



Energy consumption of water recovery from wastewater in a submerged forward osmosis system using commercial liquid fertilizer as a draw solute



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ABSTRACT

Using liquid fertilizer as a draw solute in forward osmosis (FO) to extract high-quality water from wastewater is of strong interest because it eliminates the need for regenerating draw solute, thereby requiring less energy input to system operation. However, energy consumption of such an approach has not been evaluated before. Herein, a submerged FO system with all-purpose liquid fertilizer as a draw solute was studied for energy consumption of water recovery from either deionized (DI) water or domestic wastewater. The results showed that a higher draw concentration led to higher water flux and lower energy consumption, for example $0.25 \pm 0.08 \text{ kW h m}^{-3}$ with 100% draw concentration, but reverse salt flux (RSF) was also more serious. Decreasing the recirculation flow rate from 100 to 25 mL min^{-1} had a minor effect on water flux, but significantly reduced energy consumption from 1.30 ± 0.28 to $0.09 \pm 0.02 \text{ kW h m}^{-3}$. When extracting water from the secondary effluent, the FO system exhibited comparable performance of water flux and energy consumption to that of the DI water. However, the primary effluent resulted in obvious fouling of the FO membrane and higher energy consumption than that of the secondary effluent/DI water. This study has provided important implications to proper evaluation of energy consumption by the FO system using liquid fertilizer or other non-regenerating draw solutes.

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1. Introduction

Reclaimed wastewater can be used as an alternative water resource in places where water scarcity is a problem. Agricultural and landscape irrigation is the major consumer of reclaimed wastewater; however, heavy metals (e.g. Cr, Mn, Pb and Zn) [1] and pathogens (e.g. coliforms, Streptococcus and Salmonella) [2] originally present in wastewater could result in the contamination of surface water and groundwater, thereby creating threats for public health and the environment. Ingestion of wastewater-irrigated crops will potentially introduce human body to the xenobiotics such as anticonvulsant drug, which have been detected in reclaimed wastewater and were found to be persistent in soil [3]. To obtain high-quality reclaimed water for reuse, advanced membrane treatment will be necessary. Forward osmosis (FO) has been studied as a low energy desalination process and can be applied to extract high-quality water from treated wastewater [4,5]. Unlike pressure-driven processes such as reverse osmosis (RO), FO is driven by the osmotic pressure difference between a draw solution

and a feed solution separated by a semipermeable membrane and as a result, water moves from the feed solution into the draw solution [6,7]. FO could be more cost-effective in direct fertigation and production of reusable water because of no hydraulic pressure and low fouling tendency [8].

The selection of draw solutes is critically important to enhance FO efficiency. A suitable draw solute should have high osmotic pressure, larger water solubility, acceptable cost, as well as easy regeneration or no need for regeneration [9]. The draw solute that does not need regeneration is of particular interest, because regeneration processes have a large demand for energy [10]. Fertilizer has been studied as a potential draw solute in FO so that the diluted draw solution after water extraction can be used for irrigation directly, thereby eliminating the need for regeneration [11,12]. Early studies mostly used synthetic chemicals as single-component or blended fertilizers [12–14]. Recently, commercial solid fertilizers were investigated as draw solutes in a submerged FO system, which achieved 41% of the water recovery needed for diluting the solid fertilizer for irrigation [15]. Although solid fertilizers have potential advantages of easy storage and transportation, preparation of an initial draw solution using solid fertilizers will require water and dissolution of fertilizer components can affect

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the FO performance and operation (e.g., disposal of undissolved particles and membrane fouling).

Liquid fertilizer, on the other hand, contains fully dissolved compounds and is ready for being used as a draw solution. The performance of an FO system using commercial liquid fertilizer has been examined, and it achieved more than 80% water recovery from raw sewage [16]. Several influence factors such as reverse salt flux, fertilizer concentration, cross-flow rate, and temperature have also been investigated. The effect of cross-flow rate was particularly interesting; despite its negligible impact on water flux performance, cross-flow rate can significantly affect energy consumption. One of the advantages of an FO system is high energy efficiency, but energy consumption has not been widely reported in the literatures [17]. In an FO system without the need for regenerating draw solute, for example using fertilizer as the draw, energy consumption will be dominated by liquid recirculation that provides cross flow to reduce external concentration polarization (ECP) and help control membrane fouling. In a recent study of using solid fertilizer as the draw, it was reported that reducing recirculation intensity from 100 to 10 mL min⁻¹ greatly reduced the energy consumption from 1.86 to 0.02 kW h m⁻³ [15]. Energy consumption of using liquid fertilizer has not been reported before and will be very important to properly evaluate this approach for wastewater reuse.

In this study, a commercial liquid fertilizer was investigated as a draw solute in a submerged FO system for extracting water from domestic wastewater (primary effluent and secondary effluent). A submerged FO system is expected to consume less energy (mainly by its liquid recirculation) and generate a smaller footprint [18]. Both water flux and reverse nutrient loss (N/P/K) were studied. The operating factors such as the concentration of liquid fertilizer and the flow rate of recirculation were investigated. Energy consumption by this FO system under different operating conditions was analyzed. It should be noted that in this study energy consumption was represented by energy demand of the recirculation pump, and the energy required for membrane cleaning was not included.

2. Materials and methods

2.1. Fertilizer preparation

Commercial liquid fertilizer (Miracle-Gro Quick Start Planting & Transplant Starting Solution, Marysville, OH, USA) was obtained from the local retailer with its main components (i.e. Urea-N, NH₄⁺-N, PO₄³⁻, and K⁺) summarized in Table 1. Urea was the only presented organics according to the product description. The liquid fertilizer has a pH of 6.16 ± 0.11 and was used without pH adjustment. The original liquid fertilizer was successively diluted with DI water to render a 100 mL draw solution with different concentrations (25%, 50% and 100% v/v), of which 10 mL was used for composition analysis.

Table 1
Characteristics of the commercial liquid fertilizer.

Parameters	Value
Conductivity (mS cm ⁻¹)	93.7 ± 0.8
pH (-)	6.16 ± 0.11
Urea-N (g L ⁻¹) ^a	32.2 ± 0.8
NH ₄ ⁺ -N (g L ⁻¹)	25.5 ± 1.5
PO ₄ ³⁻ (g L ⁻¹)	71.9 ± 1.1
K ⁺ (g L ⁻¹)	43.1 ± 2.8

^a Urea is the only organics presented in the liquid fertilizer.

