Chapter 11

Applications of Reverse and Forward Osmosis Processes in Wastewater Treatment: Evaluation of Membrane Fouling

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Additional information is available at the end of the chapter

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Abstract

Although reverse osmosis (RO) process is widely used for wastewater reclamation, it requires high amount of energy that has a major effect on the economic effectiveness of the process. Furthermore, RO membranes are susceptible to fouling, which further limits their effectiveness and increases the costs due to the need for frequent cleaning. Consequently, the use of osmotically driven membrane separation processes such as forward osmosis (FO) has gained increasing consideration, although its uptake in wastewater remediation is still low. This is because the FO process, unlike the RO process, is operated by the osmotic gradient between the feed and draw solutions; therefore, it requires minimal or no hydraulic pressure. Hence, it has unique advantages, such as possibility of low fouling, and high water recovery. Nonetheless, the long-standing problem of membrane fouling still remains a major challenge even in the performance of FO processes especially when treating raw wastewaters, which have various contaminants. Furthermore, the mechanism of fouling in FO process has been found to be different from an RO process, and there is need for further studies to elucidate the differences of FO and RO fouling. These aspects are evaluated in this review.

Keywords: forward osmosis, membrane fouling, osmotic pressure, reverse osmosis, wastewater

1. Introduction

For many centuries, water has been considered a renewable, unlimited resource. However, in recent decades, the awareness that fresh water is not unlimited has arisen. The two major issues around water management are, thus, water scarcity and escalating pollution. Indeed, water pollution has put a potential strain on the existing water sources resulting in scarcity of fresh water. This has been occasioned by the rapid growth in global human population, thus increasing the demand; enhanced industrial and agricultural activity leading to rampant pollution of water sources; as well as climate change resulting in water scarcity through droughts. All these issues suggest the need for a more rational use of water resources [1]. The use of alternative sources of water such as seawater desalination and the reuse of wastewater after appropriate treatment is therefore necessary. Furthermore, the protection of natural water resources and development of new technologies for water and wastewater treatment for reuse are key priorities of the twenty-first century.

Wastewater reuse offers an opportunity to reduce demand on existing water resources [2]. This is because wastewater represents a suitable water source that can be used after appropriate treatment to reduce the fresh water demand and to lower the environmental impact of wastewater discharge [3]. Consequently, effluent from municipal wastewater treatment plants (MWWTPs) is a potential source of recycled water; however, to ensure its approval by the target population, microbial, physical, and chemical pollutants need to be removed using appropriate treatment technologies [4, 5].

Conventional municipal wastewater treatment processes rely on physicochemical and biological processes. However, with increasing contamination of wastewater by organic micropollutants and microbial contaminants, the current treatment technologies are often not successful in meeting the stringent standards. The reduction or complete removal of refractory organic contaminants from wastewater is important from the viewpoint of wastewater reclamation, recycling, and reuse [5]; however, conventional municipal wastewater treatment is inefficient especially in the removal of biorecalcitrant organic micropollutants and some resistant microorganisms.

There is therefore a pressing need to develop alternative wastewater remediation technologies that are capable of complete removal of organic micropollutants; have the provision of effective disinfection; are capable of utilization of minimum resources such as energy; are economically viable; and are environmentally friendly [6]. Suitable technologies should be able to enhance water recovery as well as extract biomass from the wastewater for reuse [7]. Membrane-based technologies have gained increasing prominence for wastewater remediation. Although low pressure processes such as microfiltration (MF) and ultrafiltration (UF) have been employed to treat secondary wastewater effluent, these technologies are not effective in removing emerging micropollutants and trace metals from wastewater, thus limiting the potential application of the reclaimed wastewaters. Consequently, the use of high pressure processes such as nanofiltration (NF) and reverse osmosis (RO) have been explored. However, they too suffer limitations such as high energy demand and severe membrane fouling, which ultimately increases the operating costs. This has prompted the exploration of osmotic pressure–driven membrane processes (ODMPs) such as forward osmosis (FO) as a suitable alternative to overcome these concerns [8]. This chapter presents the water scarcity and pollution challenge, applications of membrane-based processes (RO and FO) for wastewater remediation, and recent developments in addressing membrane fouling in RO and FO processes.

