Chapter

Forward Osmosis Membrane Technology in Wastewater Treatment

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Abstract

In recent times, membrane technology has proven to be a more favorable option in wastewater treatment processes. Membrane technologies are more advantageous than conventional technologies such as efficiency, space requirements, energy, quality of permeate, and technical skills requirements. The forward osmosis (FO) membrane process has been widely applied as one of the promising technologies in water and wastewater treatment. Forward osmosis uses the osmotic pressure difference induced by the solute concentration difference between the feed and draw solutions. The proces requires a semi-permeable membrane which has comparable rejection range in size of pollutants (1 nm and below). This chapter reviews the application of FO membrane process in wastewater treatment. It considers the advantages and the disadvantages of this process.

Keywords: Desalination, Forward osmosis, FO-Based Hybrid System, Integrated FO System, Wastewater, Wastewater treatment

1. Introduction

Membrane separation processes are widely used in the last decade for industrial, commercial, and domestic activities such as water and wastewater treatment, energy-efficiency. Within the concentration-driven processes, FO has gained increasing prominence due to its advantages such as possibility of low fouling, high salt rejection, and high water recovery. However, FO does have inherently disadvantages such as; reverse solute diffusion (RSD), lower flux, concentration polarization (CP), and membrane fouling. These obstacles oblige the developing new processes, synthesis of different membrane materials or modifications, and finding new draw solution (DS). There is therefore an exigent need to develop new FO membranes by optimization of thickness, porosity, tortuosity of active/support layer of FO membrane.

This chapter is divided into two parts. In this first part of chapter, basic principles of FO phenomenon, advantages and challenges of FO over conventional membrane processes are addressed by the literature review and scholarly articles. The second part of which states applications of FO process for wastewater remediation, and recent developments in FO process.

2. General aspects of forward osmosis

2.1 Process description

Forward osmosis is one example of water separation processes and a potential acceptable alternative/complement to reverse osmosis (RO) process for power generation, wastewater treatment and desalination. Forward osmosis is a membrane process in which requires little or no hydraulic pressure. Unlike the RO process, in the FO process, an osmotic pressure gradient through a semi-permeable membrane is the driving force of water transport from the feed solution (FS) to the DS [1]. Thus, the concentrated DS generates an osmotic pressure and drives water from the feed through the membrane while most of the contaminants and salts are rejected by the membrane, then separating the water from the diluted DS [2]. **Figure 1** illustrates the principle of operation of RO and FO processes.

The general equation used to describe theoretical water flux across the RO and FO membrane (*Jw*) is calculated using Darcy's law [1]:

$$Jw = Aw \times \left(\sigma \Delta \pi - \Delta P\right) \tag{1}$$

where, Aw is the membrane pure water permeability coefficient, σ is the reflection coefficient which indicates the rejection capability of a membrane (for a perfect semipermeable membrane $\sigma = 1$), $\Delta\pi$ is the osmotic pressure differential across the membrane, and ΔP is the applied external pressure. Therefore, in FO, ΔP is zero thus making the water flux to be directly proportional to the difference in osmotic pressure, while for RO, $\Delta P > \Delta\pi$. The relation between water flux and applied pressure is illustrated in **Figure 2**.

2.2 Draw solution

Both FO and RO processes involve semi-permeable membranes as key component, which has comparable rejection range in size of pollutants (1 nm and below). One of the major factors in the development of FO membrane is selecting an appropriate DS [4]. The ideal DS should have following characteristics: high osmotic pressure, low molecular weight (MW), non-toxicity, relatively low-cost, high water solubility, and efficiently regeneration [5, 6]. Sodium chloride (NaCl)

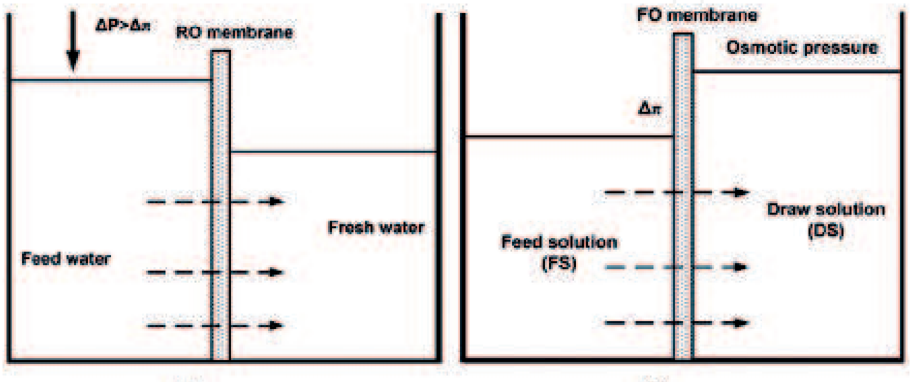

Figure 1.
Schematic illustration of the (a) RO, and (b) FO processes.