2.2. Submerged FO system setup

An FO cell was built with two pieces of cellulose triacetate (CTA) membrane (Hydration Technologies Inc, Albany, OR, USA) that had a total working surface area of 52 cm²; those membranes formed a middle draw chamber of 68 mL. The active layer of the FO membrane was oriented toward the feed to reduce fouling and achieve a lower reverse solute flux (RSF) [6,19]. Plastic meshes were installed outside the draw chamber to provide mechanical support while preventing potential membrane swelling (Fig. 1A). The FO cell was placed in a 1-L plastic beaker containing 600 mL (constant) of the feed solution (DI water or actual wastewater), creating a submerged FO system (Fig. 1B). Two types of wastewater stream were obtained from a local wastewater treatment plant (Peppers Ferry WWTP, Radford, VA, USA), primary effluent (the effluent from the primary clarifier, before the activated sludge treatment) and secondary effluent (the effluent from the secondary clarifier, after the activated sludge treatment) (Table 2). The FO system was operated in a batch mode with the fertilizer draw being circulated in the middle draw chamber. A recirculation pump was connected to the FO cell allowing the adjustment of the recirculation flow rate of the draw solution. Because external concentration polarization (ECP) could be less significant compared to the effect of internal concentration polarization (ICP) in an FO process due to a lower water flux [4], no mixing such as magnetic stirring, recirculation, or aeration, was applied to the feed solution and thus the operating energy could be saved. Samples of both draw and feed solutions were collected every 24 h for analysis.

2.3. Experimental procedure

To optimize the FO system, the operation parameters including the draw solute concentration and the recirculation flow rate of the draw solution were systematically examined with DI water as the feed. Three different concentrations of the draw (fertilizer) solution were examined (25%, 50% and 100%) with a controlled draw recirculation flow rate of 50 mL min⁻¹ (4.2 cm s⁻¹). In each batch test, the FO system was operated for 72 h, followed by physical membrane cleaning. Because no obvious fouling was observed in the experiment, only *in-situ* physical flushing with DI water was applied. The samples of both draw and feed solutions were taken every 24 h to determine RSF. A series of flow rates of recirculation, 25 mL min⁻¹ (2.1 cm s⁻¹), 50 mL min⁻¹ (4.2 cm s⁻¹) and 100 mL min⁻¹ (8.5 cm s⁻¹), were subsequently evaluated for water recovery performance and energy consumption. With the optimized operating conditions, both primary and secondary wastewater effluents were studied as the feed solution in the FO system and the key performance parameters such as water flux, RSF and energy consumption were examined. All experiments were performed in duplicates at room temperature (~20 °C).

2.4. Measurement and analysis

Water flux was determined by measuring the weight change of the draw solution using an electronic balance (Scort Pro, Ohaus, Columbia, MD, USA) that was controlled by the software LoggerPro. The permeate water flux (J_w , L m⁻² h⁻¹, LMH) of the FO system is calculated using Eq. (1):

$$J_w = \frac{m_{t+\Delta t,D} - m_{t,D}}{\rho * S * \Delta t} \quad (1)$$

where $m_{t,D}$ and $m_{t+\Delta t,D}$ (g) are the mass of the draw solution at time t and $t + \Delta t$, respectively; S (m²) represents the area of the membrane; and Δt is the operating period. For specific water flux, Δt is one hour while it equals 24 h for a 24-h cycle average specific water flux.

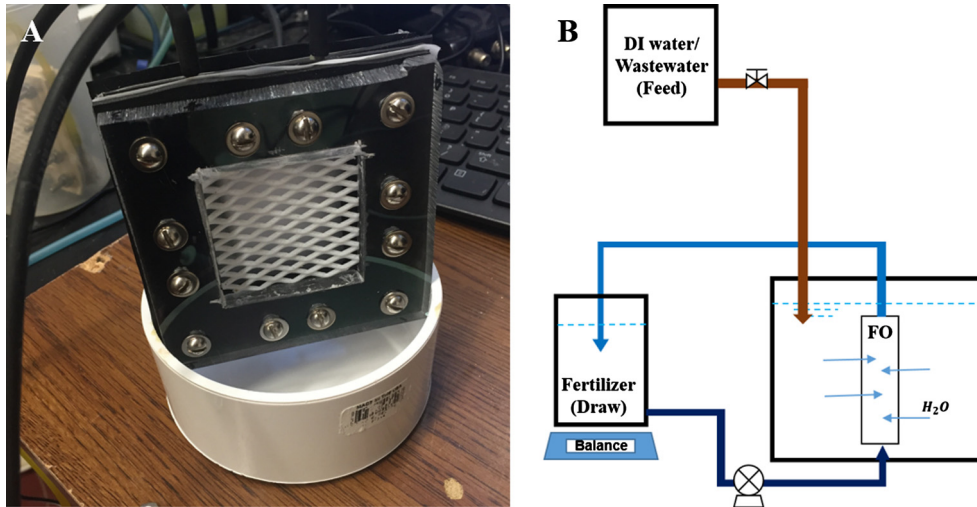


Fig. 1. The submerged FO cell regarding (A) side view with plastic mesh support and (B) schematic of whole system setup.

Table 2
Main characteristics of the actual wastewater.

Parameters	Primary effluent	Secondary effluent
COD (mg L ⁻¹)	63.3 ± 5.1	0 ^a
pH	7.25 ± 0.25	7.37 ± 0.61
Conductivity (μS cm ⁻¹)	1204.0 ± 33.9	489.5 ± 2.1
NH ₄ -N (mg L ⁻¹)	14.8 ± 0.4	0.3 ± 0.4
TN (mg L ⁻¹)	21.0 ± 0.5	12.5 ± 3.5
Total phosphorus (mg L ⁻¹)	4.2 ± 0.6	1.1 ± 0.3
Cl ⁻ (mg L ⁻¹)	144.1 ± 13.1	51.2 ± 1.3
SO ₄ ²⁻ (mg L ⁻¹)	124.4 ± 7.4	28.1 ± 1.2
K ⁺ (mg L ⁻¹)	128.4 ± 3.6	10.5 ± 1.2

^a Below the detect limit.

