



Forward osmosis: Where are we now?



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HIGHLIGHTS

- We present a critical review of the current state of forward osmosis (FO).
- We analyze the energy efficiency of FO and emphasize relevant applications.
- We discuss the key required membrane properties for FO and future implications.
- We highlight fouling reversibility of FO and relevant benefits and applications.
- We discuss applications where FO outperforms current technologies.

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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 thermolytic 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.

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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 [1,2]. 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 [1]. The introduction of the ammonia-carbon dioxide FO process in 2005 as a potential desalination process that utilizes low-grade thermal energy [3] 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 [2,4]. These studies on FO involved membrane development [5–8], mass transfer analysis [4,9], membrane characterization [10,11], fouling phenomena [12–16], and introduction and characterization of new draw solutions [17–20]. 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 [21,22], FO in osmotic dilution processes [23,24], and various hybrid systems incorporating FO [25–28].

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 [2,4], 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. Is forward osmosis a low energy process?

2.1. No “free lunch” for FO

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 [29,30]. However, the spontaneity of the FO process implies that entropy is generated [31] 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 2.2 to compare the minimum energy requirement of a standalone RO process to that of an FO–RO hybrid process.

2.2. 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 [29]. 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. 1A) and an FO–RO process (denoted as FO–RO₂ in Fig. 1A). In the RO₁ process, the feed solution is separated into the brine solution (the red block in Fig. 1A) 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, and a concentrated draw solution of the same volume and

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