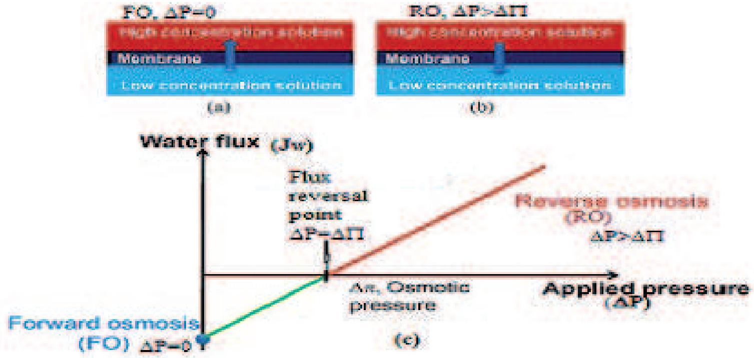

Figure 2.
Schematic representation of FO, RO process: (a) FO process where no external force is applied on the high concentration solution. The natural flow of water is from the low concentration side to the high concentration side; and (b) RO process where applied pressure on the high concentration solution exceeds the osmotic pressure difference across the membrane, so the water flux is opposite to the flux in FO process; and (c) classification of these processes in a water flux vs. applied pressure. Adapted from [3, 4].

is among the most commonly used draw solute in FO because it has highly water solubility and it is also relatively easy to reconcentrate using classical desalination processes [1]. In the past few decades, vast studies have been performed to determine desirable DSs, the different DSs are presented in **Table 1**, such as (1) inorganic compounds (e.g., NaCl, sodium nitrate ($NaNO_3$), magnesium sulfate ($MgSO_4$)) (2), organic compounds (e.g., glucose, fructose, 2-methylimidazole-based compounds) (3), functionalized nanoparticles (e.g., magnetic nanoparticles (MNPs)), Na^+-functionalized carbon quantum dots (Na-CQD).

The different DSs allow the generate of high osmotic pressure and can be easily regenerated or recovered. Nevertheless, their costs have not been successfully determined [39].

2.3 Membrane material

The identification of an ideal membrane in FO process is a key component which needs to be addressed to further advance this process. A perfect semipermeable membrane should have high water flux and solutes rejection, low propensity to fouling, and high chemical and thermal stability and so forth [2].

The FO membrane can be either synthetic or natural. In the early studies, the variety of natural materials used has included animal bladders and intestines [4]. A few decades ago, investigators have been examined different materials for FO membrane fabrication that include cellulose, rubber, and porcelain [4, 40, 41]. Although synthetic FO membranes have been currently commercially available; but this technology is still in its infancy. As a result, many types of FO membranes have been investigated that are able to perform well under a very wide range of applications [42–51]. **Table 2** provides information about membranes used in wastewater treatment.

As can be seen from **Table 2**, CTA-FO membranes have been used in the most of the experimental working on wastewater treatment due to its relatively higher tolerance to chlorine, insensitive to bio-degradation, and low fouling potential [66–68]. Despite its advantages, there are still some drawbacks such as narrow pH range, relatively low water permeability and high NaCl permeability [69–71]. Compared with CTA membranes, TFC membranes have higher fouling propensity, higher surface selectivity, a wider pH range, and better chemical stability [72–75]. Although CTA membranes have also a chlorine tolerance of up to 1 ppm (part per

Categories	Draw Solutes	Recovery Methods	Ref.
Inorganic compounds	NaCl	reverse osmosis (RO)	[7, 8]
	inorganic fertilizer	direct use	[9, 10]
	potassium sulfate (K_2SO_4)	RO	[7]
	sodium nitrate ($NaNO_3$)	direct use	[10]
	aluminum sulfate ($Al_2(SO_4)_3$)	precipitation	[11]
	magnesium sulfate ($MgSO_4$), copper sulfate ($CuSO_4$)	precipitation	[12, 13]
Organic compounds	glucose, fructose, sucrose	RO	[12, 14–17]
	2-Methylimidazole compounds	membrane distillation (MD)	[18]
	sodium polyacrylate (PAA-Na)	ultrafiltration (UF), MD	[19, 20]
	poly (aspartic acid sodium salt)	MD	[21]
	N,N-dimethylcyclohexylamine (N(Me)2Cy)	heating	[22]
	1--Cyclohexylpiperidine (CHP)	heating	[23]
	Micellar solution	UF	[24]
	oxalic acid complexes with Fe/Cr/Na	nanofiltration (NF)	[25]
	trimethylamine–carbon dioxide	heating	[26]
	CO2-responsive polymers (PDMAEMA)	UF	[27]
	poly(sodium styrene-4-sulfonate-co-N-isopropylacrylamide) (PSSS-PNIPAM)	MD	[28]
	Switchable polarity solvent (SPS)	RO	[29]
	polyelectrolyte incorporated with triton-x114	MD	[30]
	dimethyl ether	heating with solar energy	[31]
	poly(4-styrenesulfonic acid-co-maleic acid)	NF	[32]
Functional nanoparticles	Super hydrophilic nanoparticles	UF	[33]
	hydrophilic superparamagnetic nanoparticles	magnetic separation	[34]
	magnetic core-hydrophilic shell nanosphere	magnetic separation	[35]
	thermoresponsive Magnetic Nanoparticle	magnetic separation	[36]
	dextran-coated MNPs magnetic separation	magnetic separation	[37]
	hyperbranched polyglycerol coated MNPs	magnetic separation	[38]

Table 1.
Overview of the different DSs in FO process.

million), TFC membranes have limited tolerance to chlorine attack [76]. On the other hand, TFC membranes prone to membrane fouling which negatively impacts their operational and maintenance costs.

