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Selection of suitable fertilizer draw solute for a novel fertilizer-drawn forward osmosis–anaerobic membrane bioreactor hybrid system

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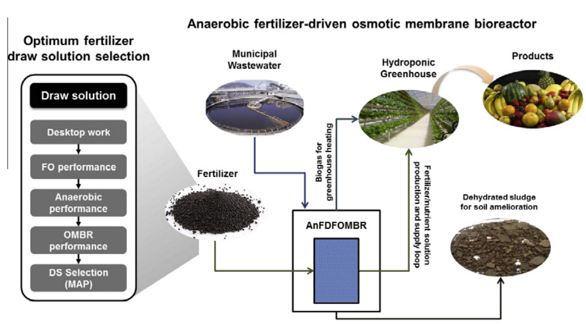
HIGHLIGHTS

- A fertilizer draw solution selection protocol was proposed for AnFDFOMBR.
- Screening includes water flux, reverse salt flux, biogas potential and simulation.
- Reverse salt flux of fertilizers except MAP may inhibit methane production.
- Low reverse salt flux induced higher water flux and less salt accumulation.
- MAP could be the most suitable draw solution for AnFDFOMBR.

GRAPHICAL ABSTRACT



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ABSTRACT

In this study, a protocol for selecting suitable fertilizer draw solute for anaerobic fertilizer-drawn forward osmosis membrane bioreactor (AnFDFOMBR) was proposed. Among eleven commercial fertilizer candidates, six fertilizers were screened further for their FO performance tests and evaluated in terms of water flux and reverse salt flux. Using selected fertilizers, bio-methane potential experiments were conducted to examine the effect of fertilizers on anaerobic activity due to reverse diffusion. Mono-ammonium phosphate (MAP) showed the highest biogas production while other fertilizers exhibited an inhibition effect on anaerobic activity with solute accumulation. Salt accumulation in the bioreactor was also simulated using mass balance simulation models. Results showed that ammonium sulfate and MAP were the most appropriate for AnFDFOMBR since they demonstrated less salt accumulation, relatively higher water flux, and higher dilution capacity of draw solution. Given toxicity of sulfate to anaerobic microorganisms, MAP appears to be the most suitable draw solution for AnFDFOMBR.

1. Introduction

Freshwater resources are getting scarcer due to the impacts of global warming, and rapid and extensive industrialization and urbanization (Rijsberman, 2006). Moreover, agricultural sector still consumes about 70% of the accessible freshwater with about 15–35% of water being used unsustainably (Clay, 2004). Therefore, countries such as in the Mediterranean region, which are stressed by water shortage, have considered wastewater reuse as a viable alternative water resource for agricultural purposes (Angelakis et al., 1999). Adequate treatment of wastewater before reuse as

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irrigation is essential not only to protect the human health from consumption and plant health but also enhance the value of the crops grown through wastewater reuse. Many researchers have studied the feasibility of wastewater reuse for irrigation by using a variety of treatment methods (Alderson et al., 2015; Ferro et al., 2015).

For wastewater reuse, however, advanced treatment processes (e.g., reverse osmosis (RO), nanofiltration (NF) or advanced oxidation) are generally required as a post-treatment process since wastewater could contain pollutants which are not removed by conventional treatment processes such as heavy metals, pharmaceutics and trace organic contaminants (Ahluwalia and Goyal, 2007). Anaerobic membrane bioreactor (AnMBR) has been studied to treat wastewater and has several advantages including complete rejection of suspended solids, low sludge production, high organic rejection and biogas production (Stuckey, 2012). Moreover, both AnMBR and post-treatment (e.g., RO and NF) exhibit high fouling issues which ultimately increase energy requirements since these processes are driven by the hydraulic pressure as a driving force (Kim et al., 2014). To overcome these issues, osmotic membrane bioreactor (OMBR) has been proposed by integrating AnMBR with forward osmosis (FO) instead of conventional pressurized membrane processes (Achilli et al., 2009; Chekli et al., 2016; Wang et al., 2016). OMBR can provide high rejection of contaminants, low fouling propensity and high fouling reversibility but also has limitations that pure water should be extracted from draw solution and reversely transported draw solute can be toxic or inhibit the biological processes (Achilli et al., 2009).