2. The RO and FO membrane processes

2.1. Principle of operation of RO and FO membranes

In the FO process, an osmotic pressure gradient across the semipermeable membrane drives water from a dilute feed solution (FS) to a concentrated draw solution (DS) [9]. In this way, the DS generates greater osmotic pressure and drives water from the feed through the membrane while rejecting solutes, thus separating the water from the diluted DS [10]. The RO process, on the other hand, employs hydraulic pressure to effect the permeation of water through a semipermeable membrane. The principle of operation of RO and FO processes is shown in **Figure 1**. The ideal semipermeable membrane for use in RO and FO processes should possess the following attributes: high water flux and salt rejection, less fouling propensity, and high chemical and thermal stability, among others [10]. The FO process has been shown to have a lower propensity to fouling and consequently, a higher reversibility of fouling than RO, and this is attributed to the lack of applied hydraulic pressure. Subsequently, FO can be used to treat low-quality feed waters such as municipal wastewater and landfill leachate, among

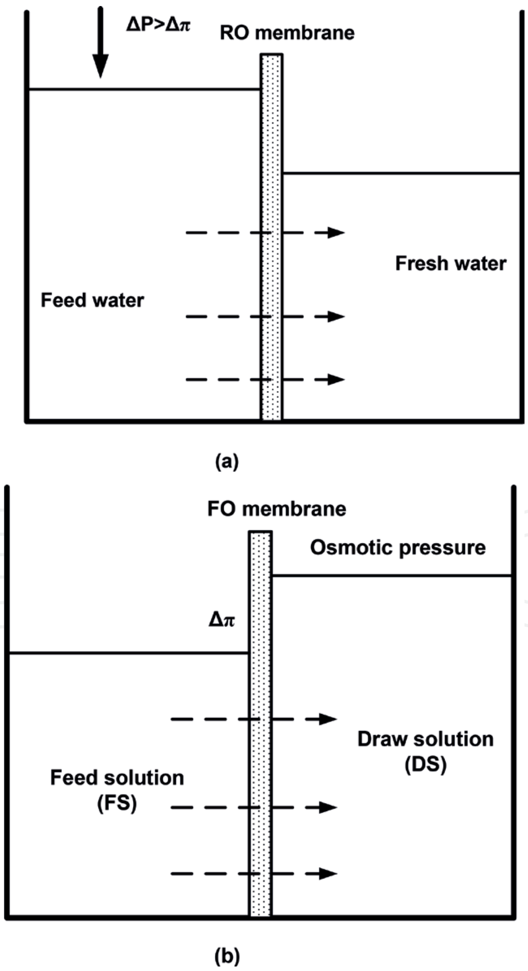

Figure 1. Working principle of (a) RO and (b) FO processes.

others [11]. Nevertheless, even in an FO-based separation process, energy is still required to extract clean water from the DS and to reuse the DS [12].

The general equation used to describe water flux across the RO and FO membrane (J_w) is calculated using Darcy's law [9]:

$$J_w = A_w \times (\sigma \, \Delta\pi - \Delta P) \tag{1}$$

where A_w is the membrane pure water permeability coefficient, ΔP is the applied hydrostatic pressure, $\Delta\pi$ is the differential osmotic pressure, and σ is the reflection coefficient indicating the rejection capability of a membrane (for an ideal membrane σ =1). Therefore, in FO, ΔP is zero thus making the water flux to be directly proportional to the difference in osmotic pressure, while for RO, $\Delta P > \Delta\pi$. This relationship is illustrated in **Figure 2**.

Despite not using hydraulic pressure, the FO process can produce permeate quality that is close to that produced by RO and superior permeate quality than that of microfiltration (MF) and ultrafiltration (UF) membranes [7]. Moreover, the FO process has benefits including high

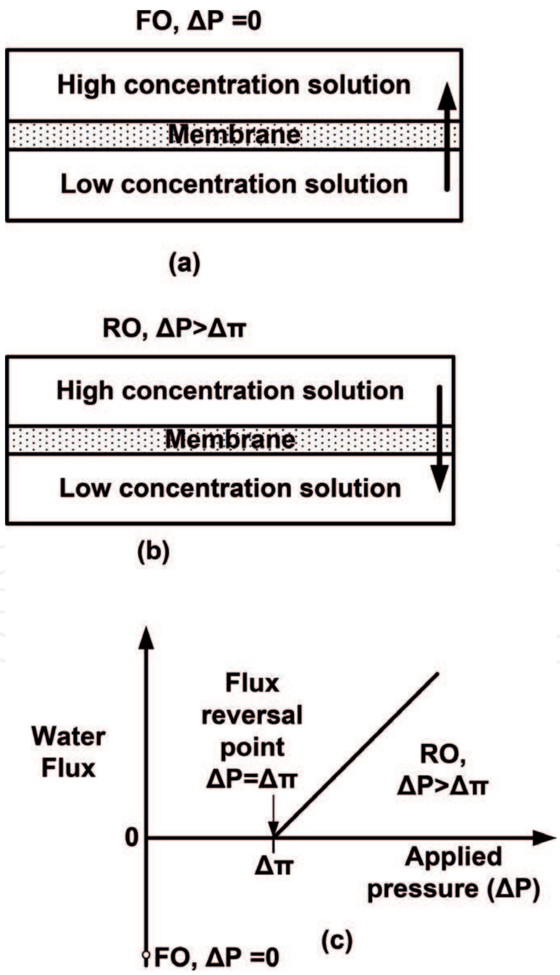

Figure 2. Schematic representation of FO (a) and RO processes (b) and a plot of water flux versus applied pressure for both processes (c). Adapted from [13].

