg/L due to secondary clarifiers limitations. Nevertheless, optimum level in MBR is around 8000-12000 mg/L.	• Higher capital and operational cost are involved with the MBR process due to the cost of membrane and antifouling strategies.
• Quality of treated water and the bioreactor MLSS can be determined with the Solid Retention Time (SRT). Fine control of SRT can be achieved in MBR due to elimination of secondary sedimentation tank.	• Complexity of the process mainly due to membrane maintenance and cleanliness methods.
• Typically, longer SRT results in increasing wastewater efficiency. Applicability of longer SRT in MBR (more than 20 days) in comparison to CAS (generally 5-15 days) provide higher effluent quality during treatment process.	• High foaming propensity is another problem which is partly caused due to the larger aeration demand of MBR.
• Generation of high quality treated effluent due to the existence of membrane with pore size smaller than suspended solids. Nevertheless, for efficient secondary clarifiers the typical SSs concentration is around 5mg/L. Hence, excluding the requirement for the tertiary treatment such as filters in MBR.	• Higher power consumption during operation. Sometimes, it is double than the electrical consumption in the CAS.

The structure and composition of the microbial community of a bioreactor varies from one MBR plant to another and across time scale for a given MBR unit. The main reason for this variation is the important features of the microorganisms in environmental engineering systems, including MBR plants. Due the influence of wastewater from the atmosphere, which is fed into the bioreaction, diverse microorganisms are structured into variety of communities. However, by adjusting operating conditions and reactor design, specific type of microorganisms can be enriched in the bioreactor [10].

The type of microorganism and their functionality are the same in both CAS and MBR plants. However, their characteristics are different due to long SRT and high concentration of biomass in MBR bioreactors which results in Ref. [11]:

1. maintaining slow-growing microorganisms compared to shorter SRTs of CAS aeration tank which is beneficial due to degradation of the recalcitrant organic matters. Nevertheless, it can also generate unwanted microorganisms such as foaming microorganisms, and
2. reducing the fraction of active biomass from total solids in the bioreactor by producing more inert solids.

2.1. Type of microorganisms

In the bioreactor, five major groups of microorganisms are generally found: Bacteria (e.g., *Proteobacteria*), Protozoa (e.g., *Amoebae, Flagellates, Ciliates*), Metazoa (e.g., *Rotifers, Nematodes, Tartigrades*), filamentous bacteria, algae, and fungi [12]. However, the majority of microorganisms (over 90%) that exist in the activated sludge are bacteria [12]. Most of the bacteria accumulate together and form pairs, chains, or clusters but they can also continue their life while living as a single cell. Regarding their metabolisms, they can use numerous sources of energy, electron donors, electron acceptors, and carbon sources. Their adaptability can be used helpfully not only to treat different types of organic and inorganic pollutants but also provides conditions to treat specific type of materials that may exist in the wastewater. Shchegolkova et al. [13] found the structural of bacteria communities in activated sludge and incoming sewage for three different wastewater treatment plants by performing 16S rRNA gene sequencing. Additionally, they provide a heatmap includes the top 40 bacteria families in AS (i.e., 94.2- 97.5% of all bacteria) [13].

Tendency of microorganism to accumulate onto the surface of membrane causes creation of biofilms. With the aid of self-produced matrix material in contrary to the planktonic cells (i.e., extracellular polymeric substance (EPS)) biofilm cells are embedded. Adhesive properties of biofilm are mainly due to the presence of proteins and carbohydrates that exist in the EPS which is an important disadvantage of MBR plants [14].

2.2. Microbial stoichiometry and kinetics in bioreactor

Balanced microbial stoichiometric equations are like the chemical stoichiometric equations while they are quite important for estimating biological performance and treatments. However, in the microbial kinetics equation consumed substrate serves as energy source and used for biomass synthesis simultaneously. In other word, microorganisms are not

Table 2
Biokinetic coefficient of different bacteria in different MBR.

MBR characteristics	Biomass type	yield coefficient	maximum specific growth rate	half-saturation coefficient	decay coefficient	Ref.
submerged hollow fiber ultra filtration MBR worked at HRT=9.5 h, T=14.7 °C, MLSS concentration=6.6 g/l.	Heterotrophic bacteria	$0.4887(\frac{mgVSS}{mgCOD})$	$0.0141(h^{-1})$	$7.467(\frac{mgO_2}{L})$	$0.0521(day^{-1})$	[16]
	Ammonium-oxidizing bacteria	$1.191\ (\frac{mgVSS}{mgN})$	$0.1612(h^{-1})$	$0.2204(\frac{mgN}{L})$	NM	
	Nitrite-oxidizing bacteria	$0.6473(\frac{mgVSS}{mgN})$	$0.0786(h^{-1})$	$0.324(\frac{mgN}{L})$	NM	
submerged hollow fiber ultra filtration MBR HRT=9.5 h, MLSS concentration=3.3 g/l.	Heterotrophic bacteria	$0.4609(\frac{mgVSS}{mgCOD})$	$0.01917(h^{-1})$	$16.47(\frac{mgO_2}{L})$	Total bacteria decay= $0.03043(day^{-1})$	[17]
	nitrifying bacteria	1.0389(	$0.27193(h^{-1})$	$0.9329(\frac{mgN}{L})$		
	nitrite-oxidizing bacteria	$0.77913(\frac{mgO_2}{mgN})$	$0.11244(h^{-1})$	$0.4364(\frac{mgN}{L})$		
Immersed MBR operated at HRT=13h, MLSS concentration=5 g/l under steady state condition.	*Serratia liquefaciens* and Aeromonas hydrophila(predominant bacteria)	$0.567\ (\frac{mg}{mg})$	$0.0233(h^{-1})$	$326.14(\frac{mgCOD}{L})$	$0.062(day^{-1})$	[18]
Microfiltration MBR operated at HRT= 33h , T=25 °C.	heterotrophic biomass	$0.756\ (\frac{mgCOD}{mgCOD})$	$3.687\ (\frac{mg}{g.\ h})$	NM	$0.353(day^{-1})$	[19]
Moving bed biofilm reactor combined with MBR operated at HRT=26.47h, T=15 °C, and MLSS concentration=2.9 g/l.	heterotrophic biomass	$0.5041(\frac{mgVSS}{mgCOD})$	$0.00484(h^{-1})$	$0.96(\frac{mgO_2}{L})$	Total bacteria decay= $0.04844(day^{-1})$	[20]
	autotrophic biomass	$0.77718(\frac{mgO_2}{mgN})$	$0.02632(h^{-1})$	$0.76(\frac{mgN}{L})$		
MBR plant with hollow fiber membrane operated at HRT=8h, T=27 °C, and MLSS concentration= 1.3 g/l.	heterotrophic biomass	$0.703(\frac{gVSS}{gCOD})$	NM	NM	$0.02(day^{-1})$	[15]
Bioreactor plant by using glucose as substrate at T=20 °C.	shewanella baltica KB30	$0.6681(\frac{mgVSS}{mgCOD})$	$0.0840(h^{-1})$	$1.608(\frac{mgO_2}{L})$	NM	[21]

used only as catalysts for biological reaction but also through microbial growth during treatment process they will reproduce themselves as well. The ratio of generated biomass to the consumed substrate (e.g., glucose) can be referred as biomass yield or growth which is depended on microbial composition and growth conditions [13].

With the aid of balanced microbial stoichiometric equations, understanding the elements that are involved in the reaction (i.e., primary electron donor, terminal electron acceptor, nutrients, biomass, and oxidized products) and the rate of consumption or production of elements are important. Nevertheless, prediction of how fast the reaction taking place is impossible. Determination of the microbial reaction rate is important in order to estimate the required volume of bioreactor as well as biomass concentration to achieve a specific result. Also, with the aid of reaction rate, estimation of the bioreactor performance at a particular operating condition and certain design is possible. Therefore, for modelling activated sludge reaction rate many specific software such as BioWin, STOAT, GPS-X and WEST were developed [15].

Bioreactor performance (e.g., the rate of biomass production and effluent substrate concentration) and design parameters (volume) are estimated by setting up mass balance equations with using microbial kinetics. Microbial kinetics is largely focus on the microbial growth rate and substrate utilization [15].

