

EMPLOYING FORWARD OSMOSIS TECHNOLOGY THROUGH HYBRID SYSTEM CONFIGURATIONS FOR THE PRODUCTION OF POTABLE/PURE WATER: A REVIEW

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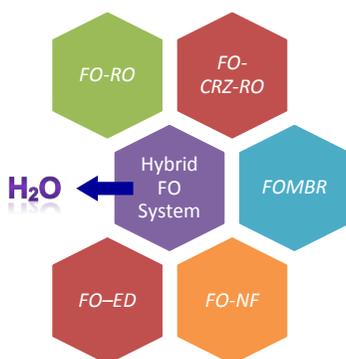
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Graphical abstract



Abstract

Forward osmosis (FO) technology has received increasing attention from many researchers since the last decade. It is an osmotically driven membrane process in which water migrates across a semi-permeable membrane from a lower osmotic pressure feed solution to a higher osmotic pressure draw solution. FO technology is often applied as a hybrid system rather than a standalone process. The purpose of this paper is to review the different types of hybrid system configurations employing FO technology for the production of potable/pure water. The integration of FO technology with other processes which include reverse osmosis, crystallisation, membrane bioreactor, nanofiltration, and electrodialysis are presented and described in-depth. With the flourishing of various FO hybrid system configurations, it is believed that FO technology will play a vital role in the water processing industry.

Keywords: Forward osmosis, hybrid system configuration, water, osmotic pressure

Abstrak

Teknologi osmosis hadapan (FO) telah mendapat perhatian yang semakin meningkat daripada ramai penyelidik sejak dekad yang lepas. Ia merupakan proses dorongan osmotik membran di mana air berpindah melalui membran separa telap dari larutan input bertekanan osmotik yang lebih rendah kepada larutan penarik bertekanan osmotik yang lebih tinggi. Teknologi FO sering diaplikasikan sebagai sistem hibrid dibandingkan sebagai proses tunggal. Penulisan ini bertujuan untuk menyemak pelbagai jenis konfigurasi sistem hibrid yang menggunakan teknologi FO untuk penghasilan air minum/tulen. Integrasi teknologi FO bersama proses yang lain termasuk osmosis songsang, penghabluran, bioreaktor membran, nanofiltrasi, dan elektrodialisis telah dibentangkan dan diuraikan dengan mendalam. Dengan kepelbagaian konfigurasi sistem hibrid FO yang semakin berkembang, teknologi FO dipercayai akan memainkan peranan penting di dalam industri pemprosesan air.

Kata kunci: Osmosis hadapan, konfigurasi sistem hibrid, air, tekanan osmotik

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1.0 INTRODUCTION

1.1 Forward Osmosis - An Emerging Membrane Technology

Forward osmosis (FO), also known as direct osmosis (DO), is an osmotic process in which water migrates across a semi-permeable membrane from a lower osmotic pressure feed solution to a higher osmotic pressure draw solution [1]. Being an emerging membrane technology, FO has received significant attention from many researchers in the last decade. Surprisingly, FO is not a new technology. It has been applied as early as 1970s for seawater desalination [2–4]. Other early applications include the concentration of fruit juices and liquid foods in the food industry [5–8]. The early year's publications hadn't attracted much attention on FO technology. The researchers only became aware of the potential of FO process when a paper presenting comprehensive overview of FO process and its latest developments was published in 2006 by Cath *et al.* [1], which has received vast citations [9]. Today, the potential applications of FO have been widely studied and extended to various disciplines including seawater desalination [10–15], water and wastewater treatment [1, 16], food processing [17–19], power generation [20, 21], and many other applications. FO is capable of performing both enrichment and dilution operations in a single step process. For instance, in some applications (i.e. wastewater treatment, food processing), the product solution (feed stream) needs to be concentrated/enriched, whereas in other applications (i.e. seawater desalination), the product solution (draw stream) needs to be diluted (as a pre-treatment process).