rejection of a wide range of pollutants without using hydraulic pressure and hence the reduced energy expenditure and low membrane fouling tendency (more reversible fouling) [14]. For instance, a study by Altaee and colleagues [15] reported that the total power consumption by the FO process was 2–4% that of the RO-FO process, which shows that the use of FO can lead to significant reduction in energy expenditure. It is due to these unique advantages of FO membranes that they have been employed in many applications such as desalination of seawater, wastewater remediation, food and pharmaceutical processing, as well as renewable osmotic energy production [16].

However, notwithstanding these advantages of FO, it still suffers from the challenges faced by RO, mainly membrane fouling that results in reduced permeate quality and quantity as well as increased operational cost [17]. Developing an understanding of fouling behavior in FO is needed since it has been found that the fouling factors and mechanism of fouling in FO are different from those of an RO process [18]. Consequently, further research is required to understand the fouling behavior of FO and RO membranes to enable the development of tailored fouling controls [19].

2.2. Applications of RO and FO membranes in wastewater treatment

The FO and RO processes have been used to treat a variety of wastewaters such as municipal wastewater [14, 16, 18, 20], oily wastewater [21, 22], produced water [23], tannery wastewater [24], dairy wastewater [25], olive mill wastewater [26], as well as synthetic wastewater [8, 27]. In some of these studies, it has been reported that FO membranes could perform better than RO membranes. For instance, a comparative study by Cui and coworkers [28] on the removal of organic micropollutants (phenol, aniline, and nitrobenzene) reported that FO membranes achieved rejections of over 72%, which the authors observed that cannot be attained by commercial or lab-synthesized RO membranes. The FO and RO membranes can also be used in combination with other processes to increase the performance effectiveness. For instance, the use of combined MBR-RO and MBR-FO systems considerably improves the performance in wastewater treatment. Since the MBR alone is not effective in the removal of color and salts, the combination with RO and FO membranes allows for effective removal of these constituents [29]. Qui and colleagues [30] recently investigated the use of a biofilm-forward osmosis membrane bioreactor (BF-FOMBR) and reported that the process achieved very high removal efficiency of organic matter and nitrogen within a hydraulic retention time of 2 h. Furthermore, a significant reduction in FO membrane fouling was achieved (24.7–54.5%) due to decreased bacterial attachment and colonization of the membranes. A summary of the recent studies and the performance attained is shown in **Table 1**.

2.3. Limitations of RO and FO membranes

The use of membrane-based processes for wastewater treatment has been driven by the need to enhance water recovery, reduce energy consumption, and improve sustainability in application [31]. Consequently, membrane-based wastewater reclamation is considered a promising solution to supplement water supply and alleviate water shortage [18]. The RO process has received wide attention; however, it requires high hydraulic pressure, thus making it

Wastewater	Membrane type	Performance	Reference
Activated sludge	Cellulose triacetate Polyamide thin-film composite membranes (FO)	96% COD rejection.	[20]
Produced water	Cellulose triacetate Polyamide thin-film composite membranes (FO)	90% rejection of neutral hydrophobic compounds.	[23]
Oily wastewater	Hybrid forward osmosis membrane distillation (FO-MD) system	Water recovery of 90%. Almost complete rejection of oil and NaCl.	[21]
Soybean oil/water emulsion	Thin-film composite (TFC) FO membranes	Oil rejection of 99.9%.	[22]
Municipal wastewater	Superhydrophilic sulfonated poly-phenylenesulfone (sPPSU) polymer matrix TFC membranes (FO)	85% water recovery.	[16]
Municipal wastewater	FO membranes	A 5% flux decline in the absence of suspended solids and a 20% flux decline in the presence of suspended solids.	[18]
Synthetic urban runoff	Cellulose triacetate FO membrane	Rejection of trace metals (98–100%); phosphorus (97–100%); nitrate (52–94%). A 70% water recovery.	[27]
Synthetic wastewater	Cellulose triacetate (CTA) membranes (FO)	Rejection of pollutants in the wastewater (> 97%).	[8]
Municipal wastewater	Cellulose triacetate (CTA) membrane (FO)	89.2% removal efficiency of NH_4^+-N.	[14]
Tannery wastewater	ESPA-1 RO membranes	>98% rejection of COD and salts.	[24]
Dairy wastewater	TFC HR SW 2540 spiral RO membranes	99.9% TOC rejection and 99.5% conductivity reduction.	[25]
Olive mill wastewater	XLE and BW30 RO membranes	96.3% COD rejection.	[26]

