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Recent developments in forward osmosis membrane bioreactors: a comprehensive review

Murat Eyvaz[a,*], Taha Aslan[b], Serkan Arslan[a], Ebubekir Yüksel[a], İsmail Koyuncu[b,c]

[a]*Department of Environmental Engineering, Gebze Technical University, 41400, Cayirova, Kocaeli, Turkey, Tel. +90 262 605 32 23; emails: meyvaz@gtu.edu.tr (M. Eyvaz), serkanarslan@gtu.edu.tr (S. Arslan), Tel. +90 262 605 32 13; email: yuksel@gtu.edu.tr (E. Yüksel)*

[b]*Department of Environmental Engineering, Istanbul Technical University, 34469, Maslak, Istanbul, Turkey, Tel. +90 212 285 34 73; email: taslan@itu.edu.tr (T. Aslan), Tel. +90 212 285 37 89; email: koyuncu@itu.edu.tr (İ. Koyuncu)*

[c]*National Research Center on Membrane Technologies, Istanbul Technical University, 34469, Maslak, Istanbul, Turkey*

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ABSTRACT

Forward osmosis or osmotic membrane bioreactor (FOMBR) has attracted great attention for wastewater treatment and reuse since conceptually introduced as a process. It has been proposed to reduce the high energy consumption in the conventional MBR, has lower membrane fouling propensity, and produce higher quality water. Moreover, RO process can be used after FOMBR to reconcentrate the diluted DS to be used for FO again. Besides significant advantages, when compared to conventional MBRs; lower water flux, concentration polarization, and salt accumulation because of high retention of FO in the bioreactor still remains as major drawbacks and challenges of FOMBR systems that need to be solved. In the last few years, many advances in development of FOMBR are stated to overcome the drawbacks of the system. The researches focused on manufacturing of high performance FO membranes and orientation, utilizing various different draw solutions providing required osmotic pressure and minimum reverse salt flux, and recently hybrid systems to alleviate the salt accumulation in bioreactor. However, the main critical challenges of FOMBR have not been completely resolved yet. This paper reviews the design and applications of FOMBR process in wastewater treatment. Particular focus was given to reverse salt flux and effects of the system performance; recent developments in FOMBR applications from beginning till today are reported.

Keywords: Forward osmosis; Membrane bioreactor; Draw solution; Salt accumulation

1. Introduction

In recent decades, due to limited footprints and high-quality water demands, MBRs have been mostly favored for the treatment of both industrial and municipal wastewaters [1–4]. MBRs have been known as coupling process, combining MF or UF membrane with a suspended growth bioreactor [5]. Contrary to CASP, these membranes in the aeration reactor conduct to an improved biological reactor performance by increasing the active microbial community and reduce sludge production. Moreover, the process resist to high or shock loadings and the effective separation of bacteria and viruses could be achieved when UF

*Corresponding author.

membranes are employed [6,7]. Therefore, product water of MBRs may be used for irrigational purposes, industrial process needs, or as potable water source (with advanced treatment) [8]. MBRs, when compared with conventional activated sludge systems, have some advantages such as having compact system, easy operation, high permeate quality, and low production of excess sludge. The MBR can no longer be considered as a novel process with mentioned advantages. This reliable and efficient technology has become a legitimate alternative to CASPs and an option of choice for many domestic and industrial applications. However, membrane fouling and its consequences in terms of plant maintenance and operating costs limit the widespread application of MBRs [9].

Membrane separation processes have been widely applied for many years in environmental, industrial applications, and domestic use such as water/surface water and groundwater/wastewater treatment, desalination, specific industrial purposes and energy recovery. Seawater/brackish water desalination [10–12], wastewater treatment [13–15], liquid food processing [16–19], generation [20–23]. These processes are classified according to driving force such as pressure and concentration difference as well as electric potential and temperature gradients in operational conditions. Among the concentration-driven operations, FO has recently attained many attraction due to its advantages such as less energy requirement [24,25], lower fouling tendency or easier fouling removal [11,12,24,26]; and higher water recovery [24,27].

In recent years, the idea of combining FO membrane with MBR has been proposed to reduce the relatively high energy consumption in the MBR and cope with the membrane fouling as FO membrane has lower fouling propensity due to utilizing osmotic pressure instead of hydraulic pressure in forward osmosis or osmotic membrane bioreactor (FOMBR) system. Moreover, due to the high retention capacity of FO membrane, FOMBR producing higher quality water has been widely preferred in recent wastewater treatment and reclamation applications. However, all drawbacks of FO process such as membrane fouling originated from internal concentration polarization (ICP), lower flux, and reverse salt diffusion deteriorating the biological activity in the bioreactor are valid for FOMBR process. Therefore, development of hybrid MBR processes with FO membrane, membrane structure, and orientation in bioreactor and determination of the best draw solute are focused on in recent FOMBR researches.

This review presents the most recent and relevant papers on the FOMBR applications. At first, a brief literature review on the basic constituents of the MBRs, FO, and FOMBR processes, are referred. Secondly, a comprehensive and specific review of main process parameters and characteristics of FOMBR such as membrane orientation, draw solutions, and membrane fouling are discussed according to the literature. Finally, a brief tabulated review of the research topics and current methods dealing with the main drawbacks and challenges of the process are presented based on all existing FOMBR studies in the literature and the future of FOMBR process is discussed. This review aims to evaluate recent approaches for FOMBR research area and provide opportunity to bring new ideas and new aspects for optimized and more sustainable FOMBR processes.

2. FOMBR process

2.1. Basics of FO

FO is a technical term describing the natural phenomenon of osmosis: the transport of water molecules across a semi-permeable membrane. The osmotic pressure difference is the driving force of water transport, as opposed to pressure-driven membrane processes [28]. A concentrated DS with osmotic pressure draw in water molecules from the feed solution through a semi-permeable membrane to the DS. The diluted DS is then reconcentrated to recycle the draw solutes as well as to produce purified water [29]. FO process is illustrated in Fig. 1.

The main advantages of using FO are that it operates at no hydraulic pressure, it can achieve high

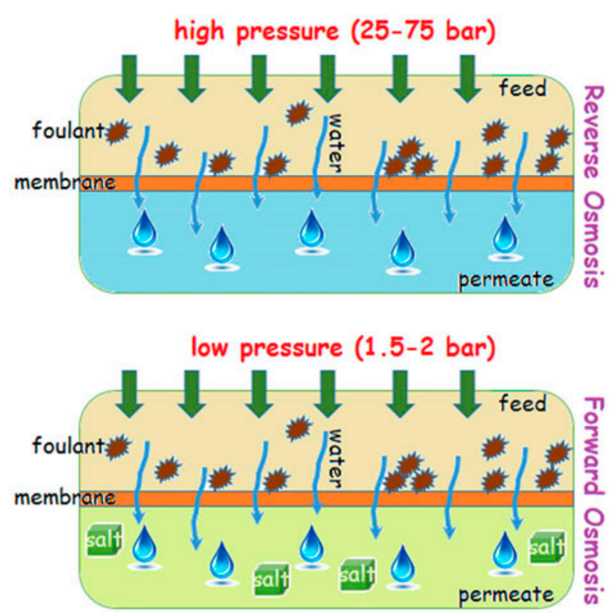

Fig. 1. Forward osmosis illustration.

rejection of a wide range of contaminants, and it may have lower irreversible fouling than pressure-driven membrane processes because of the lack of applied hydraulic pressure (Fig. 1) [30]. FO as a method to desalinate water has been investigated for almost four decades [31] and many researchers have focused on process optimization parameters of FO such as (i) selection or development of (novel) membrane materials [32–36], (ii) determining the suitable DS for easy recovery, maximum osmotic pressure and minimum reverse salt diffusion [37–41], (iii) understanding the fouling mechanism [42–46], (iv) characterization of concentration polarization [47–50]. The increased trend in research of FO and special various topics in these pure academic publications are illustrated for last 20 years in Figs. 2 and 3. As seen from Fig. 2, the number of researchers has increased continuously and the recent researches mainly focused on membrane properties.

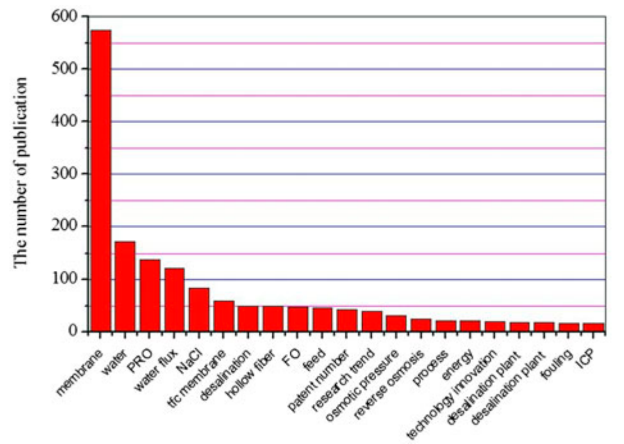

Fig. 3. The number of publication from 2006 until second quarter of 2016 in view of special topics in FO applications (retrieved from science direct database search).

2.2. Basics of FOMBR

A classical MBR comprises a CASP coupled with membrane separation to retain the biomass. Since the effective pore size is generally below 0.1 mm, the MBR produces a clarified and substantially disinfected effluent. In addition, it concentrates up the biomass and, in doing so, reduces the necessary tank size and also increases the efficiency of the biotreatment process. MBRs thus tend to generate treated waters having higher purity with respect to dissolved constituents such as organic matter and ammonia, both of which are significantly removed by biotreatment [5]. Despite several clear advantages over CASP, MBRs have several drawbacks. The main drawback of MBR technology is still high investment and operation costs. The energy demand for aeration of MBRs, up to 60–70% of the total energy costs, is the biggest contribution to operating costs [51]. Apart from this, operational problems occur due to membrane fouling, with both (MF/UF) membranes as well as the downstream (spiralwound) RO membranes [11]. Therefore, some special membrane processes such as FO or MD integrated with MBRs (FOMBR or MDMBR) have attracted more attention recently.

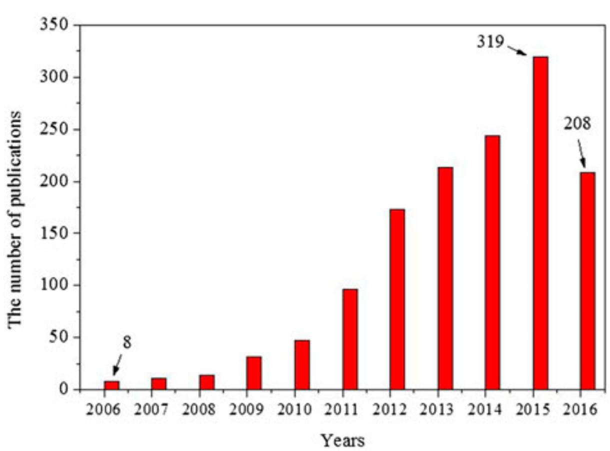

Fig. 2. The number of publication about FO studies from 2006 until second quarter of 2016 (retrieved from science direct database search).

In an FOMBR system, wastewater is fed into a reactor which is continuously aerated to supply oxygen for the biomass and to scour the membrane. By natural osmosis process, water molecules diffuse from the bioreactor across a semi-permeable membrane into a draw solution which has a lower water chemical potential [12]. In FOMBR systems, FO membranes with comparable structures as NF or RO membranes are used instead of MF/UF membranes for the separation of suspended solids, multivalent ions, natural organic matter, and biodegradable materials because irreversible membrane fouling of NF or RO membranes is less severe compared to MF/UF membranes since fluxes are generally lower and no internal fouling occurs [11].

The first FOMBR was introduced Achilli et al. [12], which utilizes a submerged FO membrane module holding a flat-sheet CTA FO membrane inside a bioreactor. The draw solution was circulated through the membrane hold in the biorector. During the circulation, draw solution was diluted with water molecules drawed from MBR bioreactor to reuse as draw solution in the system again. Achilli et al. [12] achieved removal rates greater than 99% for organic carbon and

98% for ammonium-nitrogen, respectively, which indicates that FOMBR exhibits a better compatibility with downstream RO systems than conventional MBRs. After developing osmotic MBR, the similar studies were reported as following [11,52–57]. State of the art of osmotic membrane bioreactors for water reclamation was presented in view of FO membranes, type of draw solutes, and salt accumulation in bioreactor [58]. Similarly, several tens of publications (Fig. 4) have been published in the following years related to research of osmotic MBRs applied in both water and wastewater treatment.

