Journal of Membrane Science 529 (2017) 195–206

Contents lists available at ScienceDirect

Journal of Membrane Science

journal homepage: www.elsevier.com/locate/memsci

Forward osmosis as a platform for resource recovery from municipal wastewater - A critical assessment of the literature

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ARTICLE INFO

Keywords:
Forward osmosis (FO)
Wastewater treatment
Resource recovery
Anaerobic treatment
Biogas
Phosphorus recovery

ABSTRACT

Forward osmosis (FO) is an emerging membrane separation technology that has the potential to serve as a game changer in wastewater treatment. FO-based processes can simultaneously produce high quality effluent and pre-concentrated wastewater for anaerobic treatment to facilitate the recovery of energy and nutrients. Complex wastewaters can be directly pre-treated by FO and fresh water can be produced when coupled with a draw solute recovery process (i.e. reverse osmosis or membrane distillation). By enriching organic carbon and nutrients for subsequent biogas production, FO extends the resource recovery potential of current wastewater treatment processes. Here, we critically review recent applications of FO for simultaneous treatment and resource recovery from municipal wastewater. Research conducted to date highlights the importance of successfully integrating FO with anaerobic treatment. Emphasis is also placed on the development of novel FO-based hybrid systems utilising alternative energy sources for draw solute recovery. There remain several technical challenges to the practical realisation of FO for resource recovery from wastewater including salinity build-up, membrane fouling, and system scale-up. Strategies to overcome these challenges are critically assessed to establish a research roadmap for further development of FO as a platform for resource recovery from wastewater.

1. Introduction

The recovery of water, energy, and nutrient resources from municipal wastewater presents a promising solution to a number of prevalent economic, environmental, and social issues. Wastewater reclamation can address both water scarcity and environmental pollution [1,2]. Utilisation of the biogas produced from the organic content of wastewater can offset the energy requirement for treatment [3]. Nutrient recovery from wastewater also deserves special attention due to the increasing stringency of effluent discharge regulations and uncertainties associated with minable phosphorus supply for food security [4–6]. Increasing awareness of the potential resource value of municipal wastewater has prompted significant research efforts to synergise emerging wastewater treatment processes and resource recovery techniques [3,7,8].

Activated sludge treatment is an established biological process that focusses primarily on purifying wastewater of organic matter, pathogens, and nutrients, but does not effectively facilitate energy and nutrient recovery. Activated sludge treatment is energy intensive due to the high electricity demand for aeration and also produces excessive amounts of sludge residuals [9]. During activated sludge treatment, the carbon (i.e. chemical energy) and nitrogen (i.e. nutrient) contents of wastewater are converted to biomass, carbon dioxide, and nitrogen gas. In other words, much of the energy and nutrient contents of wastewater are dissipated at the expense of significant energy input. As an alternative, anaerobic treatment converts organic substances into methane rich biogas in the absence of oxygen and transforms phosphorus to a more chemically available state for subsequent recovery [10]. Transitioning from aerobic towards anaerobic based treatment processes has significant potential to lower the energy consumption of wastewater operations (i.e. by avoiding aeration), as well as achieve energy-neutral wastewater treatment (i.e. through biogas production) [11–17].

The opportunity for wastewater treatment plants to provide a renewable source of useful heat and electricity through biogas conversion is immense [18,19]. In fact, the chemical energy content in municipal wastewater exceeds the electricity requirement of operating an activated sludge plant by at least nine times [20]. Despite this significant embedded energy content, there are a number of major challenges that currently restrict the feasibility of directly anaerobically

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http://dx.doi.org/10.1016/j.memsci.2017.01.054
Received 28 July 2016; Received in revised form 24 January 2017; Accepted 29 January 2017
Available online 31 January 2017
0376-7388/

digesting raw wastewater for energy recovery. The concentration of organic matter in wastewater is typically low. Therefore, a sufficient organic loading rate cannot be maintained in the anaerobic digester, resulting in a low biogas yield and inadequate removal of organic pollutants from wastewater. In addition, since methane is slightly soluble in water (22.7 mg/L), at a low biogas yield, much of the generated methane can be lost via effluent discharge [10]. Several membrane filtration technologies have been integrated with anaerobic treatment to overcome these challenges, aiming to improve the retention of biomass in the reactor and to increase effluent quality. Anaerobic membrane bioreactors (An-MBRs) utilising low pressure membranes such as microfiltration (MF) or ultrafiltration (UF) is a notable approach. Nevertheless, the MF/UF membranes used in conventional An-MBRs cannot retain dissolved organic carbon. Thus, they are not effective for energy recovery and cannot produce a high effluent quality [10].