Table 1. Studies on the application of RO and FO membranes in wastewater treatment.

energy intensive and costly due to the resulting membrane fouling and replacement. It is due to these concerns that in recent times the FO process has become an attractive alternative to RO due to the fact that it utilizes an osmotic pressure gradient as driving force for separation and also has additional merits such as lower energy consumption, less susceptibility to membrane fouling, and higher water recovery [32, 33]. Furthermore, FO membranes consistently reject a range of pollutants in municipal wastewater (chemical and biological contaminants), making FO an appropriate technology for wastewater remediation for reuse [20]; however, its application in wastewater treatment is still low [34]. Nevertheless, fouling still remains a formidable challenge even in FO processes limiting long-term operation, leading to flux decay and shortening of membrane lifespan [35].

3. Membrane fouling

3.1. Categories of membrane fouling

Membrane fouling arises from the accumulation of pollutants on the membrane surface leading to a reduction in flux. It has far-reaching implications since it affects the permeate quality and increases the operating costs such as process downtime leading to production losses, cleaning chemicals, energy and labor requirements, and eventually membrane replacements [36, 37]. The magnitude of membrane fouling depends on the physicochemical properties of the membrane and the wastewater composition. For instance, hydrophilic, low roughness, and neutral charge membranes present a high resistance to fouling [20]. In terms of location of foulants, fouling can be divided into surface fouling and internal fouling depending on the location of the foulants. Surface fouling is more frequent in high pressure membranes such as RO due to their compact and nonporous nature. On the other hand, based on foulant types, fouling can also be divided into biofouling, organic fouling, inorganic scaling, and colloidal fouling [20, 38].

a. Biofouling

This is the adhesion of microorganisms on the membrane surface leading to the formation of a biofilm. It occurs through the reversible attachment of planktonic bacteria, cell growth, and extracellular polymeric substance (EPS) production leading to the formation of biofilms [20]. Therefore, the two main components of biofilms are bacteria and EPS, which are excreted by bacteria. Biofouling is regarded as one of the most formidable forms of membrane fouling since bacteria reproduce on the membrane surface, thus enhancing the biofilm that leads to additional fouling [39]. This is because microorganisms are present in many water systems and they readily adhere to membrane surfaces and multiply.

b. Organic fouling

This arises from the adsorption or deposition of organic matter such as humic substances, polysaccharides, proteins, lipids, nucleic acids and amino acids, organic acids, and cell components on the membranes. It is the most common fouling experienced in wastewater treatment using membrane bioreactors (MBRs). The organics often become precursors of biofouling [40]. Effluent organic matter in wastewater arises from three sources: natural organic matters (NOMs), synthetic organic compounds (SOCs), and soluble microbial products (SMPs).

c. Inorganic scaling

This entails the chemical or biological deposition of inorganic substances on the membrane surface or within the pores, thus preventing permeation of water. It occurs when the concentration of some ions (such as metal sulfates and carbonates) in the water is high enough to exceed the equilibrium solubility product and hence become supersaturated leading to the deposition of the ions [13]. In fact, if the feed water is not well pretreated due to improper design of coagulation or oxidation processes, it may lead to the introduction of metal hydroxides into the fouling matrix, which causes significant challenges in chemical cleaning to enhance water flux.

d. Colloidal fouling

This refers to the deposition of fine suspended particles (colloids) on the membranes. Colloidal foulants can be divided into two types: inorganic foulants and organic macromolecules. Colloidal fouling leads to substantial flux decline resulting from the deposition of thick or less porous fouling layers composed of particulate matter. Consequently, this hinders back diffusion of salts that permeate water flux from the DS, thus increasing the salt concentration on the membrane surface.

A detailed analysis of the different modes of fouling in FO and RO membranes can be found in recent studies by Chun and colleagues [13] and by Jiang and coworkers [38], respectively. In addition, the following factors play a major role in fouling: the characteristics of the fouling matter, the chemistry of the DS and FS, the membrane properties (hydrophilicity and surface roughness), and hydrodynamic conditions, and they have been discussed in the literature [36].

3.2. Comparison of fouling in RO and FO membranes

Understanding the mechanisms of fouling is essential for improving membrane performance especially in FO membranes where very little has been done. For instance, the driving force for membrane separation plays a significant role in membrane fouling. It influences the fouling layer structure as well as the fouling reversibility. It has been reported that although the extent of compaction resulting from the permeate drag force is similar in FO and RO fouling layers, however, higher compressibility of foulants occurs under hydraulic pressure in RO processes. Therefore, in RO, there are two compaction mechanisms involved: compression of foulants and permeate drag force, whereas in FO, only the permeate drag force is predominant. These mechanisms reinforce one another, resulting in dense, compact, and irreversible fouling layers in RO [11].