In mentioned researches, FOMBR has been proposed (i) to reduce the relatively high energy consumption in the MBR, (ii) because of its lower fouling propensity due to not using hydraulic pressure (iii) to produce higher quality water due to the high retention capacity of FO membrane. However, all drawbacks of FO process are valid; such as, (i) ICP and membrane fouling, (ii) Lower flux, (iii) Reverse salt diffusion (especially, salt accumulation: elevated salinity condition in the FOMBR which not only leads to a reduced driving force, but also has inhibitory or toxic effects on the microbial activity and population structure in the bioreactor). Therefore, current studies on FOMBR have particularly focused on obtaining optimized membrane, determine/recovery/reuse suitable draw solutes, minimize reverse salt flux (high-salt effects on biological performance), produce high-quality product water in order to increase technical and economic efficiency of FOMBR process.

Moreover, these differences between MBRs and FOMBRs are cited; generally, MF/UF type membranes are employed in conventional MBRs and these membranes are cleaned by backwashing with the help of circulation of product water back to the membrane. Thus, circulated water flows through the pores to the feed channels, disposing internal and external foulants. In FOMBR, however, osmotic backwashing is utilized by changing the direction of the concentration gradient through adjusting the concentration of draw solution, which is benefited as energy recovery process as well.

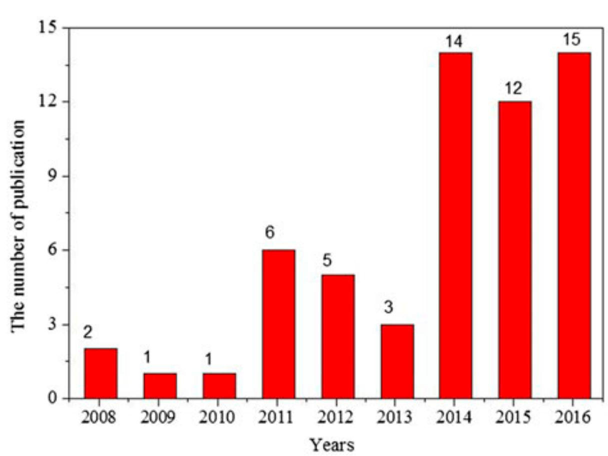

Fig. 4. The number of publication about FOMBR from 2008, origin of the FOMBR process, until second quarter of 2016 (retrieved from science direct database search).

MF/UF permeate may be an ultimate product water in conventional MBRs and could provide the discharge limits, while an additional separation process such as RO and MD is required to recover the draw solutes and generate high-quality product water in FOMBR.

3. Operating parameters affecting FOMBR performance

3.1. Operation mode

Similar to conventional MBRs, FOMBR can be designed and operated in submerged or side-stream configuration as shown in Fig. 5. In submerged system, the membranes are immersed directly in the bioreactor (aeration tank). The permeate is typically extracted by applying reduced pressure to the

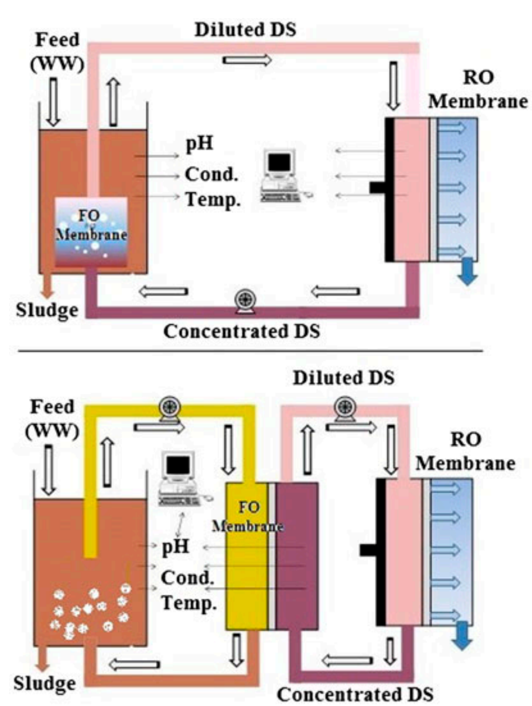

Fig. 5. Submerged (above) and side-stream (below) configuration in FOMBR.

permeate side. However, FO membranes are located at outside of the activated sludge tank (bioreactor) in side-stream mode. A crossflow pump is used to create the pressure and to prevent the build-up of solids on the membrane surface [59].

When geometry of the membrane in FOMBR is considered, there are different studies at which both submerged flat sheet and hollow fiber types are used. Zhang et al. [57] used hollow fiber TFC membrane in the bioreactor which is operated in both AL-FS and AL-DS configurations. Draw solution molarity was selected as 0.5 M and AL-FS orientation was found superior to AL-DS, because better flux stability was observed. The average water flux during the experiment was approximately 8 LMH and they concluded that permeate flux in the AL-FS configuration was less sensitive to the feed conductivity and membrane fouling.

Luo et al. [60] utilized a commercial cellulose-based FO membrane of which the active layer was reinforced by a polyester mesh for mechanical support. The FO membrane was mounted on a submersible plate and frame module. Effects of draw solution concentration on the behavior of water flux were evaluated. The range between 6 and 12 LMH of water flux values were achieved for various concentrations.

Both flat sheet and hollow fiber membranes were employed as support layer for FO membranes. Further studies are needed to clearly understand the effect of membrane types and other operational parameters as well despite the fact that there are some applications in literature as mentioned above.

In a FOMBR system, wastewater is fed into a reactor where it undergoes biological degradation. The FO membrane submerged in the bioreactor provides a barrier between the mixed liquor and circulated DS, which extracts water from the bioreactor. The membrane allows water molecules to pass and retain the contaminants in the bioreactor. Water transport from the bioreactor results in dilution of the DS. The diluted DS is sent to a reconcentration process (such as RO or MD), which reconcentrates the DS and generates a high-quality product water. Comparing to the industrial standards for high-quality potable reuse applications (bioreactor, clarifier, microfiltration, RO, and advanced oxidation), FOMBR systems (bioreactor, FO, and DS reconcentration) have a better potential for producing high-quality water with fewer processes, reduced footprint [61]. As seen by all membrane processes, turbulence promoted by aeration in submerged MBRs or by pumping in sidestream systems results somewhat higher effective cross-flow velocities increasing the mass transfer and reducing the fouling [62]. Some comparative operational parameters in FOMBR and conventional MBR are presented in terms of energy consumption in Table 1.

In this table, conventional MBR was compared with FOMBR + RO rather than comparison of MBR and FOMBR, because FOMBR system is not a single solution to obtain final product or permeate. The diluted DS is sent to a reconcentration process and generates a high-quality product water; meanwhile, reconcentrated DS could be used in draw solution preparation, by circulating it to the beginning of the process. According to our best knowledge, there is not a paper in literature with respect to comparison on costs. Energy consumption of FO-MBR should be evaluated with a reconcentration process (RO, MD, etc.).

3.2. SRT and HRT

In biological wastewater treatment systems, one of the main points to be considered is the minimization of toxicity to microorganisms. For this purpose, the wastewater is treated before biological process to remove the toxic substances, the biomass is acclimated and the SRT is optimized [65,66]. In conventional activated sludge systems, all microorganisms should have ability to grow fast or otherwise they will be washed out from the bioreactor when short SRTs are selected. Because MBR works at much longer SRTs than CASP, the bacterial ability to grow fast is less critical comparing with CASP [67]. However, MBR operations at long SRTs with low F/M resulting in reduced biological sludge discharge would induce an increase in MLSS and sometimes, the accumulation of SMP in bulk sludge liquor [68]. From this point, Meng et al. [69] reported that an optimal SRT for MBR systems should be maintained at 20–50 d. HRT and feed characteristics in submerged MBRs and external ones should also be considered separately.

As well as FOMBR process shows advantages over traditional MBRs such as low membrane fouling, high quality of product water, and low energy demand, the salt accumulation in bioreactor caused by the reverse salt flux remains as a major challenge for this process [70]. Although some researches have been carried out to minimize the reverse salt flux in FOMBR which are focused on the selection of DS [55,71,72] and development of FO membrane [71,73,74], studies for the effects of SRT on the salinity increase in bioreactor should be carried out more.

Apart from MLSS concentration and SMP, salt concentration in FOMBRs increasing because of the reverse salt flux is a prominent parameter which is affected by SRT of the biological system. Yap et al. [58] indicated that elevated salt concentration in

Table 1
Comparison of conventional MBR and FOMBR + RO process

Process component	Conventional MBR	FOMBR + RO
Membrane area	– [63]	**Higher;** because of relatively low water flux (5–10 LMH), larger submerged membrane area is required
Membrane aeration (scouring)	56% [64]	**Higher;** because cake layer and fouling in surface of forward osmosis membrane is occurring lower, but membrane aeration is needed to be high in FOMBR due to larger membrane surface area
Aeration	11% [64]	**Equal;** air needed for community structure can be approved as equal for both of the systems
Mixers	9% [64]	**Equal;** mixers needed in submerged FOMBR can be approved as equal for both of the systems
Recirculation (pumps)	6% [63]	**Higher;** more energy is needed in the drawing solution recovery process to compensate the free energy loss in the drawing of permeate
Rest MBR (permeate pumps, sludge discharge, pretreatment, chemicals, membrane replacement)	17% [63,64]	**Higher;** because RO is reconcentrate system, FOMBR can be operated as zero discharge but regeneration of the salt by RO (25–50 bar) is required high consumption of energy compared to conventional MBR+RO, here RO is run on 7–15 bar

bioreactor could directly affect the biological removal efficiencies of carbon, phosphorus, and nitrogen negatively. Above all, the high salt concentration affect vital process parameters such as physical aspects (oxygen transfer, density, turbidity, and viscosity of suspension, salt precipitation, solute interactions, and colloid chemistry); microbiological aspects (microbiology in elevated salt environment, biomass characteristics, and biological operating conditions) and membrane aspects (driving force, concentration polarization, flux and product quality, membrane fouling) [69]. According to Wang et al. [72], the salt accumulation in bioreactor could only be reduced through the daily sludge discharge during the operation of FOMBR. Therefore, SRT is a critical parameter to be optimized for controlling of reverse salt accumulation in bioreactor [58,70].

Achilli et al. [12] introduced the first FOMBR operated at SRT of 15 d and with daily wasting of excess sludge. They achieved to maintain the salt concentration in bioreactor stabilized at around 4 g/L during the operation time of 14 d. This value is a typical level for the conventional biological treatment plants by which microorganisms are not able to acclimate to higher salt environments (>10 g/L) [73]. Similarly, Xiao et al. [54] reported that steady state salt concentration in the bioreactor is directly related to SRT and they suggested a theoretical salt accumulation model in bioreactor of FOMBR in view of membrane properties and operational conditions. According to their experimental results, different SRTs have no significant effects on the initial water flux, however, especially optimizing the SRT/HRT ratio is essential to minimize the salt accumulation in the bioreactor (Fig. 6).

Winson Lay et al. [74] operated FOMBR system in their study for pharmaceutical removal at 20 d of SRT and 33 h of initial HRT, employing 0.5 M NaCl of DS. A clear observation could not be achieved whether the salt accumulation has effects on micro-pollutant removal performance. However, Qiu and Ting [75] observed that salt accumulation wiped out the denitrifying bacterial community from α- to γ-Proteo-bacteria members and the rest microbial community adapted to the elevated salinity conditions. The SRT was 50 d and the HRT, 15.4 h in their study. In another study with relatively high SRT of 90 d, the salinity in the bioreactor was observed not to be effective on the performance of biological process. However, an increase of the salinity in the bioreactor enhanced the accumulation of SMP at a relatively stable concentration of extracellular polymeric substances (EPS) [76].

According to Ersu et al. [77] the ideal SRT would be short to reduce the concentration of TDS in FOMBR, however short SRTs restricted the nitrogen removal of the system. Therefore, Holloway et al. [78] suggested a new alternative FOMBR process including an UF membrane parallel to the FO membrane in the bioreactor (UFO-MBR) (Fig. 7). Thus, they would operate the system for minimizing TDS and nutrient

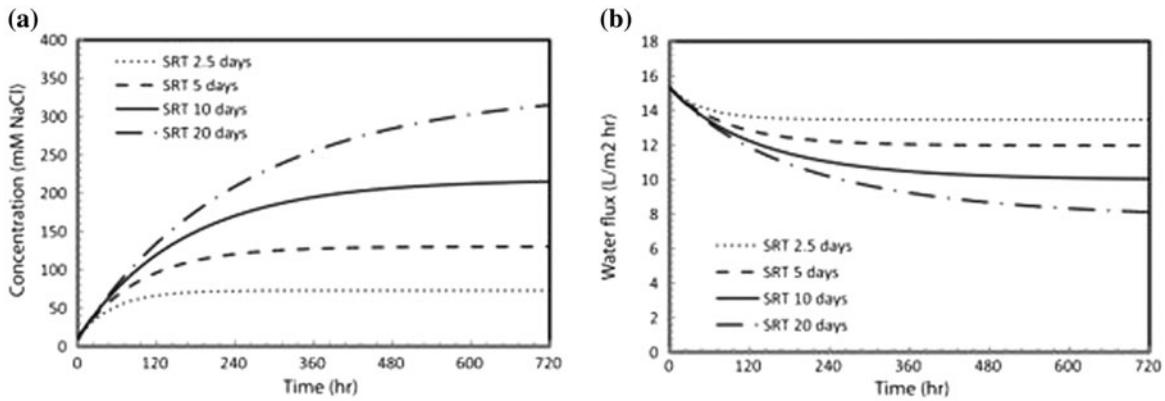

Fig. 6. Relationships between theoretical salt accumulation (a) model in bioreactor and water flux (b) under different SRT [54].