Feed	Membrane	Findings	Ref.
Wastewater containing heavy metals	Lab scale (thin film composite) TFC membrane	Synthetic, good flux in PRO mode only	[52]
Synthetic dye wastewater	Cellulose-acetate (CA) hollow fiber Lab Scale	High viscosity, synthetic.	[53]
Wastewater with sludge	Cellulose tri-acetate (CTA)-HTI	Phosphorous recovery from sludge.	[54]
Polyvinyl chloride (PVC) latex	CTA-HTI	No regeneration required.	[55]
Synthetic wastewater	CTA-HTI	No regeneration.	[56]
Synthetic wastewater	Flat sheet biomimetic membrane by aquaporin A/S	Microbial cells in DS can lead to biofouling. No regeneration required.	[56]
Biorefineries	Flat sheet biomimetic membrane by aquaporin A/S	DS can be toxic. No regeneration.	[57]
Textile wastewater	Biomimetic aquaporin A/S	High RSF for dye mixtures. No regeneration is required in case of dye mixture DS.	[58]
Printed circuit board (PCB) plant wastewater	TFC porifera	DS leads to inorganic scaling. No regeneration required.	[59]
Medical radioactive liquid wastewater	TFC polyamide (PA) membrane porifer	NaCl has a higher rejection for Iodine.	[60]
Synthetic wastewater & municipal treatment plans wastewater	CTA-HTI	Same flux for FO and FO$_w$EO (electrochemical oxidation).	[61]
Seawater	CTA-HTI	Feed flow rate of 2.9 L/min, No space and pretreatment.	[62]
Oily wastewater	Lab scale TFC-polyethersulfone (PES) membrane	In PRO mode oxalic acid had good flux.	[63]
Oily wastewater	TFC Cellulose acetat butyrate(CAB) holow fiber Lab scale	The experiment was done in the PRO mode. This membrane had excellent oil rejection.	[64]
Synthetic wastewater	TFC-ES HTI	Presence of cations in feed aggravates fouling in FO.	[65]

Table 2.
Some previous and recent researches on FO membranes.

In addition to fouling of membrane, concentration polarization has an impact on the water flux, particularly at the support layer, which leads to the severity in internal concentration polarization (ICP). A low ICP requires a low S-value (structural parameter) [43, 77].

The membrane structural parameter S is defined as [2]:

$$S = KxD = \frac{ts \text{ x } \text{Ʈ}}{\varepsilon} \tag{2}$$

where *D* is the diffusion coefficient of the draw solute, *ts* is the thickness of the support layer, Ʈ is the tortuosity, and ε is the porosity of the support layer.

Recently, new materials have been investigated for FO membrane fabrication to increase water flux, reduce ICP, and enhance the tolerance to water quality.

3. Application in wastewater treatment

As an emerging membrane technology, FO has been investigated over the last decade for seawater or brackish water desalination, wastewater treatment, power generation, pharmaceutical applications, and food&dairy processing in both academic research and industries [78, 79].

The most attractive usage of FO is its application for wastewater treatment. Consequently, there are two clusters of applications (i) desalination and (ii) water reuse (**Figure 3**) [80].

Key attributes of this process are:

- high rejection of a wide range of contaminants,
- lower energy consumption,
- high water recovery,
- lower brine discharge,
- lower membrane fouling propensity.

However, the main challenges in this process are related to:

- Development of high performance, such as higher permeate water flux and lower reverse salt flux of FO membranes,
- Reducing concentration polarization in membranes,
- Ensuring low DS reverse solute diffusion through the membrane,
- Adaptive reuse
- Regeneration of the DS.

3.1 Desalination

Saline water (e.g. seawater or brackish water) and an osmotic reagent (e.g. a non-volatile or a volatile salt) are used as the FS and DS, respectively, in the *direct FO desalination* [81, 82]. In this process, after the FO process, an additional step is needed to recycle the draw solutes as well as to produce purified water [83, 84]. One of the first examples of FO application in water desalination was published in 1975. This study was intended to desalinate Atlantic Ocean seawater to produce an emergency water supply on lifeboats by *direct* osmosis (**Figure 4**) across a CA-FO membrane with a hypertonic glucose solution as the DS [85]. In another study, a flat-sheet CTA-FO membrane was used in seawater desalination, yielding a high water flux and high salt rejection (over 95%) with 6 M ammonium bicarbonate (NH_4HCO_3) as DS [84]. Also, polymer hydrogels particles have been studied as draw agents in FO desalination. Smaller polymer hydrogel particles led to higher FO water flux in these tests. Similarly, higher salt concentration led to lower FO

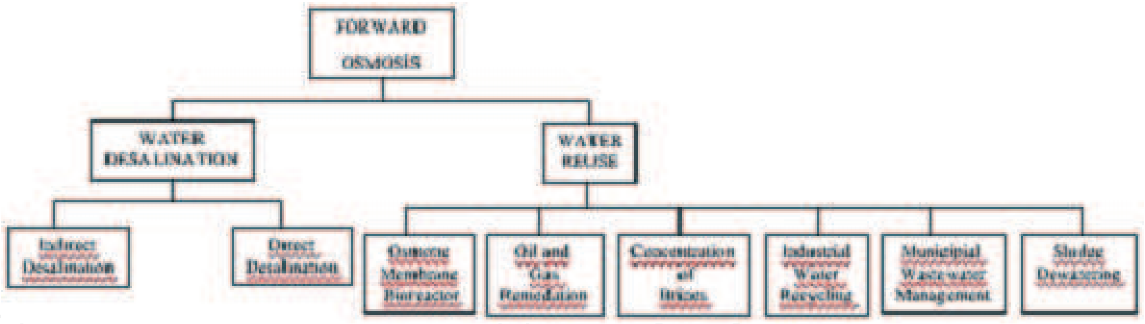

Figure 3.
Applications of FO in the water treatment industry.