Furthermore, in the RO processes, the hydraulic pressure–driving force remains constant during operation and hence the fouling effect can be readily determined. On the other hand, the fouling properties of FO process are different because of the changing osmotic pressure difference, accompanied by changes in concentration polarization. This makes it difficult to use the FO flux to accurately show the actual effect of membrane fouling [36]. Moreover, permeate flux and transmembrane pressure are commonly used to indicate membrane fouling in RO membranes, but these are not used in the FO process [36]. Additionally, in terms of transport, in the FO process, permeate water transports from the FS to DS; hence, the DS is diluted and FS concentrated steadily. Subsequently, the osmotic pressure decreases, leading to permeate flux decline along the membrane channel. However, in the RO processes, the concentration of the FS is only observed along the membrane channel [41]. Overall, studies have shown that the lack of hydraulic pressure in the FO system has a positive effect in that the membrane fouling generated is in most cases reversible and the water flux can be almost fully recovered using hydraulic washing, thus eliminating the use of chemical cleaning [37].

It has also been reported that membrane fouling in FO is less severe than in RO membranes. For instance, Yu and colleagues [42] compared the fouling propensity in RO and FO membranes treating activated sludge effluent and reported that the membrane fouling based on flux reduction was lower in FO membranes than in RO membranes. However, despite this, it is still necessary to pretreat the wastewater to prevent excessive fouling of FO membranes and decelerate membrane degradation [23]. A comparative study on the fouling of FO and RO membranes using polysaccharides (alginate, xanthan, and pullulan) depicted that alginate and xanthan resulted in more pronounced fouling in RO than in FO. Similarly, the study reported that polysaccharides naturally produced by marine bacteria improved the permeate flux instead of causing fouling in FO membranes [32]. Tow and coworkers, on the other hand, observed similarities in fouling in FO and RO membranes in terms of swelling and wrinkling of the fouling matter. They suggested that this could be leveraged to develop cleaning protocols for both FO and RO membranes [43]. In another study, Kwan and colleagues [44] evaluated biofouling in FO and RO membranes under similar hydrodynamic conditions and observed significant differences such as the following: (i) water flux decline was significantly lower in FO than in RO and (ii) biofilms in FO were loosely organized and in a thick layer, whereas in RO, they were tightly packed (due to hydraulic pressure). Consequently, the more packed biofilms in RO resulted in high resistance to water flow leading to higher flux decline. In another study, organic fouling has been reported to be dominant in RO membranes used for the treatment of municipal wastewater [45]. **Table 2** summarizes some of the recent studies on membrane fouling in RO and FO membranes.

Nevertheless, the fouling mechanism is complex and depends on numerous aspects such as water quality, process conditions, module design, and membrane properties, among others. It is therefore imperative to consider these factors in process design and development to mitigate fouling [9]. Moreover, the fouling behavior in the FO processes is unique because both sides of the FO membrane are involved [13], whereby there is membrane fouling and a drop in driving force [46]. A comprehensive evaluation of mass transport and fouling in FO and other ODMPs has been provided by She and colleagues [19].

3.3. Characterization of membrane foulants

Characterization of the fouling layer is important to enable the evaluation of membrane fouling especially the interaction of foulants with membranes and the composition of fouling matter.

Process	Water matrix	Type of fouling	Reference
FO, PFO, and RO	Sodium alginate	Organic fouling	[11]
FO and RO	Alginate, xanthan, and pullulan	Organic fouling	[32]
FO and RO	Activated sludge	Organic fouling	[42]
FO	Municipal wastewater	Cake layer formation	[46]
RO and FO	Alginate and methylene blue dye	Organic fouling	[43]
RO	Municipal wastewater	Organic fouling and inorganic scaling	[45]
FO and RO	Synthetic wastewater containing *Pseudomonas aeruginosa*	Biofouling	[44]

Table 2. Studies on membrane fouling in RO and FO membranes.

Process	Characterization technique	Water matrix	Reference
RO and FO	Fouling visualization apparatus	Alginate gel and methylene blue dye	[43]
RO and FO	CLSM	Sodium alginate	[11]
FO	SEM and LC-OCD	Synthetic wastewater	[33]
FO	SEM, FTIR, EDS	Oily wastewater	[37]
FO and OMBR	SEM, FTIR, EEM, EDX	Municipal wastewater	[14]
FO and RO	AFM and contact angle	Activated sludge	[42]
RO	FTIR, EEM	Municipal wastewater	[45]

Table 3. Studies on characterization techniques for RO and FO membranes.