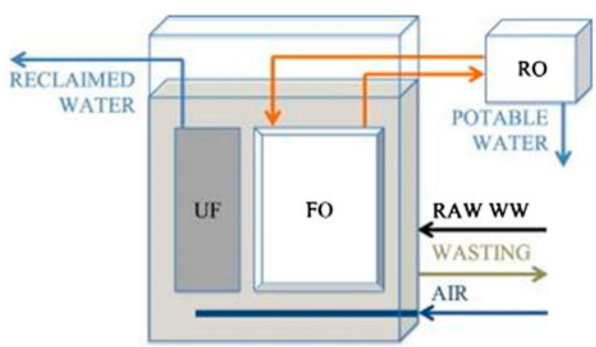

Fig. 7. UFO-MBR system used in [78].

concentrations in the bioreactor without changing the SRT. In mentioned study, after more than 120 d of continuous operation, averagely 82, 99, and 96% of removal rates for nitrogen, phosphorus, and COD were exceeded, respectively, in both FOMBR and UFO-MBR, however, membrane fouling was significantly reduced by employing UFO-MBR compared to the FOMBR.

Holloway et al. [78] concluded that membrane fouling originated cations in the bioreactor could be reduced by drawing salts—similar to wasting sludge—from the bioreactor by UF. In another similar study, Wang et al. [79] operated a hybrid FOMBR including MF membrane and effectively controlled the salinity in the bioreactor at a lower value of about 5 mS/cm and achieved 5.5 LMH of FO membrane flux under 10 d of SRT and 90 d of operating time, which leads to a higher removal efficiencies of the activated sludge for TOC and NH_3-N compared to conventional FOMBR.

Except the hybrid FOMBR studies adjusting the SRT of the system, recent studies on FOMBR come to the forefront to alleviate the salinity in the bioreactor. Reducing the SRT decreases the amount of nitrification microorganisms which causes inhibition of the nitrification process in bioreactor. As a result, ammonia concentration would increase in the mixed liquor and higher concentrations of ammonia exhibit toxic effects on other microorganisms in the FOMBR also [58,79]. Therefore, Qiu and Ting [75] have suggested a new approach to increase the rejection performance of FO membrane by enable the ammonia removal and recovery of phosphorus. In mentioned study, discharging of municipal wastewater supernatant from bioreactor containing rich phosphorus and ions such as Ca^{2+}, Mg^{2+}, K^{+}, and NH_4^+ would also moderate the salt accumulation in the FOMBR. The pH value was adjusted to 8.0–9.5 to precipitate the phosphate with the other cations than calcium and magnesium. Under these operational conditions, 98% overall removal of TOC and NH_4^+-N was achieved, 98% of $(PO_4)^{3-}$-P was rejected by the FO membrane, and more than 95% of PO_4^{3-}-P was recovered with amorphous calcium phosphate precipitation.

Effects of HRT on FO membrane fouling is rarely found in the literature, but Meng et al. [69], Wang et al. [79], and Fallah et al. [80] reported that the low HRTs (<18 h values) lead to release of EPS. Therefore, SMP amount could increase resulting in the sludge deflocculation in bioreactor. Low HRTs lead also to overgrowth of filamentous bacteria and the formation of irregular flocs [69,79,80].

Most of the researches on FOMBR indicate that the primary challenge of the FOMBR process is the salt accumulation in bioreactor due to the reverse salt flux from draw solution circulated through FO membrane. Therefore, it is crucial to investigate the optimization of both existing and alternative methods to solve the salinity accumulation problem in FOMBR to maintain the treatment performance of the microbial community at sufficient level.

3.3. Feedwater characteristics

MBR process has been widely preferred for both municipal and various industrial wastewater treatments such as textile wastewaters [81–84]; oily wastewaters [85–88]; landfill leachates [89–92]; tannery wastewaters [93–96]; pulp and paper industry wastewaters [97–100]; food processing wastewater [101–104]; pharmaceutical wastewaters [105–108], due to its obvious advantages over CASP. As it is widely known, among these wastewaters, oily and petrochemical wastewaters are represented with toxic and refractory characteristics; pharmaceutical industry generates wastewaters containing organic chemicals which are structurally complex and resistant to biological degradation; landfill leachate contains high organic and ammonium nitrogen; tannery wastewaters contain high salt concentrations and inhibitory compounds such as Cr^{6+} and sulfur; textile wastewaters include dye and polymer products; pulp and paper industry wastewaters include acids, alcohols and have high temperature; food industry wastewaters exhibit variable COD, pH and temperature values [66]. All these characteristics of industrial wastewaters both directly and indirectly affect the membrane fouling, which is one of the challenging concerns of MBR processes to be solved. To overcome this challenge, using a semipermeable FO membrane instead of microporous membrane (MF or UF) in MBR process was firstly suggested by Achilli et al. [12] as FOMBR. They obtained approximately 9 LMH of average water flux in bioreactor during the experiment by which a commercial CTA FO membrane was used. The flux value was 11 LMH for pure water which indicates a 18% difference between two fluxes. Reverse salt transport played also a substantial role by flux decline in the first 14 d operation. The results in the mentioned study confirms that the fouling propensity is lower than the MBRs operated with pressure-driven membranes by which the water flux can decrease till a small part of initial flux [12,109]. Besides, Luo et al. [110], reported that the permeate fluxes by HR-MBRs were lower than 10 LMH demonstrated in recent studies, while Judd [5] reported that the permeate fluxes of conventional MBRs vary between 10 and 150 LMH.

In processes employing FO membrane, the performance of the membrane is directly related with osmotic pressure difference between the solutions of both side of the membrane. Feedwater salinity plays an important role as well as DS in FO system. Therefore, it is substantial to consider the osmotic pressure of the feed side in most cases such as the industrial wastewater treatment by which the wastewater may have high salinity. For instance, McCutcheon et al. [14] investigated water fluxes and salt rejections by employing a commercially available FO membrane. The flat- sheet FO-Membrane hold in a mebrane filtration cell was operated in crossflow mode in a wide range of draw and feed solution concentration (Fig. 8). According to Fig. 8, higher salt concentrations at feed side results in flux decline because of net driving force decrease which is based on the osmotic pressure difference between the bulk feed and draw solution ($\pi D - \pi F$). It can be also concluded that the effect of DS salinity at draw solution side has higher effect on net drving force than the salinity at the feed side.

While salinity accumulation in bioreactor and membrane and osmotic pressure difference between feed and draw solution sides affect directly the flux, some parameters related with organic compounds and microorganisms (such as MLSS concentration, biomass fractionation, floc characteristic, EPS, and SMP) representing the organic character of wastewater could be also important for controlling the fouling mechanism on the membrane which affects the water flux. Generally, while proteins are more hydrophobic than carbohydrates and carbohydrates in part possess the hydrophilic nature, carbohydrate fractions of both EPS

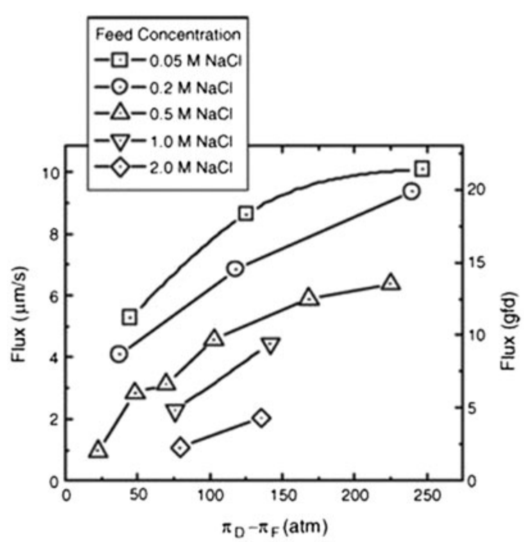

Fig. 8. Flux data for a variety of feed solution [NaCl] concentrations. Thewater flux is presented as a function of the difference in bulk osmotic pressures of the draw and feed solutions. Experimental conditions: crossflow velocity and temperature of both feed and DS of 30 cm/s and 50°C, respectively [14].

and SMP contribute to higher fouling on membrane over the protein fractions [111,112].

Cornelissen et al. [53] investigated three types of activated sludge (compositions of the different activated sludge varied between 5 g/L of MLSS, 630–780 μS/cm of conductivity, 230-1,300 mg/L of COD, and 140–380 mg/L of BOD, and approximately 0.3 bar of negligible osmotic pressure) in their laboratory scale FOMBR employing commercial membrane and various NaCl draw solutions with osmotic pressure values ranged of 25–75 bar and they achieved similar FOMBR process performance for these different types of activated sludge, around 6–7 LMH of water flux of which are in accordance with some other researches in literature [11,12]. They concluded as a result that FO performance is independent from the type of activated sludge with different compositions in COD, BOD, and conductivity. Moreover, no membrane fouling was observed during the experiments, while partially reversible membrane fouling only occurred for the FO membrane when it is operated in PRO mode. However, this study was a bench-scale study and the fouling was observed only in 7–8 h, which might be not long enough for consisting of fouling on FO-Membrane. In addition, the feed was not handled as in a conventional MBR, hence the results did not represent enough the performance of a FOMBR operated for domestic wastewater treatment [113].

Junyou [113] operated in a long time study, set ups of laboratory-scale FOMBRs with NF post-treatment for the reconcentration of the DS (Fig. 9). The feedwater was collected from a water reclemation plant in Singapore with water properties; about 1 ms/cm of conductivity, 300–400 mg/L of COD, and 400–500 mg/L of SS. The activated sludge was taken from the same plant and seeded into the FOMBRs at the beginning of operations. The HRT was adjusted to 6 h for all setups.

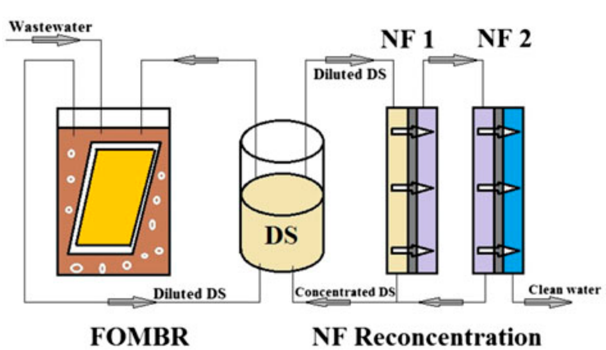

Fig. 9. Schematized FOMBR system with NF reconcentration process.

At the end of 39 d operation without any backwashing and chemical cleaning, the conductivities for all three MCRTs increased at the feed side as the operation time increased. The longest MCRT (10 d) exhibited the most significant increase and the shortest MCRTs (3 d) with the lowest increase by salinity in feed solution. The wastewater treatment performances were also considered in the study. 95 and 97% removal efficiencies for TOC and COD were achieved, respectively. Ionic conductivities and TDS concentrations of final permeates from the three FO- MBR-NF coupled systems were all lower than 500 μs/cm and 400 mg/L, respectively.

In FOMBR, the net driving force is the osmotic pressure difference which plays the major role to produce the water compared to conventional MBRs by which the water flux is attained through the vacuum pressure. Therefore, both reversible and irreversible membrane fouling are not severe in FO process using activated sludge as a feed [11] due to the reduced contact between SS. Osmotic pressure and air scouring decrease also fouling on membrane surface under favor of combining effects of [5].

In another long-term FOMBR study, a lab-scale FOMBR system was operated during 73 d. In the study, NaCl was used as DS. Synthetic wastewater simulating the domestic sewage (the derived COD:N:P ratio was 100:6:1) as feed solution and cartridge type commercial CTA membrane as FO membrane were employed in FOMBR. No deterioration in membrane performance was detected and fouling was mild during the operation. ICP was observed inside the membrane support layer faced to the draw solution side [113].