Microbial growth is only possible by metabolizing biodegradable substrates. However, all matters exist in wastewater influent are not degradable. Thus, calculation of the biodegradable fraction of influent is the first essential step in estimating the microbial growth rate. Also, during growth, microorganisms have a tendency to decay themselves. Hence, the differences between growth rate and the decay rate are called the net growth rate that can be defined as below:

$$R_{g,net} = R_{growth} + R_{decay} \tag{1}$$

$$R_{g,net} = \frac{dX}{dt} = \frac{\mu_m SX}{K_S + S} - k_d X \tag{2}$$

Where $R_{g,net}$ is the net growth rate ($\frac{g\ \ VSS}{m^3.day}$), X is the biomass concentration ($\frac{g\ \ VSS}{m^3}$) and S is the biodegradable substrate concentration ($\frac{g\ \ COD}{m^3}$).μ_m shows the maximum specific growth rate (day^{-1}).$K_S$and k_d represent the half saturation constant for biodegradable substrate ($\frac{g\ \ COD}{m^3}$) and the decay coefficient ($\frac{g\ \ VSS}{g\ \ VSS.day}$) separately [16]. Table 3 summarize biokinetic coefficient of different MBR plants for different types of bacteria.

As microorganisms use biodegradable pollutants, i.e. substrate, being as their food source to grow, the wastewater is treated. Thus, the rate of substrate utilization is tightly related to the growth rate of microorganisms with the biomass yield coefficient. However, substrate removal rate is more important for engineers rather than microbial growth rate since it represents the progress of the treatment [15].

It is also worthy to mentioned that the rate production of VSS in bioreactor is an important parameter to design and operated facilities of bioreactor. The VSSs of mixed liquor in bioreactor are produced due to three main sources: growth of microorganism, nonbiodegradable VSSs via biomass decay that cannot be use by microorganisms as their substrates and finally nonbiodegradable VSSs generated from influent wastewater which is dependent on wastewater characteristics. Hence, the total VSS production rate ($R_{VSS,t}$) can be expressed as below:

$$R_{VSS,t} = \frac{\mu_m SX}{K_S + S} - k_d X + f_d k_d X + \frac{X_0 Q}{V} \tag{3}$$

Where f_d is the fraction of product of biomass decay that accumulate in a bioreactor. $X_0$is concentration of nonbiodegradable VSS in wastewater influent ($\frac{g\ \ VSS}{m^3}$); Q and V represent the influent flow rate ($\frac{m^3}{day}$) and bioreactor volume (m^3) separately.

3. Membrane separation process

3.1. Membrane material

Different materials can be used for the fabrication of membranes. However, limited number of them have been commercialized till now. In the field of wastewater treatment and due to the several operational restrictions, the number of materials that can be used to construct a membrane is different than that in the other fields. High acidic, basic, chemical, and mechanical resistance over 5 years of operation as well as possibility to expose to a wide range of pH from 1 to 12 (i.e., in both

Table 3
Pros and cons of different polymers with their fabrication process [8].

Polymer	Fabrication	Advantage	Disadvantage
PSF	NIPS	• Safe from leaching • High mechanical strength • Easy to form structure	• Low chemical durability • Rigid/ brittle
PES	NIPS	• Good control in leaching • Simple formation	• Stiff/brittle • Low chemical durability
PE	MSCS	• Cost effective • ductile	• Large pore size
PP	MSCS	• Cost effective • Ductile	• Large pore size
PVC	MSCS	• Cost effective • Ductile	• Large pore size • Not strong enough to basic conditions
PVDF	NIPS, TIPS	• High fracture elongation • Excellent mechanical properties • Narrow pore size distribution • Strong chemical resistance	• weak performance in basic conditions • Forming structure is not easy
PTFE	MSCS	• Low fouling potential • High water permeability • Excellent chemical resistance	• High overall cost • Hard fabrication design
CA	NIPS	• Low contact angle • Simple formability	• Low chemical durability • Low base/acid resilience

operation and recovery process) [22], are some of the required characteristics of the membrane wastewater treatment applications. To meet these requirements dor the membrane, such material such as plastics, ceramics and stainless-steel materials can be used. Polymer-based membranes are the most common used material in water and wastewater treatment. Polysulfones (PSFs), polyvinylidenedifluoride (PVDF), which is the most popular one due to its long lifetime, polytetrafluoroethylene (PTFE) and cellulose acetate (CA) are the most common polymer-based materials are used recently [22]. Table 4 summarized characteristics of different polymer-based materials used for membrane fabrication.

3.2. Membrane fabrication methods

Manufacturing of membrane is possible through different methods. Non-solvent Induced Phase Separation (NIPS), Melt-Spinning and Cold-Stretching (MSCS), and Thermal Induced Phase Separation (TIPS) are the most common methods for fabrication of membranes which are discussed below.

3.2.1. NIPS

This method is the most popular method where membrane is fabricated due to the solubility difference of polymers in different solvent. Two solvents are used in this method which are compatible with each other while polymers have different solubility levels with them. One of the solvent, in which the polymer has low solubility with it, is called poor solvent or nonsolvent, while =the other solvent, in which the polymer has a good solubility with it, is called good solvent [23]. In the fabrication process, at the beginning the polymer is mixed with with the good solvent. Then the prepared solution is added to the poor solvent with the aid of injection nuzzle that results in hardening (or gelation) of the polymer since the good solvent is permeate into the poor solvent. Appearance and creation of pores on the membrane structure is the result of diffusion of good solvent into the poor solvent solution. Fig. 2 represents the schematic of the NIPS fabrication method.

To remove the excess amount of the good solvent, the poor solvent solution as well as additives, the polymer is washed out and then dried.

Table 4
Recent studies to mitigate membrane fouling phenomena during wastewater treatment in MBR plants.

Novel strategi	Performance in fouling retardation	Brief result	Reference
Membrane structure modification	Modification of membrane using metal- organic framework to improve photocatalyst performance. (blending of CdS/ MIL101 (Cr) as a visible light photocatalyst into the PVDF membrane in a practical anammox MBR by waterproof lights underwater)	• Advantages of fabricated membrane over original one: higher antifouling characteristic, lower flux decreasing rate, higher fouling rejection, reducing TMP increase and diminish of membrane fouling in long term operation. • Similar nitrogen removal in both membranes.	[46]
Microbial community properties	Evaluation of dissolved organic carbon contribution and microbial dynamics to membrane fouling control in anoxic/ oxic(A/0) MBRs under long starvation to provoke membrane fouling.	• Important role of TM6, OD1, and Chlamydiae in biofilm based on the microbial community in fouled MBRs since they were the predominant phylum in the biofilm. • Existence of Xanthomonadaceae might be related to fouling due to its abundant concentration in fouled membrane. • Regarding the mitigated membrane data, Chitinophagaceae and Candidatus Promineofilum played a key role in reducing fouling due their abundance in mitigated fouled MBR. • Keeping and controlling microbial diversity is one of the important parameters in fouling control	[47]
Modification of biomass properties	Evaluation of the performance of MBRs and fouling characteristics by adding nanoparticles as adsorbents. (comparison of addition Ag-NP (referred to NP1) as an antibacterial ingredient and Fe3O4-NP (called NP2) as magnetic material in MBR plants)	• Increasing COD removal in both systems due to the adsorption of organic matters by NPs • Better performance of NP1 in removing EPS and SMP comparing to original system. (49% and 66% deduction in EPS and SMP for NP1 while for NP2 was 38% and 54% respectively) • Increase flux rate by 41% for NP1 while for NP2 was reported 32%	[48]
Hydrophilic membrane surface modification	Assessment of Antifouling performance of hydrophilic modification for anammox since it showed a promising strategy as antifouling in aerobic and anaerobic MBRs. (preparing hydrophilic membrane(Mh) by	• Higher gel layer resistance on Mh comparing to Mp. creation of thin and compact gel layer on Mh while for Mp was thick and loose. • Rapid flux reducing short filtration cycles in long term operation of anammox MBRs • Decreasing nitrogen removal by Mh mainly because of reducing	[49]