In recent years, many efforts have been made in proposing various technologies for the production of potable water owing to water scarcity and increasing demand of clean water [22–25]. Seawater desalination has become an alternative to secure freshwater supply since seawater accounts for approximately 97% of the overall global water [26]. Several studies have suggested that zero liquid discharge (ZLD) or reduction of solution volume in brackish water or wastewater provides great benefit to the environment and becomes an added highlight to membrane technology [27, 28]. Being an osmotic driven membrane process, FO has emerged as one of the potential technologies for seawater desalination and potable water production [11]. This paper aims to review the different types of potential hybrid system configurations employing FO technology. The review begins with a brief description of the basic principle of FO process. Next, the production of potable water through FO hybrid system is discussed. At least five types of potential hybrid system configurations are presented and described in-depth. The review ends with a discussion

on future potential research and challenges in this area.

1.2 The Basic Principle and Advantages of Forward Osmosis

FO is an osmotic process that utilises the natural phenomenon of osmosis [29]. A typical bench-scale FO system configuration consists of an FO module and other easily assembled instruments such as peristaltic pump, solution reservoir, and water bath. Semi-permeable membrane is inserted between the compartments, separating the feed solution and the draw solution. At the beginning of the FO process, the osmotic pressure gradient between the two compartments is highest, and results in a large flow of water molecules across the membrane. As the process continues, the feed solution becomes concentrated, whereas the draw solution becomes diluted. The migration of water molecules causes changes in the water level in both compartments. The water level in the feed solution compartment is reduced, making it more concentrated. At the same time, the draw solution is being diluted by the increased water level accordingly. Since the migration of water molecule is driven by the osmotic pressure driving force, it can be said that FO does not require any external energy input for the process to occur, but instead the energy required by the process is supplied by the osmotic pressure gradient due to the selected draw solution. Hence, the types and concentration of the draw solution is vital in the FO process.

FO has advantages when compared to other membrane separation processes. Unlike conventional pressure-driven and thermal-driven processes, such as reverse osmosis or other distillation technologies, FO operates at very low hydraulic pressures and ambient temperature, which significantly reduce capital costs as a result of the lower energy consumption [13, 30–32]. FO is also favoured for its low membrane fouling propensity compared to pressure-driven membrane processes, allowing the proper separation and concentration of difficult feed solution such as waste streams. In FO, water molecules selectively pass through a semi-permeable membrane via osmotic pressure difference into a more concentrated stream, thus avoiding membrane fouling and compaction [33]. Loose and lower compaction of the foulant layer on the FO membrane could be easily removed [33–38]. Lee *et al.*, (2010) compared the fouling behaviours in FO and reverse osmosis (RO) modes, and reported that the foulant layer formed on the FO membrane surface is considered reversible and can be removed by simple physical cleaning, whereas the densely and higher compaction of the foulant layer formed on the RO membrane may require chemical cleaning methods [33]. Hence, it is expected that the lifespan of the membrane used for the FO process is longer compared to the membrane process that utilises hydraulic pressure such as RO. Nevertheless,

there are increasing interests in studying the fouling mechanism of the FO process [39]. Membrane rejection is also an important factor in evaluating the FO performance. Typically, feed solutions such as wastewater or seawater consist of a variety of dissolved solutes and contaminants; however, most of the dissolved solutes can be effectively rejected using the FO process [40, 41]. These advantages have drawn great attention to the FO process, making it a great potential technology.

FO is commonly found in hybrid system configuration depending on the applications and purposes. In order to eliminate the disposal of diluted draw solution, the standalone FO process is usually associated with other processes for the regeneration of draw solution. Additionally, the integration of FO with other regeneration process can eliminate the cost for draw solution replenishment. Nevertheless, the regeneration step has been a great challenge to FO technology. Inappropriate selection of regeneration method may place FO technology at a significant energetic disadvantage and reduce its attractiveness. Interestingly, some researchers have initiated the exploration of novel draw solution which eliminates the regeneration step. Phuntsho *et al.*, (2011) has highlighted a novel concept of desalination process involving an integration of FO process and fertigation system, for which the diluted draw solution (fertiliser) could be directly applied for fertigation, eliminating the separation and regeneration of draw solution [42].

Majority of the literature studies of FO have been focused on desalination or water production [26,43]. The FO process was used as a pre-treatment unit to improve the quality of the feed solution going into the RO process by reducing the salinity and contaminants of the solution depending on the type of source solution [43–46]. In addition, the pre-treated feed solution that contains fewer dissolved constituents and fouling materials would significantly reduce the membrane fouling propensity during the RO process. The energy saving could also be further enhanced in an integrated configuration when FO is coupled with pressure-driven processes, such as RO or nanofiltration (NF) processes, due to the reduction of feed solution salinity, thereby causing lower hydraulic pressure during operation [45]. Other advantages include volume reduction of the impaired solution and the lower salinity of the discharged brine solution, both of which could reduce the environmental impact [45, 47].