Winson Lay et al. [74] operated an FOMBR system continuously over 73 d, during which pharmaceuticals were dosed on two occasions (47th and 56th days) into the system. It was found that other process parameters such as TOC, MLSS, and EPS were clearly affected while the removal efficiency of pharmaceutical was rather high (>96%). The major percentage of TOC which permeates through the FO membrane was the part of neutral compounds which have low-molecular weight and associated with the impaired biological process. Microbiological analysis confirmed that microbial populations are affected negatively due to the increased salinity and dosage of the pharmaceuticals in bioreactor. They indicated the importance of an effective biological process for an optimal FOMBR system performance.

Qiu and Ting [75] operated an FOMBR with synthetic wastewater and NaCl or $MgCl_2$ as DS. They concluded that short-term membrane fouling behavior was generally insignificant. Water flux and membrane fouling were not severely affected by MLSS concentration which varied between 5 and 13 g/L. However, according to the results, EPS was found to be an important factor governing the membrane fouling. Small sludge flocs/particles have much higher fouling potential than larger flocs/particles according to the analysis of membrane fouling layer.

In conventional MBRs, MLSS is another important parameter for controlling the fouling mechanism. Inspite of that Rosenberger et al. [114] reported that there are some controversial findings indicated by scientists about the relation between MLSS concentration and fouling, the experiments revealed this relationship for municipal wastewater treatment.

Accordingly, it seems to result in less fouling at low MLSS concentrations (<6 g/L) and more fouling at high MLSS concentrations (>15 g/L). In a recent study, Qiu and Ting [75] determined that no significant fouling on FO membrane was observed due to the higher anti-fouling property of the FO membrane compared to the microporous membranes, even when the MLSS concentration reaches 12.6 g/L. It is likely that the denser surface characteristics of FO membrane provides the fouling effect is met much less than the microporous membranes (MF, UF) which indicates that the membrane surface morphology plays an important role in membrane fouling.

Uygur and Kargı [115] indicated that higher salt concentrations in bioreactor cause to cell plasmolysis and death of microorganisms usually presented in the sewage because of the increase of osmotic pressure. According to Uygur and Kargı, it is important also that increasing of salt concentration will reduce the amount of filamentous bacteria which is very important for mechanical integrity and floc structure. Reid et al. [116] reported that salt concentration greatly affects EPS (carbohydrate and protein) concentrations. Plasmolysis and release of intracellular constituents cause increasing of EPS as well as incomplete degradation of organic substances and microbial produced polymers. Han et al. [68] determined that microbial diversity decreases at high salt concentrations in bioreactor. In regard to this situation, DOC removal at high salt concentrations (5–20 g/L NaCI) did not significantly change, while ammonia removal efficiency decreased considerably from 87 to 46%. In addition, they indicated that the membrane fouling was accelerated by increased pore blocking resistance at high salt concentrations impacting also the biomass properties.

As it is well known, floc characteristic of activated sludge is affected by multivalent cations, which have bridging ability with negatively charged sites of biopolimeric substances. As a result of this situation, sludge settleability and effluent quality of wastewater will be deteriorated. In a study carried by Kara et al. [117], the effect of monovalent cations (potassium and sodium) on the chemistry, structure, and physical characteristics of activated sludge flocs were investigated. They indicated that the floc characteristic greatly depended on sodium concentration in comparison with potassium concentration in sludge. This study verified also that synthesis of more extracellular biopolymers occur at increasing concentrations of sodium and potassium ions.

3.4. Membrane structure

Zhang et al. [56] determined that the pore size distribution of FO membranes is different from MF or UF membranes. They indicated also that small particles such as bacteria, colloidal material, and protein could pass inside the pores of MF and UF membranes and block them due to their larger pore sizes than FO membranes. However, FO membrane pores do not permit the colloidal materials and particles to pass toward inside of the membrane. Lee et al. [118] showed in their study that the accumulation of small particles on FO-Membrane cause thinner cake layer than the bigger ones. This results in more back diffusion of salt and the salt does not accumulate near the surface of the membrane dramatically. On the other hand, bigger particles cause a thicker cake layer on membrane resulting in a non-negligible salt build-up near the membrane which decline the flux by FO membranes substantially. The thicker cake layer caused by bigger colloidal particles exhibits also a bigger resistance against the water flow, which decreases the flux additionally.

It could also be stated that the average pore size and pore size distribution are key parameters to evaluate the fouling mechanism in osmotic membranes. A uniform pore size distribution is important to provide an efficient operation of FO membranes. Uniform distribution of pore size by FO membranes is depending on support layer structure and TFC coating procedure. It can be expected that the related parameters affecting the uniformity of pore size distribution will be investigated in more detail in the near future [119].

Yu et al. [120] investigated the properties of commercial PA and CTA membranes. Major properties of FO membrane such as thickness of membrane layers, hydrophilicity, and membrane structure were evaluated in this study. In the study, water flux and reverse salt flux of fabric and non-fabric PA membranes were determined. The two membranes exhibited the same hydrophilicity values. The non-fabric membrane exhibited a water and reverse salt flux 2 and 10 times more than fabric PA membranes due to the removal of fabric backing material used by fabric PA membrane. The study compared also the water and reverse salt fluxes of fabric PA and fabric CTA membranes. These membranes had the same backing material and similar membrane thickness of about 150 μm. Contact angle values were 72.20 and 52.88, respectively, which indicates that the CTA membrane had more hydrophilic structure than PA membrane. This resulted in an increase of water flux about fourfold by CTA membrane. On the other hand, no remarkable difference was approached by reverse salt flux of both membranes. In the same study, water and reverse salt fluxes were compared also for non- fabric PA and mesh-CTA membranes related to their sub-structures. Selected membranes had similar hydrophilicity and thickness (50 μm). Non-fabric PA membrane had a very dense sponge shaped structure, while layer of CTA membrane had very loose finger shaped structure. Water flux value of mesh CTA membrane was two times more than non-fabric PA membrane due to its finger like shaped structure and there was no remarkable difference in reverse salt flux.

As conclusion, it can be said that it is not an ideal solution to decrease the thickness of FO membrane to increase the water flux. Because, this time the reverse salt flux is becoming higher in thinner FO membranes. Therefore, it makes more sense to increase the membrane selectivity to have the optimal operational conditions by FO membranes which can be achieved through increasing of the hydrophilicity of membrane. She et al. [121] reported also that higher selectivity of FO membrane could reduce the rate and extent of membrane fouling. Therefore, application of FO membranes with higher selectivity is an effective fouling control strategy for FOMBR systems.

3.5. Draw solution type

Generally, aqueous solution of NaCl was preferred as draw solution in FOMBR. Similar concentrations between ranging of 0.5–1.5 M were used and reported in some studies on domestic wastewater treatment by FOMBR [122–125]. However, She et al. [121] investigated the effect of different types of DS on FO membrane fouling. In this study, draw solutes including Cl^- anion (NaCl, $MgCl_2$, and $CaCl_2$) were used for to see the effect of DS on fouling behavior of the FO-membrane. In the study, the initial water flux was adjusted to the same value to compare the fouling behavior under operations with different draw solutes. Alginate stock solution was used as foulant to reach the selected foulant concentration of 100 mg/L in system. During the experiments with NaCl as DS, no loss of water flux was observed. On the other hand, loss of water flux for draw solutions, $MgCl_2$ and $CaCl_2$, occurred immediately. Relative flux losses were determined for draw solutions used as following; $CaCI_2$ (50%) >> $MgCl_2$ (5%) >> NaCl (0%). This situation indicates that the cation type of DS can influence the FO membrane fouling behavior, which is predicted to be related to reverse salt diffusion. Davis et al. [126] reported that divalent cations can build up chelate with carboxylic groups in alginate which results in egg box shaped gel network.

Arkhangelsky et al. [127] investigated the effect of different foulants on water flux by hollow fiber FO membranes in presence and absence of Ca^{2+} ions. During the experimental baseline test, water flux stayed relatively constant. However, during the tests in the absence and presence of Ca^{2+} ions by which foulants were used also, water flux declines of 12 and 30% were observed, respectively. This indicates that the flux decline resulted from fouling and the effect of concentration polarization on the water flux drop is negligible. Also, it can be resulted from the study that the presence of calcium ions increases the fouling effect on FO-Membrane due to the forming of gel structure resulted from the binding of Ca^{2+} ions to the carboxylic functional groups of foulant. This cake layer gelation prevents the back diffusion of draw solute which results in the accumulation of draw solute near the membrane and hereby water flux decline additionally.

Fig. 10 shows the effect of the different DS concentrations on the water flux. It is naturally expected that higher DS concentrations result in increasing of water flux due to the increase of osmotic pressure difference which is the main driving force by FO membrane operations. What from Fig. 10 to make an important inference is that the water flux drop is more rapid by high DS concentrations due to the reverse salt flux increase at the same time. Therefore, it could be a better solution to improve the membrane properties rather than to increase the DS concentration with the aim of flux increase.

Another important parameter which affects the fouling of FO-membrane is the cross flow velocity. Fig. 11 shows the effect of cross flow velocity (same for both draw and feed solution) on FO membrane fouling. Membrane fouling tends to increase with decreasing of cross flow velocity. This can be explained with higher shear forces by higher cross-flow velocities which prevents the accumulation of foulants on membrane. It must also evaluated that increasing of cross flow velocities increase also the water flux and reverse draw solutions flux at the same time which can result in a more concentration polarization by the FO-membrane in time.

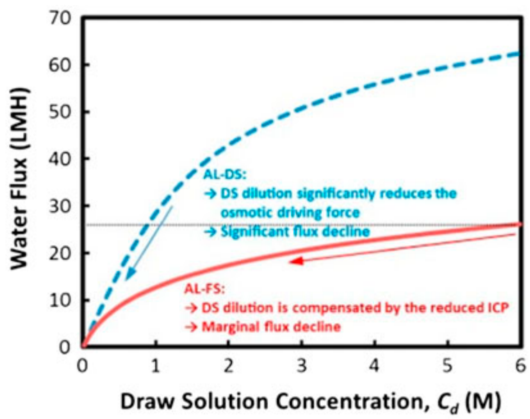

Fig. 10. Fouling effect of different DS concentrations (figure obtained from Ref. [128] with copyright permission).

4. Challenges in FOMBR process

4.1. Membrane fouling

The main problem associated with MBRs is the fouling on/within the membrane. Membrane fouling is caused mainly by microorganisms, colloids, solutes, and cell debris. These constituents in biological treatment system accumulate within the membrane pores or on the membrane surface. Meng et al. [69] explained that the membrane fouling occurs through five mechanisms: (i) adsorption of solutes or colloids within the membrane pores; (ii) deposition of sludge flocs onto the membrane surface; (iii) formation of a cake layer on membrane surface; (iv) detachment of foulants attributed mainly to shear forces; (v) the spatial and temporal changes of the foulant composition during the long-term operation.

Fouling reduces permeate flux and increases the frequency of membrane cleaning and replacement [12]. Foulants can be organic or inorganic materials depending on the operational conditions and physical, chemical, and biological characteristics of feedwater. Some part of fouling seen in MBR systems is reversible and other part is irreversible which causes unrecoverable loss in flux. Reversible fouling exhibited by cake layer can be removed with physical washing (backwashing or hydrodynamic scouring). On the other hand, irreversible fouling occurs due to pore blocking and can only be removed by a fine chemical cleaning. Chemical cleaning can also be insufficient even sometimes to remove this blocking materials from the membrane. In such a case, membrane replacement is required to maintain the MBR operation. In MBRs, fouling is a difficult process to explain due to the complicated nature of activated sludge system. Therefore, a three-stage fouling mechanism was proposed by [130] to simplify the phenomena from the operational view:

(1) Stage 1: an initial short-term rise in TMP due to conditioning.
(2) Stage 2: long-term rise in TMP, either linear or weakly exponential.
(3) Stage 3: a sudden rise in TMP (a sharp increase in dTMP/dt) known as TMP jump.