(continued on next page)

Table 4 (*continued*)

Novel strategi	Performance in fouling retardation	Brief result	Reference
	depositing polyvinyl alcohol solution on primeval nylon fabric meshes (Mp))	amount of anammox bacteria in the anammox MBR plant and increasing the heterotrophic bacteria community.	
Optimizing operating condition	Evaluating of the effect of temperature on the methanogenic activity in An-MBR	• Decreasing energy demand because of reducing viscosity of liquids due to decrease in temperature • Increasing flux by decreasing temperature • Reducing methanogenic activity by decreasing temperature in two An-MBR plant runed at 15oC and 25oC.	[40]
Membrane cleaning method	Effect of granular activated carbon with the recycling of liquid to control fouling as a replacement for biogas sparging in An-MBR	• Offering large surface area for biofilm growth • Low energy consumption • Effective fouling mitigation	[50]
Mechanical cleaning	Basic and comprehensive assessment of the mechanical cleaning with using porous and non-porous scouring agents in MBR plants to control fouling.	• Reduction either cleaning cycles or amount of required energy for gas sparging • High efficiency of fouling control due to diffusion of agents inside the laminar boundary layer that created on the membrane surface. • Complete cake layer elimination on the membrane by scouring agents. However, increasing irreversible fouling due to removal of cake layer	[51]
Pre-treatment of feed	Applying advanced oxidation technique as a pretreatment to mitigate fouling propensity of the membrane and comparing its effect with coagulation technique. (UV/ H2O2 treatment and coagulation with aluminum chloralhydrate was utilized as pretreatment to control fouling of a ceramic MF membrane)	• Both mechanisms have a promising effect in reducing total fouling resistance. Mainly due to the breakdown of the very high MW biopolymers • The coagulation method results in a lower irreversible fouling type in comparison to the advance oxidation technique. • Production of lower MW substance happened in the application of UV/ H2O2	[26]
Modifying activated sludge	Addition of flux enhancer to control fouling. However, there are lots of difference in the exact amount of dosage of FE for different type of sludge. (cationic polymer Adifloc KD451 applied as a FE on seven An-MBR sludge samples collected from the industrial wastewater treatment)	• Significant variance of the optimum and critical dosage of the FE between samples. (DOPT and DCrit ranged from 0.02 to 1.16 $\left(\frac{g}{l}\right)$ and 0.1-2.5 $\left(\frac{g}{l}\right)$ separately.) • Linear relationship of DOPT with capillary suction time and SMP-PS according to Anaerobic Delf Filtration Characterization method (AnDFCm) • A negative effect of the excess addition amount of FE on membrane fouling mitigation. • Driving empirical models to predict a proper optimum dosage of FE for a new sludge sample.	[52]
Hydraulic membrane cleaning	Effect of different backwash (BW) scheme (i.e., different BW duration and temperature), as a main hydraulic membrane cleaning method, on a fouled membrane (same hollow fiber membranes) in MBR plants treating municipal wastewater was investigated. Particularly, effect of them on a TMP drop and the membrane penetrability increase.	• By increasing BW temperature from 80C to 380C, fouling intensity was decreased where reduction of TMP, was 7.1%, 14.2% separately. • Duration of BW also result in a better performance of MBR. As an example, at BW temperature of 380C, TMP drop was increase from 14.2% to 30.2% for 1min duration of BW to 8 min duration separately. • Membrane permeability was increased by increasing both BW temperature and BW duration.	[53]

Composition of polymer and good solvent, shape and dimension of the injection nuzzle are parameters that affect the inner and outer membrane pore size in this method [23].

3.2.2. MSCS

Polymers are generally made of two different structures. Crystalline lamella structure which has an ordinary arrangement and amorphous interlamellar structure which is the flexible part. Hence, polymers have two transition temperatures. Melting temperature (Tm) is the one where above it crystalline structure is active while above glass temperature (Tg) amorphous structure become active (usually Tm is higher than Tg). In the fabrication of membranes based on MSCS method, first the polymer is melted. Then it is cooled down just under the Tm while simultaneously applying one or two directional stretching. In this process, crystalline morphology will remain the same while the amorphous structure is lengthened and creates wide range of pore size. Although this process can generate the cheapest membrane, but impossibility of controlling pore size distribution and large averaged pore size of the membrane are the two main disadvantages of it [24].

3.2.3. TIPS

According to this process, membranes are fabricated based on the differences between solubility and thermal melting point. In other words, TIPS has an intermediate position between two previous methods. By adding solvent or diluents, polymers are dissolved or diluted at high temperatures. Then it rapidly cooled by cold liquid to remove all the remaining solvent or diluents and producing membrane pores. Occasionally, to improve mechanical strength of membrane stretching process is applied. However, weakness of fabricated membrane is one the significant problem that is associated with this process which has received a lot of attention to address this issue [25].

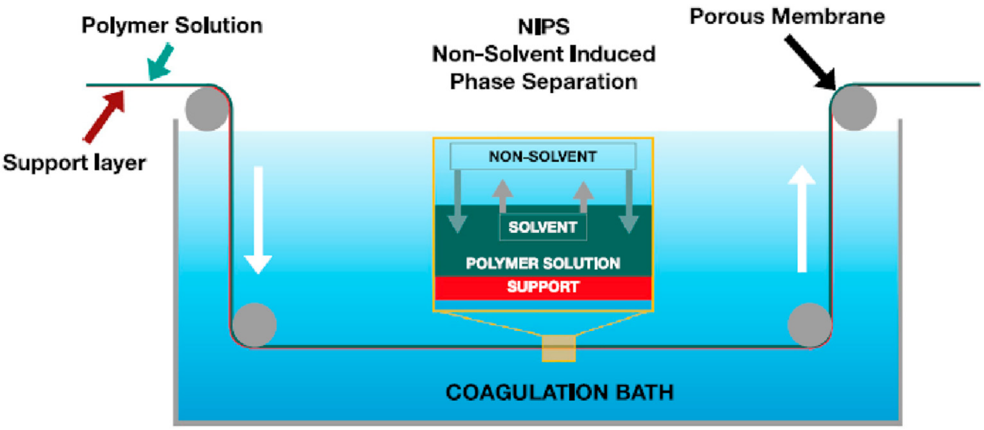

Fig. 2. Representation of NIPS fabrication process [23].

3.3. Membrane characterization

3.3.1. Membrane modules

Hollow fiber, tubular and flat sheet are three main forms of membranes. In the case of hollow fiber and tubular membranes, the significant dimensions are the outer diameter, the inner diameter, and the membrane length while for flat sheet type, thickness, length, and width are the considerable dimensions. Based on the diameter, the hollow fiber membrane can be classified into two different groups [3]. All dimensions can be determined accurately with the help of field emission scanning electron microscope (FE-SEM), micrometers and calipers.

Simple cleaning and replacement methods, good efficiency for commercial usage are the main advantages of the flat sheet membranes; however, high cost is their main disadvantage while researchers attempting to fabricate a cost effective ones. In the case of hollow fiber membranes, high area per unit volume, cost effective fabrication process, and capability to withstand severe operating conditions make them attractive. However, high rate of fouling, and thus high washing frequency, is their main disadvantage [26]. Tubular membranes are also attractive due to their high mechanical strength, low fouling rate, long life, and simple cleaning and replacement. Nevertheless, low packing density as well as high capital and operational cost prevent their usage on a large scale [26].

3.3.2. Pore size distribution

Membranes utilizes in wastewater treatment are usually classified into two groups; porous and non-porous. The porous membranes use sieving size exclusion to separate particles such as Microfiltration (MF), Ultrafiltration (UF) and Nanofiltration (NF). The non-porous membranes work on the principle of solubility or diffusivity in system to separate particles (e.g., tight end NF and Reverse Osmosis).

Size of the particles in wastewater and membrane pore size can affect membrane fouling. If the membrane pore size increased, as fine particles can more easily enter the membrane and trapped there, pore blocking mechanisms leads to increase as well. Nevertheless, with smaller pore size, smaller particles can be collected on the layer formed on the membrane by large particles. This formed layer can be simply removed by different methods such as air scouring.