2.0 FORWARD OSMOSIS AS A HYBRID SYSTEM CONFIGURATION

Over the last decade, there has been growing interest in the exploration of FO technology since commercial FO membranes have become available [13]. FO hybrid system configuration is the combination of FO technology with other existing

processes including various membrane processes, which are also known as integrated systems. Many attempts have been proposed which involve the integration of FO technology with other processes such as RO, crystallisation, membrane bioreactor, NF, and electrodialysis (ED). A hybrid system configuration should contain more than one system unit in the entire downstream system. In this section, flow diagrams that illustrate a variety of FO hybrid system configurations are presented and described in-depth. In some of the literatures, FO is claimed to be a pre-treatment process [41, 48]. RO, ED, and NF are also known as water recovery or draw solution regeneration/reconcentration step in the FO-RO, FO-ED, and FO-NF systems, respectively. An overview of the various FO hybrid system configurations is depicted in Table 1. By presenting at least five types of potential hybrid system configurations in the production of potable/pure water, we foresee huge potential and recurring interest in FO technology over the coming decades.

2.1 Hybrid Forward Osmosis – Reverse Osmosis (FO-RO) Configuration

As the demand of clean water is increasing and water scarcity is observed, seawater desalination has become one of the practical solutions in producing high quality potable water. Membrane based seawater or brackish water desalination processes have been widely reported. Among the various desalination technologies, RO remains an attractive alternative which offers a number of advantages such as high water recovery, high salt rejection, high quality drinking water, and clean technology [49–51]. Despite all of the aforementioned advantages, limitations such as energy consumption and membrane fouling propensity remain the obstacles [12, 33, 52, 53]. In the last few years, the hybrid system of the FO and RO processes, namely the FO-RO configuration, has attracted growing interest among researchers [41, 48, 54–56]. The hybrid system configuration consists of two stages. In the first stage, the fresh water migrates from the seawater feed solution to join the draw solution. In the second stage, the fresh water is separated from the draw solution in the RO unit. Recently, Altaee *et al.*, (2014) performed a comparison between the hybrid FO-RO process and the standalone RO process for seawater desalination as a continuation of previous works [55]. Comparisons were made using the developed RO and FO software models to obtain simulated results [15, 57]. The study showed that the hybrid FO-RO configuration could be very competitive depending on the salinity of seawater and selection of the draw solute. Interestingly, higher total power consumption was exhibited by a hybrid FO-RO process compared to the RO process, yet the FO process only contributed 2% to 4% of the total power consumption in the FO-RO system. Higher total power consumption in the hybrid FO-RO configuration was due to the high hydraulic pressure RO unit [55].

Table 1 Overview of FO hybrid system configurations for the production of potable/pure water

Hybrid System	Feed Solution	Draw Solution	Ref.
FO-RO	Seawater (TDS = 32000 - 45000 mg/L)	NaCl, MgCl ₂	[55]
	Wastewater effluent (Al Ruwais wastewater treatment plant, Jeddah, Saudi Arabia)	Red Sea seawater (TDS = 40.5 g/L)	[56]
	Synthetic feed (NaCl); groundwater (Mawson Lakes, South Australia)	NaCl, Na ₂ SO ₄ , MgSO ₄	[41]
FO-CRZ-RO	Seawater	(NH ₄) ₂ C ₂ O ₄ , NH ₄ AlSO ₄ ·12H ₂ O, NaIO ₄ , Na ₃ PO ₄ , Na ₂ SO ₄	[58]
FOMBR	Synthetic wastewater (meat extract, C ₆ H ₁₂ O ₆ , (NH ₄) ₂ SO ₄ , and K ₂ HPO ₄); wastewater (Truckee Meadows Water Reclamation Facility, Reno, Nevada)	NaCl	[16]
	Synthetic domestic sewage (glucose, sodium acetate, meat extract, peptone, KH ₂ PO ₄ , MgSO ₄ ·7H ₂ O, FeCl ₃ , NH ₄ Cl)	NaCl	[63]
FO-NF	Brackish water from Mawson Lakes, South Australia (TDS = 3970 mg/L)	Na ₂ SO ₄	[32]
	Simulated seawater (0.6 M NaCl)	NaCl, KCl, CaCl ₂ , MgCl ₂ , MgSO ₄ , Na ₂ SO ₄ and C ₆ H ₁₂ O ₆	[68]
FO-ED	Secondary wastewater effluent (wastewater treatment plant, Aquafin, Flanders, Belgium), synthetic brackish water (NaCl, NaHCO ₃ , MgSO ₄ , CaCl ₂)	NaCl	[70]