This provides insight into the fouling mitigation strategies that can be adopted. Furthermore, a classification of fouling into chemical, physical, and microbiological enables also the identification of the appropriate techniques for characterization. Physical characterization can be performed by visual examination using environmental scanning electron microscopy (ESEM) and atomic force microscopy (AFM). Chemical characterization can be done using Fourier transform infrared (FTIR) and excitation emission matrix (EEM) analyses to determine the organic composition; energy dispersive X-ray spectroscopy (EDS) to determine the elemental composition of the fouling layer; evaluation of zeta potential to determine the surface charge and membrane hydrophilicity; and liquid chromatography with organic carbon detection (LC-OCD) to determine the different fractions of dissolved organic carbon. On the other hand, microbiological characterization can be accomplished using adenosine triphosphate (ATP) measurements, EPS quantification, and CLSM analysis for biofilm visualization and thickness estimation [8, 13, 14, 20]. More details can be found in a recent work by Li and coworkers [47] who reviewed the use of membrane fouling research methods to study fouling in RO and FO membranes. They also identified the main foulants involved in the various types of membrane fouling; however, they did not evaluate the mitigation strategies for membrane fouling. **Table 3** shows some of the studies that have been conducted and the characterization of membrane foulants.

4. Addressing membrane fouling

Municipal wastewater contains a variety of contaminants such as organic matter, inorganic matter, and microorganisms that can lead to membrane fouling [14]. Since membrane fouling is inevitable, it is imperative to develop strategies to address this challenge. Approaches for tackling fouling are twofold: (i) fouling mitigation through membrane and module development and optimization of hydrodynamic conditions and (ii) adapting cleaning approaches [48]. These strategies can further be broken down into the following: feed pretreatment, membrane monitoring and cleaning, membrane surface modification, or the use of novel membrane materials [38].

4.1. Feed pretreatment

It involves improving the feed water quality to minimize contaminant concentration prior to membrane filtration. It is aimed at ensuring reliable membrane operation and prolonging the membrane lifespan. Some of the most commonly used pretreatment technologies for RO include UF [49], coagulation/flocculation, and MF. In fact, FO can also be used as a pretreatment for RO because the former does not require hydraulic pressure and hence reduces the overall energy required and process costs by decreasing RO membrane fouling, minimizing the cleaning frequencies, and also increasing the water recovery [49, 50]. Nanofiltration has also been employed as a pretreatment for RO membranes. This is reported to have resulted in an increase in water recovery and water flux and also a reduction in RO membrane scaling and thus contributing to lowering the operating costs [51]. In another study on the treatment of geothermal water, NF was used as pretreatment for RO to reduce the concentration of divalent ions [52]. Combined pretreatment technologies have also been employed such as the use of ozonation, ceramic MF, and biological activated carbon (BAC) together as pretreatment for RO as reported by Zhang et al. [53]. In this combination, ozonation increased the oxidation of organic matter leading to its dissolution and facilitating removal by the ceramic MF and BAC prior to treatment by RO.

4.2. Membrane monitoring and cleaning

It entails the in situ monitoring of the membrane performance to evaluate the extent of fouling so as to conduct cleaning timeously. Some of the proven effective cleaning approaches of FO membranes include hydraulic cleaning and osmotic backwashing [23]. Osmotic backwash entails the reversed flow of water from the permeate side to the feed side based on the osmotic pressure difference. Lotfi and coworkers [33] observed that physical cleaning of FO membranes was effective leading to almost full restoration of the initial flux. In addition, treatment of oily wastewater using FO membranes indicated that osmotic backwashing resulted in over 95% water flux recovery and performed better than chemical cleaning using oxidants and acids [37]. Bell and colleagues employed chemically enhanced osmotic backwashing to clean FO membranes. The study showed that the cleaning removed cations and anions from the membrane surface but only slightly improving the water flux [23]. Similarly, Yu and colleagues demonstrated that during treatment of activated sludge using FO membranes, the flux was fully recovered using osmotic backwashing rather than cleaning by changing the cross-flow velocity or air scouring. They concluded that osmotic backwashing is a more efficient way to clean the FO membrane. A study by Wang and colleagues [54] investigated the chemical cleaning of FO membranes using different chemicals. They reported that disodium-ethylene-diamine-tetra-acetate (EDTA-2Na), sodium dodecyl sulfate (SDS), NaOH, HCl, and citric acid were not effective in removing the foulants after severe fouling; on the other hand, 0.5% hydrogen peroxide applied for 6 h at 25°C resulted in 95% recovery of permeability suggesting that almost all the foulants were removed. **Table 4** provides a summary of strategies employed in cleaning RO and FO membranes.