One of the methods to measure pore size distribution of the membrane is by measuring FE-SEM images of the membrane surface. However, determining the total pore size distribution of membrane is very difficult using this method since the fraction of the taken image in comparison to the entire membrane surface is small. Hence, we need to calculate based on bulk information of the pore size. Bubble point, particle rejection, and polymer rejection are three typical methods to calculated pore size distribution based on bulk information [27].

3.3.3. Hydrophilicity

Fouling propensity of membrane is highly affected by hydrophilicity. Hydrophilicity is a parameter that indicates how much a membrane can be wetted with water. If air in the membrane pores cannot easily replaced with water, then the membrane is hydrophobic. Most of the polymer-based polymer are hydrophobics, in which high fouling potential is their main disadvantage. Microbes in the MBR produce biomass in the form of activated sludge floc and organic matters which are usually hydrophobic. Hence, there will be a strong adhesion between biomass and membrane surface which reduce the membrane efficiency upon creation of a layer on the membrane surface, i.e., fouling phenomena. To overcome this problem certain hydrophilic materials can be added during membrane fabrication to increase hydrophilicity of the membrane [28]. Also, to allow penetration of water inside membrane pores, wetting agents are used to enhance permeation of water. Nevertheless, without the use of wetting agents, the hydraulic pressure is essential to eject the air from pores. Minimum required hydraulic pressure depends on the average pores diameter, surface tension of the water and the contact angle [28].

3.3.4. Electric charge (Zeta potential)

Beside hydrophilicity, another parameter that can affect the fouling propensity is the electric charge on the membrane surface. The main foulants in the MF and UF membranes (i.e., mainly used in MBR) are the organic matters which have negative surface charge. Thus, less fouling potential can be experienced by using a membrane that has a higher negative charge on its surface [29].

Zeta potential is a parameter that represents the electric charge on the membrane surface. The most recent method to measure zeta potential is the streaming potential, which is the potential occurs when electrolytes flow between two materials in aqueous solution. Other methods may include electrophoresis, electroosmosis and sedimentation potential characteristics [29].

3.3.5. Surface rougchness

The roughness of a membrane surface can also contribute to fouling. Rough membrane surface provides wide contact areas and extreme interaction between foulants and the membrane surface. Hence, rougher surface of the membrane results in more fouling tendency [30].

With the aid of Atomic Force Microscope (AFM), the roughness of a membrane can be measured, i.e. a type of Scanning Probe Microscopes (SPM) [31]. By analyzing membrane surface roughness with AFM, it has been shown that surface roughness is higher for membrane with large pore size than that of smaller pore size. Additionally, fouling rate and degree of roughness have a direct impact on each other; an increase in the degrees of surface roughness results in an increase in the rate of fouling [31].

4. Membrane fouling

Fouling is the main problem encountered during the operation of the membrane separation processes. Hence, the efficiency of the MBR process is largely depended on how to manage it. Fouling phenomena is depended on many factors such as operating conditions, membrane cleaning strategies, characteristics of wastewater influent, and membrane properties. Fig. 3 represents the outline of the Membrane fouling phenomena and associative cleaning methods.

4.1. Fouling phenomena

Membrane fouling can be recognized either by the reduction in permeation flux while holding Transmembrane pressure (TMP) constant or an increase in Transmembrane Pressure in constant flux mode. Nevertheless, most of the wastewater treatment plants are operated in constant flux mode. Hence, fouling phenomena generally is perceived by observing the variation of TMP with time [32].

Typically, TMP variation with time follows two main patterns. The first pattern involves two-stage TMP jump, where in the first stage there is a slight increase in TMP due to the adsorption of particles and microbial flocs into the membrane pores while the local filtration flux is still lower than the critical amount (i.e., the number of open pores will decrease where simultaneously TMP will increase). The second stage involves occurrence of a sharp jump in TMP after long times of operation. The reason for this abrupt jump could be due to either critical flux theory where the local flux becomes higher than critical flux or by an abrupt increase in the concentration of EPS in the lower layer of the cake on the membrane surface [33]. The second pattern is the three-stage TMP where the rapid and small jump of TMP at the initial operation of the MBR is mainly due to the participation of the sludge particles or membrane compacting which results in the rapid obstruction of the pores. However,

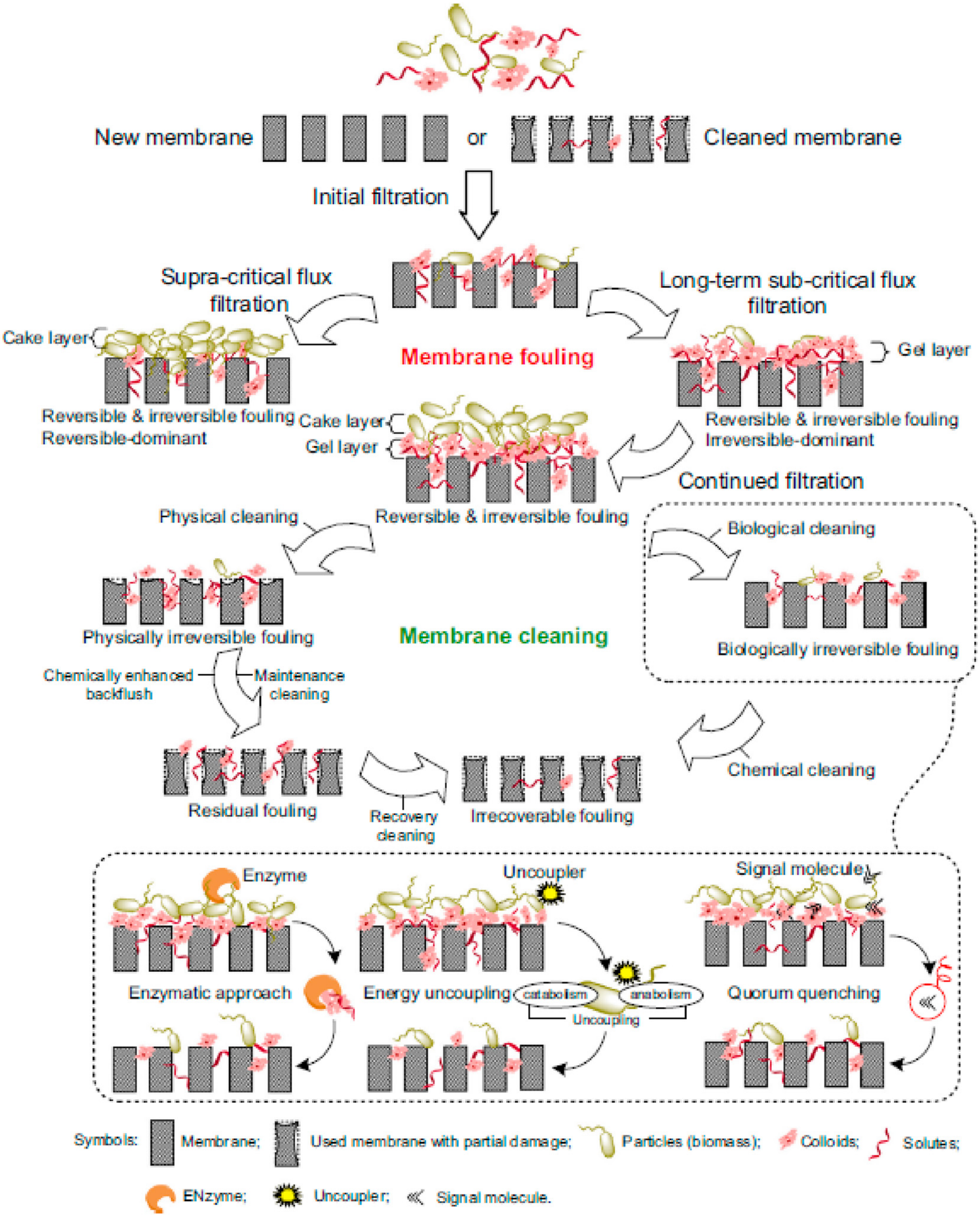

Fig. 3. Membrane fouling and cleaning outline [35].

the remaining stage (i.e., second and third) followed the same mechanisms mentioned earlier. The first stage is usually hidden by the second stage. Thus, the overall pattern often looks like a two-stage jump [34].