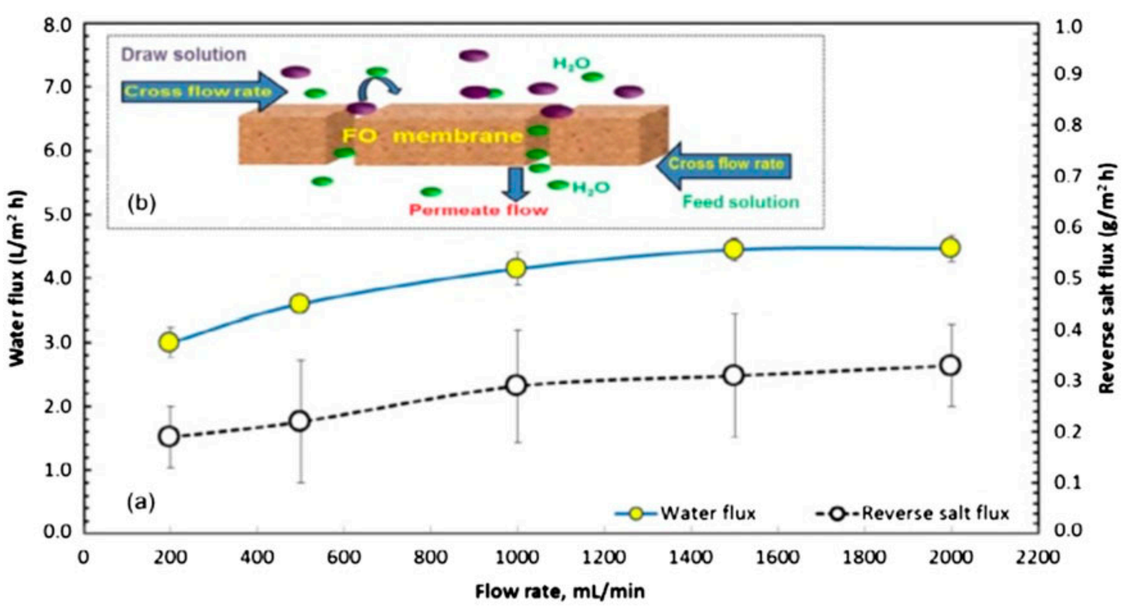

Fig. 11. Water flux and reverse salt flux as a function of draw solution flow rates (FS: DI water; DS: 1 M EDTA-2Na; CTA-NW FO membrane in AL-FS mode) (figure obtained from Ref. [128] with copyright permission).

Fig. 12 shows the three stages of fouling. Stage 1 can represent pore blocking which increases the TMP at initial time at which small organic and inorganic foulants deposit inside the membrane pores. In Stage 2, cake layer occurs through the accumulation of organic and inorganic foulants on the membrane surface which causes a smaller tendency of TMP increase than Stage 1. At the stage 3, the bacteria in the inner biofilms tend to die due to oxygen transfer limitation and release more EPS which can be shown as the reason of the TMP jump. Hai and Yamamoto [131] reported also that deposited cells inside the membrane pores clog the pores and form a strongly attached fouling layer ended with the TMP jump which causes a high flux decrease.

Fouling problem in FOMBRs is a less critical issue comparing with the biological reactors operated with pressurized membranes [132]. The accumulation mechanism in FOMBR is affected by physical, chemical, and biological properties of feedwater and operational conditions such as sludge age, hydraulic retention time, MLSS, cleaning method, and frequency of membrane similar to conventional MBRs (see Fig. 13). Membrane configuration is a very critical operational issue by FOMBRs which affect the fouling intensity.

Two membrane configurations based on the contact between feed/draw solution and active layer of membrane are applied in FO membrane modules. While these configurations provide different hydrodynamic conditions affecting the membrane fouling, this effect can be used as an indicator for the role of hydrodynamic conditions by membrane fouling [133]. For example, Zhang et al. [57] indicated that AL-FS configuration is less sensitive to the feed conductivity and membrane fouling from the view of water flux decline. Similarly, both the AL-DS and AL-FS configurations were evaluated in a study [47]. In this study, the AL-DS orientation is found not practical for FOMBR operation due to the aquatic environment causing high fouling.

Since the FO membranes have an asymmetric structure, characterized with a dense active layer coated on a porous support layer, membrane fouling occurs on different surfaces in AL-FS and AL-DS configurations. In AL-FS configuration, in which active layer of membrane is positioned against the feed solution, foulant deposition/accumulation occurs on active layer. Therefore, foulant deposition is affected by both permeation drag and shear force, resulting from the permeate flux and bulk cross-flow, respectively, which do not allow that the cake layer becomes thicker. This prevents the dramatic water flux declines. However, in AL-DS configuration, in which porous support layer of membrane is against the feed solution, foulant deposition takes place within the porous structure of the membrane. Since cross flow velocity vanishes within the pores of support layer, the influence of hydrodynamic shear forces is absent at the initial stage of fouling in AL-DS configuration [133].

Bi and Elimelech also concluded that the fouling is more severe (for BSA and AHA in their study) in AL-DS configuration than in the AL-FS configuration, because the absence of cross flow within the porous

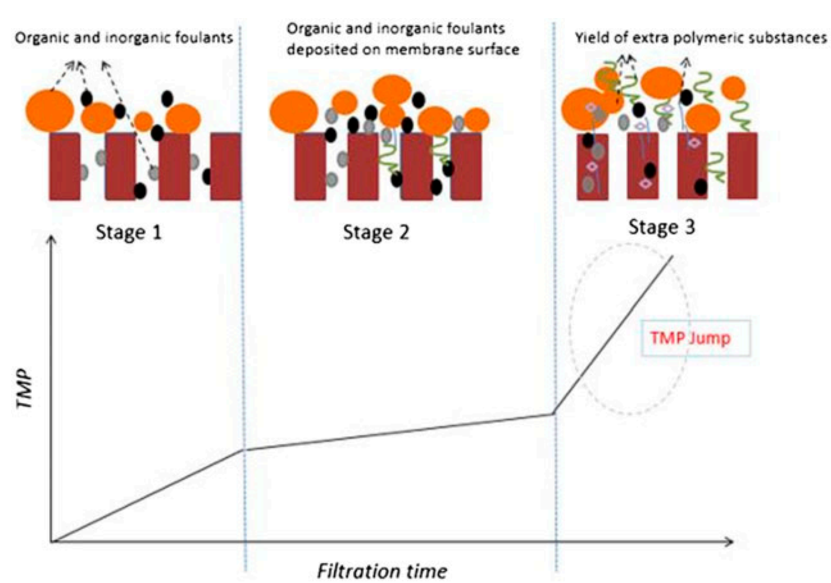

Fig. 12. Schematic illustration of the occurrence of TMP jump.

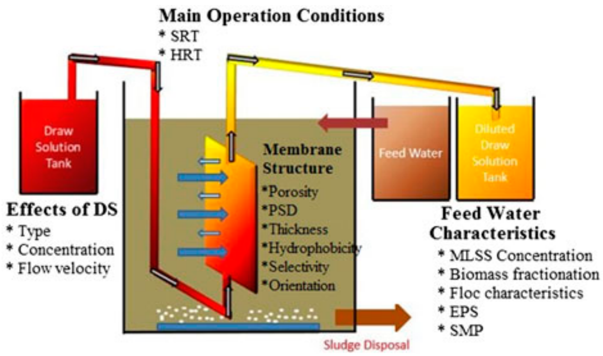

Fig. 13. Parameters affecting fouling in FOMBRs.

support layer of membrane in AL-DS orientation precludes shear force as a mechanism to drive foulant away from the membrane [133].

4.2. Reverse salt flux

One of the requirements to operate the osmotically driven membrane processes effectively is that the reverse flux of draw solute from the DS into the feed solution is minimized [134]. No semi-permeable membrane is an ideal barrier which prevents any DS to permeate into the feed solution. A small amount of dissolved solute is not to prevent to be transported across the membrane. If the draw solute is expensive, it makes the process less economical because of the draw solute lost to the feed side. Moreover, most of the draw solutes used could have detrimental effects on the aquatic environment which make the additional treatment of feed solution concentrate necessary before the discharge. Nawaz et al. [135] indicate that reverse flux of draw solute to the feed site in an FOMBR system can affect the microbial system and herewith the treatment efficiency could decrease. Therefore, the phenomenon of reverse solute permeation has critical role by operation of osmotically driven membranes and has to be understood better to minimize its effect on FO membrane technologies.

The solutes used by FO processes are also very important in the mean of membrane performance. The B parameter which is related to the salt rejection capacity of the membrane, was used by mathematical models of previous studies [134,136]. The solutes used by FO processes are not rejected same because of some different selectivity properties of membrane or different ion or molecule size of solute. Therefore, the best solute should be selected according to the osmotic pressure provided and rejection rate by used FO-membrane.

Lay et al. [137] operated an aerobic MBR with cartridge type membrane of HTI during 73 d. The reason why the reactor was operated in FO mode (the feed is on the active layer side) was to prevent the clogging resulted by fouling. The concentration of the DS was 0.5 mol/kg NaCl (~22.8 bar) at the beginning which provides a water flux with 3.2 L/m^2/h. Until the system was stabilized, the water flux was decreased to 2.7 L/m^2/h. The reason of this flux decrease was the declination of the net driving force (net osmotic pressure). It is estimated also that relatively low water flux was resulted from the ICP in support layer. In this study, also a gel like layer was determined by SEM views (see Fig. 14). The layer estimated to be derived from EPS, showed similarity with layers seen by conventional MBRs. The low salt flux obtained in the study could also be explained with this layer due the repairing of defects on membrane and adsorption of cations through this layer. If the effects of biological layer are evaluated as a whole, it can be concluded that the ratio between parameters A and B (A/B) increased under influence of the biological layer which results in the decrease of reverse salt flux.

The right choice of the solute also plays an important role in economical operation of FOMBR system. Actually, NaCl is mostly used by application of FO systems because:

(1) It is highly soluble in water.
(2) It is not toxic for biological system at low concentrations.
(3) It is easy to reconcentrate without scaling problem [37].

On the other hand, the other chemicals are investigated to increase the FO-membrane performances. Achilli et al. [37] tried to develop a procedure to select the most suitable draw solutes for FO applications. As the performance indicator parameters, water flux Jw,

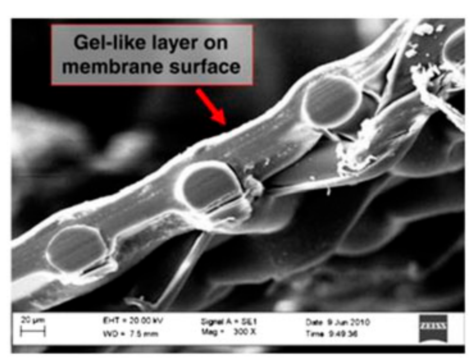

Fig. 14. SEM image of the cross section of the used membrane together with the thin gel-like layer [137].

solute flux, and economical reconcentration situation of DS were selected. 500 chemicals were scanned according to the selection procedure showed in Fig. 15.

As seen from Fig. 15, the chemicals with low solubility in water, and which provide low osmotic pressure are eliminated in first step of procedure. The rest chemicals after first elimination were tested with flat sheet CTA membrane of HTI. The results were summarized as:

(1) The used membrane rejected the divalent solutes better than monovalent.
(2) The ICP increased by experiments with draw solutions which have higher diffusion coefficient.
(3) The highest water flux was seen by KCl.
(4) The solutes of hydrated ions with big molecule size has the lowest reverse salt flux.
(5) The affinity of membrane against the solute increases the reverse salt flux. This is the reason why NH_4HCO_3 has the highest reverse salt flux in spite of the fact that it has hydrated ions with big molecule size.

As a result, the FO membrane used properties as tensile properties of the solute in the DS also affects the performance of the FO system like the membrane properties. The affinity of membrane against the solute is an important parameter for reverse salt flux. The solubility of solute in water increases the osmotic pressure which results in increasing of water flux and reverse salt flux. But this should not be the case always. In the study of Achili et al. [37], the water flux was higher by the experiments with KCl than NaCl although water solubility of NaCl is higher than KCl flux was higher than in water. Additionally, the reverse salt flux is also detected lower than operation with NaCl. This results show that the performance of solute such as reverse salt flux by FOMBR applications is not determined solely through solute properties. Parameters such as affinity to membrane, is also very important beside solute properties such as diffusion coefficient and ion or molecule size of solute.