The conductivity of the feed and draw solution was determined by using a benchtop conductivity meter (Mettler-Toledo, Columbus, OH, USA). The concentrations of ammonium nitrogen (NH₄⁺-N) and total nitrogen (TN) were measured using a spectrophotometer according to the manufacturer's instruction (DR/890, Hach, Loveland, CO, USA). The concentrations of phosphate (PO₄³⁻) and potassium (K⁺) was determined by using ion chromatography (Dionex LC20 ion chromatograph, Sunnyvale, CA, USA) with an ED40 electrochemical detector. Because urea is the dominant organic compound in the liquid fertilizer, the concentration of urea-nitrogen (Urea-N) was indirectly estimated by total organic carbon (TOC-V_{CSN}, Shimadzu, Japan), which measures the concentration of organic carbon in urea (CH₄ON₂) that can be converted to the concentration of Urea-N by Eq. (2):

$$C_{\text{Urea-N}} = \frac{28 * C_{\text{Org,C}}}{12} \quad (2)$$

where $C_{\text{Urea-N}}$ is the concentration of urea nitrogen and $C_{\text{Org,C}}$ is the concentration of TOC, both in mg L⁻¹.

The reverse solute flux (RSF) of nutrient (i.e. Urea-N, NH₄⁺-N, PO₄³⁻, and K⁺) was calculated according to the increment of the corresponding concentration in the feed solution. The RSF (mmol m⁻² h⁻¹) was quantified by the following equation:

$$\text{RSF} = \frac{V_{\text{F}} * C_{\text{f,F}} - (V_{\text{F}} + V_{\text{recovered}}) * C_{\text{i,F}}}{S * t} \quad (3)$$

where V_{F} and $V_{\text{recovered}}$ represent the volume of the feed solution (600 mL constant) and the volume of the recovered water, respectively; $C_{\text{i,F}}$ and $C_{\text{f,F}}$ (mmol mL⁻¹) are the initial and final concentration in feed solution correspondingly. When DI water is applied as

the feed, $C_{\text{i,F}}$ is zero and the solute built-up (SBU) is only affected by RSF. However, when wastewater is used as the feed ($C_{\text{i,F}} \neq 0$), the concentration effect contributes to SBU in the feed solution as Eq. (4):

$$\text{Concentration Effect} = \frac{(V_{\text{recovered}} * C_{\text{i,F}})}{S * t} \quad (4)$$

A dilution rate (DR, %) is defined as the volume ratio between the recovered water ($V_{\text{recovered}}$, L) and the required water (V_{required} , L) that will make the fertilizer applicable. Due to the fact of nutrient loss through RSF and ammonia volatilization, the water to dilute the fertilizer is less than the suggested value by the liquid fertilizer manufacturer. The volume of the required water is related to the remaining percentage of cumulative total nitrogen (CTN) in the DS (Eq. (5)):

$$\text{DR} = \frac{V_{\text{recovered}}}{V_{\text{required}}} = \frac{V_{\text{recovered}}}{V_{\text{theoretical}} * \text{CTN}} \times 100\% \quad (5)$$

In a submerged FO system, energy is mainly consumed by the recirculating pump. The factors that may affect energy consumption include concentration of draw solution, circulation flow rate, the composition of the draw and feed solutions, and diameter of the tubing. The energy (E , kW h m⁻³) for unit recovered water is assessed as Eqs. (6) and (7):

$$E = \frac{P_{\text{system}}}{Q} \approx \frac{P_{\text{pump}}}{Q} \quad (6)$$

$$P_{\text{pump}} = \frac{3600 * (H_{\text{hydraulic}} + H_{\text{dynamic}}) * Q}{1000} \quad (7)$$

where P_{system} and P_{pump} are the consumed power of the FO system and the recirculation pump in kW, respectively; $H_{\text{hydraulic}}$ and H_{dynamic} are the hydraulic and dynamic head of the pump in Pa, respectively; and Q is the recovered water flow rate in m³ h⁻¹. It should be noted that additional energy may be required by other processes, e.g. membrane cleaning (not studied here). All measurements and calculations were obtained in triplicate experiments.

3. Results and discussion

3.1. Effects of the draw concentration

The liquid fertilizer was used as it is (100%), or diluted (25 or 50%) to reduce RSF. Three concentrations of the draw (fertilizer)

solution were investigated for water flux and RSF using DI water as the feed. The results showed that the initial draw concentration was in positive correlation with the volume of the recovered water