4.2. Fouling rate

Fouling is associated with four successive steps. Initially smallest pores are blocked, followed by obscuring the inner surface of larger pores. Direct blockage and accumulation of particles on the larger pores is the next step, and finally the formation of the cake layer is followed. However, the identification of each step is not easy. Hence, instead of focusing to determine each step, quantification of overall fouling propensity is usually practical [34].

Fouling rate is used as a parameter representing fouling propensity during the membrane operation which can be expressed by derivative of TMP or calculation of fouling resistance at a certain time. It can be shown that the fouling rate has a direct relation with operating flux. Thus, by increasing operating flux, the fouling rate becomes faster until the critical point where the fouling rate abruptly increases. The corresponding operating flux to this critical point is called critical flux which separates the subcritical region from the supercritical region [34].

4.3. Classification of fouling

Fouling can be classified based on different criteria. The most common classification is the one which takes into consideration flux recovery after a simple cleaning strategy, location where fouling occurred, and solid deposition pattern. These are discussed in the following paragraphs.

1. Flux recovery after cleaning: this classification is the simplest one to categorize fouling which is based on the capability of the flux to be recovered after a single cleaning method. It can be divided into reversible, irreversible, and irrecoverable fouling. Reversible fouling is referred to the one where flux can be readily recovered with the aid of simple cleaning methods (e.g., air scouring, pressure relaxation, and backwashing). On the other hand, in irrecoverable fouling physical cleaning methods cannot recover the flux and remove the gel and adsorbed layers in the pore; it requires chemical cleaning methods [35]. Irreversible fouling refers to the flux that cannot be recovered by conventional cleaning method nor chemical cleaning. Different fouling patterns can be followed during operation. The ratio of reversible fouling to total fouling can be increased by using more frequent and serious backwashing before chemical cleaning [35].
2. Location of fouling: this composed of clogging, cake layer, and internal pore. Poor design membrane modulus usually results in clogging where small particles and debris (e.g., natural organic matters, extracellular organic matters, and soluble microbial products) are accumulated between hollow fiber or flat sheet membranes inside the membrane module and blocking the flow into the membrane surface [36]. Formation of cake layer on the membrane surface contributes to the most important type of fouling in literally any kind of operation with different membrane types, operating condition, and wastewater influent characteristics. The formation of the cake layer starts at the initial stage of the filtration process and reaches a plateau due to the existence of aeration. Usually, a thick cake layer produces higher cake resistance that is closely related to the membrane filterability [36]. In addition, a thicker layer may have higher efficiency in removing particles only if the wastewater influent consists of bigger particles and hence reduction of cake resistance [32]. The internal pore fouling is due to the adhesion of fine and small particles to the internal pore walls which cause narrowing of the pore diameter. This type also starts at the beginning of the process [37]. However, upon formation of cake layers, particles prefer to attach to the cake layer rather than diffuse and adsorbed on the membrane internal walls. It has been reported that cake layer resistance is much higher and dominant in fouling in comparison to the internal fouling resistance [37].
3. Solid deposition pattern: fouling can be classified according to how the solids and solutes can be deposit on the membrane. This classification consist of cake layer formation, pore narrowing (particles with a smaller diameter than pore diameter which deposit onto the pore internal walls), and pore plugging (i.e., when the particle's size is slightly bigger than the pore entrance size of the membrane or even, they are the same) [38].

4.4. Types of foulants

Since the presence of fouling is related to the physicochemical interaction between biofluids and membrane surface, profound studying of the biofluid constituent is a necessary step to identify possible foulant. In contrary to the simple and uniform chemical nature of membrane characteristics, mixed liquor in the aeration tank where a membrane exists contains different particles which has complicated properties. Fundamentally, mixed liquor constituents can be divided into two parts: particulates (i.e., insoluble particles) and soluble matters. Particulates part mainly contains sludge flocs (main term), individual microbial cells, and debris, secretion of soluble products by microorganisms (main part), and soluble inorganic which are the main source of soluble matters in the mixed liquor [39].

4.5. Factors affecting membrane fouling

Fouling propensity is extremely affected by three factors: operating conditions, membrane characteristics, and the properties of the mixed liquor in the tank where the membrane exists. Fig. 4 summarizes parameters which can influence membrane fouling separately or communally. Each factor will the discussed in the subsequent sections. Description of the effect of each parameters in membrane fouling is presented in Fig. 4 [40].

4.5.1. Membrane characteristics

Membrane average pore size has a direct impact on membrane fouling which should be determined based on the particle size in the influent. This is because if the membrane pore size and particle size become the same then clogging occurs and results in a decrease in the permeate flux. In MBR plants, usually ultrafiltration membranes are in favor because generally, the smallest size of the activated sludge is around sub-micrometer which is close to microfiltration membranes [41]. Hydrophobic membranes usually result in lower flux compared to hydrophilic membranes due to the strong interactions with solution constituents. As most of the commercially available membranes are hydrophobic ones, further modification of their surface with hydrophilicity material is required to eliminate fouling on their surface [42]. Membrane material can be considered as another parameter that impacts fouling. Most of the membranes are made of polymeric materials, but unfortunately, they cannot stand properly in extreme conditions. Ceramic membranes provide a higher chemical and thermal resistance compared to polymeric membranes. Recently inorganic materials (e.g., Alumina, zirconia, and silicon carbide) have received more attention, especially in the food and dairy industries. Their ability to withstand operating conditions under robust and strong cleaning in extreme conditions (e.g., high/low pH, high temperature) is their main benefit which can be utilized to control fouling. Nevertheless, their cost and module manipulation (i.e., most of them are fabricated in tubular shapes that have a lower packing density comparing to hollow shapes) limited their development [42]. As mentioned earlier, packing density is another important factor. Higher packing density decreases the number of membrane modules that should be used which finally results in a smaller footprint. However, there is a limitation because overpacked membranes can reduce mass transfer efficiency [42].

4.5.2. Microbial characteristics

Microbial components are ranging from biomass solids to dissolved

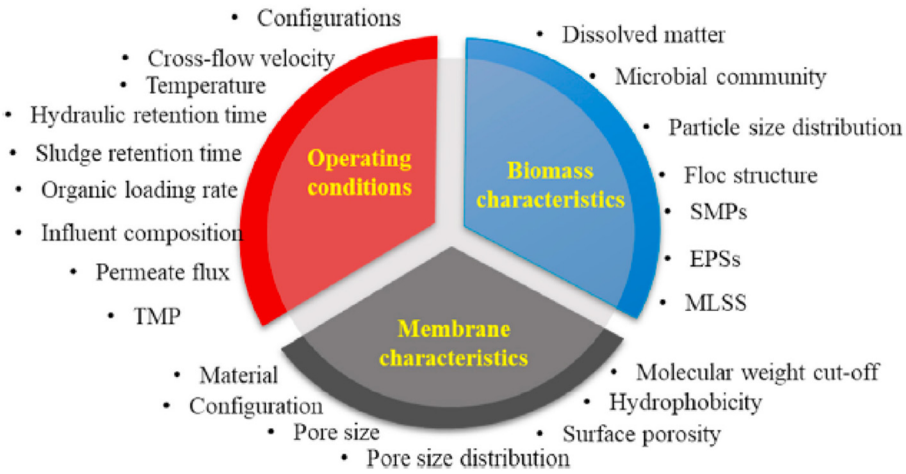

Fig. 4. Effective parameters in membrane fouling [40].

biopolymers such as EPS. Their characteristics are highly influenced by the operating conditions. Therefore, their relation can strongly affect the fouling propensity of the membrane. MLSS is a factor that represents the biomass concentration in MBR plants. Increasing the MLSS concentration would increase the thickness of the cake layer. But, because of the existence of the shear force on the membrane surface, the accumulation of the biomass on the cake layer cannot extend unlimitedly. Hence, irreversible fouling cannot be directly influenced by the MLSS concentration. MLSS has a direct effect on the EPS or SMP production which are responsible for irreversible fouling [39]. DOMs in aeration basins can considerably influence both internal and external fouling by either absorbing to the pore's surface and walls or in the spaces of the cake layers during their freeway to the membrane [43]. Also, influent characterizes have a direct impact on microbial metabolisms. The performance of the microbial community can badly influence by the unbalanced amount of nutrients which led to partial failure of the treatment process [43].

