quarterly journal of new horizons in chemistry

Online ISSN: 1159-2783

https://science-journals.ir , https://onsh.science-journals.ir

Evaluation of forward osmosis properties and benefits

Akram Shabani[1], Fereshteh Ashena[1]

1Master of Science in Chemical-Polymer Engineering

Abstract

Forward osmosis (FO) has been extensively investigated in the past decade. Despite significant advancements in our understanding of the FO process, questions and challenges remain regarding the energy efficiency and current state of the technology. Here, we critically review several key aspects of the FO process, focusing on energy efficiency, membrane properties, draw solutes, fouling reversibility, and effective applications of this emerging technology. We analyze the energy efficiency of the process, disprove the common misguided notion that FO is a low energy process, and highlight the potential use of low-cost energy sources. We address the key necessary membrane properties for FO, stressing the importance of the structural parameter, reverse solute flux selectivity, and the constraints imposed by the permeability–selectivity tradeoff. We then dispel the notion that draw solution regeneration can use negligible energy, highlighting the beneficial qualities of small inorganic and thermo lytic salts as draw solutes. We further discuss the fouling propensity of FO, emphasizing the fouling reversibility of FO compared to reverse osmosis (RO) and the prospects of FO in treating high fouling potential feed waters. Lastly, we discuss applications where FO outperforms other desalination technologies and

emphasize that the FO process is not intended to replace RO, but rather is to be used to process feed waters that cannot be treated by RO.

Key words: Forward osmosis, FO process, reverse osmosis (RO), Desalination.

1- Introduction

Forward osmosis (FO), an emerging separation/desalination process, has received increased attention in the past decade in both academic research and industrial development (Cath et al, 2006). In FO, a semipermeable membrane is placed between two solutions of different concentrations: a concentrated draw solution and a more dilute feed solution. By using the osmotic pressure difference to drive the permeation of water across the membrane, FO can address several shortcomings of hydraulic pressure-driven membrane processes, such as reverse osmosis (RO).

Early studies focused on various potential applications of FO in the food, water, and energy sectors (Zhao et al, 2012). The introduction of the ammonia– carbon dioxide FO process in 2005 as a potential desalination process that utilizes low-grade thermal energy has stimulated academic and industrial interest in FO, which resulted in a dramatic increase in the number of research articles and patents in subsequent years (Klaysom et al, 2013). These studies on FO involved membrane development, mass transfer analysis (McCutcheon et AL, 2005), membrane characterization (Tirafferi et al, 2013), fouling phenomena, and introduction and characterization of new draw solutions (Achilli et al, 2010). Concurrently, conceptual and bench-scale studies on various potential applications of FO have been published, including the use of FO coupled with a draw solution separation/regeneration stage (Zhao et al, 2012), FO in osmotic dilution processes (Hoover et al, 2011), and various hybrid systems incorporating FO (Wang et al, 2011).

Despite the recent advancements in FO, there remain several challenges to overcome for successful implementation of the technology. Moreover, confusion exists regarding the energy consumption by the FO process, triggered by misguided studies defining FO as a “low energy process.” Other studies present FO as an alternative to RO, a robust pressure-driven membrane desalination process. While several review articles on FO have been published recently (Klaysom et al, 2013), none has critically addressed the energy efficiency of FO, the viability of the technology, and the applications where FO has clear advantages over conventional desalination processes. A review that analyzes these key points as well as other enabling aspects of FO is crucially needed. In this review article, we critically discuss the energy efficiency, membrane performance, optimal draw solutes, and suitable applications of FO. Specifically, we address the following key questions: Is FO a low energy process? What are the key required membrane properties for FO? Is finding a magic draw solution the Holy Grail in FO? Is FO a low fouling process? Where does FO outperform other desalination technologies? Addressing these questions and understanding the limits of FO will provide vital information to further advance the technology and expand the range of its applications.

2- Desalination/Concentration

To produce desalinated water using a forward osmosis process, there is always at least two steps (the first is FO) with the second step to separate the draw solution/osmotic agent to provide the desalinated water, as simply illustrated in Figure 1. The subsequent step or steps are dependent on the nature and type of draw solution used. It has been suggested that this may involve precipitation, thermal breakdown, membrane separation or magnetism for example. This basic process scheme may also be used for dewatering and/or concentration of the feed water stream without phase change, so to think of it as just a desalination process is somewhat restrictive.