Similar interest has also been shown by Yangali-Quintanilla *et al.*, 2011 [56]. Yangali-Quintanilla *et al.*, (2011) conducted experimental work for desalination

using secondary wastewater effluent without pre-treatment as the feed solution and real Red Sea seawater as the draw solution [56]. Comparing a high pressure RO desalination system, the FO coupling with a low pressure RO (net driving pressure of 15 bar) was found to be more energy efficient. The energy consumption was estimated to be between 1.3 and 1.5 kWh/m³ using a hybrid FO-RO system [56], which is much lower than the energy consumption in a standalone RO process (2.5-4 kWh/m³), as reported in other literature [49]. Zaviska and Lou (2014) developed models specifically used to describe the FO process as a pre-treatment process for a hybrid FO-RO desalination system [41]. Optimisations of parameters such as water flux and water recovery of the FO process were made possible using the developed empirical models, and experimental results were used for validating the predicted values.

2.2 Hybrid Forward Osmosis – Crystallisation – Reverse Osmosis (FO-CRZ-RO) Configuration

Kim *et al.*, (2013) recently proposed an integrated process for seawater desalination known as the hybrid forward osmosis/crystallisation/reverse osmosis (FO-CRZ-RO) process [58]. The proposed hybrid system was aimed to reduce the energy consumption for seawater desalination. As can be seen in Figure 1, the proposed system consists of three major units employing the FO, crystallisation and RO process. The hybrid process begins with the migration of fresh water causing the seawater to become concentrated. The diluted draw solution stream was then flowed into the crystallisation unit operating below ambient temperature. Draw solute in the draw solution was cooled and precipitated via the crystallisation process, thus further diluting the remaining draw solution. The remaining solution with lower osmotic pressure was fed to the RO unit for regeneration of draw solution and fresh water production.

In comparison with the hybrid FO-RO system, as discussed earlier [55, 59, 60], the integration of crystallisation into the system configuration could be seen as an improvement alternative for reducing the energy consumption in the hybrid system [58]. The precipitation of draw solute in the solution during the crystallisation stage reduced the osmotic pressure of the draw solution making it much lower than the seawater feed. As a result, the energy consumption relating to the operational hydraulic pressure could be reduced by the low osmotic pressure feed (output stream of crystallizer) of the RO unit. Nevertheless, this work did not quantify the cost of investment for the crystallisation unit. Five inorganic draw solutes (ammonium oxalate, ammonium aluminium sulphate, sodium periodate, sodium phosphate, and sodium sulphate) were selected for the comparative evaluation of the performance in terms of energy efficiency. The overall energy consumption, including the energy required for the cooling process during crystallisation and high

hydraulic pressures during the RO process were obtained. The energy requirement of 2.15 kWh/m³ was calculated for the hybrid FO-CRZ-RO desalination system employing sodium periodate draw solute [58]; however, a much lower energy consumption of 1.3 to 1.5 kWh/m³ had been reported using hybrid FO-RO system [56].

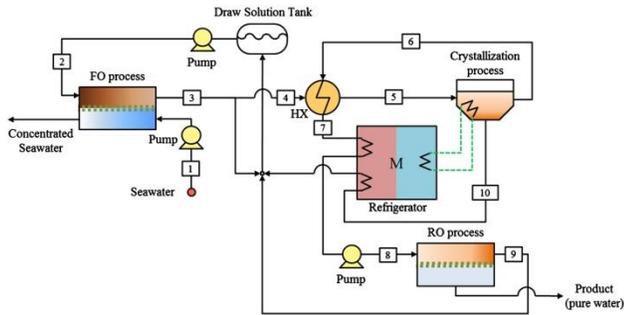


Figure 1 Schematic diagram of the proposed hybrid process consisting of FO, crystallisation and RO units [58]