4.5.3. Operating conditions

Performance of the reactor, either CSTR or PFR, can be determined with HRT parameter which is a ratio of reactor volume over the influent flow rate. HRT is directly related to the food to microorganism ratio (i.e., F/M) in such a way that increasing HRT will decrease the F/M ratio. On the other hand, decreasing the F/M ration means high oxygen consumption by microorganisms in the endogenous steps. Nevertheless, HRT has an indirect effect on fouling as membrane fouling is more pronounced in the exponential phase than the endogenous phase. The mean cell's resident time (SRT) is another parameter that may also influence membrane propensity. SRT has a direct relation to the MLSS concentration and inverse relation with the free EPS levels. Increasing SRT leads to a decrease in the EPS level which provides lower fouling on the membrane surface. On the other hand, the increase in the MLSS concentration results in the elevation of the mixed liquor's viscosity that may worsen fouling and also require more demand for aeration. Hence, assessing optimum SRT is essential to control fouling phenomena [44].

To scour the cake layer on the membrane surface in the side-stream MBRs, shear forces are applied through a recirculation loop from the bioreactor to the membrane with the aid of a pressurized pump. The shear force directly affects microbial characteristics in both flocs and microorganisms in the loop and the one in the bioreactor. The main contribution of the shear stress is the breakage of the flocs which has two main impacts. Firstly, the structure of the flocs can be collapse and therefore decrease the floc size which negatively affects fouling propensity. Secondly, EPSs are released to the bulk because of this floc collapse which also increases the fouling. In other words, choosing a suitable pumping device to apply acceptable shear stress on the microbial floc plays an important key to mitigate fouling. On the other hand, for submerged MBRs, there isn't any pressurized pump to generate shear force. However, membrane fouling control, as well as an oxygen source for microorganisms, is supported by aeration. The performance of the submerged MBRs is highly affected by the aeration process. If aeration is not satisfactory enough then coarse air supply cannot effectively remove or reduce the cake layer size, thus fouling might be enhanced. Too excessive aeration can also breakdown the fragile floc that its effect was discussed earlier. Hence, aeration intensity can be considered as an important design factor for submerged MBRs [45].

4.6. Fouling control strategy

Different fouling control methods have been utilized to minimize fouling in MBRs. Their effects, in both lab-scale and pilot scale as well as their potential to developed on a large-scale usage have been investigated for a long time. Pre-treatment, substrates modification, membrane surface modification, optimization of operating conditions, and physical or chemical cleaning methods are some examples of these strategies. Table 5 summarized some of the novel and recent techniques with their assumption as well as their brief results to mitigate fouling phenomena.

5. Types of MBR and novel configurations

5.1. Aerobic and anaerobic membrane bioreactor (AnMBR)

To treat wastewater and effluent from industries, aerobic treatment technology has been utilized for a century. However, high energy demand for aeration process, generating high amount of sludge, emission of greenhouse gases such as nitrous oxide (N_2O), large footprint and high maintenance cost are main drawbacks of such technolgy. For wider application of aerobic MBR, reduction of required energy is crucial where aeration control strategies in aeration tanks plays a significant rule to deduct overall energy consumption of the process. In full scale MBRs, recent studies showed reduction in aeration and energy consumption rate of 20% and 4%, respectively, by employing ammonia-N-based aeration control strategy [54]. It is worthy to mention that reduction of airflow rate to decrease energy consumption may have a direct influence on the GHG emissions due to incomplete nitrification. Hence, understanding the relation between operating conditions and direct/indirect GHG emissions is an important key to reduce the environmental footprint. It was reported that a successful reduction in the operational cost of MBRs plant by 13–17% depends on influent dynamics with applying close loop aeration while keeping dissolved oxygen concentration inside the aerobic reactor constant rather than open loop [55].

Usually, to treat effluent with biodegradable COD content lower than

Table 5
Operational and performance of different MBR configuration with different feedstock.

Configuration	Feedstock	Operating condition	Performance	Ref
AnMBR (external)	Synthetic molasses wastewater	• T= 35–37 °C, HRT=30h in pilot scale • Silver (as nanoparticles) coated PVDF • Backwashing the membrane with the air and produced gas from anaerobic baffled reactor	• COD removal=82% • 91% reduction in EPS formation on the nanocomposite PVDF membrane surface.	[64]
AnMBR (submerged)	Synthetic wastewater	• T= 35.7 °C, HRT=10 days in lab scale • Flat sheet membrane with 0.014m^2 filtration area • 2 kg COD/m3/d as OLR.	• COD removal=99.5% • Provide shorter start-up period, higher biogas production, and better COD removal in comparison to external one.	[65]
AnMBR (external)	Pharmaceutical wastewater	• T= 14-38 °C, HRT=36 h in pilot scale • Hollow-fiber membrane with 1m^2 surface area • 3.48 kg COD/m3/d as OLR	• TCOD removal=88–92.5% • 77-171 L/d for biogas production	[66]
Aerobic MBR	Pharmaceutical wastewater	• Reactor was operated until clogging (around one month) • Hollow-fiber membrane with 0.125m^2 surface area • Using natural quorum quencher (i.e., endophytic Penicillium restrictum) to control biofouling and increasing removal efficiency of antibiotics.	• COD removal=82% • Longer operation before clogging happened in comparison to the reactor without addition of P.restrictum (35days and 24days respectively) • 4.5% increase in removal efficiency of antibiotics.	[67]
Aerobic MBR	Municipal wastewater	• SRT= 50 days, HRT=10 h in pilot scale • PVDF flat sheet membrane with 0.1m2 surface area • Average TSS of 9.6 g/l and 10.1 g/l without and with addition of powdered activated carbon (PAC) to evaluate the effect of fouling.	• COD removal=89% • 19% increase in the critical flux by using PAC in comparison to sludge without PAC	[68]
Aerobic Dynamic Membrane Bioreactor. (ADMBR)	Municipal wastewater	• SRT= 106day, HRT=0.87 day, and MLSS= 5 g/l • Hollow-fiber membrane with 0.015m2 surface area • 0.66 kg COD/m3/d as OLR	• COD removal=92.8% • Faster clogging and decreasing COD removal efficiency was experienced by increasing sludge concentration.	[69]
AFMBR	Synthetic wastewater	• T= 37.1 °C, HRT=12h in a lab scale. • PVDF tubular membrane • 0.6 kg COD/m3/d as OLR • Using polymeric materials as fluidized agents	• COD removal=87.6% • Major foulant material on the membrane surface, corresponds to EPS which fluidization wasn't sufficient enough to eliminate pore blockage. • Low energy consumption, stability of PVDF provide excellent surface for biofilm formation.	[70]
MPBR	High ammonia nitrogen wastewater	• T= 25-30 °C, HRT=24 h, and SRT= 30 d • Using novel hollow fiber membrane with enhanced antifouling properties and hydrophilicity (i.e., polyvinylpyrrolidone (PVP)-graphene oxide (GO)/PVDF)	• COD removal=93% • Increase permeability and flux rate in filtration in comparison to normal PVDF • Great potential of PVP-GO/PVDF for high-density chlorella cultivation effective treatment of high nitrogen ammonia wastewater	[71]
MFC-MBR	Synthetic wastewater	• Submerging anode and cathode in the submerged aerobic MBR at both side of membrane module • Using PVDF hollow fiber membrane with 0.2 m^2 surface area.	• 4.4% increase in COD removal efficiency when compared to control MBR • Maximum power density and average voltage were 2.18w/m^3 and 0.15 v respectively. • Improvement in filterability and dewaterability of the sludge • Alleviate the membrane fouling	[72]
MFC-MBR	Synthetic medium	• T=30 °C • Integration of anode as microfiltration membrane in side stream crossflow AnMBR configuration • Using stainless steel filtration membrane	• Achieving 4-fold higher current density in comparison to experiment without filtration (6 A/m^2 for 0.5 um filter grade) • Improving the current density was mainly due to permeate flow	[73]

1000$\frac{mg}{l}$ aerobic process is used while for highly and strong pollutant effluents (i.e., biodegradable COD content over 4000$\frac{mg}{l}$) anaerobic process is commonly used [56]. Anaerobic treatment is a versatile process that can produce renewable fuel (i.e., biogas) by decomposing organic matter existing in wastewater and simultaneously treat wastewater to retrieve water and lastly recovering nutrient to be used for agriculture production by generating fertilizers [56].