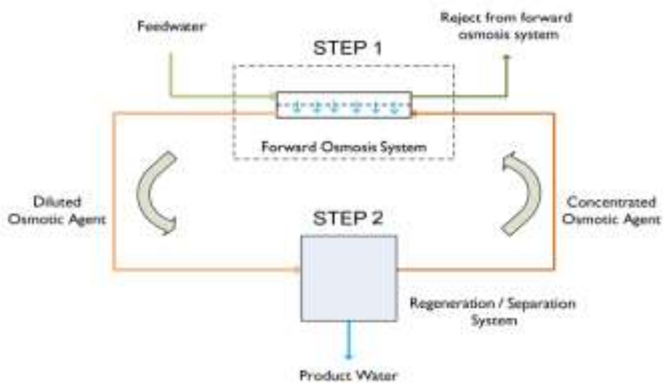

Figure 1: Simplistic desalination or dewatering / concentration process

Volume2, Issue1, Spring 2021, PP 1 - 16

3- Cooling tower make-up water

Evaporative cooling requires significant amounts of good quality water to replace the water lost by evaporation drift and blow down. This water may be provided by conventional desalination processes or by the use of tertiary treated sewage effluent, in particular in the Middle East region and India. This process effectively changes the recirculating feed water into a draw solution, so that the make-up water is drawn across a forward osmosis membrane. As there is contamination of the draw solution from ions transferred across the forward osmosis membranes and from possible contaminants in the air, a blow down recovery system is employed to retain the draw solution but remove contaminate species such as monovalent ions. Nicolle et al. describe the development and testing of this system (Zhang et al, 2010), where it is also claimed that the draw solution kills Legionella pneumophila, yet the draw solution was nontoxic.

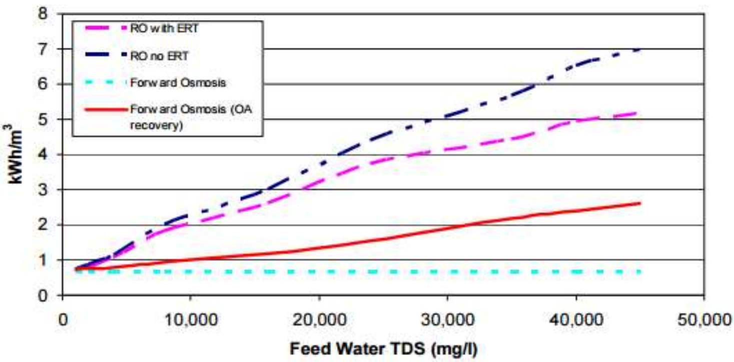

Figure 2: Power consumption of FO relative to RO. Adapted from (Zhang et al, 2010)

4- Emergency Drinks

FO can be used to make a sugar drink from a seawater, brackish or impaired water source and is one of the few current commercial applications of FO, which was originally developed for the US military. A sugar solution is contained within a bag (Figure 3) acts as a semipermeable FO membrane. In this way when the bag is immersed in an aqueous solution, water gradually flows through the membrane to dilute the drink, which can then be consumed. The process can take a long time, for instance 10 to 12 hours (Phuntsho et al, 2011) for personal use and as such a number of these pouches need to deploy to provide a continuous source of water. Larger systems using a replaceable draw solution have also been used in disaster relief situations.

Figure 3: Osmotic hydration bag before use

5- Is forward osmosis a low energy process?

The fact that water in FO permeates spontaneously through a semipermeable membrane does not mean that FO is more energy efficient as a separation process than other membrane processes. In fact, FO is not only a separation process, but is simultaneously a separation and mixing process. The water molecules that transport across the membrane from a salty feed solution mix with the draw solution to reduce its chemical potential. In order to obtain fresh water as a product, further separation of the diluted draw solution is required subsequent to the FO process. Based on thermodynamic principles and practical kinetic requirements, the theoretical minimal energy for desalination with FO is always higher than that without FO. In other words, using FO cannot reduce the minimum energy of separation.