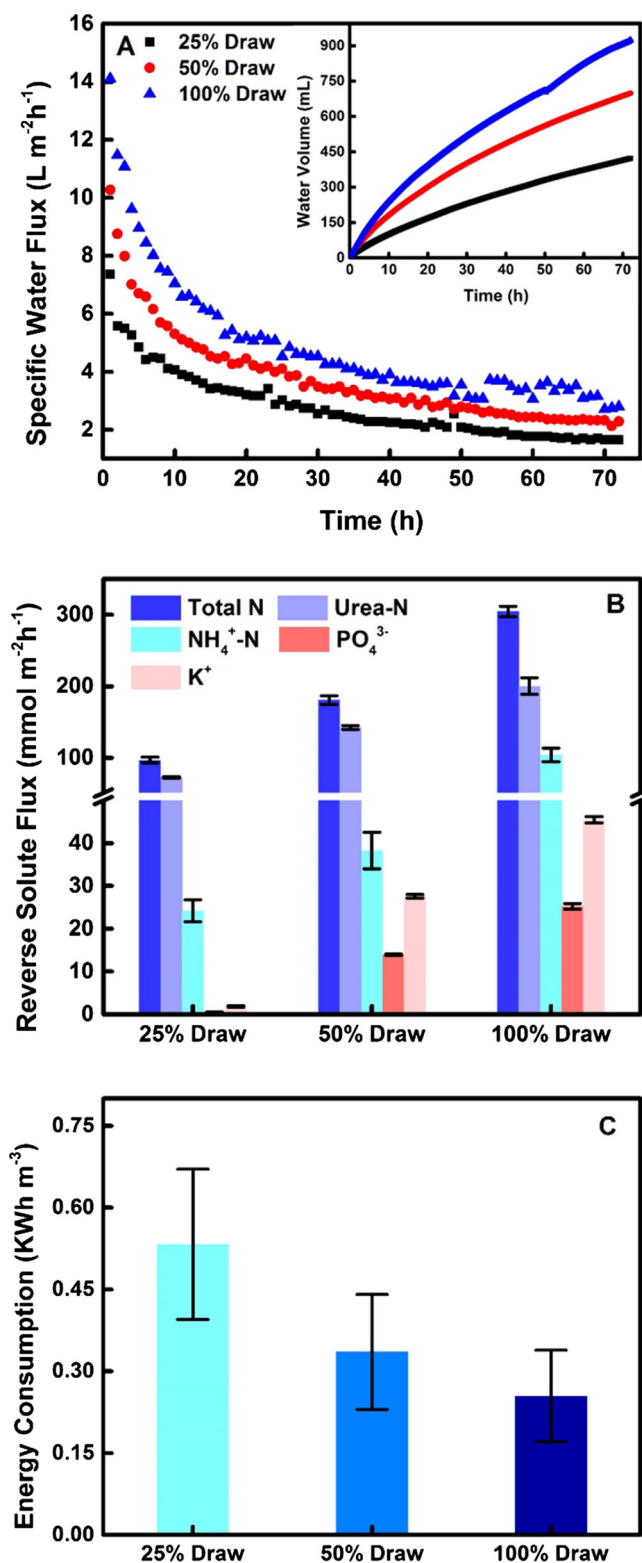


Fig. 2. The effects of the draw concentration on the FO system using DI water as the feed: (A) specific water flux and reclaimed water volume in 72 h; (B) the reverse solute flux of the nutrients; and (C) energy consumption. The draw solution was circulated at 50 mL min⁻¹. Error bars represent the standard deviation of three measurements.

and the nutrient loss rate (Fig. 2). The recovered water volume and the specific water flux under three draw concentrations were presented in Fig. 2A. The water flux increased in response to a higher draw concentration due to the resulted larger osmotic driving force [20]. In a batch mode, the draw solution was gradually diluted by the reclaimed water from the feed side, leading to a reduced osmotic gradient and decreased specific water flux. After 72-h operation, the specific water flux decreased from 14.0 to 2.8 L m⁻² h⁻¹ (LMH) (100% draw), 10.0 to 2.3 LMH (50% draw), and 7.4 to 1.7 LMH (25% draw). Although a higher draw concentration could extract more water, it also required more water to dilute the fertilizer for direct use, rendering a lower dilution rate. For example, the 100% draw reclaimed the highest amount of water (924 mL), but it achieved the lowest dilution rate of 37%. In contrast, the 25% fertilizer had the highest dilution rate of 80% (498 mL of total fresh water, including 423 mL of recovered water and 75 mL of initially added fresh water).

RSF is inevitable in an FO process due to the inherent limitation of membrane materials, and will cause undesired nutrient loss from the draw solution (diluted fertilizer). Clearly, a more concentrated draw solution exhibited a greater RSF (Fig. 2B). Compared with the 25% draw, the 100% draw had a much larger RSF for all the major nutrients. For example, the RSF of total nitrogen for 100% draw was 304.5 ± 7.5 mmol m⁻² h⁻¹ while that for 25% was 96.9 ± 4.0 mmol m⁻² h⁻¹. The disproportional increase of RSF with the increase of draw concentration may be affected by the internal concentration polarization (ICP), which can reduce the net osmotic driven pressure across the membrane and thus influence RSF [21]. RSF was highly variable for different nutrient compounds: TN > Urea-N > NH₄⁺-N > K⁺ > PO₄³⁻. Using 25% fertilizer draw as an example, total nitrogen (TN) exhibited the highest RSF (96.9 ± 4.0 mmol m⁻² h⁻¹) owing to the cross-membrane leakage of Urea-N and NH₄⁺-N. Consistent with the previous study [15], urea has the highest membrane permeability among major nutrient compounds resulting from its low hydrated diameter and small molecular weight [13]. In addition, the urea molecule is neutral and thus helps enhance its movement through the membrane [11]. Having a relatively smaller hydraulic diameter, NH₄⁺-N had a lower RSF (24.2 ± 2.6 mmol m⁻² h⁻¹) than Urea-N (72.7 ± 1.1 mmol m⁻² h⁻¹) but still contributed significantly to RSF of TN. PO₄³⁻ had the lowest RSF (0.5 ± 0.1 mmol m⁻² h⁻¹) for the 25% draw, related to the fact that its hydraulic diameter was the largest compared with other nutrient molecule/ions. The lowest leakage of phosphate was also benefited from its negative multivalent charge, which led to a stronger electrostatic force than that of ammonium and potassium [16].

The concentration of the draw solution affected energy consumption of the FO system through influencing the volume of the recovered water. The defined energy consumption is directly related to the power of the recirculation pump and the recovered water flow rate. At a recirculation flow rate of 50 mL min⁻¹, the higher initial concentration of the draw solution tended to consume less energy: the specific energy consumption was 0.53 ± 0.14 kW h m⁻³, 0.34 ± 0.11 kW h m⁻³ and 0.25 ± 0.08 kW h m⁻³ for the draw concentration of 25%, 50%, and 100%, respectively (Fig. 2C). The transmembrane osmotic pressure governs the water flux and water recovery volume, and thus a higher draw concentration would correspond to a higher osmotic gradient, thereby increasing the water flux and leading to reduced energy consumption. Although 25% draw (fertilizer) solution had relatively higher energy consumption, it was still more preferred considering its higher dilution rate and lower RSF of major nutrients.