2.3 Hybrid Forward Osmosis Membrane Bioreactor (FOMBR) Configuration

Hybrid forward osmosis membrane bioreactor (FOMBR), which is also known as osmotic membrane bioreactor (OMBR), is an integration process of FO and activated sludge processes for the production of high quality potable water [16, 34, 61, 62]. The membrane bioreactor (MBR) has been used to integrate the conventional biological treatment, clarification and filtration process with membrane separation processes such as microfiltration (MF) or ultrafiltration (UF) [16, 37]. Although the use of wastewater in MBR has lower osmotic pressure compared to the seawater feed, there is some concern regarding the higher membrane fouling propensity [13]. The integration of FO technology into the conventional MBR has added attractions; the osmotic pressure, as the driving force for the FO process, reduces the membrane fouling propensity, while contaminants from the wastewater feed are highly rejected [16, 34, 60]. Hence, FO is also seen as the pre-treatment process in the hybrid FOMBR system [13, 34].

Achilli *et al.*, (2009) investigated the feasibility of a hybrid OMBR system for wastewater treatment [16]. Figure 2 shows the schematic diagram of the hybrid system configuration that consists of a submerged FOMBR and RO unit (post-treatment) for the recovery of purified water. Synthetic wastewater consisting of 5 g/L meat extract, 1 g/L C₆H₁₂O₆, 0.6 g/L (NH₄)₂SO₄, and 0.14 g/L K₂HPO₄ was fed into the bioreactor as the feed solution, whereas NaCl was used as the draw solution. The FO unit was immersed into the bioreactor and an aerator was installed at the bottom. Aeration and homogenisation was constantly maintained in the FOMBR via agitation. Water molecules migrated from the synthetic feed

solution in the bioreactor to the NaCl draw solution and the diluted NaCl solution was subsequently fed into the RO unit for reconcentration and the generation of high quality water. The FOMBR has showed high removal efficiencies on organic carbon (99.8%) and ammonium-nitrogen (97.7%). Similar high removal efficiencies were recorded for the entire hybrid system (FOMBR and RO). Compared with the conventional MBR system using UF and MF, FO offers higher feed solute rejection and lower membrane fouling due to the lower hydraulic pressure employed [16].

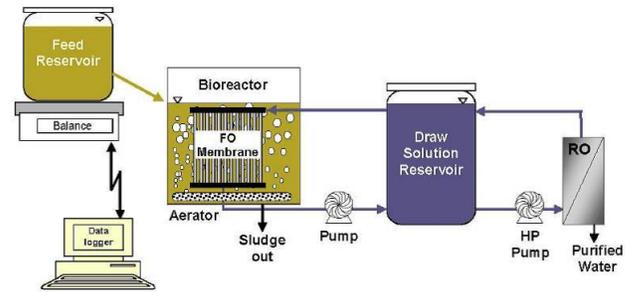


Figure 2 Schematic diagram of the hybrid FOMBR or OMBR system for the production of potable water [16]

Lay *et al.*, (2011) investigated the long-term operation of OMBR system, which there is still very little knowledge on the feasibility of this hybrid system for pilot scale application [63]. A dual-track hybrid system configuration that consists of two FOMBR submerged bioreactors was employed for the long-term operation investigation of 73 days. Synthetic feed solution and NaCl draw solution were used in the study. Despite the elevated salinity, the result indicated a slight decrease of water flux from 3.2 L/m².h to 2.7 L/m².h in the first 15 days and was maintained at a relatively stable level until day 73. Encouragingly, mild membrane fouling was reported [63]. Qin *et al.*, (2009) conducted an optimisation study for an FO pilot system as a baseline study for FOMBR [61]. Unlike the submerged FOMBR design that was employed by Achilli *et al.*, 2009 [16], Zhang *et al.*, (2012) used a separate external FO unit and bioreactor in their hybrid FOMBR system [64]. Two partial least squares (PLS) models were developed to predict the flux decline rate in different activated sludge properties. The flux decline rates could be accurately performed by the models using parameters such as initial flux of the draw solution, solute and bound polysaccharides in the activated sludge, and relative hydrophobicity (%). During the FO process, the migration of water molecules from the feed solution to the draw solution increases the salt accumulation in the bioreactor and might affect the physical and biological activities in the bioreactor [62]. With regard to that, Xiao *et al.*, (2011) developed a model to study the salt accumulation behaviour in OMBR and its effect on FO performance [65]. Bench scale FO experiments were conducted to

validate the salt accumulation model and the model was subsequently used for an OMBR performance study.

