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Research article

Evaluation of fertilizer-drawn forward osmosis for sustainable agriculture and water reuse in arid regions

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ABSTRACT

The present study focused on the performance of the FDFO process to achieve simultaneous water reuse from wastewater and production of nutrient solution for hydroponic application. Bio-methane potential (BMP) measurements were firstly carried out to determine the effect of osmotic concentration of wastewater achieved in the FDFO process on the anaerobic activity. Results showed that 95% water recovery from the FDFO process is the optimum value for further AnMBR treatment. Nine different fertilizers were then tested based on their FO performance (i.e. water flux, water recovery and reverse salt flux) and final nutrient concentration. From this initial screening, ammonium phosphate monobasic (MAP), ammonium sulfate (SOA) and mono-potassium phosphate were selected for long term experiments to investigate the maximum water recovery achievable. After the experiments, hydraulic membrane cleaning was performed to assess the water flux recovery. SOA showed the highest water recovery rate, up to 76% while KH_2PO_4 showed the highest water flux recovery, up to 75% and finally MAP showed the lowest final nutrient concentration. However, substantial dilution was still necessary to comply with the standards for fertigation even if the recovery rate was increased.

1. Introduction

Freshwater resources are getting scarcer, particularly in arid, semi-arid and coastal areas, while agricultural sector consumes about 70% of the accessible freshwater with about 15–35% of water being used unsustainably (Assessment, 2005; Clay, 2013). In arid regions, the development of agriculture is not only hindered by the limited freshwater resources but also by the scarcity of fertile lands. Hydroponics is a subset of hydroculture with several advantages over conventional soil culture. In fact, it is a soilless process using synthetic mineral solution to grow crops (Jensen, 1997). As such, it eliminates the problems associated with soil culture; i.e. poor soil culture, poor drainage, soil pollution and soil-borne pathogens. Therefore, hydroponics has been widely used in commercial greenhouse vegetable production around the world. However, hydroponics requires a nutrient solution to fertilize the plants under a controlled environment (e.g., concentration, flow rate, temperature). As a result, this process also consumes a large amount of fresh water to prepare the fertilizer solution. This water-food nexus is becoming a critical issue in most arid regions and therefore, sustainable solutions to assure water and food security must be explored.

Recently, increased consideration has been given to the concept of fertilizer drawn forward osmosis (FDFO) process. In fact, the novelty of the concept relies on the low-energy osmotic dilution of the fertilizer draw solution (DS) which can then be applied directly for irrigation since it contains the essential nutrients required for plant growth. Although early studies on FDFO (Phuntsho et al., 2011; Phuntsho et al., 2012a) demonstrated that most fertilizers can be suitable DS, the limit posed by the osmotic equilibrium between the feed and the draw solutions will dictate the final nutrient concentration, which, in most cases, was found to exceed the standards for irrigation. This means that the final DS still requires additional dilution which is not acceptable, especially in the

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context of freshwater scarcity. To circumvent this issue, nanofiltration (NF) was proposed as pre or post-treatment for FDFO with the aim of reducing the nutrient concentration in the final product water (Phuntsho et al., 2013a). Results from this study showed that the product water was suitable for direct application when NF was used as post-treatment and when brackish water with low TDS (i.e. <4000 mg/L) was employed as feed solution (FS). However, the use of an additional process will increase the energy consumption of the system and thus the final cost of produced water especially because NF is a pressure-driven membrane process. Recently, pressure-assisted forward osmosis (PAFO) was tested as an alternative solution to eliminate the need for NF post-treatment (Sahebi et al., 2015). The PAFO process used an additional hydraulic driving force to simultaneously enhance the water flux and dilute the DS beyond the point of osmotic equilibrium. In this study, it was concluded that the use of PAFO instead of NF can further dilute the fertilizer DS, thereby producing permeate water that meets the acceptable nutrient concentrations for direct fertigation.

To date, all FDFO studies have either used brackish water (Phuntsho et al., 2013a; Phuntsho et al., 2014; Raval and Koradiya, 2016), treated coalmine water with a TDS of about 2.5 g/L (Phuntsho et al., 2016) or seawater (Phuntsho et al., 2011; Phuntsho et al., 2012a; Phuntsho et al., 2012b; Phuntsho et al., 2013b) as the FS. However, the relatively low salinity of most impaired waters makes them potentially suitable candidate for such dilution (Lew et al., 2005). Besides, drawing the water from impaired sources to produce nutrient solution for hydroponic culture seems a very promising and sustainable approach to solve the freshwater scarcity issue in most arid regions. This concept can be further extended if the concentrated impaired water from the FDFO process is sent to an anaerobic membrane bioreactor (AnMBR) for additional treatment and biogas production to supply energy to the hybrid process.