4.2.1. Effects on water flux

The reverse permeation of a draw solute across an asymmetric membrane in a FO operation is the most important challenge of the nature of FO membrane, which affects membrane fouling and water flux. The mathematical model of William et al. [134] indicates that the reverse flux selectivity is determined solely by the selectivity of the active layer A/B and the ability of the draw solute to generate an osmotic pressure, nR_gT. A high concentration of draw solute at the support layer—active layer interface is necessary to

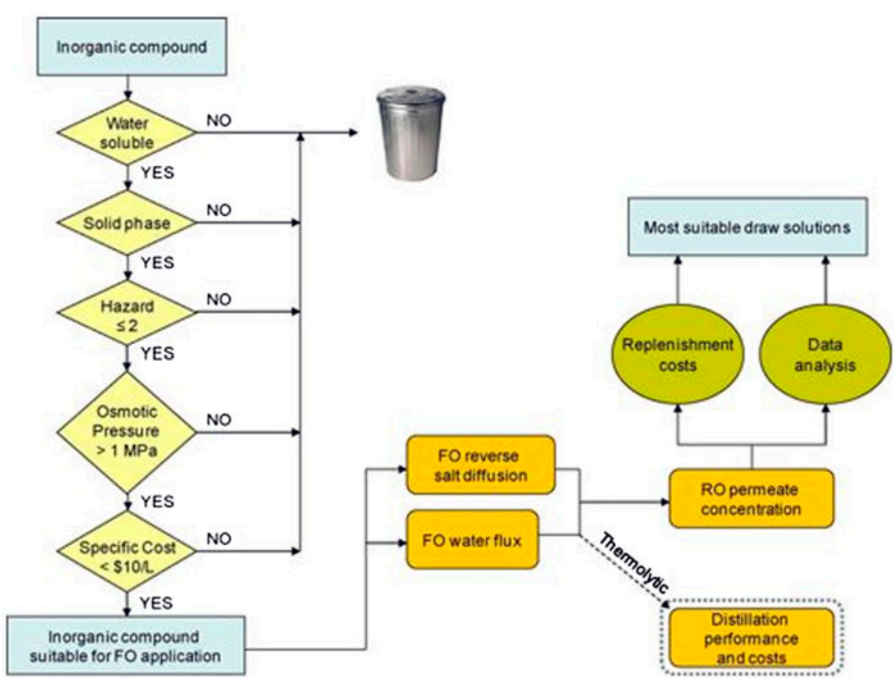

Fig. 15. Selection procedure for chemicals used as solutes by FO applications [38].

generate a large osmotic gradient, which provides a higher water flux. However, this higher concentration of draw solute also increases the concentration gradient across the active layer, which increases the reverse salt flux. The analysis above highlights the need to select a membrane with a highly selective active layer (i.e. high A and low B) and a draw solute capable of generating a large osmotic pressure, but it does not diminish the importance of reducing the structural parameter, S of forward osmosis membranes. The term S characterizes the average distance, a long which the solute molecule must travel across the support layer transporting from the bulk towards to the active layer. An FO process needs to achieve high water fluxes at low draw solution concentrations to minimize the energy required to separate fresh water from the diluted draw solution and to reconcentrate/recycle the draw solution. Reducing this energy can be realized by having FO membranes with small S so that the effects of ICP are minimized.

In study of Lay et al. [74], a FO membrane bioreactor was operated with AL-FS mode to avoid the clogging in support layer. The water flux started from an initial value around 3.2 LMH under a constant draw solution concentration at 0.5 mol kg^{-1} NaCl (~22.8 bar), and is about one fourth of what could be achieved with RO using an equivalent hydraulic pressure on the same type of membrane. The reason for the lower water flux is explained with the presence of ICP in the membrane support layer, which is an inherent feature of the FO system and diminishes the effective driving force (osmotic pressure difference) across the membrane. Considering the mathematical model of William et al. [134] which is validated with experimental data, it is possible to increase the water flux through using FO-membrane with good selectivity (high A/B ratio) and with DS which can provide a sufficient osmotic pressure.

Similar to previous studies, Suh and Lee [136] conducted the experiments with different DS concentrations between 1 and 4 M. Increasing the DS concentration increased also the osmotic pressure and consequently the water flux. Suh and Lee detected a decrease by the tendency to increase of water flux by higher DS concentrations. This could be explained with ICP which is effected also by the ECP on the support layer side. Suh and Lee [136] also indicated that under some specific conditions such as low cross-flow velocity and high water flux, ECP has a significant effect on ICP also and this causes to a decrease by osmotic pressure and water flux. The experiments conducted with different DS concentrations showed that the concentrative ECP at feed side has no significant effect on water flux, but it must be noted that if the solute concentration at feed side increases, this causes the increase of concentrative ECP and dilutive ICP which results the decrease of water flux.

Regarding the above mentioned studies at which mathematical models are verified with experimental data, it can be concluded that the most important parameters which determine the performance of FO-membranes are the selectivity of membrane described by the ratio of A/B and structural parameter of membrane, S. The ICP increases by high values of structural parameter of membrane which results the decreasing of membrane performance. Suh et al. [136] indicated that by some special conditions such as low cross flow velocity or high water flux, the dilutive ECP could play important role on the membrane performance, because it also results increasing of ICP.

Xiao et al. [54] studied a mathematical model including also the behavior of FO membranes in bioreactor. The study differs from the models of William et al. [134] and Suh et al. [136] in this respect. In this study, Xiao et al. [54] reported the high capacity of FO membranes to retain the organic matter and various other contaminants. They indicated also that this high rejection nature leads salt accumulation in the bioreactor which can inhibit the biological activity and decline the water flux because of the concentration polarization in the support layer. They reported that some operational parameters such as membrane orientation and HRT/SRT and structure of forward osmosis membrane have significant effect on the ICP and flux decline. ICP is especially important if the active layer is oriented towards the draw solution (the AL-DS membrane orientation) because of the salt accumulation in support layer with solute coming from feed side and diffusing from active layer into the support layer. A salt concentration difference between solute and feed sides decreases if the salt is concentrated in the bioreactor resulting lower osmotic pressure difference (lower effective driving force) and less water flux. So, ICP has negative effect on the water flux in two ways. Once, it builds up a barrier against the water molecules diffusing to the draw solution side. Secondly, it increases the reverse salt flux which causes the higher solute concentration at the feed side and decrease of effective driving force [54,134,136].

4.2.2. Effects on biological system

Ammonia oxidizers which belong to the β-subclass Proteobacteria are reported as the dominant group in MBR systems constituting about half of other bacteria which is shifted away from the microbial population by long SRTs. Nitrospira bacteria are responsible for

Table 2
Effect of inorganic solutes on *Escherichia coli* in active sludge system [135]

Draw solute	Mol. wt (g/mol)	Osmotic potential at 1 M conc. (MPa)	J_s/J_w (g/L)	% Growth of control at min conc.	% Growth of control at max conc.	Growth trend	Use in FOMBR
NaCl	55.5	4.8	0.75	61	93	Increasing	Recommended
KCl	74.5	4.1	1.14	55	95	Increasing	Recommended
$CaCl_2$	110	6.3	0.82	73	115	Increasing then decreasing	Highly recommended
$MgCl_2$	94	5.6	0.58	182	65	Decreasing	Highly recommended
NH_4HCO_3	79	3.6	2.01	32	51	Increasing then decreasing	Not recommended
$(NH_4)_2SO_4$	132	6.6	0.36	102	115	Fluctuating	Highly recommended
Na_2SO_4	142	6.4	0.33	95	69	Increasing then decreasing	Recommended
K_2SO_4	174	5.6	0.40	105	94	Fluctuating	Recommended

Table 3
Effect of surfactant solutes on *Escherichia coli* in active sludge system [135]

Surfactant used type and mol. wt. (g/mol)	J_s/J_w (g/L)	Osmotic potential at 1 M conc. (MPa)	CMC (mol/L)	% Growth at min conc.	% Growth at max conc.	Morphology under experimental concentration	Use in FOMBR
$C_8H_{17}N(CH_3)_3Br$ Cationic 252	0.06	2.72	0.140	1.1	0	Monomeric	Recommended
$C_{12}H_{25}N(CH_3)_3Br$ Cationic 308	0.043	0.12	0.015	0	0	Monomeric	Recommended
$C_{14}H_{29}N(CH_3)_3Br$ Cationic 336	0.040	0.15	0.004	0	0	Monomeric	Recommended
$C_{12}H_{25}OSO_3Na$ Anionic 288 (SDS)	0.003	0.035	0.008	27	14	Monomeric/ micelles	Highly Recommended

the reduction of nitrite and long SRTs are recommended to complete nitrification for slow-growing nitrifying autotrophs. Microorganisms in MBR systems can be classified according to the process type and energy requirement; aerobic microorganisms are employed for aerobic biodegradation of organic carbon and nitrification of ammonia, while facultative microorganisms are used for denitrification of nitrate and anaerobic ones participate to the sulfate reduction and methanogenesis of organic carbon [5].

Microbial growth depends on bioreactor conditions such as, TDS concentration, pH and temperature. Most microorganisms can only be active in neutral pH and at ambient temperature, while some bacteria (extremophiles) can grow under extreme conditions, such as acidic or basic medium or psychrophilic, mesophilic, and thermophilic temperatures [5]. High salinity in the bioreactor [138] is known to have inhibitory or toxic effects on bacteria which cannot adopt themselves to high salinity. High salt concentrations (>1%) are also known to cause plasmolysis and/or loss of activity of cells. Additionally, salinity significantly affects the physical and biochemical characteristics of the biological system, leading to changes in surface charge, hydrophobicity, filterability, settlement, and bio-flocculation [116].

High salinity conditions in the bioreactor come to the forefront in FOMBRs very often, which is

Table 4
A brief literature review of studies on FOMBR (in chronological order)

Problem/research object	Operational parameters investigated	Conclusion/summary of the work	Refs.
Membrane fouling and process performance	DS	(1) Monovalent electrolytes performed twice better than bivalent electrolyte solutions	[11]
Novel process	Osmotic backwashing frequency	(1) FOMBR required substantially less backwashing	[12]
Water flux/fouling	DS and air scouring	(1) Higher concentration of the DS decrease the enhancement of water flux due to much higher DICP at the draw side (2) Air scouring may promote energy saving and minimization of the fouling	[52]
Industrial wastewater treatment and reuse	New MBR design (OsMBR™)	(1) >99.7 and 97.5% removal of TOC and NH_4-N, respectively were achieved	[143]
Innovative process/reuse of wastewater	Membrane orientation, DS concentration and the air and feed flow velocity	(1) Higher flux values were obtained in AL-DS mode because of lower ICP effects (2) Partially reversible fouling only occurred in AL-DS mode	[53]
Membrane performance	Elevated salinity in the bioreactor	(1) Lab-scale FOMBR system was able to achieve stable water flux (2) No deterioration in membrane performance and mild fouling (3) The gel-like layer was observed on the membrane surface and the layer could moderate the reverse salt flux	[137]
Salt accumulation modeling	Membrane type, wastewater salt concentration DS, HRT, SRT	(1) The salt accumulation is directly proportional with π_{inf} and B/A (2) When B/A << π_{inf}, solute reverse diffusion has negligible effect (3) B/A ~ $0.1\pi_{inf}$ is optimal (4) SRT/HRT ratio should be minimized to decrease salt accumulation and increase water flux	[54]

(*Continued*)

Table 4 (*Continued*)

Problem/research object	Operational parameters investigated	Conclusion/summary of the work	Refs.
Novel process/salinity build-up	Removal of trace organics	(1) The removal trace organic compounds was possibly governed by the interplay between physical separation of the FO membrane and biological degradation or biological degradability (2) Continuous deterioration of biological activity of the FOMBR, possibly due to salinity build-up in the reactor	[123]
Novel process performance	Trace organics effects	(1) Increased salinity and dosage of the pharmaceuticals shifted the microbial populations. (2) The biological process was found to play key role in the overall performance of the system	[74]
Increase water flux	Salt type	(1) Organic ionic salts are biodegradable and not accumulate in the bioreactor, but expensive	[61]
FOMBR process	Review of the operational parameters’ effects in former studies	(1) Development and demonstration of an integrated FOMBR system for production of high-quality product water were reviewed and discussed	[58]
Flux behavior	Activated sludge properties	(1) The main factor affecting flux decline is the osmosis pressure of the activated sludge solution (2) Polysaccharides affected the flux decline rate negatively (3) Initial flux and bound protein were the key factors to control the flux behavior in FOMBR	[56]
Membrane biofouling and scaling	Membrane orientation	(1) FO fouling is governed by the coupled influences of biofilm formation (bacterial clusters and EPS) and inorganic scaling (Ca, Mg, Al, Si, Fe and P) that in AL-DS mode (2) AL-FS configuration was less sensitive to the feed conductivity and membrane fouling	[57]

(*Continued*)

Table 4 (*Continued*)

Problem/research object	Operational parameters investigated	Conclusion/summary of the work	Refs.
Reverse salt flux effects on microbial community	Different types and concentrations of inorganic and novel surfactant draw solutes	(1) Generally, chloride salts can be used without any danger to biomass (2) All sulfate salts are good for microbial growth (3) (Anionic) surfactants with 100–150 times lower specific reverse transport of draw solute as compared with inorganics and above CMC are suitable alternatives as draw solutes	[135]
Reverse salt flux effects on microbial community	–	(1) Salinity elevation caused to deterioration of biological activity and significant accumulation of organic matter and NH_4^+-N (2) Almost all the dominant species in the bioreactor was taken over by high salt-tolerant new species (3) Biofouling and inorganic scaling occurred in the foulant layer, with magnesium/calcium phosphate/carbonate compounds	[75]
Bisphenol A removal	FOMBR and MF-MBR comparison	(1) Overall BPA removals in MF-MBR and FOMBR were obtained as 93.9 and 98%, respectively. (2) FO membrane can remove approximately 70% BPA from the feed, which is much higher than that of the MF membrane (below 10%). (3) After 30 d of operation, salt accumulation in the bioreactor reached about 3.5 g/L equivalent NaCl concentration calculated from the conductivity	[142]
Low-strength wastewater treatment with submerged FO-AnMBR	Compare to conventional AnMBR systems	(1) The reduction of membrane flux (9.5–3.5) was contributed to the membrane fouling and the increasing salinity in the reactor	[144]