Lately, fertilizer-drawn forward osmosis (FDFO) has received increased interest since the diluted draw solution can be used directly for irrigation purposes and therefore no recovery process is required (Phuntsho et al., 2011, 2012). In FDFO, fertilizers are used as draw solution and the fertilizer solution is continuously diluted during operation (Phuntsho et al., 2011). In the early studies, only single fertilizers, which didn't provide sufficient nutrient composition for direct application, were examined. Thus, blended fertilizers were investigated for targeted crops (Phuntsho et al., 2012). However, the final nutrient concentration was still high and the final fertilizer solution required substantial dilution for direct fertigation. To solve this problem, NF was adopted as post-treatment and the produced fertilizer solution by NF could meet the water quality requirements for fertigation since it has lower rejection rates (i.e., 80–90%) than RO (Phuntsho et al., 2013). Nevertheless, high energy consumption is still an issue since NF is a pressurized desalting process and should overcome osmotic pressure of diluted fertilizer solution. Finally, pressure-assisted fertilizer-drawn forward osmosis (PAFDFO) was recently developed for enhancing final dilution of fertilizer draw solution without beyond the point of osmotic equilibrium between the draw and feed solutions (Sahebi et al., 2015).

In this study, we propose for the first time a FDFO–AnMBR hybrid system (AnFDFOMBR) for simultaneous wastewater treatment for greenhouse hydroponic application based on the concept described in Fig. S1 of the supporting information. This hybrid system consists of two parts (i.e., AnMBR and FDFO). In conventional AnMBR, microfiltration (MF) or ultrafiltration (UF) are employed to separate the treated wastewater from the anaerobic sludge. In this study, a FO membrane is used instead and submerged into the bioreactor. In addition, the FO process is here driven by fertilizers (FDFO process) and thus the treated water drawn from the wastewater is used to dilute the fertilizer solution which can then be directly used for fertigation. In this system, raw municipal wastewater will be utilized as influent and a highly concentrated fertilizer solution will be used as draw solution for the AnFDFOMBR process. The diluted fertilizer solution can then be obtained and supplied to greenhouse hydroponics irrigation.

The main objective of this study is to investigate a protocol for selecting the optimum draw solution for the novel AnFDFOMBR process. For selecting a suitable fertilizer as draw solute, FO performance was first investigated in terms of water flux and reverse salt flux (RSF). Bio-methane potential (BMP) was then measured to evaluate the potential effect of the fertilizer due to reverse diffusion on inhibiting the microbial activity in the bioreactor for methane production. Finally, salt accumulation in the AnFDFOMBR was simulated based on theoretical models derived from mass balance.

2. Methods

2.1. FO membrane

The FO membrane used in this study was provided by Hydration Technology Innovations (Albany, OR, USA). This membrane is made of cellulose-based polymers with an embedded polyester mesh for mechanical strength. Detailed characteristics of this commercial membrane can be found elsewhere (Tiraferri et al., 2013).

2.2. Draw solutions

All chemical fertilizers used in this study were reagent grade (Sigma Aldrich, Australia). Draw solutions were prepared by dissolving fertilizer chemicals in deionized (DI) water. Detail information of fertilizer chemicals are provided in Table S1. Osmotic pressure and diffusivity were obtained by OLI Stream Analyzer 3.2 (OLI System Inc., Morris Plains, NJ, USA).

2.3. Lab-scale FO system

2.3.1. FO membrane characterization

Properties of FO membrane are commonly classified into the water permeability coefficient (A), the salt permeability coefficient (B) of the active layer, and the structure parameter (S) of the support layer. The mathematical method (Tiraferri et al., 2013) which can simultaneously measure three parameters under the non-pressurized condition was used in this study. Experimental measurements were conducted in a lab-scale FO unit with an effective membrane area of 20.02 cm^2. Operating temperature was 25 °C and the cross-flow velocities of both the solutions were maintained at 25 cm/s. The methods to determine the A, B and S parameters (see Table S2) are described elsewhere in detail (Tiraferri et al., 2013; Yip and Elimelech, 2013).

2.3.2. FO performance experiments

FO performance experiments were carried out using a lab-scale FO system similar to the one described elsewhere (Kim et al., 2015b; Lee et al., 2015). The FO cell had two symmetric channels on both sides of the membrane each for the feed and draw solutions. Variable speed gear pumps (Cole-Parmer, USA) were used to provide crossflows under co-current directions at a crossflow rate of 8.5 cm/s and solution temperature of 25 °C and the solutions were recirculated in a loop resulting in a batch mode of process operation. The draw solution tank was placed on a digital scale and the weight changes were recorded by a computer in real time to determine the water flux. Conductivity and pH meters (HACH, Germany) were connected to a computer to monitor RSF of draw solutes in the feed tank.

FO experiments were conducted in the FO mode with the active layer facing the feed solution. The fertilizer draw solution concentrations were fixed at 1 M for all the experiments. Before each performance experiment, the FO membrane was stabilized for 30 min with DI water as feed solution and 1 M fertilizer solution as draw