This general conclusion regarding the FO desalination energy has fundamental underlying thermodynamic rationales. In an isothermal separation process, energy is required to reduce the entropy of the system (Mistry et al, 2011). However, the spontaneity of the FO process implies that entropy is generated and that the system entropy of the intermediate state (i.e. when draw solution is diluted and feed solution is concentrated) is higher than that of the initial state. Regardless of the process used, separation of the feed solution to the same degree should result in identical system entropy in the final state. Therefore, the minimum energy for the post-FO separation stage, which is required to reduce the system entropy from the intermediate to the final state, is obviously higher than the minimum energy for a standalone separation, which is required to reduce the system entropy only from the initial to the final state. To further elucidate this qualitative argument, an analysis is conducted in Section 2 to compare the minimum energy requirement of a standalone RO process to that of an FO–RO hybrid process.

6- FO–RO consumes more electric energy than RO alone

For comparison of overall energy consumption between an RO process and an FO–RO process, it is a reasonable approximation to consider only the energy required for the RO separation. This approximation assumes that the energy requirement in RO for generating the hydraulic pressure to overcome the osmotic pressure difference between the concentrated and dilute solutions dominates the overall energy consumption, rendering the energy for flow circulation and other practical considerations in the RO and FO systems relatively insignificant (semiat, 2008). Therefore, comparing the energy consumption of a standalone RO system and a hybrid FO–RO system can be approximately reduced to the comparison between the energy consumption of the RO stages in these respective systems.

We now compare the energy consumption between a standalone RO process (denoted as RO1 in Fig. 4A) and an FO–RO process (denoted as FO–RO2 in Fig. 4A). In the RO1 process, the feed solution is separated into the brine solution (the red block in Fig. 4A) and the permeate solution (the blue block). In the FO process, water molecules in the feed solution migrate across the semipermeable membrane to mix with the draw solution (the green block), resulting in the diluted draw solution (the blue and green composite block) and the same brine solution as in RO1. The diluted draw solution is then separated by the RO2 process to produce a permeate solution of the same volume as in the RO1 process.

D.L. Shaffer et al. / Desalination xxx (2014) xxx–xxx

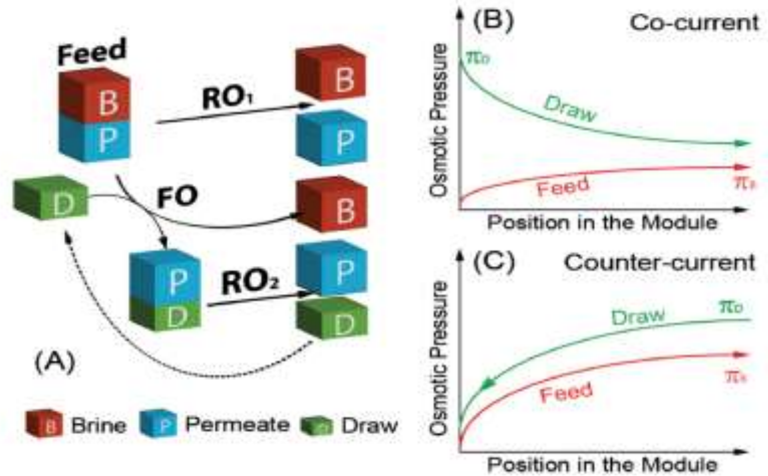

Fig 4. (A) A schematic comparison of a reverse osmosis (RO) process (RO1) with a hybrid forward osmosis and reverse osmosis (FO–RO) process (FO–RO2). The blocks with letters B, P, and D represent the brine, permeate, and draw solutions, respectively. The composite block with both B and P represents the feed solution for both systems, while the block with P and D indicates the diluted draw solution that needs further separation by RO2. The size of the blocks is proportional to the solution volume. Both the RO1 and the FO–RO2 systems lead to the exact same separation of the feed solution with identical recovery. (B, C) Qualitative illustration of the osmotic pressures of the feed and draw solutions in FO in a co-current flow module (B) and in a counter-current flow module (C).

7- FO fouling is highly reversible and low fouling process

7- FO fouling is highly reversible and low fouling process

Fouling involves the deposition and adsorption of feed water constituents, such as organic and inorganic compounds, colloidal particles, and microbes, to the membrane surface. As water permeates the semipermeable membrane, foul ants in the feed solution accumulate on the membrane surface, forming a cake layer, which creates hydraulic resistance and cake-enhanced concentration polarization that reduce the net driving force for permeation (Lee et al, 2010). Fouling deteriorates membrane performance and decreases membrane lifespan, both of which increase operating costs for membrane desalination (Misdan et al, 2012).