2.4 Hybrid Forward Osmosis – Nanofiltration (FO-NF) Configuration

Nanofiltration (NF) is a relatively lower pressure driven membrane process in comparison with RO. The coupling of FO technology with NF for different purposes has been reported [32, 66, 67]. Instead of using the FO-RO configuration, as proposed in majority studies [32, 41, 55, 56], a desalination of brackish water using a hybrid FO-NF system configuration was performed by Zhao *et al.*, 2012 [32]. A schematic diagram of the hybrid FO-NF system is illustrated in Figure 3. Real brackish water from Mawson Lakes, South Australia was used as the feed solution without any pre-treatment and divalent inorganic solute (Na_2SO_4) was used as draw solution. In the hybrid FO-NF system, the water molecules were initially drawn from the brackish water feed solution to the Na_2SO_4 draw solution in the FO unit. Potable water was produced and collected at the permeate of the NF unit. NF membrane has high rejection for divalent ions, hence divalent inorganic solute such as sulphate could be a suitable draw solute because it can be rejected effectively by the membrane [26,32,68]. Comparisons of performance efficiency between the hybrid FO-NF system configuration, and standalone RO (and NF) for brackish water desalination processes was shown by Zhao *et al.*, 2012 [32]. Several noticeable outcomes were highlighted. Greater fluxes decline were observed for the standalone RO indicating more pronounced membrane fouling propensity. Additionally, a much higher operational hydraulic pressure was required for the RO system. As for the standalone NF, lower salt rejection was obtained for brackish water feed with total dissolved solids (TDS) of the final permeate as high as 2530 mg/L. On the other hand, the hybrid FO-NF system could achieve higher water quality attributed to the additional barrier protection offered by the FO unit [32]. Tan *et al.*, (2010) proposed a similar hybrid FO-NF system that consists of dual-stage NF process for better water quality production [68]. Interestingly, high solute rejection (FO membrane) exceeding 99.4% was attained for all the selected draw solutes. It is noteworthy that good quality potable water with TDS of 113.6 mg/L was obtained, which is lower than the World Health Organisation drinking water guideline (500 mg/L) for TDS [68].

At present, RO technology remained an established industrial practice for desalination process, attributed to its reliability and efficiency [32, 69]. However, alternative methods such as hybrid FO-NF system are continuously being discovered and studied. The real interest of employing NF water recovery in the hybrid process is to reduce the costs relating to both operational hydraulic pressure and

membrane fouling propensity in the RO desalination process.

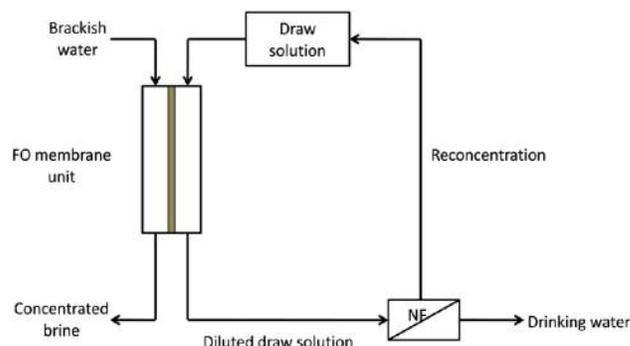


Figure 3 Schematic diagram of the hybrid FO-NF system configuration for desalination process. Real brackish water from Mawson Lakes, South Australia was fed in as feed solution [32]

2.5 Hybrid Forward Osmosis – Electrodialysis (FO-ED) Configuration

In the aforementioned sections, most researchers have shown great interest in integrating pressure-driven membrane processes such as RO or NF with FO technology for the production of potable water [32, 41, 48, 54–56, 58,59]. An interesting hybrid configuration system combining FO and ED, was proposed by Zhang *et al.*, 2013 [70]. Unlike the pressure driven membrane processes, ED is an electrochemical separation process in which electrically charged membranes are used to separate ions from an electrolyte solution or to concentrate this solution under the driving force of an electrical potential difference [71–73]. The principle of ED is the combination of dialysis and electrolysis and is based on the properties of ion exchange membranes to selectively reject anions or cations.