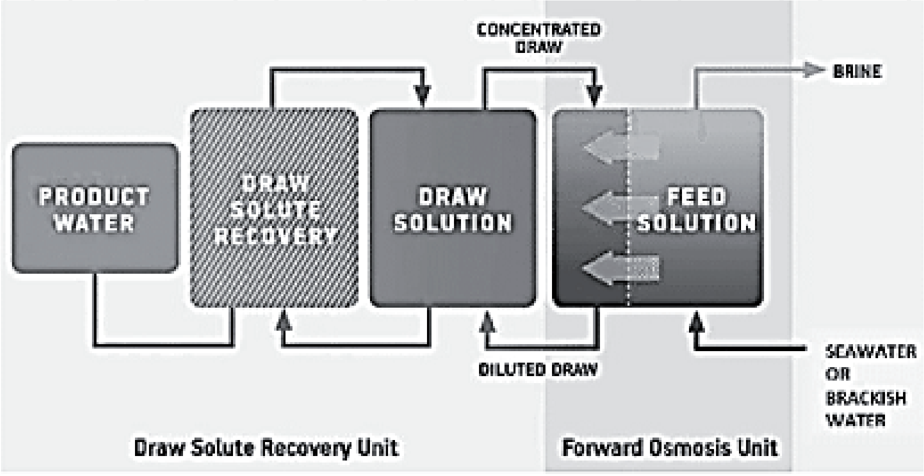

Figure 4.
FO process for desalination of seawater or brackish water.

water flux. Meanwhile, the use of a commercial FO membrane was more suitable than RO membrane [83]. Another study modified magnetic particles covered with thermo sensitive polymer investigated as DS and about 93% of salt recovery was obtained [34]. The world's first commercial forward osmosis desalination plant for direct sea water treatment was established in Al Najdah, Oman. This facility is still in operation and has reduced chemical consumption and provides higher throughput and longer membrane life, significant operational and capital costs and to be more reliable than traditional methods [86]. Membrane fouling and scaling problems at RO stage mitigate due to the use of FO as a pretreatment step for the RO process.

Indirect FO desalination uses a high salinity water (e.g. seawater or brackish water) as a natural DS and quality-impaired water source (e.g. wastewater effluent or urban storm water runoff) as the feed solution [87, 88]. The diluted seawater or brackish water can potentially couple with low pressure reverse osmosis (LPRO). The FO-LPRO hybrid process has lower costs for producing water compared to pure reverse osmosis [89]. These experiments have demonstrated the ability of FO membranes to reject nutrients from wastewater, especially chemical oxygen demand (COD) and phosphate, and moderately nitrogen compounds [88, 90]. As an example, a submerged membrane module which makes it possible to adapt the process to a primary clarifier tank has been employed for partial desalination of seawater. The findings indicated that FO membranes have high rejection of heavy metals present in the wastewater (~99%). This study also showed that the use of biopolymers-like substances resulted in the fouling layer on the membrane surface [88]. A similar result has been reported in the use of osmotic membrane bioreactor (OMBR) for municipal wastewater treatment [91].

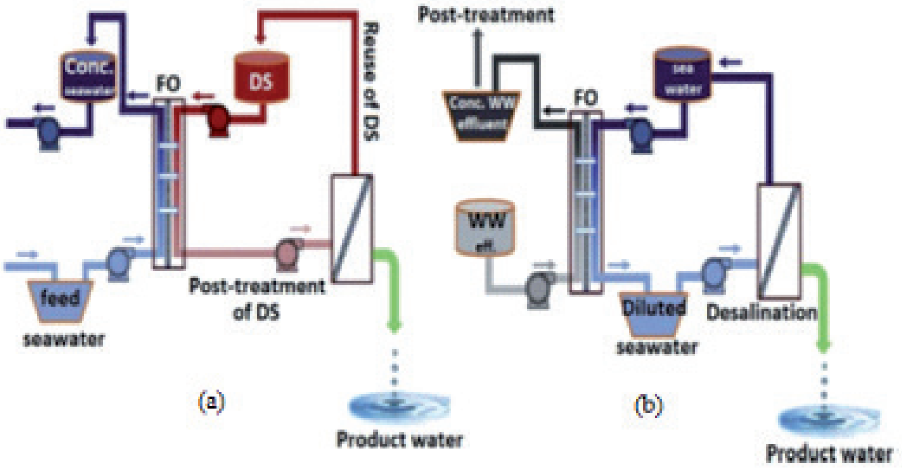

Figure 5.
Scheme of the two FO processes for desalination (a) direct, (b) indirect (adapted from [92]).