3.2. Effect of recirculation flow rate

The recirculation of the draw solution exhibited limited influence on water flux and reclaimed water volume (Fig. 3A). Similar

insignificant change of water flux affected by cross-flow rate was also reported in a previous study using liquid fertilizer as the draw [16]. The average water flux was comparable between the flow rate of 25 mL min^{-1} ($3.2 \pm 0.6 \text{ LMH}$) and 50 mL min^{-1} ($3.1 \pm 0.7 \text{ LMH}$) with similar water recovery (196 mL and 194 mL, respectively). The recirculation flow rate of 100 mL min^{-1} resulted in water flux of $3.6 \pm 0.1 \text{ LMH}$ with recovering 225 mL of water. Ideally, water flux increases at a higher recirculation flow rate, because of faster

mixing of the permeated water within the bulk draw solution and reduced effect of ECP on water flux due to the amplified hydraulic shear force across the membrane [22]. However, in the present FO system the effect of ECP was negligible as the water flux of this FO was relatively low [23]; this explains why the improvement of water recovery was limited at the enhanced recirculation flow rate from 25 to 100 mL min^{-1} . The amount of RSF was similar among three recirculation flow rates, and the same RSF trend of nutrient compounds ($\text{TN} > \text{Urea-N} > \text{NH}_4^+\text{-N} > \text{K}^+ > \text{PO}_4^{3-}$) was also observed (Fig. 3B). This is likely due to the same initial draw concentration and the similar water flux for the tested recirculation flow rates. A higher flow rate of the draw solution recirculation significantly increased the energy consumption (Fig. 3C). The energy consumption at the recirculation flow rate of 25 mL min^{-1} , 50 mL min^{-1} and 100 mL min^{-1} was $0.09 \pm 0.02 \text{ kW h m}^{-3}$, $0.37 \pm 0.08 \text{ kW h m}^{-3}$, and $1.30 \pm 0.28 \text{ kW h m}^{-3}$, respectively. Therefore, considering the comparable water recovery and RSF among different recirculation flow rates, a low recirculation flow rate (e.g., 25 mL min^{-1}) will have a more significant energy benefit with much less demand for energy than a high flow rate. However, it should be recognized that a low water flux will create a high demand for FO membrane area, which will result in a higher capital cost. To fully understand the tradeoff between energy consumption and reduced water flux at lower recirculation flow rates, a detailed cost-benefit analysis must be performed for pilot- or full-scale FO systems.

3.3. Water recovery from wastewater

To investigate the performance of using the commercial liquid fertilizer to recover water from actual wastewater, both the secondary effluent and primary effluent were applied as the feed in the optimized FO system, which was operated with 25% fertilizer draw solution and a recirculation flow rate of 25 mL min^{-1} . The performance of the FO system in terms of water flux, RSF as well as fouling was studied.

When the secondary effluent was applied as the feed, the 24-h water recovered in the first trial was 198.6 mL, while that of the second trial was 198.4 mL; there was no membrane washing in between. This indicates that fouling of the FO membrane with using the secondary effluent was not significant, due to its relatively good effluent quality. The water flux with the secondary effluent was $3.1 \pm 0.2 \text{ LMH}$, comparable to $3.2 \pm 0.6 \text{ LMH}$ with the DI water (Fig. 4A). The variation trend of RSF for major nutrient compounds was also similar between the secondary effluent and the DI water (Fig. 4B). After 24 h experiment, the conductivity of the secondary effluent was $1050 \pm 6.4 \mu\text{S cm}^{-1}$, higher than $344 \pm 1.4 \mu\text{S cm}^{-1}$ of the DI water, because of the concentrating effect on the remaining compounds in the secondary effluent. The secondary effluent achieved a slightly higher dilution rate of 33% than that of the DI feed (30%) in 24 h operation. There are two mechanisms for the solutes built-up in the feed, the RSF that brings the solute from the draw into the feed and the concentrating effect that concentrates the solutes originally present in the feed. More than 95% of the solutes built-up for total N, Urea-N, and $\text{NH}_4^+\text{-N}$ were observed due to RSF, while the concentrating effect only took up less than 5%. However, the RSF contributed less in the built-up of PO_4^{3-} (50%) and K^+ (22%).

Using the primary effluent as the feed resulted in rapid fouling at the feed side of the FO membrane. Three 24-h trials without cleaning the FO membrane between the tests were conducted and their water flux was presented in Fig. 5A. The first trial recovered a water volume of 189 mL, slightly lower than that from the DI water (196 mL). The second trial achieved 136 mL of water recovery, which was further decreased to 104 mL in the third trial, representing 45% reduction compared to the first trial and indicating the fouling of the FO membrane. The primary effluent con-