A hybrid configuration of novel photovoltaic powered FO-ED system used to produce potable water from secondary wastewater effluent or brackish water is shown in Figure 4 [70]. In the first stage of the FO system, NaCl was used as the draw solution to draw water molecules from the wastewater or brackish water feed solution. The diluted NaCl solution was then fed into the solar energy driven ED system to produce high quality potable water. The ED stack consists of several cell pairs, ion exchange membranes, and compartments. When diluted NaCl solution was fed into these compartments, the ions that could pass through the membranes were retained in the next compartment since the next membrane in its path would be of the opposite charge. As a result, diluate and concentrate streams can be obtained in the stack. The desired product contained less than 10 mmol L^{-1} NaCl , which met the target for potable water quality; this was collected in the diluate stream, whereas the

concentrated stream of regenerated draw solution was recycled back to the draw solution compartment in the FO system [70]. Similar to the hybrid FO-RO and FO-NF configurations, the FO-ED system enabled the production of water and regeneration of the draw solution simultaneously. Unlike the conventional ED process, the hybrid system was combined with the abundant readily available solar resources as the driving force for the ED process. A similar combination of hybrid membrane processes with renewable energy has also been used by other researchers [74–78]. Economic analysis study was performed for a small-sized potable water production system taking into the consideration of electricity generation for 4 solar panels, irradiation period, annual production period, membrane (FO and ion exchange membranes) area and lifespan. The production cost estimation of 3.32 to 4.92 EUR m⁻³ was obtained for 300 days of annual production [70].

Comparing the desalination process involving RO or NF water recovery process, no hydraulic pressure supply is needed for the photovoltaic powered FO-ED system. It must be noted that despite being photovoltaic driven, it does not shift the energy required, it only shifts the source of energy. The membrane fouling propensity of ion exchange membrane need to be further investigated and compared to the NF or RO membrane, and correlated with the water recovery cost. Some drawbacks of the ED process for desalination purposes have also been raised. The principle of the ED process is based on the migration and separation of ions or charge compounds in the solution; hence, it can only remove salts or charged organic compounds, and most of the uncharged compounds remain in the water [70, 79, 80]. In view of that, hybrid FO-ED system can be an alternative for existing processes, with selective source of feed solution.

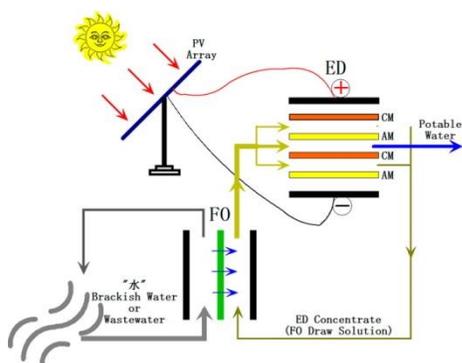


Figure 4 Schematic diagram of a novel photovoltaic powered FO-ED configuration for the production of potable water [70]

3.0 FUTURE POTENTIAL AND CHALLENGES

Different types of FO hybrid system configurations have been presented and thoroughly discussed. The

literature studies showed that FO has to be integrated with the other separation processes in order to produce potable water. In spite of the recent advancements in FO technology, a number of technical barriers have impeded the growth and commercialisation of FO technology.

With regard to the energy consumption, we know that the standalone FO process does not consume too much electricity. When FO is integrated with other processes, the energy consumption might be increased or reduced, depending on configuration of the hybrid process. Comparisons are often made between the FO and RO desalination processes [81–83]. The fact that the FO process uses solely high salinity draw solution as the driving force of the separation process instead of high hydraulic pressure in the RO process does not entirely explain the energy consumption of the system. The osmotic water transport across the semi-permeable membrane should be mixed with the draw solution in the FO process. As a consequence, a hybrid FO configuration is needed to further recover pure water. Without proper addressing the recovery of water from diluted draw solution, it places the FO desalination process at a significant energetic disadvantage compared to the standalone RO desalination process. On the other hand, some researchers have shown interest in integrating the FO process with the RO desalination process in the FO-RO hybrid configuration. Comparisons were made between the standalone RO process with an FO-RO configuration in terms of energy efficiency and confusing, contradictory results have been reported by researchers [45, 55, 56]. Van der Bruggen *et al.*, (2015) argued that the estimation of energy consumption should be based on pilot plant operation instead of small laboratory scale experiments [9]. This indicates that thorough economic analysis study is needed to further clarify the performance of the process. Some of the influencing factors such as feed solution resources, the selection of draw solute, operating conditions, and purity of the water produced are reasonable considerations that need to be included. Alternatively, other integrated processes such as FO-ED, FOMBR and FO-NF can also be used for desalination processes. At present, there is a lack of comparative studies among the FO hybrid processes as well as other existing desalination technologies; therefore, it is a great challenge for FO to be selected as the favourable desalination technology.