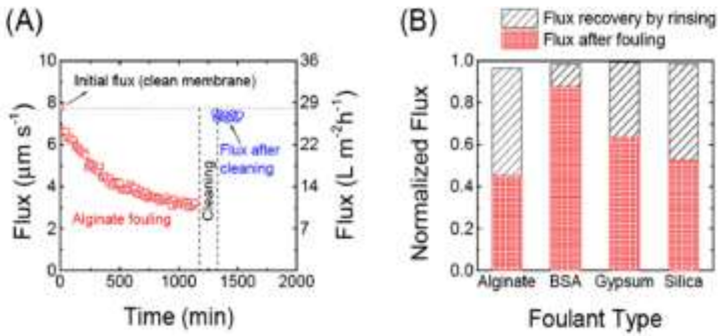

Fig. 5. (A) Water flux decline during a forward osmosis (FO) fouling run with a model organic foulant (alginate) (red squares). Fouling solution (pH 5.8) consisted of 200 mg L−1 of alginate, 50 mM sodium chloride, and 0.5 mM calcium chloride. Fouling run was conducted with a cellulose triacetate FO membrane (Hydration Technology Innovations) at an initial water flux of 27 L m−2 h−1, with a cross-flow velocity of 8.5 cm s−1, and at a temperature of 25.5 °C. Cleaning was performed by rinsing with a 50 mM sodium chloride solution at high cross-flow velocity (21 cm s−1) for 15 min. Data from Mi and Elimelech. (B) Flux recovery with different types of organic and inorganic foulants: alginate and bovine serum albumin (BSA) as model organic foulants, and silica and gypsum as model sealants. Data sources: alginate fouling, silica scaling, and gypsum scaling. BSA results are based on unpublished data of Mi and Elimelech.

Recent studies indicate that FO is a low fouling process because the foulant layer formed in FO is structurally different from fouling in pressure-driven membrane processes (Wang et al, 2011). The structure of the cake layer formed during RO is densely compacted, whereas the cake layer in FO is thicker but much less compact (Lee et al, 2010). Because of the loosely-packed fouling layer, FO can recover as much as 80–100% of the initial water flux through periodic rinses to clean the membrane surface (Kim et al, 2014). In comparison, RO fouling is mostly irreversible without chemical cleaning (Lee et al, 2010).

Fig. 4A demonstrates how simple rinsing at a high cross-flow velocity with a low ionic strength solution accomplishes complete removal of an alginate fouling layer from an FO membrane (Mi et al, 2010). Reversibility is illustrated by the recovery of the water flux after rinsing (blue circles) to the initial water flux prior to fouling (red squares). Such high reversibility is similarly observed with scaling by gypsum (Mi et al, 2010) and silica (Mi et al, 2013), and fouling by proteins (Fig. 4B).

8- Membrane surface properties are important for fouling control

Fouling propensity in FO is dictated by hydrodynamic operation conditions, as discussed in Section 5.1, and also by the affinity between foulants and the membrane surface (Elimelech et al, 2011). As such, a fouling-resistant FO membrane is characterized by an inert surface chemistry to prevent attracting foulants and a smooth surface topography that impedes foulant entrapment. Membranes utilized thus far in FO have predominantly been either asymmetric cellulose triacetate (CTA) or polyamide thin film composites (TFC). Although organic fouling of FO has been a prevalent topic in recent publications, the vast majority of the fouling studies were conducted with CTA membranes (Loeb et al, 1997) because no TFC-FO membranes were commercially available until recently. As discussed in Section 3, TFC membranes are the current state-of-the-art for FO because they exhibit a higher water permeability and salt rejection than CTA membranes (Cath et al, 2006). Thus, there is a critical need for systematic research on the fouling resistance of TFC-FO membranes, which are inherently prone to fouling because of their high surface roughness, relative hydrophobicity, and the presence of carboxyl groups on the membrane surface (Phuntsho et al, 2011). In the few studies on FO fouling that have used TFC membranes, efforts have focused on surface modification of the membrane active layer to mitigate their fouling propensity (Lu et al, 2013). A common method to impart antifouling properties is by grafting hydrophilic polymers, such as poly(ethylene glycol) (PEG), to the membrane active layer to create a polymer brush, which acts as a steric barrier to the adsorption of foulants (Morra et al, 2000: Lu et al, 2013). These modified membranes exhibit a significant decrease in water contact angle and reduced foulant–membrane adhesion forces, indicating an increase in fouling resistance. However, this improvement in fouling resistance is achieved at the cost of reduced water permeability that is attributed to the hydraulic resistance of the grafted polymer layer (Lu et al, 2013).

