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A comprehensive review of hybrid forward osmosis systems: Performance, applications and future prospects

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ABSTRACT

Forward osmosis (FO) has been increasingly studied in the past decade for its potential as an emerging low-energy water and wastewater treatment process. However, the term "low-energy" may only be suitable for those applications in where no further treatment of the draw solution (DS) is required either in the form of pretreatment or post-treatment to the FO process (e.g. where the diluted DS is the targeted final product which can be used directly or simply discarded). In most applications, FO has to be coupled with another separation process in a so-called hybrid FO system to either separate the DS from the final product water or to be used as an advanced pre-treatment process to conventional desalination technologies. The additional process increases the capital cost as well as the energy demand of the overall system which is one of the several challenges that hybrid FO systems need to overcome to compete with other separation technologies. Yet, there are some applications where hybrid FO systems can outperform conventional processes and this study aims to provide a comprehensive review on the current state of hybrid FO systems. The recent development and performance of hybrid FO systems in different applications have been reported. This review also highlights the future research directions for the current hybrid FO systems to achieve successful implementation.

Contents

Abbreviations: BSA, bovine serum albumin; BWRO, brackish water reverse osmosis; CA, cellulose acetate; CAc, citric acid; CQDs, carbon quantum dots; CTA, cellulose triacetate; DS, draw solution; ED, electrodialysis; EDTA, ethylenediaminetetraacetic acid; FDFO, fertiliser driven forward osmosis; FO, forward osmosis; FS, feed solution; GAC, granular activated carbon; rGO, reduced graphene oxide; HF, hollow fibre; ICP, internal concentration polarisation; IPN, interpenetrating network; LCST, lower critical solution temperature; LPRO, low pressure reverse osmosis; MBC, membrane brine concentrator; MD, membrane distillation; MDC, microbial desalination cells; MED, multi effect distillation; MF, microfiltration; MNPs, magnetic nanoparticles; MSF, multi stage flash; MW, molecular weight; NF, nanofiltration; OD, osmotic dilution; OMBR, osmotic membrane bioreactor; OMDC, osmotic microbial desalination cells; PA, polyamide; PAA, polyacrylic acid; PAFO, pressure-assisted forward osmosis; PRO, pressure-retarded osmosis; PV, photovoltaic; RO, reverse osmosis; ROSA, reverse osmosis system analysis; RSF, reverse solute flux; SPS, switchable polarity solvents; SWRO, seawater reverse osmosis; TDS, total dissolved solids; TEM, transmission electron microscopy; TFC, thin-film composite; TMA, trimethylamine; TOC, total organic carbon; TrOCs, trace organic compounds; UF, ultrafiltration; VMD, vacuum membrane distillation; WHO, world health organization; ZLD, zero-liquid discharge

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1. Introduction

The continuous and exponential growth of population has raised considerable concerns on the sustainability of water and energy resources [1–4]. Therefore, one of the main challenges of this century is in meeting the increasing water demand at low-energy cost. In fact, water and energy are closely linked together since the production of clean water is still an energy-intensive process while generating power often requires a fair amount of water [5,6]. The development of low-energy separation technologies for clean water production is therefore crucial and has gained an increasing interest in the last few decades. Nowadays, membrane technologies are the most widely used methods to produce clean water and, among them, reverse osmosis (RO) is currently the most promising membrane separation process for desalination [7]. The state-of-the-art RO technology has significantly improved the scope for the use of saline water and impaired wastewater effluent as an alternate source of water to augment fresh water or to reduce pressure on freshwater resources [8]. However, the energy required for seawater RO has almost reached a plateau, and any more efforts towards reducing energy consumption requires additional processes thereby increasing the total cost of the final water. Besides, even if RO desalination plants consume significantly less energy than it was three decades ago, it still remains an energy-intensive process due to the high hydraulic pressure required to surpass the osmotic pressure of the saline feed water [8,9]. Finally, RO suffers from severe membrane fouling which greatly affects its long-term performance and the management of concentrated brine is still a major environmental issue. Therefore, any low energy desalination technologies could make desalination more affordable and have a significant impact in meeting the increasing water demand.

In the last decade, forward osmosis (FO) has gained increased attention as an emerging membrane technology. Therefore, many contributions have been made to improve the overall FO process efficiency from both academic researchers and industries [3,6,10,11]. The principle of FO process relies on using the natural osmotic process to draw the water molecules across a semi-permeable membrane from a saline feed water to a higher concentrated solution, namely the draw solution (DS). The driving force is therefore created naturally by the difference in osmotic pressure between the DS and the feed solution (FS). This offers several advantages over conventional hydraulic pressure-driven membrane processes (e.g. RO) such as lower energy requirements and reduced membrane fouling potential [12]. In fact, in the FO process, the absence of applied hydraulic pressure has not only the potential to reduce both capital and operation cost but can also be beneficial for fouling control compared to pressure-driven membrane processes. Besides, in most cases, fouling in the FO process has been found to be physically reversible which reduces the need for chemical cleaning like the RO process [13,14].

However, FO technology still suffers from some major technological barriers. The first barrier is the lack of suitable membranes designed for the FO process. The conventional membranes such as RO membranes are asymmetric and was proved not suitable for the FO process as it aggravates concentration polarisation effects, some of which are not only unique to the FO process but also pose a significant decrease in process efficiency [12]. However, significant progress has been made in FO membrane fabrication recently, with thin film composites (TFC) FO membrane now reaching comparatively higher water flux than the existing commercial cellulose triacetate (CTA) FO membrane [15,16]. The second barrier is the separation of the produced water from the DS and its reconcentration and recovery, especially when high quality water is required (e.g. for drinking water production). In fact, the separation and recovery of the DS require an additional processing unit, which can consume energy and therefore still remains a significant challenge for drinking water applications [17–19]. The success of FO for potable purpose will therefore greatly depend on how easily and efficiently the draw solute can be separated from the water after the FO process, once the DS is fully diluted.

Therefore, early FO studies focused on finding efficient draw solute recovery methods and therefore started to develop hybrid FO systems (i.e. FO coupled with another physical or chemical separation process). These initial bench-scale studies (e.g. [20]) were aimed at evaluating the performance of recovery processes for specific/novel draw solutions. Recent review papers on the FO process have been published on the development of either draw solution or their recovery methods [6,11,17]. However, in the last couple of years, several hybrid FO systems have been developed for various applications including seawater and brackish water desalination (about 60%), wastewater treatment (about 13%) or both (i.e. simultaneously, about 13%) (Fig. 1a). Other applications include fertigation, protein concentration or dewatering of RO concentrate. Table 1 shows the different configurations of hybrid FO systems where FO has been integrated into the existing or combined processes to either replace conventional pre-treatment technologies or as a post-treatment to reduce the volume of industrial waste. In fact, it has been demonstrated that FO used as a pre-treatment process can improve the overall efficiency of conventional desalination processes in applications with challenging feed waters (i.e. having high salinity, high fouling potential or containing specific contaminants) [21]. One good example is the coupling of FO with membrane distillation (MD) to desalinate waters that are usually challenging for MD alone. Using this hybrid FO–MD system, FO is used as a pre-treatment to reduce inorganic scaling and/or organic fouling which have adverse effect on the MD process whereas the latter is used to recover and reconcentrate the DS using low-grade heat [22]. FO coupled with nanofiltration (NF) has also been recently proposed [23] in the context of