However, implementing costly cleaning protocols such as air scouring or chemical cleaning may be detrimental to the economic sustainability of the FO process. Therefore, it is necessary

Process	Cleaning strategy	Performance	Reference
TFC-FO	Water rinsing without using chemicals	97% water flux recovery.	[22]
FO	Hydraulic cleaning (cross-flow rate of 800 mL/min for 15 min)	90% water flux recovery.	[33]
FO	Hydraulic cleaning (cross-flow velocity 33 cm/s for 30 min) Osmotic backwash	75–80% flux recovery using hydraulic cleaning and 95% flux recovery using osmotic backwash.	[37]
FO OMBR	Hydraulic cleaning (cross-flow velocity of 10 cm/s for 60 min)	49.37% flux recovery in FO and 10.60% flux recovery in OMBR.	[14]
	Chemical cleaning (1% NaClO, 0.8% EDTA, and 0.1% sodium dodecyl sulfate (SDS) in sequence. Each lasted for 60 min.)	58–67% flux recovery in FO and 2–18.5% flux recovery in OMBR.	[14]
RO and FO	Hydraulic cleaning (cross-flow velocity of 25 cm/s for 60 min)	After hydraulic cleaning, the foulant peels off the membranes in both RO and FO.	[43]
FO, PFO, and RO	Hydraulic cleaning (cross-flow velocity 17 cm/s for 30 min)	Flux recovery: FO (99%); PFO (58%); and RO (10%).	[11]
FO and RO	Physical cleaning (cross-flow velocity of 8.5–25.5 cm/s for 1 min) Osmotic backwashing (1 min)	75% flux recovery by physical cleaning; 99.9% flux recovery by osmotic backwashing.	[42]
FO	Chemical cleaning (0.5% hydrogen peroxide for 6 h)	More than 95% recovery of permeability.	[54]

Table 4. Cleaning strategies employed for RO and FO membranes.

to explore proven strategies such as osmotic backwash, which has recently been demonstrated to successfully clean fouled FO membranes and has been extensively studied in the RO literature. This will allow for sustainable operation without use of chemicals [48]. In addition, real-time monitoring of the membrane process can provide useful information essential for efficient cleaning. To overcome the limitations of the individual cleaning methods, it is necessary to explore the use of multiple methods to take advantage of synergy in the use of multiple cleaning strategies such as a combination of osmotic backwashing and surface backwashing to further improve the performance of FO membrane [42]. For instance, a study by Sun and colleagues [14] showed that even in cases of severe membrane fouling, the use of hydraulic and chemical cleaning resulted in effective recovery of water permeability.

4.3. Membrane surface modification and the use of novel materials

It is based on the fact that membrane properties such as smoothness and hydrophilicity greatly influence performance. For instance, smooth surface and hydrophilic membranes are less prone to fouling compared to those with rough and hydrophobic surfaces. In addition to surface modification, the development of novel membrane materials with unique characteristics tailored to meet specific applications is another promising avenue. These novel materials include carbon nanotubes, zwitterionic materials, and metal oxide nanoparticles [38]. Li and coworkers [10] reviewed developments in materials and strategies for enhancing properties and performances of RO and FO membranes. They noted that surface modification of RO and FO membranes has received wide attention due to it being less costly and easy to perform compared to developing novel polymeric materials. However, surface modification may also have adverse effects such as pore blockage on the membrane active layer when some modifiers such as polyelectrolytes may promote concentration polarization and consequently reduce water flux. Asadollahi and colleagues [55] have recently also reviewed the enhancement of the performance of RO membranes through surface modification. They reported that the fact that membrane fouling has a strong dependence on membrane surface morphology and properties makes surface modification using physical and chemical methods a key tool to address membrane fouling. However, they also observed that surface modification has its demerits too such as the following: (i) it increases the membrane resistance, thus impeding permeation and reducing the water flux and (ii) the stability of surface modifiers during membrane cleaning and long-term operation has not been well studied. A study by Kochkodan and Hilal [56] evaluated the surface modification of polymeric membranes targeting the control of biofouling. The authors reported that generally high membrane hydrophilicity, smooth membrane surface, and the use of bactericidal or charged particles on the membrane surface result in a reduction in membrane biofouling. However, the challenge of developing membranes that can overcome the complexities of biofouling without having adverse effects still remains.

Therefore, understanding the mechanisms of fouling in membranes is paramount to develop the appropriate mitigation strategies. As an example, recently, Tow and colleagues [43] developed a fouling visualization apparatus to elucidate the mechanisms of organic fouling and cleaning in RO and FO processes. They identified one internal fouling mechanism that is unique to FO membranes based on vapor phase formation within the membrane. They further reported that although the use of feed spacers is advantageous in reducing the rate of fouling, it may also obstruct cleaning by preventing pieces of detached gel from flowing downstream.