An alternative MBR configuration has been developed by integrating anaerobic digestion treatment with membrane filtration to treat wastewater and overcome some obstacles of MBR processes. In this case, the energy requirement of wastewater treatment is reduced during through the decomposition of organic matters to methane-rich biogas. Additionally, nutrient recovery is possible with following precipitation due to converting nutrients into chemically available forms [40]. However, membrane stability, membrane fouling, dilute resources, and salinity built-up are some of the main challenges that prevents its development [40].

Anaerobic bioreactor and membrane models composed the two parts of AnMBR plant. In terms of bioreactor configurations, up-flow anaerobic sludge blanket (UASB), completely stirred tank reactor (CSTR), and anaerobic fluidized bed bioreactor (AFBR) are the most frequent ones for AnMBR with the CSTR being the most commonly structure that is used in AnMBR due to simple operating and construction process (Fig. 5) [57].

Membrane models can be integrated with anaerobic bioreactor in three as shown in Fig. 6: (a) side-stream AnMBR, where membrane module is located outside the bioreactor tank; (b) internal submerged AnMBR, by submerging membrane inside the bioreactor tank; and (c) external submerged AnMBR, where the membrane unit is immersed in a different chamber from the working bioreactor [58].

Recently, External submerged configuration is used largely in pilot scale applications and showed a great capacity to be implemented in large scale usage to treat domestic wastewater. Shin and Bae [59] reported lower energy demand for pilot scale external submerged AnMBR configuration (commonly hollow fiber membrane were used) compared to lab scale AnMBR and aerobic MBRs (ranged from 0.04 to 135 $\frac{kWh}{m^3}$).

5.2. *Anaerobic fluidized membrane bioreactor (AFMBR)*

As mentioned in the previous section, membrane fouling of AnMBRs prevents their widespread even though they showed promising results for

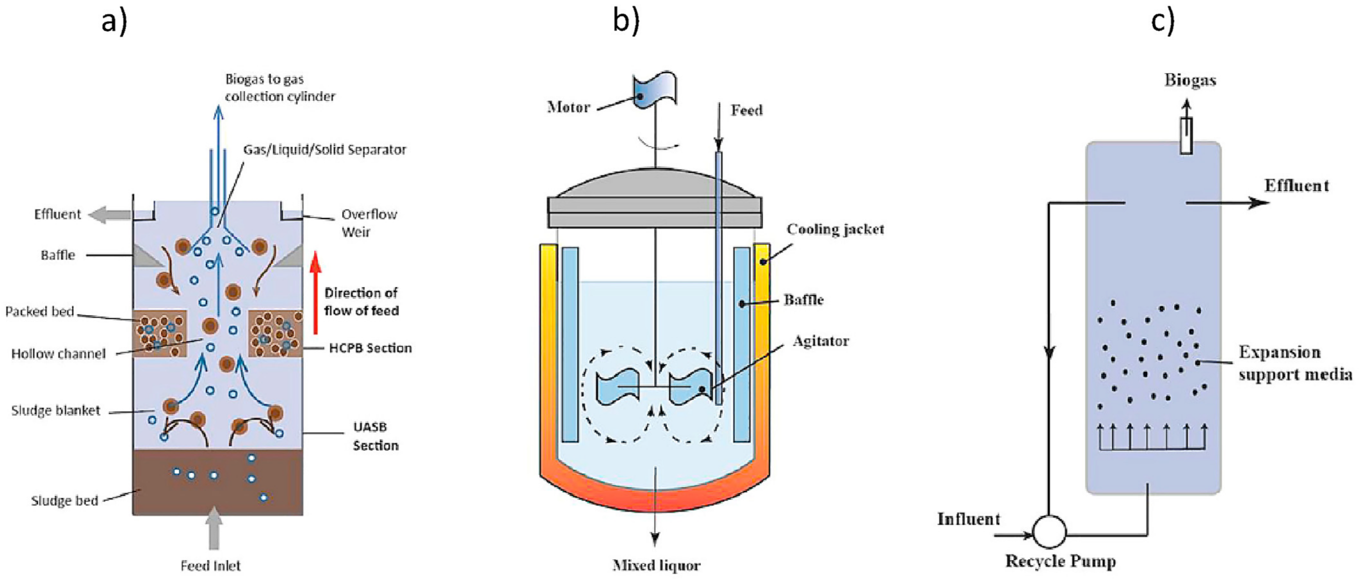

Fig. 5. Typical anaerobic bioreactors a) up-flow anaerobic sludge reactor; b) continuous stirred-tank reactor; c) anaerobic fluidized bed reactor [57].

removing antibiotics and other advantages associated with them. To reduce the formation rate of cake layer and simultaneously increase removal of antibiotics from wastewater, AFMB has been recently developed. It is a combination of membrane technology and circulation of liquid and sprinkle of particles. Increasing growth rate of bacteria that can degrade antibiotics (i.e., increasing antibiotics removal), reduction of EPSs and SMPs concentration, and more stable sludge with higher size are its main advantages over conventional AnMBR. However, understanding the performance of such a novel model, require a further investigation. It has been reported that by addition of carriers the energy needed for the performance of AFMBR is much lower compared to the consumption amount in the conventional AnMBR; for the AFMBR it was in the range of 0.039-0.13 $\frac{kWh}{m^3}$ while for the simple AnMBR it was 0.25-7.3 $\frac{kWh}{m^3}$ [60].

5.3. Membrane photobioreactor (MPBR)

MPBR usually consist of different submerged micro or ultrafiltration membranes such as hollow fibers or flat sheets that combine with PBRs. Effective separation of microalgae, keeping the system stable and improving the quality of effluent are some of the advantages associated with MPBR. However, a major obstacle of developing this configuration is the lack of its efficiency to treat primary raw domestic wastewater containing high organic matters. This is because it mainly contains a low concentration of organic matters which can be used as food source for microalgae and help them grow to treat wastewater [61].

The effects of different parameters such as HRT and organic loading rate (OLR) on the MPBR performance have been studied. It was shown that the amount of OLR up to 0.014 $\frac{kg}{m^3.day}$ with 2days HRT is the most suitable condition for MPBR performance to maintain 0.016 day^{-1} as a fouling frequency while domestic wastewater is treated. According to the same authors, the system does not require any external aeration source and can effectively create microalgal biomass as simultaneously remove organics and nutrients [61].