(*Continued*)

Table 4 (*Continued*)

Problem/research object	Operational parameters investigated	Conclusion/summary of the work	Refs.
		(2) The conductivity in the bulk phase increased from 1.0 to 20.5 ms/cm and the increment of salinity in the reactor did not exhibit toxic effects on the wastewater treatment (3) Compared to conventional AnMBR systems, the FO-AnMBR system was able to produce higher quality permeate (4) However, CTA FO membrane had a low tolerance to both the high temperature solution and the biological attachment, hence the uncertainty of the stability of membrane made it difficult to sustain the operation for a long time	
Characterization of organic membrane foulants in a FOMBR treating AN-MBR effluent	Comparison of mesophilic and atmospheric anaerobic MBR (M-FOMBR and P-FOMBR)	(1) The internal foulants from P-FOMBR was less than that from M-FOMBR, and the membrane fouling was lower in P-FOMBR	[124]
Post-treatment of MBR-treated landfill leachate	Membrane orientation	(1) The fouling of FO membranes in the AL-DS mode was more rapidly developed than that of AL-FS mode	[145]
Novel hybrid UF-FOMBR	Long-term pilot scale operation performance	(1) Membrane fouling was significantly reduced with integration of UF with MBR	[78]
Novel hybrid UF-FOMBR	Trace organic chemicals removal	(1) The UFO-MBR was found that can operate sustainably and has the potential to be utilized for direct potable reuse applications	[146]
Scale-up of FOMBR	Modeling salt accumulation and DS dilution	(1) Water flux in full-scale FOMBR is much smaller than that in lab-scale tests due to salt accumulation and DS dilution (2) ECP adversely affects water flux considerably; SRT increases at larger membrane areas until it reaches a limit	[71]

(*Continued*)

Table 4 (*Continued*)

Problem/research object	Operational parameters investigated	Conclusion/summary of the work	Refs.
Effects of salinity build-up	Biomass characteristics and trace organic chemical removal	(1) Salinity build-up could adversely affect the removal of nutrients, organic matters, and some hydrophilic TrOCs (2) The removal of hydrophobic TrOCs in MBR was not affected by salinity build-up (3) The concentrations of both SMP and EPS in MBR increased at elevated salinity conditions	[136]
A new approach to direct phosphorus recovery from municipal wastewater	pH adjustment	(1) The system achieved up to 98% overall removal of TOC and NH_4^+-N (2) >95% PO_4^{3-}-P recovery was achieved via amorphous calcium phosphate precipitation	[147]
Short-term fouling propensity and flux behavior	–	(1) Water flux and membrane foul- ing were not severely affected by MLSS concentration but were highly affected by elevated salinity (2) EPS was found to be an important factor governing membrane fouling (3) Due to the lower salt accumulation effect, $MgCl_2$ is likely found to be more suitable as the DS	[148]
Sludge characteristics and membrane fouling	SRT	(1) The lower SRT was helpful for alleviating the salt accumulation and flux decline	[72]
Salt accumulation	Integration of microfiltration	(1) MF-FOMBR decreases salinity, increases flux and TOC removal when compared to FOMBR	[79]
Novel AnFOMBR Performance	Different draw solutions comparison	(1) While the use of Na_2SO_4 allowed for higher OLR sulfate concentration in the bioreactor increased due to reverse salt flux (2) Using NaCl as draw solute caused bacterial washout due to much higher steady-state salinities, however absence of sulfates allowed higher methane composition in the biogas in steady state	[149]

(*Continued*)

Table 4 (*Continued*)

Problem/research object	Operational parameters investigated	Conclusion/summary of the work	Refs.
Characterization of biofouling	High and low aeration conditions	(1) The flux in the FOMBR was much lower than conventional MBRs, so the convective forces towards the membranes would be lower (2) The average DO value does not represent the effective shear forces on the membranes. Therefore, a moderately high aeration is needed as a potential control strategy of fouling in FOMBRs	[150]
Effects of silver nanoparticles	–	(1) TOC removal was not evidently affected by Ag-NPs (2) Ag-NPs significantly caused to decrease in nitrifying activity and increase in EPS	[70]
Biodegradation of phenol from saline wastewater	Sodium chloride concentration, phenol concentration membrane orientation, DS concentration, and DS flow rate	(1) Cell attachment to the membranes depended primarily on permeate flux (2) Biofouling of membranes was reversible and membrane performance was recovered by osmotic backwashing	[151]
Novel AnFOMBR developed	Mesophilic conditions	(1) Good and stable sCOD removal and nearly complete total phosphorous removal were obtained (2) The system removal rate was limited due to total nitrogen and ammonia accumulation in the bioreactor	[125]
In situ observation of the growth of biofouling layer	Operation time (fouling duration)	(1) The development of biofouling layer could be divided into three stages: (2) EPS deposition (3) EPS and microorganisms growth rapidly and flux decrease (4) In further operation (stable water flux), some microorganisms and EPS would be detached from the FO membrane surface	[152]
Novel osmotic membrane bioreactor (MBBR–FOMBR)	Different ds solutions	(1) Close to 100% nutrient removal efficiency in the biofilm layer on the carriers	[153]

(*Continued*)

Table 4 (*Continued*)

Problem/research object	Operational parameters investigated	Conclusion/summary of the work	Refs.
Membrane fouling and biomass characteristics assessment	Different concentration of DS solution	(1) The increase in the fouling of the FO membrane was much less severe than that of the MF membrane (2) Fouling of submerged FO membranes can be effectively controlled by aeration (3) The fouling severity of the FO membrane increased as the initial water flux was elevated by increasing the draw solute concentration (4) Salinity build-up led to an increase in the SMP concentration and a reduction in EPS	[60]
Modeling full-scale FOMBR systems	FO membrane and module type, water recovery, DS flow rate, and DS concentration	(1) Selecting an optimal DS flow rate and concentration is a trade-off problem. FO membrane cost decreases at higher DS flow rates and concentrations, but RO energy consumption and water product concentration increases in the meantime (2) Higher DS flow rate and concentration should be selected for an optimal FOMBR–RO hybrid system if the FO membrane cost is the most dominant factor	[154]
Salinity build up	MF-MBR and MF-FOMBR comparison	(1) The concentration of hydrophilic and biologically persistent TrOCs in the FO permeate was much lower than that in the MF permeate (2) Due to the high rejection of the FO membrane, these TrOCs could accumulate in the bioreactor and be transferred into the MF permeate	[122]
Comparison of biofouling on CTA FO and TFC FO membranes in osmotic MBR	Membrane type (surface type)	(1) There were no impacts of membrane materials on TOC and NH_4^+-N removals	[155]

(*Continued*)

Table 4 (*Continued*)

Problem/research object	Operational parameters investigated	Conclusion/summary of the work	Refs.
		(2) More severe fouling of TFC FO membrane resulted in its higher flux decline in FOMBRs (3) Biofouling was more pronounced for CTA FO membrane compared to TFC FO membrane	
Simultaneous phosphorus and clean water recovery from raw sewage	Operating type	(1) Phosphorus was periodically drawn by MF from the mixed liquor of FOMBR–RO system (2) MF extraction prevented salinity build-up in the bioreactor	[156]
Comparison of microbial structures in two FOMBRs fed with different wastewaters	Feed characteristics (the effluent of mesophilic(M) and ambient(A) anaerobic bioreactors)	(1) Different removal efficiencies between the A-FOMBR and M-FOMBR were obtained (2) SMP content was higher in the M-FOMBR, resulting in lower flux of M-FOMBR than that of A-FOMBR with operation time	[157]
Comparison of full-advanced treatment (FAT) approach and hybrid UF-OMBR in terms of life-cycle assessment (LCA)	Construction material, energy demand, and chemical use	(1) The LCA illustrate that the life-cycle impacts of FAT are much lower than UFO-MBR treatment (2) FO permeability should be increased, RO energy should be recovered, and nutrient recovery should be included in FOMBR process to lower the LCA impacts	[158]
Selection of suitable draw solute to achieve less salt accumulation, relatively higher water flux, and higher dilution capacity of DS	Different commercial fertilizer were employed	(1) MAP exhibited the highest biogas production (2) MAP had less salt accumulation and relatively higher water flux among the other draw solutes	[159]
Decrease biofouling and increase water flux of the CTA-FO membrane	Surface-modified (PD coating and PEG grafting) and pristine CTA-FO membranes were compared	(1) The modification changed the membrane surface properties; increase hydrophilicity and improve the anti-adhesion for the biopolymers and biocake (2) Modified membrane exhibited lower flux decline than the pristine membrane	[160]

(*Continued*)

Table 4 (*Continued*)

Problem/research object	Operational parameters investigated	Conclusion/summary of the work	Refs.
Investigating the resistivity of FO membranes in activated sludge	Membrane types (CTA or PA TFC)	(1) CTA FO membranes were found to more resistant to biodegradation caused by prolonged exposure to activated sludge (2) Biodegradation increased the pore size, water permeability, and salt flux of the membrane (3) Commercially available CTA TFC FO membranes may not be readily compatible for long-term FOMBR operations	[161]
An innovative concept of combining SMB and an OsMBR was proposed	Draw solution type ($MgCl_2$ and/or Triton X114)	(1) Employing mixed Triton X-114 and $MgCl_2$ as DS exhibited higher water flux and lower reverse salt flux (2) The new hybrid OsMBR removed ammonium and phosphorus in single reactor successfully (3) Thanks to the sponge carriers, during the 90-d operation the hybrid system achieved a stable water flux and low biofouling was obtained	[162]
A novel OsMBR was proposed (AGB-OsMBR) to nutrient removal and reduce biofouling	Draw solution, flow rate, operating time	(1) Low salt accumulation (<1.5 g/L) was observed during 60 d operation (2) High nutrient removal (99.94% of NH_4-N and 99.73% of PO_4-P) was achieved (3) Diluted draw solution could be effectively recovered (100%) by PTFE MD membrane	[129]
Phenol biodegradation	Phenol concentration, osmotic backwashing	(1) Phenol concentrations up to 2,500 mg/L were completely removed at HRT varying in 3–14 h (2) A biofilm removal strategy including osmotic backwashing employing NaCl solution and water was formulated to improve bioreactor sustainability	[163]

(*Continued*)

Table 4 (*Continued*)

Problem/research object	Operational parameters investigated	Conclusion/summary of the work	Refs.
An osmotic membrane photobioreactor (OMPBR) was designed and operated for N and P removal	HRT (2–4 d), osmotic backwashing	(1) High removal efficiencies of more than 90% NH_4^+-N, 50% NO_3^--N and 85% PO_4^{3-}-P were achieved (2) Polysaccharides were found to be the major constituent of the EPS (3) Microalgae accumulated a large quantity of sugars and chlorophyll in the bioreactor	[164]

evaluated as one of the main challenge of the FO-MBR process. The halophilic bacteria are the functionally dominant species in the bioreactor. Halophilic bacteria among the extremophiles are saline conditions-adopted bacteria with growth optima in NaCl concentrations in excess of 1% and are further categorized into three groups according to the salinity of their growth optima: slightly halophilic (1–3% w/v), moderately halophilic (3–15% w/v), or extremely halophilic (>15% w/v) [138]. Studies have shown that the microbial morphology and the dominant species of the population change with increasing salt concentration and protozoa and rotifers tend to be absent when the salt concentration is increased beyond 10 g/L. The salt accumulation would cause changes to the microbial community and only microorganisms with adequate salt tolerance could adapt and thrive in an elevated salty media in the bioreactor [139].

Luo et al. recorded in their study notable increases in the content of SMP and EPS within the saline MBR which can be attributed to the autolysis of cells and secretion of organic cellular constituents as well as the accumulation of unmetabolized and/or intermediate products derived from the incomplete degradation of organic substances. They concluded also that salinity build-up in MBRs could adversely affect the microbial activity and thus lower the system performance regarding the removal of nutrients and organic matters. Additionally, SMP and EPS increase in salty bioreactors resulting in severe membrane fouling [140]. Similarly, Qiu and Ting observed that almost all dominant species in the activated sludge were taken over by high salt-tolerant new species with elevation of salinity in the bioreactor [75]. Nawaz et al. investigated the reverse salt flux of various draw solutions and salt accumulation effects on the microbial community and growth in a FOMBR. They reported that chloride salts can be used without any danger to biomass in the FO-MBR. However, bicarbonates could only be used by enough oxygen concentration and mixing conditions presented in the system in order to avoid anoxic zone formation. All sulfate salts can be readily preferred for microbial growth and anionics surfactans should only be used above the CMC preferably [135]. The results of the study conducted by Nawaz et al. are shown in Tables 2 and 3 as summary.