5. Future perspectives

The performance of the FO process can be improved through its integration with other technologies to take advantage of the unique strengths of the individual processes. As an example, the FO-MD hybrid process has been employed for oily wastewater treatment [21]. The findings indicated that water recovery of greater than 90% was attained even at high salinities and also almost complete rejection of oil and sodium chloride. In another study [57], the FO-MD process was also applied for raw sewage; water recovery of 80% was achieved, and removal efficiency for trace organics was 91–98%. In addition, the use of FO-ED hybrid system for the treatment of secondary municipal wastewater resulted in treated water that met potable water standards (low concentration of TOC, carbonate, and low conductivity) [58]. Another promising hybrid process is the combination of FO and RO (FO-RO). Based on the unique advantages of RO and FO processes, it is important to exploit these to solve the challenges of wastewater remediation and even desalination. For instance, the potential of FO to reduce the

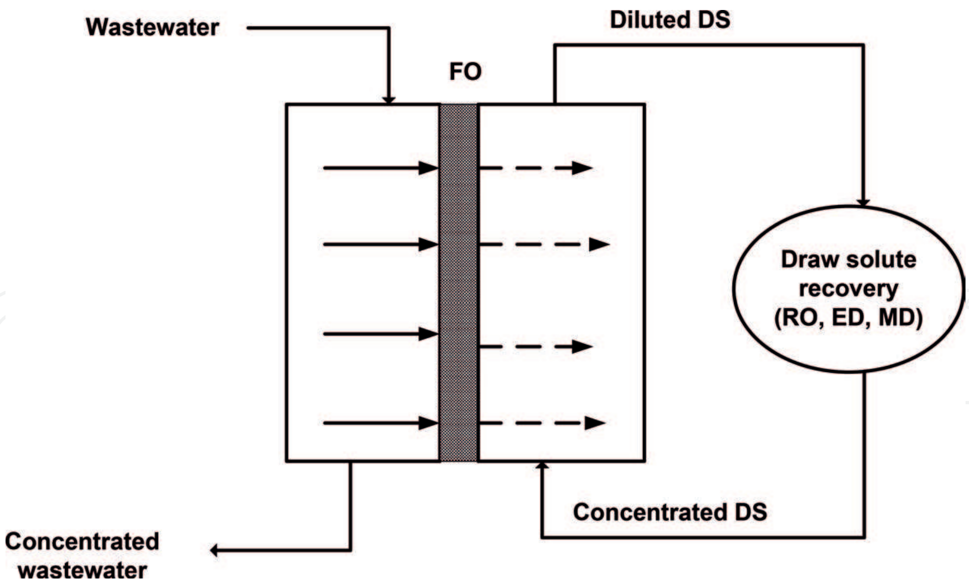

Figure 3. FO-based hybrid technologies (FO-MD, FO-RO, and FO-ED). Adapted from [63].

energy consumption of RO is very important. This can be done using an FO-RO hybrid process in which FO is implemented as a pretreatment step before RO. Furthermore, this FO-RO hybrid has the additional benefit of being a double-barrier protection leading to high-quality treated water [48]. Linares and coworkers [59] have recently shown that hybrid FO-RO systems are economically advantageous compared to other technologies for desalination or even wastewater treatment and recovery systems. Another integrated technology is the coupling of FO and microbial osmotic fuel cell (MOFC), which was performed by Werner and coworkers [60]. The key benefits reported were that the system could simultaneously treat wastewater treatment and desalinate seawater within the same reactor [60]. Furthermore, the integration of FO and conventional MBR can result in reduced energy consumption [61]. A coupled forward osmosis and microbial desalination cell (FO-MDC) was employed to simultaneously treat wastewater and desalinate seawater and the COD removals were satisfactory as well as high levels of desalination were achieved [62]. Therefore, these hybrid systems can greatly improve FO performance and increase its feasibility for commercial application. However, before the integrated processes can be implemented, there is a need for detailed studies on the energy consumption to determine their economic viability [34]. **Figure 3** shows a schematic representation of some of the FO-based hybrid technologies.

6. Conclusions

The review has provided insights into the use of forward osmosis either individually or in combination with other processes for wastewater treatment. Forward osmosis is gaining wide acceptability and application because of its unique advantages such as not requiring hydraulic pressure and less fouling propensity compared to conventional pressure-driven membrane processes. Inasmuch as the literature has indicated that the lack of hydraulic pressure in FO

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processes alters the extent of membrane fouling; further studies are required especially on how this influences the cleaning strategies to be adopted. Furthermore, it is necessary to develop new FO membranes taking into account the effect of the membranes on fouling and cleaning behavior. It is also imperative to explore the synergy in the use of multiple cleaning strategies such as a combination of osmotic backwashing and surface backwashing to further improve the performance of FO membrane.

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