Direct and indirect arrangements of desalination systems using FO membrane are shown in **Figure 5**.

On the other hand, the pretreatment of wastewater has not yet been reported in the study of FO process. The reason, probably, is that the FO system is considered as a pre-treatment step to concentrate wastewater and then concentrated wastewater can be used to recover biogas or other valuable compounds [88, 93, 94].

3.2 Wastewater treatment

Forward osmosis has been utilized to treat various types of wastewater such as municipal wastewater (sewage) [95–98], oily wastewater [67, 99, 100], tanner effluent [101], automobile effluents [102], dairy streams [102, 103], produced water [104–106] besides synthetic wastewater [107, 108].

Lately, the current systems on FO application on wastewater treatment may be classified into two groups: FO and FO-based hybrid processes, and integrated FO processes. Both in FO and FO-based hybrid systems, the FO membrane is used to recover fresh water and reject of pollutants from the feed solution. In the integrated FO system, the FO membrane gradually replaces conventional membrane in the bioreactor, such as the FO membrane in membrane bioreactor (MBR). The function of the membrane is to concentrate the wastewater and improve the performance of the modified system.

Therefore, FO has been extensively applied in wastewater treatment and reuse, resource recovery, seawater desalination, and food/medicine manufacturing as shown in **Table 3**.

The FO process shows promising results for the treatment of wastewater, and has many advantages in comparison to the conventional wastewater treatment processes. When high process recoveries are obtained, FO processes become viable. Forward osmosis also provides a more sustainable flux and reliable removal of contaminants.

3.2.1 FO and FO-based hybrid system

Hybrid desalination systems using emerging FO process and combined with traditional process like reverse osmosis, membrane distillation, nanofiltration, electrodyalsis (ED) could potentially reduce the energy consumption of the desalination process, and decrease obstacles in the implementation of process. In these systems, FO is used as a pre-treatment step, while RO, NF, and ED are

Field		FS	DS	Process	Ref.
Wastewater treatment and reuse	Tannery wastewater	Tannery wastewater	NaCl solution	FO	[101]
	High-salinity oil-bearing wastewater	Oil-bearing wastewater	3 M NaCl	FO	[109]
	Oil sands tailings water	OSPW	Basal depressurization water	FO	[110]
Resource Recovery	P and N recovery from urine	Fresh urine	Mg-based fertilizer DS	FO	[111]
	Precious metal recovery	Pd ion waste solution	Electroless (E'less) nickel (Ni) waste solution	FO	[112]
	Energy recovery	algae culture wastewater	Seawater	FO	[113]
Seawater desalination	/	Wastewater	Seawater	FO + DS	[62]
Food and medicine manufacturing	/	Sugarcane juice	Sea bittern	FO	[114]
	/	Protein	Superabsorbent polymer(SAP) hydrogels	FO	[115]
	/	Medical radioactive liquid waste	NaCl	FO	[60]

Table 3.
Application of FO in different industries.

known as water recovery or draw solution regeneration/reconcentration step [116, 117]. An overview of FO and FO-based hybrid system configurations is depicted in **Table 4**.

3.2.1.1 Hybrid FO-MD system

The performance of the FO process can be improved by its combination with other system to take advantage of the unique strengths of the individual processes. For this reason, FO process is often combined with an MD process (**Figure 6**). As an example, the FO-MD hybrid system was employed for raw sewage [93] at water recovery up to 80%. This process also achieved high removal efficiency for trace organic contaminants (TrOCs) that rates 91–98%. In another study, this hybrid system was used for oily wastewater treatment. The findings indicated that 90% feed water recovery could be readily attained with trace amounts of oil and NaCl [99]. A vapor pressure driving FO-MD system was studied for treatment high salinity hazardous waste landfill leachate [129]. Total organic carbon (TOC) and total nitrogen (TN) rejection rates were higher than 98% while rejection rate of salt was higher than 96%. NH_4^+-N, and heavy metal ions were also completely removed. Similar performance could also be seen in the application of dairy wastewater and grain possessing wastewater treatment [103, 130].

Hybrid System	DS	FS	Ref.
FO	Fertilizer chemicals	Municipal wastewater	[9]
FO	3 M NaCl	Oil-bearing wastewater	[109]
FO	Basal depressurization water	OSPW	[110]
FO	10% NaCl	Coal gasification wastewater	[118]
FO-MD	$MgCl_2$	Digested sludge	[94]
	NaCl	Oily wastewater	[99]
	NaCl	Salinity landfill leachate	[129]
	$MgSO_4$	Dairy and grain wastewater	[130]
FO-RO	NaCl, Na_2SO_4, $MgSO_4$	Synthetic feed (NaCl); groundwater (Mawson Lakes, South Australia)	[116]
	NaCl, $MgCl_2$	Seawater (TDS = 32000–45000 mg/L)	[119]
	Red Sea seawater (TDS = 40.5 g/L)	Wastewater effluent (Al Ruwais wastewater treatment plant, Jeddah, Saudi Arabia)	[120]
	Seawater after UF	Coal-fired power plant wastewater	[121]
FO-NF	Na_2SO_4	Brackish water from Mawson Lakes, South Australia (TDS = 3970 mg/L)	[122]
	NaCl, KCl, $CaCl_2$, $MgCl_2$, $MgSO_4$, Na_2SO_4 and $C_6H_{12}O_6$	Simulated seawater (0.6 M NaCl)	[123]
	NaCl, $CaCl_2$, $MgSO_4$, Na_2SO_4	A site located in northwest Italy	[124]
	$MgCl_2$	Municipal wastewater	[108]
FDFO + ED	1 M DAP	Treated wastewater (secondary effluent)	[125]
FO + ED-RO	NaCl	Seawater	[126]
FO + ED	/	brackish and wastewater	[127]
FO + ED-RO	/	Seawater	[128]

Table 4.
An overview of FO and FO-based hybrid systems.