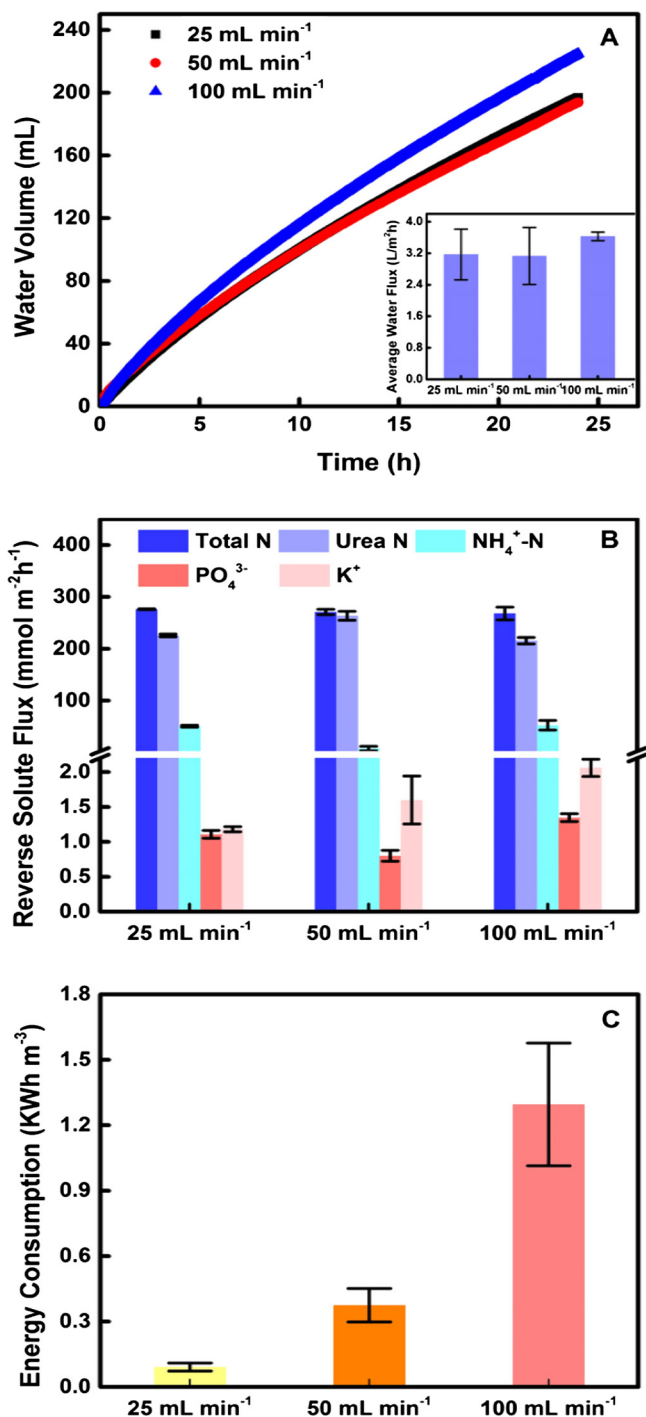


Fig. 3. The performance of the FO system at different recirculation flow rates: (A) reclaimed water volume and average water flux in 24 h; (B) the reverse solute flux of major nutrients; and (C) energy consumption. The concentration of the draw solution was 25% with DI water as the feed. Error bars represent the standard deviation of three measurements.

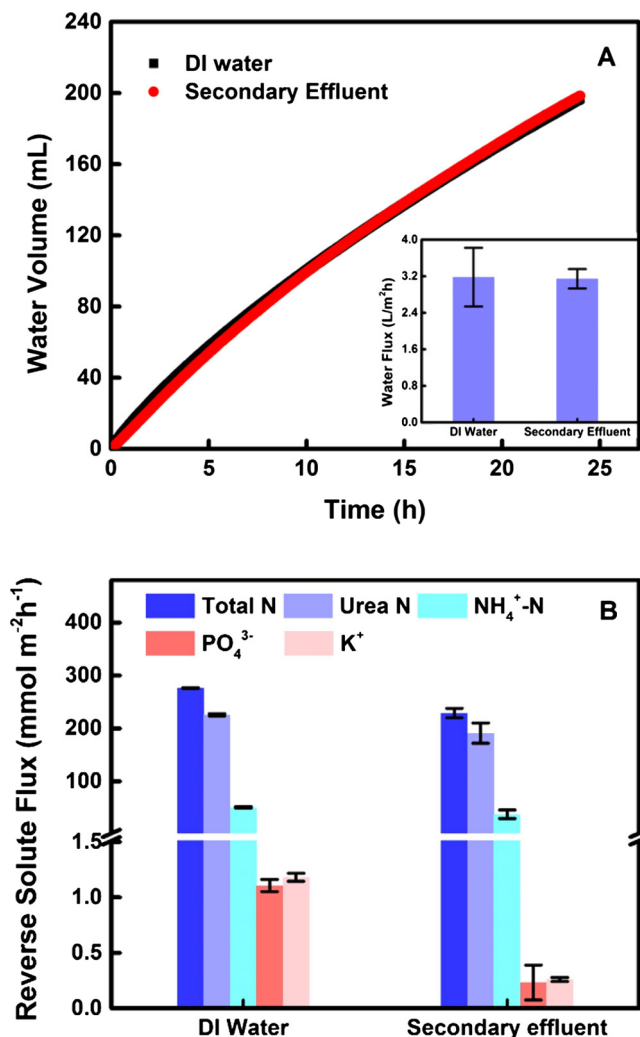


Fig. 4. Water recovery from the secondary effluent as the feed and comparison to that of the DI water (25% draw solution and recirculation flow rate of 25 mL min⁻¹): (A) average water flux and reclaimed water volume in 24 h; and (B) the reverse solute flux of major nutrients. Error bars represent the standard deviation of three measurements.

tained relatively high concentrations of organic and other contaminant compounds, which could result in both biofouling (biofilm formation on the membrane surface) and inorganic scaling; a higher ECP on the surface of the active layer could become more significant due to the relatively high solute concentration in the wastewater [24]. Like the prior tests, the RSF of NH₄⁺-N (102.1 ± 27.2 mmol m⁻² h⁻¹) and Urea-N (92.0 ± 12.4 mmol m⁻² h⁻¹) was much higher than that of PO₄³⁻ or K⁺ (Fig. 5B). The RSF of K⁺ (1.9 ± 0.0 mmol m⁻² h⁻¹) was slightly lower than that of PO₄³⁻ (3.0 ± 0.6 mmol m⁻² h⁻¹), likely due to the relatively higher concentration of potassium in the primary effluent (Table 2), and thus the corresponding concentration gradient of potassium became smaller. The solutes built-up primarily attributed to the RSF includes (Fig. 5C): total N (92%), Urea-N (96%), NH₄⁺-N (91%), and PO₄³⁻ (97%). Because of a low RSF of K⁺, 95% of potassium built-up in the feed was caused by the concentrating effect. Meanwhile, there was about 80% COD built-up by the concentration effect in the feed.

The effect of the composition of the feed solution on energy consumption was significant (Fig. 6). The primary effluent had the energy consumption of 0.17 ± 0.04 kW h m⁻³, significantly higher than 0.10 ± 0.05 kW h m⁻³ with the secondary effluent