In organic fouling tests, FO membranes modified with PEG demonstrated reduced flux decline due to organic fouling and were capable of recovering 100% of the initial water flux after rinsing, as illustrated in Fig.5 (Lu et al, 2013). As such, surface modification reduces the propensity for membrane fouling and improves the reversibility of fouling, thereby enabling the treatment of high fouling potential feed waters by FO. A review on surface modifications for antifouling membranes can be found elsewhere (Rana and Matsuura, 2010).

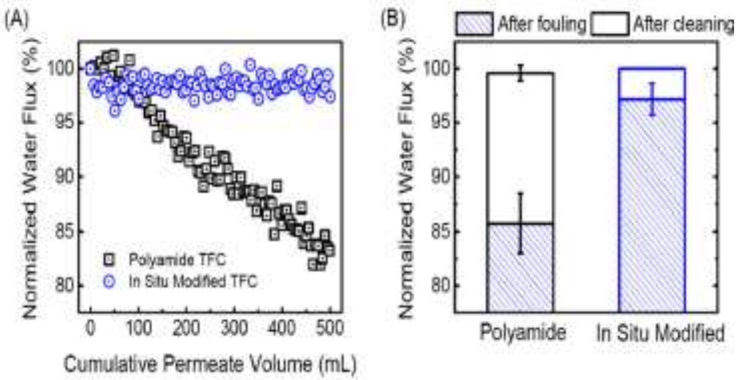

Fig. 6. (A) Representative fouling curves for a control forward osmosis (FO) polyamide thin-film composite (TFC) membrane and membrane modified in situ with poly (ethylene glycol). Fouling conditions were as follows: synthetic secondary wastewater effluent solution (pH 7.4) supplemented with 250 mg L−1 alginate as model organic foulant, initial permeate water flux of ~20 L m−2 h−1 , and cross-flow velocities of 8.5 cm s−1 for the feed and draw solutions. After the fouling run, the system was cleaned by circulating 15 mM sodium chloride solution for 15 min at a cross-flow velocity of 21.4 cm s−1 through the feed and draw solution channels. (B) Water flux decline and water flux recovery results for triplicate FO organic fouling experiments with control polyamide (black) and poly(ethylene glycol) in situ modified (blue) membranes. The percentage of water flux recovered after the physical cleaning step is shown as blank columns. Data from Lu et al. (Lu et al, 2013).

9- Conclusion

Through simple thermodynamic arguments, we have shown that FO cannot reduce the minimum energy required for desalination, regardless of the type of draw solution used. An FO–RO desalination system cannot consume less energy than a standalone RO system to achieve a certain recovery. However, FO hybrid systems can outperform other desalination technologies when they are applied to the desalination of high-salinity feed waters using thermo lytic draw solutions to consume less total energy for separation. One apparent advantage of the FO process is the relatively lower fouling propensity and higher fouling reversibility compared to RO. A thermodynamic energy analysis of the FO–RO process does not capture this important benefit of FO, which can potentially outweigh the energetic costs of using FO in hybrid systems and may enable these systems to treat feed waters with high fouling potential. Discerning fouling mechanisms in FO and developing fouling mitigation strategies will allow FO to reach its full commercial potential in a variety of applications. Development of FO membranes should continue to be focused on increasing fouling resistance. FO excels with challenging feed waters, and its future applications will be in treating high-salinity or high fouling potential waters, or waters that contain specific contaminants like boron or TrOCs. The unique advantages of FO that will drive these future applications are its low fouling propensity, capacity for high osmotic pressure driving forces that exceed the operating limits of RO, and high rejection of feed water contaminants. Hybrid FO systems employing thermo lytic draw solutions, such as the ammonia–carbon dioxide system, can be used to desalinate high-salinity feed waters while consuming less total energy than applicable thermal desalination technologies. FO may also be applied as advanced pretreatment to improve water quality and enable higher system recovery for conventional desalination technologies by rejecting feed water foulants, scablands, and contaminants of concern.

References

- Cath, T.Y. Childress, A.E. Elimelech, M. (2006), Forward osmosis: principles, applications, and recent developments, J. Membr. Sci. 281: 70–87.

- Zhao, L. Zou, C.Y. Tang, D. (2012), Mulcahy, Recent developments in forward osmosis: opportunities and challenges, J. Membr. Sci. 396: 1–21.