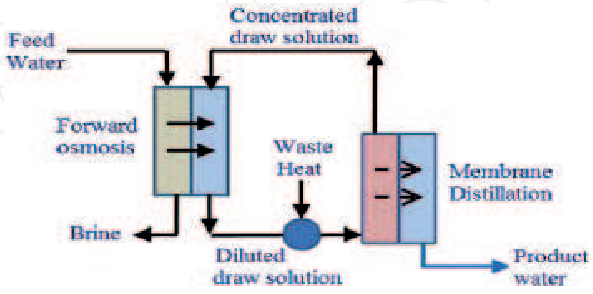

Figure 6.
Schematic diagram of hybrid system consisting of FO and MD processes.

3.2.1.2 Hybrid FO-RO system

Due to the current scenario of global water crisis, seawater desalination has become one of the practical solutions to produce water of potable quality. Membrane based desalination processes have been used to desalinate seawater have been widely reported. Among the various desalination processes, RO is the most consistent and reliable process which offers a number of advantages due to its high salt rejection rate, high quality drinking water, high water recovery, and green technology [131]. Despite the aforementioned advantages, several shortcomings, such as high energy consumption and severe fouling propensity remain the obstacles [132]. In recent years, the hybrid system of the FO and RO processes has gained increasing prominence among researchers [8, 116, 117, 119]. As can be seen in **Figure 7**, the hybrid system consists of two stages. The first stage begins with the migration of fresh water from the seawater feed solution to join the draw solution. In the second stage, the product fresh water is separated from the draw solution in the RO unit [89].

In the first study focusing on this FO-RO hybrid system, the authors demonstrated that the approach may provide four major benefits over stand-alone RO desalination: lower energy use, multi-barrier protection of drinking water, beneficial reuse of impaired water, reduction in RO membrane fouling [89]. Similar interest has also been conducted that compaires the hybrid FO-RO system and the stand-alone RO process for seawater desalination [119]. The study showed that the hybrid FO-RO system can be highly competitive depending on the salinity of seawater and type and concentration of the draw solute. Interestingly, total power consumption in a hybrid FO-RO system was higher than that in RO process, yet the FO process alone was only contributed 2–4% of the total power consumption in the FO-RO hybrid system. Therefore, most of the power consumption in the FO-RO system was realized in the high hydraulic pressure RO regeneration unit [119]. In another study, FO process used as a pre-treatment for a hybrid FO-RO desalination system. The optimal parameters such as water flux, water recovery and final draw solution of this FO pre-treatment process were determined by modeling and were experimentally validated by using real brackish water [116]. In a further study, FO-RO hybrid system for coal-fired power plant wastewater treatment, seawater after UF was investigated as DS. Results showed that the total energy consumption of the FO-RO system was 15% less than that of a typical seawater desalination RO [121].

3.2.1.3 Hybrid FO-NF system

The literature includes theoretical studies on the strengthening economic and environmental potential of the large-scale FO-based systems but very few experimental reports exist on these issues [133–135]. Examples include discussion on pilot-scale FO coupled with NF and other distillation processes for treating wastewater effluents. For example; a pilot-scale FO-NF hybrid closed loop system was developed for the treatment of tannery wastewater at a rate of 52–55 L/m^{2}h and rejections of 98.5% COD, 97.2% chlorides and 98.2% sulfate were achieved [136].

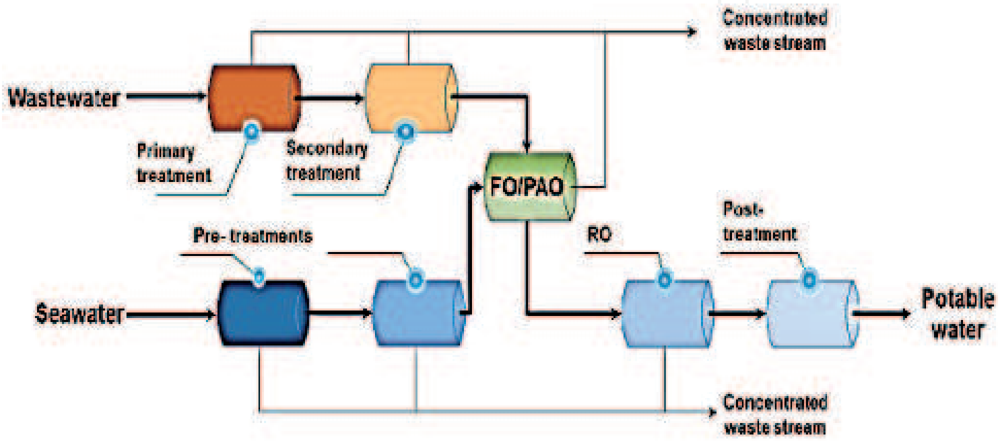

Figure 7.
Schematic diagram of the hybrid FO-RO system (adapted from [89]).