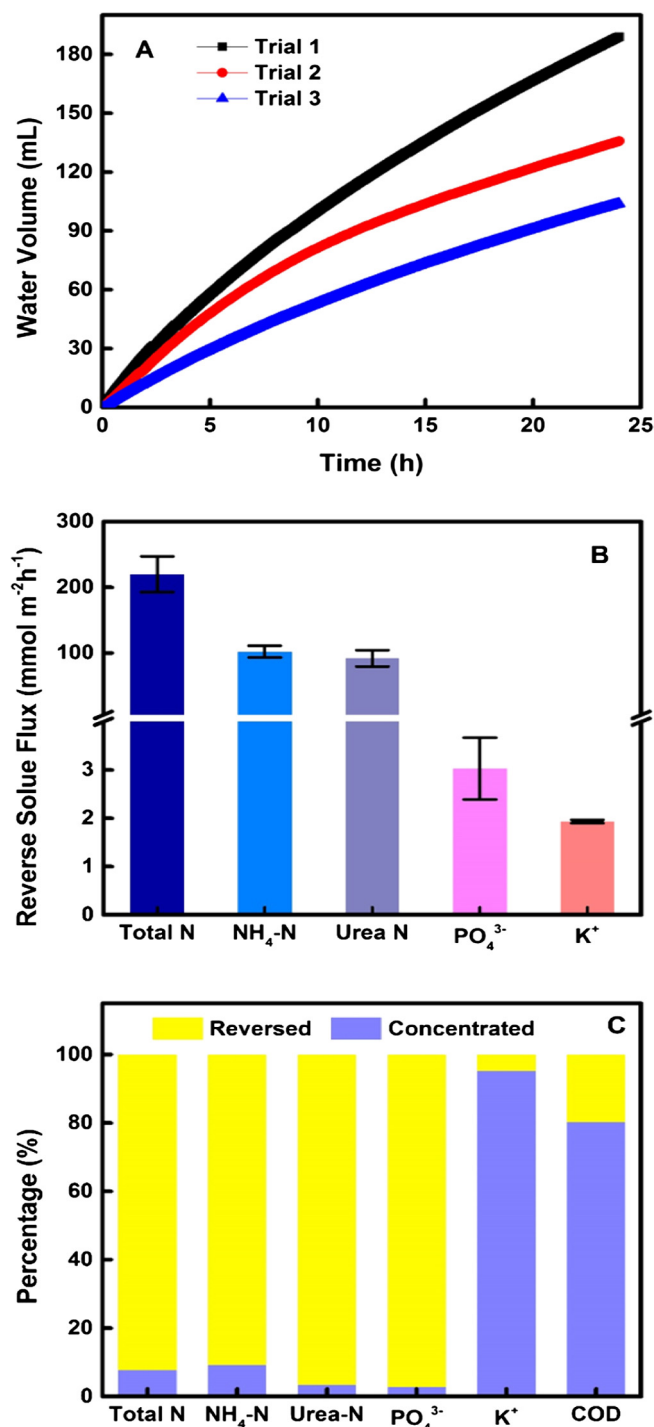


Fig. 5. Water recovery from the primary effluent as the feed (25% draw solution and recirculation flow rate of 25 mL min⁻¹): (A) recovered water volume of three continuous trials; (B) reverse solute flux; and (C) percentage of solute built-up in the feed. Error bars represent the standard deviation of three measurements.

and 0.09 ± 0.02 kW h m⁻³ with the DI water (according to the two sample t-tests with $p < 0.05$). The energy consumption with the primary effluent was estimated using the data of the 3rd trial; an extended operating period with the primary effluent would expect more serious fouling of the FO membrane, which could result in even lower water flux and thus higher energy consumption. Proper cleaning of the FO membrane and certain operating strategies such as backwashing can alleviate fouling and help to maintain stable water flux, but those actions would create a need

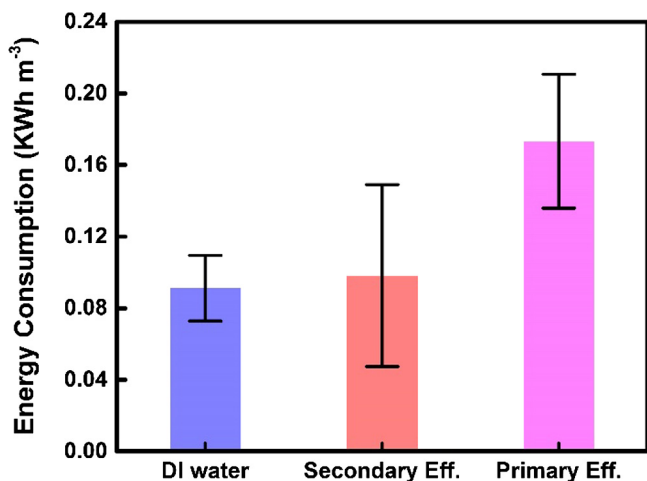


Fig. 6. Energy consumption of the FO system with three types of the feed solution: DI water, secondary effluent and primary Effluent. The draw was 25% fertilizer solution with a recirculation flow rate of 25 mL min⁻¹. Error bars represent the standard deviation of three measurements.

for energy, which was not included in this study. Because of the concentrating effect and the RSF, contaminants can accumulate in the feed solution (wastewater) and reach a concentration that may be over the discharge limit. Therefore, post-treatment or disposal of the feed solution will be required and need additional energy input. This may be conducted through linking FO to other processes such as filtration, biological treatment, electrodialysis, or microbial electrochemical systems [25–28].

4. Conclusions

This study has demonstrated that water recovery from wastewater using a submerged FO system could be an energy-efficient process for promoting wastewater reuse. All three tested operating factors, the draw solute concentration, recirculation flow rates of the draw solution, and the type of the feed solution, had significant influence on energy consumption via affecting water flux or varying power consumption by the recirculation pump. A lower recirculation flow rate would be more advantageous in terms of low energy consumption and without significantly sacrificing the performance of water flux. To obtain a complete evaluation of energy consumption, future studies will need to consider the energy requirement by other operation factors, such as pre- and/or post-treatment of the feed/draw solutions, and fouling control (especially during the long-term operation with actual wastewater as the feed). This study also implies that, to better understand the energy advantages of an FO system, it is important to analyze and present the data of energy consumption.

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References

[1] S. Raja, H.M.N. Cheema, S. Babar, A.A. Khan, G. Murtaza, U. Aslam, Socio-economic background of wastewater irrigation and bioaccumulation of heavy metals in crops and vegetables, *Agric. Water Manag.* 158 (2015) 26–34.

[2] S. Almuktar, M. Scholz, Mineral and biological contamination of soil and Capsicum annum irrigated with recycled domestic wastewater, *Agric. Water Manag.* 167 (2016) 95–109.

[3] O. Paltiel, G. Fedorova, G. Tadmor, G. Kleinstern, Y. Maor, B. Chefetz, Human exposure to wastewater-derived pharmaceuticals in fresh produce: a randomized controlled trial focusing on carbamazepine, *Environ. Sci. Technol.* 50 (2016) 4476–4482.