5.4. Membrane bioreactor integrated with microbial fuel cell (MFC-MBR)

Fouling phenomena in MBR is one of the major problems preventing

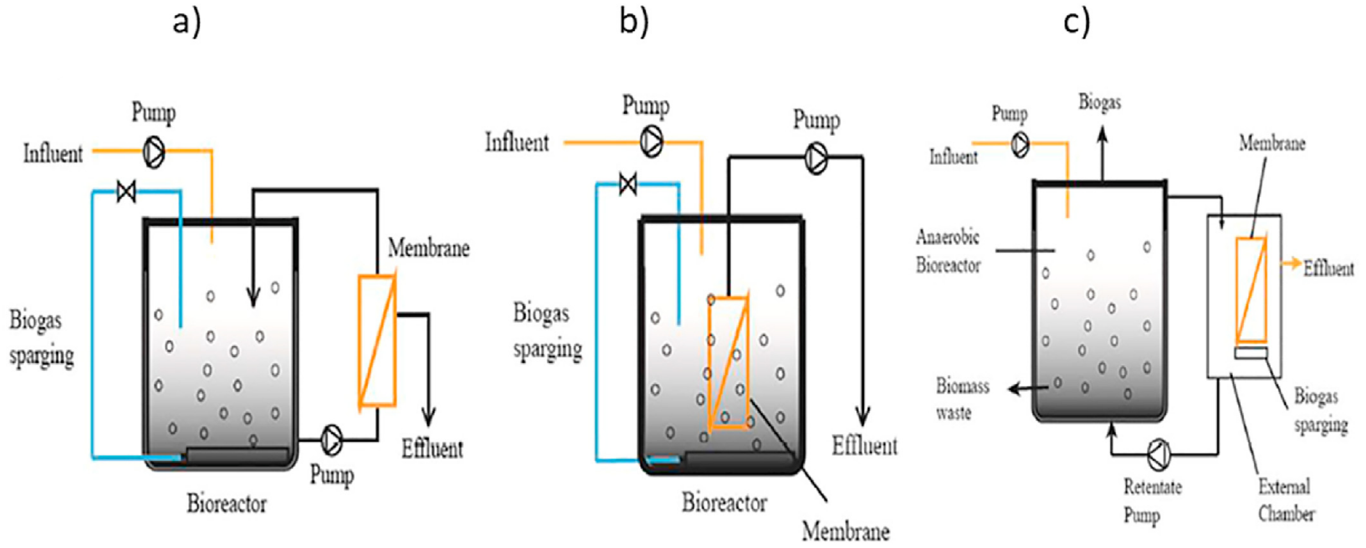

Fig. 6. Basic configurations of anaerobic membrane bioreactor (AnMBR): (a) external AnMBR, (b) internal/submerged AnMBR, and (c) external submerged AnMBR [58].

its widespread use. It has been shown that the deposition of foulant on the membrane surface can be reduced by applying an electric field in MBR which results in the diminish of fouling phenomena [62]. Hence, in recent years a novel configuration has attracted researcher's attention where MFCs are integrated with MBRs. The electricity produced from wastewater treatment by MFC can be used in MBR to control fouling propensity of MBRs [62]. In contrast to applying direct electricity in MBR, within this new configuration required energy for process is reduced and simultaneously performance of the bacteria is not affected due to high electric fields [62].

Fouling characteristics of sludge in MFC-MBR has been investigated by Hui Li et al. [63] where anodic and cathodic chambers of MFC was immersed in aerobic MBR by using hollow fiber membrane. The extended Derjaguin-Landau-Verwey-Overbeek (XDLVO) model was used to analyze the fouling process. The results showed that free energy of adhesion between the SMPs and clean membrane or SPM-fouled membrane is reduced in MFC-MBR compared to those in control systems (C-MBR). The authors also concluded that the SMPS in MFC-MBR are faced with higher energy barriers to be absorbed on the membrane surface which result in inhibition of adsorption and finally reducing fouling process. Lower hydrophobicity and less negative surface charge of sludge flocs in MFC-MBR is another advantage of this configuration [63].

Many studies have been considered the performance of different configuration of MBRs to treat various type of wastewater as their feedstock, either synthetized wastewater or real industrial ones. Studies have been carried out in different levels to evaluate the potential of the proposed configuration in industrial levels. Hence, the efficiency of MBRs was calculated in pilot scale as well as lab scale during different operating conditions. Table 5 summarize the operational and performance of different configuration of MBR plants fed with different feedstock as mentioned above to provide a rough idea about recent progress in the MBR technology. Their performance was assess in terms of percentage of COD removal, fouling propensity of membrane, biogas production, and lastly the maximum power and current density generation with the aid of novel configurations.

6. Challenges and perspectives

Due to the current status of water resources as well as considering the true value of water, implementation of the innovative techniques is required to treat wastewater as a highly valuable resource. Of on the advanced and novel technology is MBR [1]. The extensive three-decade development of the MBR technology for wastewater treatment has grown since the 2000s. Investigations on full scale MBRs have demonstrated that MBR based processes result in sufficient treatment of ordinary pollutants and also have the ability to remove pathogens and emerging pollutants.

In order to operate MBRs, the severe membrane fouling in colder seasons is a necessity and the specific filtration flux can potentially elevate. Should MBR be compared to CAS in terms of capital cost (per unit capacity and operational cost (per unit volume of treated wastewater), the cost of MBR is on a higher scale without tertiary treatment in CAS. However, MBR takes a smaller footprint although it has a higher energy consumption than CAS. Below is a list of challenges proposed by this review that could be faced by the full-scale MBR application:

- To achieve the highest fouling control, the hydrodynamic condition of the membrane module/ cassette/tank configurations should be optimal. With that being noted, the aeration is in need of further improvement and membrane chemical cleaning needs to be thoroughly implemented to cater the complexity of membrane fouling. The conditioning of mixed liquor for fouling control should be assessed as per the seasonal fluctuation of fouling propensity in order to sustain the increasing flux during long term operations.
- Different novel research has been carried out by the introduction of various materials with the typical membranes to increase the hydrophilicity of the blended mixture and consequently improved either the permeation performance or anti-biofouling properties of the membranes. The incorporation of PES membranes with Ag3PO4/g-C3N4 nanoparticles or the introduction of lignin to the PVC ultrafiltration membranes are some examples of novel techniques that create a significant contribution to enhance membrane properties in terms of increasing hydrophilicity, fouling resistance ratio and critical flux [74,75]. Ultimately, blending membranes provide a great potential to increase viability of the MBRs systems and made them applicable in the industrial level by overcoming the problems associate with it that required further research to be carry out in the experimental section to confirm their superiority in the MBR application.
- Higher cost effectiveness is another challenge; however, it is possible to reduce the capital and operating cost of MBRs. One cannot predict the market price of membranes thus constant efforts are essential to extend the membrane lifetime which will reduce the depreciation cost. Furthermore, the specific flux during practical operations is to be elevated and finally, energy consumption needs to be reduced in order to meet the operating cost. A development of more efficient membrane, bioreactor combination modes, sharpness in designing of membrane scouring. and biological aeration systems are essential to higher cost effectiveness.
- Process optimization for low strength wastewaters is needed to keep energy production at the maximum capacity and improve the efficiency to remove various chemicals such as nitrogen and phosphorus in order for the AnMBR effluent to be directed for water reuse or discharging into water receiving bodies clear of environmental concerns. This can be possibly achieved through hybrid/intergrated AnMBRs using post treatment processes (e.g., anammox, and FO). All costs and requirements must be evaluated thoroughly.
- Even though MBR has been applied successfully to several wastewater types, it is wise to consider its competitiveness and application fields. The advantages of MBR on a competitive basis include efficient pollutant removal, stable effluent quality, smaller footprint, compatibility with existing systems, and flexibility when combined with other processes. These benifits can assist to maximize the practical value of the technology; however, from a technological standpoint, it is worth mentioning that MBR is more suitable in cases of strictly required qualities such as high-quality water reclamation, and combination of multiple technologies for various specific purposes such as industrial wastewater treatment. MBR is also suited for increasing the capacity and treatment efficiency of a wastewater treatment plant among limited land use in areas with a dense population and construction of underground wastewater treatment plants.
- Many challenges are to be met to improve the energy recovery from the AnMBR, this includes controlling the process inhibition and facilitating the logistics of biohydrogen, recovery of dissolved methane, extraction and purifying the VFA and the utmost necessity to lower costs while utilizing the AnMBR.

7. Conclusions

Effective fouling prevention methods and proper operation can truly sustain the performance of MBRs. This was determined after several investigations on important aspects of MBRs such as design strategies and fouling phenomenon. This review has summarized each basic concept pertaining to each section of MBRs such as biological bioreactor, membrane modules, membrane fouling phenomena among developments in control strategies. In terms of the successful curtailing membrane fouling control, fouling itself is a major challenge in the applications of membrane technologies despite of all the efforts that have been done. In order to provide a proposal for future research and development/application of MBR technology, some challenges and thoughts on the same have also been suggested.

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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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