The main objective of this study is therefore to evaluate the potential of FDFO process for simultaneous water reuse and sustainable agriculture. The optimum recovery rate for feeding the AnMBR process will be first determined through bio-methane potential measurements. Then, bench-scale FO experiments will be carried out to optimize the fertilizer formula and process configuration in order to simultaneously achieve the optimum recovery rate and favourable nutrient supply for hydroponics.

2. Materials and methods

2.1. FO membrane and draw solutions

The FO membrane used in this study was a commercial thin film composite (TFC) polyamide (PA) FO membrane (Toray Industry Inc.).

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 1. Osmotic pressure and diffusivity were obtained by OLI Stream Analyzer 3.1 (OLI System Inc., Morris Plains, NJ, USA).

2.2. Bio-methane potential experiments

The bio-methane potential (BMP) experiment was carried out using the BMP apparatus described in our previous study (Kim et al., 2016) to investigate the effect of water recovery in the FO process on the performance of the post-AnMBR process. The BMP apparatus consisted of 6 fermentation bottles submerged in a water bath connected to a temperature control device to maintain a temperature of 35 ± 1 °C. These bottles were connected to an array of inverted 1000 mL plastic mass cylinders submerged in the water bath filled with 1 M NaOH solution to collect and measure the biogas. The NaOH solution plays an important role to sequester both CO_2 and H_2S to evaluate only CH_4 production potential. Air volume in each mass cylinder was recorded twice a day. Detailed description of BMP apparatus used in this study is given elsewhere (Nghiem et al., 2014; Ansari et al., 2015).

Six different recovery rates were tested in this study (i.e. 0%, 20%, 40%, 60%, 80% and 95%) and the concentrated synthetic wastewater was prepared accordingly. 50 mL of each solution was then mixed with 700 mL of digested sludge. All bottles were purged with nitrogen gas, and connected to the biogas collecting equipment. The BMP experiment was carried out until the methane production stopped.

2.3. Bench-scale FO system

The performance of the FO process was conducted in a closed-loop bench-scale FO system (Fig. S1, Supporting Information) in which detailed characteristics can be found elsewhere (Lee et al., 2010; Kim et al., 2015b). This lab-scale FO unit has an effective membrane area of 20.02 cm^2 with a channel dimension of 77 mm long, 26 mm wide, and 3 mm deep. The FO cell had two symmetric channels on both sides of the membrane for co-current flows of feed and draw solutions. Variable speed gear pumps (Cole-Parmer, USA) were used to pump the liquid in a closed loop. The DS tank was placed on a digital scale and the weight changes were measured by a computer in real time to determine water flux. Conductivity and pH meters (HaCH, Germany) were connected to a computer to monitor the reverse salt flux (RSF) of draw solutes in the FS tank.

FO experiments were conducted in the FO mode where the active layer is facing the FS. Before each performance experiment, the FO membrane was stabilized for 30 min with DI water as FS and fertilizer solution as DS. Once stabilized, the water flux was measured continuously throughout the experiment with a 3 min time interval. All experiments were conducted at a cross-flow velocity of 8.5 cm/s, and a constant temperature of 25 °C.

Table 1
Properties of the fertilizer solutions used in this study. Thermodynamic properties were determined at 1 M concentration and 25 °C by using OLI Stream Analyzer 3.2.

Chemicals	Formula	Molecular weight (g/mol)	Osmotic pressure (atm)	Diffusivity (10^{-9} m^2/s)
Ammonium nitrate	NH_4NO_3	80.04	33.7	1.65
Ammonium sulphate (SOA)	$(NH_4)_2SO_4$	132.1	46.1	1.14
Ammonium chloride	NH_4Cl	53.5	43.5	1.85
Calcium nitrate	$Ca(NO_3)_2$	164.1	48.8	1.01
Potassium chloride	KCl	74.6	44	1.79
Ammonium phosphate monobasic (MAP)	$NH_4H_2PO_4$	115.0	43.8	1.06
Ammonium phosphate dibasic (DAP)	$(NH_4)_2HPO_4$	132.1	50.6	0.912
Potassium nitrate	KNO_3	101.1	37.2	1.78
Potassium phosphate monobasic	KH_2PO_4	136.09	36.5	1.02