[4] T.Y. Cath, A.E. Childress, M. Elimelech, Forward osmosis: principles, applications, and recent developments, *J. Membr. Sci.* 281 (2006) 70–87.

[5] T.S. Chung, S. Zhang, K.Y. Wang, J. Su, M.M. Ling, Forward osmosis processes: yesterday, today and tomorrow, *Desalination* 287 (2012) 78–81.

[6] N. Akther, A. Sodiq, A. Giwa, S. Daer, H.A. Arfat, S.W. Hasan, Recent advancements in forward osmosis desalination: a review, *Chem. Eng. J.* 281 (2015) 502–522.

[7] R. Thiruvenkatachari, M. Francis, M. Cunnington, S. Su, Application of integrated forward and reverse osmosis for coal mine wastewater desalination, *Sep. Purif. Technol.* 163 (2016) 181–188.

[8] T.-S. Chung, L. Luo, C.F. Wan, Y. Cui, G. Amy, What is next for forward osmosis (FO) and pressure retarded osmosis (PRO), *Sep. Purif. Technol.* 156 (Part 2) (2015) 856–860.

[9] L. Chekli, S. Phuntsho, H.K. Shon, S. Vigneswaran, J. Kandasamy, A. Chanan, A review of draw solutes in forward osmosis process and their use in modern applications, *Desalination Water Treat.* 43 (2012) 167–184.

[10] D.L. Shaffer, J.R. Werber, H. Jaramillo, S. Lin, M. Elimelech, Forward osmosis: where are we now?, *Desalination* 356 (2015) 271–284.

[11] S. Phuntsho, H.K. Shon, S. Hong, S. Lee, S. Vigneswaran, A novel low energy fertilizer driven forward osmosis desalination for direct fertigation: evaluating the performance of fertilizer draw solutions, *J. Membr. Sci.* 375 (2011) 172–181.

[12] S. Phuntsho, H.K. Shon, T. Majeed, I. El Saliby, S. Vigneswaran, J. Kandasamy, S. Hong, S. Lee, Blended fertilizers as draw solutions for fertilizer-drawn forward osmosis desalination, *Environ. Sci. Technol.* 46 (2012) 4567–4575.

[13] Y. Kim, L. Chekli, W.G. Shim, S. Phuntsho, S. Li, N. Ghaffar, T. Leiknes, H.K. Shon, Selection of suitable fertilizer draw solute for a novel fertilizer-drawn forward osmosis-anaerobic membrane bioreactor hybrid system, *Bioresour. Technol.* 210 (2016) 26–34.

[14] S. Phuntsho, H.K. Shon, S. Hong, S. Lee, S. Vigneswaran, J. Kandasamy, Fertiliser drawn forward osmosis desalination: the concept, performance and limitations for fertigation, *Rev. Environ. Sci. Bio-Technol.* 11 (2012) 147–168.

[15] S. Zou, Z. He, Enhancing wastewater reuse by forward osmosis with self-diluted commercial fertilizers as draw solutes, *Water Res.* 99 (2016) 235–243.

[16] M. Xie, M. Zheng, P. Cooper, W.E. Price, L.D. Nghiem, M. Elimelech, Osmotic dilution for sustainable greenwall irrigation by liquid fertilizer: performance and implications, *J. Membr. Sci.* 494 (2015) 32–38.

[17] S. Zou, H. Yuan, A. Childress, Z. He, Energy consumption by recirculation: a missing parameter when evaluating forward osmosis, *Environ. Sci. Technol.* 50 (2016) 6827–6829.

[18] A.C. van Haandel, J.G. van der Lubbe, Handbook of biological wastewater treatment: design and optimisation of activated sludge systems, *Water Intell. Online* 11 (2012), 9781780400808.

[19] M. Xie, W.E. Price, L.D. Nghiem, Rejection of pharmaceutically active compounds by forward osmosis: role of solution pH and membrane orientation, *Sep. Purif. Technol.* 93 (2012) 107–114.

[20] T. Husnain, Y. Liu, R. Riffat, B. Mi, Integration of forward osmosis and membrane distillation for sustainable wastewater reuse, *Sep. Purif. Technol.* 156 (Part 2) (2015) 424–431.

[21] W. Luo, F.I. Hai, W.E. Price, L.D. Nghiem, Water extraction from mixed liquor of an aerobic bioreactor by forward osmosis: membrane fouling and biomass characteristics assessment, *Sep. Purif. Technol.* 145 (2015) 56–62.

[22] D.H. Jung, J. Lee, D.Y. Kim, Y.G. Lee, M. Park, S. Lee, D.R. Yang, J.H. Kim, Simulation of forward osmosis membrane process: effect of membrane orientation and flow direction of feed and draw solutions, *Desalination* 277 (2011) 83–91.

[23] B.S. Chanukya, S. Patil, N.K. Rastogi, Influence of concentration polarization on flux behavior in forward osmosis during desalination using ammonium bicarbonate, *Desalination* 312 (2013) 39–44.

[24] C. Suh, S. Lee, Modeling reverse draw solute flux in forward osmosis with external concentration polarization in both sides of the draw and feed solution, *J. Membr. Sci.* 427 (2013) 365–374.

[25] X. Li, Y. Lu, Z. He, Removal of reverse-fluxed ammonium by anammox in a forward osmosis system using ammonium bicarbonate as a draw solute, *J. Membr. Sci.* 495 (2015) 424–430.

[26] W. Luo, F.I. Hai, J. Kang, W.E. Price, L.D. Nghiem, M. Elimelech, The role of forward osmosis and microfiltration in an integrated osmotic-microfiltration membrane bioreactor system, *Chemosphere* 136 (2015) 125–132.

[27] Y. Lu, Z. He, Mitigation of salinity buildup and recovery of wasted salts in a hybrid osmotic membrane bioreactor-electrodialysis system, *Environ. Sci. Technol.* 49 (2015) 10529–10535.

[28] H. Yuan, I.M. Abu-Reesh, Z. He, Mathematical modeling assisted investigation of forward osmosis as pretreatment for microbial desalination cells to achieve continuous water desalination and wastewater treatment, *J. Membr. Sci.* 502 (2016) 116–123.