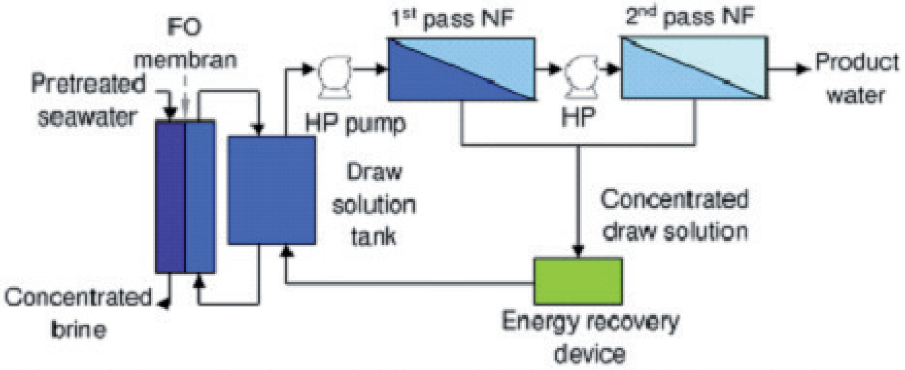

Figure 8.
Schematic diagram of the hybrid FO-NF system for seawater desalination (adapted from [137]).

In addition, a hybrid FO–NF system designed for brackish water desalination was investigated and also presented promising results such as lower hydraulic pressure, less flux decline [122]. In another study, a hybrid FO-NF system with two NF passes for the post treatment was used for desalinating seawater [123]. A proposed configuration of a hybrid FO-NF process for seawater desalination is shown in **Figure 8** [137].

3.2.1.4 Hybrid FO-ED System

Electrodyalsis is a membrane-based separation process in which ions across ion-selective membranes under an electric field. A FO-ED hybrid system was investigated by using diammonium phosphate (DAP), as DS to achieve wastewater reuse and mitigation of salinity buildup on the feed side. Electrodyalsis was able to significantly recover the 96.6 ± 3.0% reverse-fluxed DAP under 3.0 V 1-h daily operation [125]. Forward osmosis process was tested upstream to ED-RO system for an access to DS with higher electrical conductivity in the FO-ED-RO hybrid system [126]. In another study, FO-ED-RO hybrid system proposed to produce high-quality water from secondary-effluent or brackish water is shown in **Figure 9**. Results showed that the water from this system contains a low concentration of total organic carbon (TOC), carbonate and cations derived from the feed water [127].

3.2.2 Integrated FO system

The integrated FO system includes an osmotic microbial fuel cell (OsMFC) and osmotic membrane bioreactor (OMBR). Recent research has elucidated how

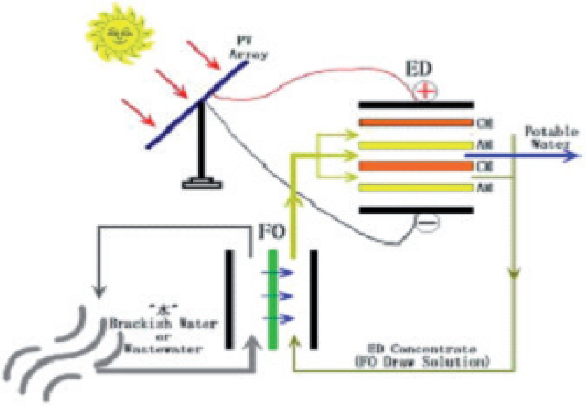

Figure 9.
Schematic diagram of a novel photovoltaic powered FO-ED system (adapted from [127]).

the integration of osmosis in MFC and MBR was used through the application of FO membrane for simultaneous recovery of osmotic water, the concentration of wastewater, and the improvement of effluent quality [138, 139].

3.2.2.1 OsMFC

The system uses FO integrated into a microbial fuel cell (MFC) to improve the quality of the treated wastewater and the performance of the fuel cell. A FO membrane is placed between the anode chamber with wastewater and the cathode chamber full of DS and water flux through this membrane transports protons from the anode to the cathode [140–145]. An OsMFC (**Figure 8**) achieved water flux of 3.94 ± 0.22 L/m^{2}h with a catholyte containing 2 M NaCl, while there was no obvious water flux in a conventional MFC [140]. In a further study, FO membrane is integrated into an air-cathode MFC (AAFO-MFC) for enhancing bio-electricity and water recovery from low-strength wastewater. The AAFO-MFC system produced a high quality effluent, with the removal rates of organic contaminants and total phosphorus (P) of more than 97% [145].

There are also some drawbacks for OsMFC application in wastewater treatment such as the lower water flux of the FO membrane, membrane fouling and salt accumulation (**Figure 10**) [146].