- Klaysom, T.Y. Cath, T. Depuydt, I.F. (2013), Vankelecom, Forward and pressure retarded osmosis: potential solutions for global challenges in energy and water supply, Chem. Soc. Rev. 42: 6959–6989.

- McCutcheon, R.L. McGinnis, M. Elimelech, (2005), A novel ammonia–carbon dioxide forward (direct) osmosis desalination process, Desalination 174: 1–11.

- Tiraferri, N.Y. Yip, A.P. Straub, S. Romero-Vargas Castrillon, M. Elimelech, (2013), A method for the simultaneous determination of transport and structural parameters of forward osmosis membranes, J. Membr. Sci. 444: 523–538.

- Achilli, T.Y. Cath, A.E. Childress, (2010), Selection of inorganic-based draw solutions for forward osmosis applications, J. Membr. Sci. 364: 233–241.

- Zhao, L. Zou, D. Mulcahy, (2012), Brackish water desalination by a hybrid forward osmosis–Nano filtration system using divalent draw solute, Desalination 284: 175–181.

- Hoover, W.A. Phillip, A. Tiraferri, N.Y. Yip, M. (2011), Elimelech, Forward with osmosis: emerging applications for greater sustainability, Environ. Sci. Technol. 45: 9824–9830.

- Wang, M.M. Teoh, A. Nugroho, T.-S. Chung, (2011), Integrated forward osmosis–membrane distillation (FO–MD) hybrid system for the concentration of protein solutions, Chem. Eng. Sci. 66: 2421–2430.

- Zhang, K.Y. Wang, T.-S. Chung, H. Chen, Y.C. Jean, G. Amy, (2010), Well-constructed cellulose acetate membranes for forward osmosis: minimized internal concentration polarization with an ultra-thin selective layer, J. Membr. Sci. 360: 522–535.

- Phuntsho S., Shon H.K., Hong S., Lee S., Vigneswaran S., (2011), A novel low energy fertilizer driven forward osmosis desalination for direct fertigation: evaluating the performance of fertilizer draw solutions, Journal of Membrane Science 375: 172–181.

- Mistry, R.K. McGovern, G.P. Thiel, E.K. Summers, S.M. Zubair, J.H. Lienhard, (2011), Entropy generation analysis of desalination technologies, Entropy 13: 1829–1864.

- Semiat, R (2008), Energy issues in desalination processes, Environ. Sci. Technol. 42: 8193–8201.

- Lee, C. Boo, M. Elimelech, S. (2010), Hong, Comparison of fouling behavior in forward osmosis (FO) and reverse osmosis (RO), J. Membr. Sci. 365: 34–39.

- Misdan, W.J. Lau, A.F. Ismail, (2012), Seawater Reverse Osmosis (SWRO) desalination by thin-film composite membrane—current development, challenges and future prospects, Desalination 287: 228–237.

- Kim, M. Elimelech, H.K. Shon, S. Hong, (2014), combined organic and colloidal fouling in forward osmosis: fouling reversibility and the role of applied pressure, J. Membr. Sci. 460: 206–212.

- Mi, M. (2010), Elimelech, Organic fouling of forward osmosis membranes: fouling reversibility and cleaning without chemical reagents, J. Membr. Sci. 348: 337–345.

- Mi, M. (2013), Elimelech, Silica scaling and scaling reversibility in forward osmosis, Desalination 312: 75–81.

- Elimelech, W.A. Phillip, (2011), The future of seawater desalination: energy, technology, and the environment, Science 333: 712–717.

- Loeb, L. Titelman, E. Korngold, J. Freiman, (1997), Effect of porous support fabric on osmosis through a Loeb–Sourirajan type asymmetric membrane, J. Membr. Sci. 129: 243–249.

- Lu, S. Romero-Vargas Castrillón, D.L. Shaffer, J. Ma, M. Elimelech, (2013), In situ surface chemical modification of thin-film composite forward osmosis membranes for enhanced organic fouling resistance, Environ. Sci. Technol. 47: 12219–12228.

- Morra, N (2000), On the molecular basis of fouling resistance, J. Biomater. Sci. Polym. Ed. 11 (2000) 547–569.

- Rana, D. Matsuura, T (2010), Surface modifications for antifouling membranes, Chem. Rev. 110: 2448–2471.