According to Tables 2 and 3, it could be said that the surfactants and organic substances can be used as draw solutes alternatively against inorganic solutes. These substances will support also the bacterial growth which is not the case by inorganic solutes. Moreover, the organic solutes exhibit lower reverse salt fluxes comparing with inorganic solutes. However, they provide less osmotic pressure than inorganic solutes which results in lower water fluxes and long HRTs. The operational conditions of MBRs should be evaluated by using these alternative draw solutes. On the other hand, the organic load of system could not provide sufficient food for bacterial growth because of low water flux provided by organic solutes. Inorganic solutes provide a more stabilized operational conditions but, they could inhibit the biological system because of high reverse solute flux which the case is by high concentrations at draw solution side [37].

It must also be noted that organic draw solutes such as micellar solutions have lower potential of reverse solute transport toward the feed side. Therefore, they cause less fouling resulted from the reverse solute flux in comparison with inorganic solutes [39]. However, the effect of flux increase on membrane fouling resulted by humic and colloidal particles was investigated in a study. The results show that the humic and colloidal particles cause more flux decline at higher fluxes by FO-membrane in bioreactor in comparison with lower fluxes [141]. Because the water

Table 5
Specific operation conditions of FOMBR studies availably found in literature

Configuration	Membrane type	Membrane orientation	DS concentration/osmotic pressure	SRT (d)	Stable flux (LMH)	Reverse salt flux (GMH)/steady salinity (g/L or mS/cm)	Refs.
Side-stream	CTA	AL-DS	0.5 M NaCI	–	6.2	3.2 GMH	[11]
Submerged	CTA	AL-FS	50 g/L NaCI	15	9	6.5 GMH	[12]
Submerged	CTA	AL-FS	5 MPa	–	10		[75]
Submerged	CTA	AL-FS	1 M NaCI	–	8	5.7 GMH	[60]
Submerged	CTA and TFC FO	AL-FS	1 M NaCI	10	5 and 3	–	[155]
Side-stream	CTA	AL-FS	58.5 g/L	–	1.7	–	[122]
Submerged	CTA	AL-FS	0.5 M NaCI	20	2.8	7.6 g/L	[137]
Side-stream	CTA	AL-DS	1.5 M NaCI	–	3	4.13 g/L	[123]
Submerged	TFC FO	AL-DS	0.5 M NaCI	10	3.9	6.5 g/L	[57]
Submerged	CTA	AL-FS	EDTA sodium coupled with surfactants	–	7	0.09 GMH	[153]
Submerged	CTA	AL-FS	49 g/L	50	5.67	–	[70]
Submerged	CTA	AL-FS	0.5 M NaCI	90	6	–	[125]
Submerged	CTA	AL-FS	1.0 M NaCI	10	2.45	24–25 g/L	[72]
Submerged	CTA	AL-FS	1.0 M NaCI	15	1.82	33–34 g/L	[72]
Submerged	TFC	AL-FS	1.0 M NaCI	10	10	–	[54]
Submerged	CTA	AL-FS	HCOONa, CH_3COONa, $Na(C_2H_5COO)$, $Mg(CH_3COO)_2$ (4.2 MPa)	30	3.25, 2.89 2.97, 1.59	7.63, 3.55, 2.29, 1.06	[61]
Submerged	TFC	AL-FS	0.5 M NaCI	10	4	–	[57]
Submerged	CTA	AL-FS	0.5 M NaCI	90	3.67(min flux)	–	[144]
Submerged	CTA	AL-FS	32 g/l NaCI	70	1.5	20 g/l NaCI	[78]
Submerged	CTA	AL-FS	1.0 M NaCI	50	6.46	–	[147]
Submerged	CTA	AL-FS	1.0 M NaCI	10	5.5	5 mS/cm	[79]
Side-stream	CTA	AL-FS	1.0 M NaCI	10	2	15 mS/cm	[152]
Submerged	CTA	AL-FS	0.5 M NaCI	50	3	7–14 mS/cm	[72]
Side-stream	CTA and TFC FO	AL-FS	1.0 M NaCI	10	3	22 mS/cm	[155]
Submerged	CTA	AL-FS	1.0 M NaCI	–	–	–	[157]
Submerged	CTA (low and high permeability)	AL-FS	20–50 g/L NaCl	–	3.5–9.65	2.3 GMH	[158]
Submerged	CTA	AL-FS	Various fertilizer chemicals 1.0 M mono-ammonium phosphate (optimum)	10	~10	–	[159]
Submerged	CTA and modified CTA	AL-FS	1.0 M NaCI	–	10–15 (pristine or modified CTA)	~5 GMH	[160]
Submerged	CTA and TFC FO	AL-FS	0.5 M NaCI	30	~5	3.4–35 GMH	[161]
Submerged	CTA-ES	AL-FS	1.5 mM Triton X-114 and 1.5 M $MgCl_2$	–	10.6	2.1 GMH	[162]
Submerged	CTA-NW	AL-FS	$NaEDTA^{3-}$ and $HEDTA^{3-}$	–	3.62	0.31 GMH	[129]
Submerged	CTA	AL-FS	50 mS/cm NaCl	–	1.2–7.2	–	[163]
Submerged	Commercial TFC	AL-FS	NaCl	–	1.59	34 mS/cm	[164]

flux is higher by inorganic draw solutions, it can be resulted that organic and colloidal fouling could be higher in comparison with operations in which the organic solutes were used as draw solution.

5. Overall system performance of FOMBR

High rejection membrane separation with conventional biological treatment in a single step is referred as HR-MBR systems and includes NF, FO, and MD. In these systems, organic contaminants can be effectively retained in the bioreactor prolonging their retention time and thus enhancing their biodegradation. Therefore, HR-MBR can offer a reliable and elegant solution to produce high quality effluent [140]. Among these processes, compared to the MF or UF membrane in a conventional MBR, the FOMBR exhibits the advantages of much higher rejection of contaminants at a lower hydraulic pressure. FO processes are also likely to have lower fouling propensity than pressure-driven systems [15]. Achilli et al. [12] firstly presented a novel submerged FOMBR followed by RO. In this system, the effluent water of FOMBR showed lower fouling effect on following RO which provided a more stable operation compared with system combination of conventional MBR and RO. FOMBR-RO might lead also to a higher quality RO product water when compared with a conventional MBR followed by RO. In the study of Achilli et al. [12], the system including FOMBR and following RO removed more than 99% of organic carbon and 98% of ammonium-nitrogen, respectively and after this study, many following researches on FOMBR were carried out. These researches some of which are presented in the previous sections are presented in Table 4 including main research object. The availably founded experimental data in studies were summarized in Table 5 also.

In another study, Zhu and Li [142] compared a FOMBR and a conventional MBR in view of bisphenol A removal. They found that the total removal rate of bisphenol A by the conventional MBR and FOMBR was as high as 93.9 and 98%, respectively. They concluded that biodegradation plays a dominant role in the total removal of bisphenol A in both configurations. When the membrane rejections are compared, it was found that the FO membrane can remove approximately 70% bisphenol A from the feed which is much higher than MF membrane (below 10%).

6. Conclusions and further suggestions

FOMBR is a promising novel process for wastewater treatment and reclamation which are the main reasons why the MBR systems have secured their position against the conventional systems in last few years. However, the main critical challenges of FOMBR such as CP and membrane fouling, reverse solute diffusion and lower flux have not been completely overcome yet. These issues are directly related to design of new FO-membranes and employment of new draw solutes. Moreover, the following aspects should be kept to be investigated further to enhance the performance of FOMBR as well:

(1) Beside the properties of *draw solution* such as salt type, concentration, and valent properties and availability, operational parameters like solution flow velocity and operation mode (FO or PRO) should be considered to maximize the water flux and minimize the reverse salt flux and operating costs.
(2) *Membrane type and orientation* should be investigated at further studies to mitigate the decreasing of water flux caused by various concentration polarizations in different membrane layout between the feed and draw solutions.
(3) The influence of cross flow velocity and characteristics of *feed solution* on the product water should be investigated further.
(4) *Air scouring* should be optimized to reduce the fouling on the membrane surface beside providing the required oxygen in MBR.
(5) Spacer properties and geometry of the *membrane module* should be investigated further to obtain the best hydrodynamic flow conditions in the modules.
(6) *Osmotic backwashing procedure* including frequency and duration should be carefully addressed to minimize the irreversible membrane fouling.
(7) *Sludge retention time* should be optimized for efficient nutrient removal and regulating the salt accumulation in the bioreactor.
(8) *MF/UF integration with FOMBR* can be further investigated to alleviate the salt accumulation in the bioreactor.
(9) Contrary to common methods of RO concentrate disposal, FO process which is an emerging technology on RO concentrate management could be employed to provide ZLD in FOMBR.

According to the recent studies on FOMBR, the reverse salt flux of FO membranes and salt accumulation problem in MBR could be alleviated and controlled by adjusting the SRT parameter and/or combining the FO membrane with a MF or UF membrane in the same bioreactor of the FOMBR system. However, although there are more than 50 papers about FOMBR now, the low flux of the FO, which further decreases when FO membrane is submerged into the bioreactor, still remains as a main challenge of the FOMBR processes and FO processes, as well. That the diffusion phenomena is not effective alone to increase the water flux of FO membrane may be concluded eventually from all evaluated studies, therefore, some promoting conditions such as hydrodynamic behaviors or filtration could be provided together with diffusion phenomena in further studies.

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Nomenclature

A	—	pure water permeability coefficient
AGB	—	attached growth biofilm
AHA	—	aldrich humic acid
AL	—	active layer
AL-DS	—	active layer facing draw solution
AL-FS	—	active layer facing feed solution
B	—	active layer salt permeability coefficient
BOD	—	biological oxygen demand
BSA	—	bovine serum albumin
CASP	—	conventional activated sludge process
c_D	—	concentration of solute in draw solution side
C_{Db}	—	solute concentration in the draw solution side
c_F	—	concentration of solute in the feed side
C_{Fb}	—	solute concentration in the feed side
c_i^A	—	draw solute concentrations on the active layer side of interface
c_i^S	—	draw solute concentrations on the support layer side of interface
CMC	—	critical micellar concentration
COD	—	chemical oxygen demand
CTA	—	cellulose triacetate
D	—	diffusion coefficient of bulk
DI	—	deionized
DOC	—	dissolved organic carbon
DS	—	draw solution
D^s	—	diffusion coefficient of solute
	—	porosity of support layer
ECP	—	external concentration polarization
EPS	—	extracellular polimeric substances
F/M	—	food to microorganisms
FO	—	forward osmosis
FOMBR	—	forward osmosis membrane bioreactor
FS	—	feed solution
H	—	partition coefficient
HMIS	—	hazardous materials identification system
HR-MBR	—	high retention membrane bioreactor
HRT	—	hydraulic retention time
ICP	—	internal concentration polarization
J_s	—	solute flux
J_{sw}	—	ratio between reverse solute flux and water flux
J_w	—	water flux
K	—	solute resistivity for diffusion within the support layer
k_D	—	mass transfer coefficient at draw solution side
k_f	—	mass transfer coefficient at feed side
LMH	—	liter per square meter hour
MAP	—	mono-ammonium phosphate
MBR	—	membrane bioreactor
MCRT	—	mean cell retention time
MD	—	membrane distillation
MF	—	microfiltration
MLSS	—	mixed liquor suspended solids
n	—	number of dissolved species created by the draw solute
NF	—	nanofiltration
OMPBR	—	osmotic membrane photobioreactor
OSMBR	—	osmotic membrane bioreactor
PA	—	polyamide
PD	—	polydopamine
PEG	—	polyethyleneglycol
PSD	—	pore size distribution
R_g	—	ideal gas constant
RO	—	reverse osmosis
S	—	membrane structural parameter
sCOD	—	soluble chemical oxygen demand
SEM	—	scanning electron microscope
SMB	—	sponge-based moving bed
SMP	—	soluble microbial products
SRT	—	sludge retention time
T	—	absolute temperature
t_A	—	thickness of active layer
TDS	—	total dissolved solids
TFC	—	thin film composite
TMP	—	trans membrane pressure
TOC	—	total organic carbon
t_S	—	thickness of support layer
UF	—	ultrafiltration
WW	—	wastewater
π_{Db}	—	osmotic pressure in the bulk draw solution
π_{Di}	—	osmotic pressure of the draw solution at the active layer surface
τ	—	tortuosity of support layer
ZLD	—	zero liquid discharge

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