3.2.2.2 OMBR

Hollow fiber or flat-sheet MF and UF membranes are commonly used membranes in MBR. A major problem associated with the operation of MF-UF-MBRs is membrane fouling. A novel MBR-named OMBR- has been developed and widely used to reduce fouling and promote the reuse of treated wastewater. In OMBR, FO membrane module is displaced in the wastewater. A combination biological treatment and an OMBR uses to remove water from the mixed liquor to the draw side under the osmotic pressure gradient. The pollutants, activated sludge and solids are all rejected by the membrane. The OMBR-based hybrid system, for the first time, was utilized to direct recovery nutrient from municipal wastewater with over 90% of nutrient. In this study, nutrient and mineral salts were rejected via FO membrane and enriched within the bioreactor and then recovered by chemical precipitation [147]. The OMBR has several advantages, including higher rejection rate, lower energy consumption, and higher quality of treated wastewater compared to the traditional MBR. However, OMBR still has some disadvantages, such as salinity accumulation and membrane fouling. Based on the OMBR hybrid system, an integrated UF or MF membrane system in the OMBR system was investigated to remove the soluble inorganic salts in the reactor [148]. This process has a longer sludge

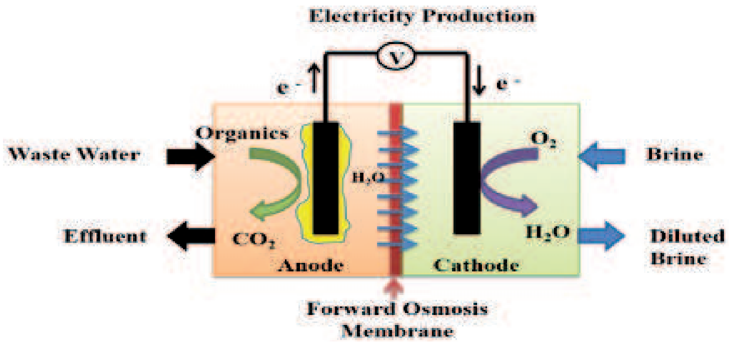

Figure 10.
Schematic diagram of an OsMFC (adapted from [140]).

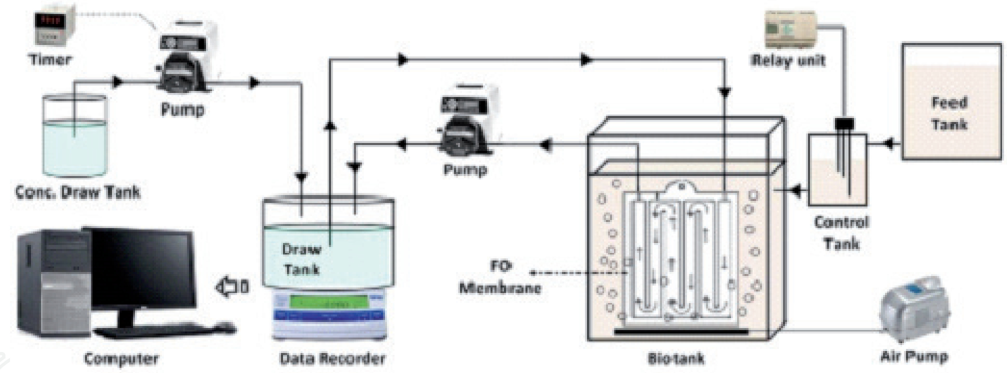

Figure 11.
Schematic diagram of an OMBR (adapted from [150]).

residence time (SRT) than the traditional OMBR system, so a higher sludge concentration can be obtained. Similarly, MF membrane was added to the system for phosphate recovery from the raw sewage, in which MF and FO membranes function in parallel. The results show that the phosphate can be recycled up to 98%. The MF membrane retained phosphate and mineral salts in the bioreactor, so phosphate was precipitated as calcium phosphate precipitates without the input of Ca^{2+} ions. [149]. In another study, the OMBR system was operated in treating of Chromium (Cr) and Lead (Pb) metals of the high strength wastewater. The findings revealed that industrial wastewater containing more than 5 mg/L of Cr and more than 2 mg/L of Pb is not recommended for the OMBR due to poor sludge characteristics, and high membrane fouling (**Figure 11**) [150].

4. Conclusions

The FO membrane process is a promising process for drinking water purification and wastewater treatment technology due to its excellent high rejection rate performance and relatively low membrane fouling characteristics. Hence it is likely to gain an very important place in the membrane technology.

The engineering of the FO process application is relatively scarce, due to the FO investigations and applications are still in the laboratory scale and progress in practical applications still requires further proof of the pilot. The research on membrane fouling mechanism is also needed, which still has a large gap in the current research results. Over the past decade, a large number of research papers has been published on membrane development (to increase water flux) and process design (i.e., to increase osmotic pressure, to change sludge retention time) and the number of papers in these issues has also increased year by year. The researchers' focus is to develop next-generation membranes by advanced membrane fabrication methods as well as hybrid systems where the FO process can really add value.

This chapter focuses mainly on forward osmosis either individually or in combination with other processes for wastewater treatment. For example; the FO removes the large molecular weight trace organic compounds while the combination of the MBR and NF/RO process for removing TrOCs from synthetic wastewater is feasible. The key concepts mentioned in the chapter provide better understanding for further promoting the utilization of FO process and its new applications for water resource recovery and wastewater treatment development.

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