Another cost factor comes from the choice of draw solute. The selection of draw solute remains one of the major challenges facing development of the FO technology. Draw solution plays a substantial role in the FO process and the inappropriate selection of draw solute can have a large impact on its performance. Numerous characteristics have been found to influence the performance of draw solution, including osmotic pressure, molecular weight, solubility, viscosity, diffusivity, stability, toxicity, and concentration of the draw solution [84]. Other

considerations such as type of feed solution and membrane properties in an FO process also affect the selection of a draw solute. Due to these varieties and conflicting criteria, the selection of a suitable draw solute has become a difficult task. Things are even more complicated, as a selected draw solute might be technically feasible, but economically unviable due to energy considerations. In the last decade, many researchers have proposed numerous novel draw solutions including valuable findings regarding their performances. However, very few studies have focused on the regeneration of draw solution, particularly the comparison of different types of regeneration method. The recovery and regeneration of draw solution has been a major factor and probably comprises a large part of the operating costs of a hybrid FO process. The regeneration process should not be energy intensive, otherwise the hybrid FO process will lose its attractiveness. Among the available regeneration methods, RO has been the common method used by most researchers due to high water recovery and rejection efficiency. Nevertheless, high operating pressure requirement of RO is not economically feasible. On the other hand, UF regeneration seems to be more feasible as it requires a low operating pressure. However, there are concerns regarding the rejection efficiency, as UF membranes consist of larger pore sizes (>10 nm). Membrane distillation regeneration is a thermally driven separation process with high water recovery and good quality water, but high operating costs are also a concern. NF regeneration appears to be a promising method with high water recovery and multivalent ion rejection, and a relatively lower operating pressure is required [85]. We also note that hybrid FO system configuration coupling with renewable energy could be another possible future trend. Renewable energies such as solar, wind, wave, and hydrostatic pressure energy could be economically feasible as well as environmentally attractive [76]. For example, the hybrid FO–solar system configuration could eliminate the energy intensive regeneration step, whereas the integrated FO–ED–solar system configuration could reduce the energy consumption of an ED process [70, 78].

FO has been regarded as a clean water and clean energy membrane technology in numerous article publications [11]. At present, most of the FO applications are focused on desalination of seawater/brackish water attributed to water scarcity concern. Hence, FO is often denoted as a desalination technology. However, this is somehow misleading considering FO technology is mainly used for the concentration and dilution process [9]. Comparing the RO desalination process, the product of FO process is not a pure water ready stream. A second stage of separation process must be employed to produce pure water from the diluted draw solution stream. Apparently, the potential of FO technology is further extended though hybrid system configuration. In the previous section, we discussed

some of the advantages and attractiveness of FO technology through hybrid system configuration. One noticeable advantage is that FO is favoured for its low membrane fouling propensity as compared to other conventional pressure-driven membrane processes. In addition, the use of FO coupled with the RO process can improve the quality of feed into the RO unit, thereby reducing the membrane fouling propensity in the RO system and enabling higher water recovery. Nevertheless, the development of an effective FO membrane might be another challenge for FO, as has been thoroughly reviewed by Chung *et al.*, 2012 [11]. The energy analysis of FO technology such as FO-RO as mentioned earlier does not consider the essential of its application (such as higher product purity, which eventually results in higher profit), which can potentially outweigh the energy consumption of the entire hybrid system [45]. Overall, the development of FO hybrid system configuration should be in accordance with the selection of an appropriate draw solute and membrane development. Other aspects such as cost efficiency, energy consumption, and environmental impact are also crucial for sustainable development of FO technology.

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