Further development in An-MBR technology has resulted in the novel hybridisation of anaerobic treatment with high retention membrane processes including nanofiltration (NF), reverse osmosis (RO), membrane distillation (MD), and forward osmosis (FO) [21]. Among these high retention membrane processes, FO stands out as the most promising candidate for integration with anaerobic treatment due to a combination of high separation efficiency and high fouling reversibility [22–25]. The integration of FO with anaerobic treatment has been widely reported in the literature [26–30]. FO is a unique membrane process that utilises the physical phenomenon of osmosis to transport water across a semipermeable membrane. As a major advantage, the FO process itself can operate with minimal external energy input [31]. However, further treatment of the draw solution is required to extract fresh water and can be achieved using pressure driven or thermally driven membrane processes [32]. Lutchmiah, et al. [33] provided a critical assessment of FO applications for water reclamation. They also highlighted the need to develop new membrane materials and optimise draw solute selection as well as key operating conditions to facilitate full-scale implementation of FO for water reclamation applications [33]. In another excellent review, Holloway, et al. [34] systematically summarised and reviewed all relevant works related to osmotic membrane bioreactors for the production of high quality potable water from impaired sources including wastewater. In particular, Xie, et al. [7] identified the untapped potential of FO amongst several other membrane separation processes for recovering nutrients from municipal wastewater. Indeed, there is a consensus that FO has the potential to be an important technology in the future of wastewater treatment [31,33,35,36].

Integrating FO with anaerobic treatment is essential for energy and nutrient recovery. The viability of the anaerobic osmotic membrane bioreactor (An-OMBR) has been demonstrated where the FO membrane is submerged inside the anaerobic bioreactor [26,28,29]. An alternative approach uses FO to firstly pre-concentrate raw wastewater to a high strength for subsequent anaerobic treatment. The concept of wastewater pre-concentration is yet to be fully explored, but it holds significant opportunities for resource recovery applications. Preliminary investigations into FO draw solution selection [27,37] and process efficiency [38–40] have been conducted. However, issues of salinity accumulation, membrane fouling, and anaerobic treatment integration have not been adequately addressed.

Here, we critically review recent applications of FO for recovering energy and nutrients from municipal wastewater by integrating with existing resource recovery techniques (i.e., anaerobic digestion and phosphorus precipitation) and other complementary processes (e.g., MD and RO) for clean water extraction. The challenges and potential opportunities associated with FO-based treatment processes are evaluated in terms of treatment efficiency and resource recovery potential. The outlook of an integrated FO membrane-based system for simultaneous wastewater treatment and resource recovery is discussed. A research roadmap for further development of FO for resource recovery from wastewater is also provided and discussed.

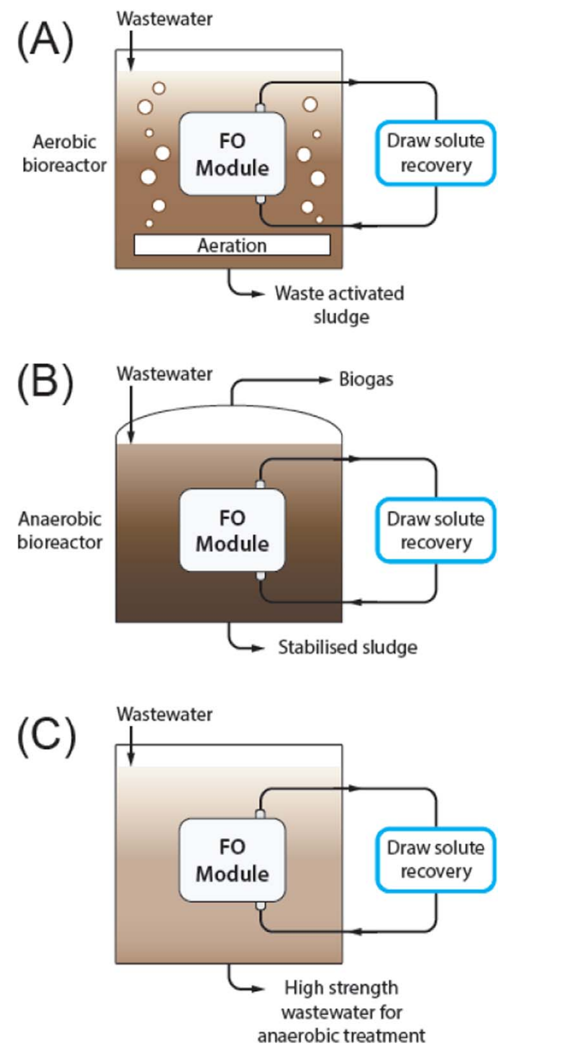

Fig. 1. : Schematic representation of three major FO system configurations for wastewater treatment: (A) Ae-OMBR, (B) An-OMBR, and (C) wastewater pre-concentration intended for subsequent anaerobic digestion.

2. FO for wastewater treatment

Interest in applying FO for wastewater treatment has grown significantly in recent years [32,33,35,41–43]. These potential applications are motivated by several advantages of FO over current wastewater treatment technologies. Given its high fouling reversibility, FO can be directly applied to a complex solution without extensive pretreatment [44]. High rejection of dissolved contaminants is another important advantage of FO for wastewater treatment. When FO is combined with a draw solute recovery process, clean water can be produced from the draw solution, furthering water reuse opportunities. These unique features of FO have spurred the development of several system configurations for wastewater treatment and water reclamation.

2.1. FO system configurations for wastewater treatment

Three major system configurations have been developed for FO wastewater treatment applications and vary depending on the type of solution in contact with the FO membrane (Fig. 1). Firstly, the most widely recognised approach is the aerobic osmotic membrane bioreactor (Ae-OMBR) [45–51] (Fig. 1A) whereby wastewater is fed into an activated sludge reactor. Secondly, several research groups have