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Application of forward osmosis on dewatering of high nutrient sludge

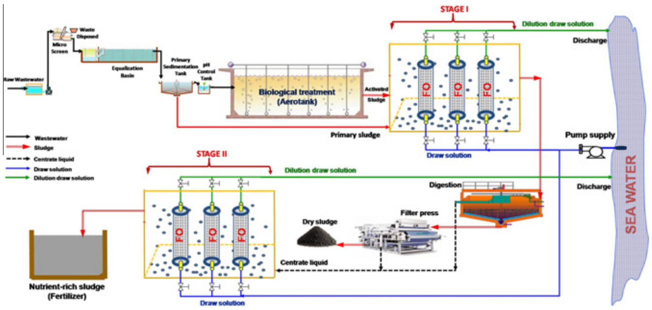
Nguyen Cong Nguyen, Shiao-Shing Chen *, Hung-Yin Yang, Nguyen Thi Hau

Institute of Environmental Engineering and Management, National Taipei University of Technology, No. 1, Sec. 3, Chung-Hsiao E. Rd, Taipei 106, Taiwan, ROC

HIGHLIGHTS

- ▶ High nutrient sludge dewatering by forward osmosis was systematically investigated.
- ▶ Higher biomass loading achieved higher nutrient removal but more flux water decline.
- ▶ Membrane pore radius and sludge barrier layer played main role to remove nutrient.
- ▶ Membrane fouling was subject to cake formation and concentration polarization.
- ▶ Two FO stages are designed to incorporate with conventional biological treatment.

GRAPHICAL ABSTRACT



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ABSTRACT

A novel approach was designed to simultaneously apply low energy sludge dewatering and nutrient removal for activated sludge using forward osmosis (FO). In this study, the municipal wastewater sludge was spiked with different nutrient concentrations to evaluate FO dewatering performance. The results showed that sludge concentration reached 21,511 and 28,500 mg/L after 28 h from initial sludge concentration of 3000 and 8000 mg/L with flow rate of 150 mL/min. Moreover, nutrient and organic compounds in sludge solution were also successfully removed (around 96% of NH_4^+-N, 98% of PO_4^{3-}-P and 99% of dissolved organic carbon (DOC)) due to steric effect of FO membrane and multi barrier layer of sludge forming on membrane surface. Furthermore, the analysis from Scanning Electron Microscopy & Energy Dispersive X-ray Spectroscopy (SEM–EDS) images recorded that FO membrane was fouled by cake layer of sludge in the active layer and NaCl in the support layer.

1. Introduction

Conventional activated sludge process produces a large amount of high water-content sludge. Hence, sludge dewatering process is obligatory for traditional wastewater treatment plant (TWWTP) and often occurs approximately 50–60% of the total operating cost of the whole wastewater treatment plant (Appels et al., 2008; Rai et al., 2004). Basically, reducing volume of sludge is first performed by clarification, gravity thickening, then anaerobic process is used for digestion to stabilize biomass of concentrated sludge, and finally mechanical dewatering process such as filter press is applied (Tuan et al., 2012). Although these conventional technologies are simple, major problems for application are that effluent of clarification process is difficult to achieve stringent regulations and sludge retention time (SRT) is long (Kim et al., 2010; Wang et al., 2008). Moreover, the nutrient-rich centrate from dewatering of digested biomass increases the influent nitrogen load of 15–20% and phosphorus load of 8% after combining with the raw wastewater (Fux et al., 2002; Wild et al., 1997). This is a big challenge for TWWTP since the bioprocess significantly reduced biochemical oxygen demand (BOD), but it did not reliably achieve target discharge limits of nitrogen and phosphorus. In the present work, a novel applica-

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* Corresponding author. Tel.: +886 2 27712171x4142; fax: +886 2 27214142.
E-mail address: f10919@ntut.edu.tw (S.-S. Chen).

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tion of FO on high nutrient sludge dewatering was conducted since low energy dewatering and nutrient removal are achieved at the same time.

As mentioned above, since conventional sludge treatment has some drawbacks, various advanced methods have been proposed for dealing with the problem of sludge dewatering. Wang et al. (2008) used flat-sheet membrane for waste activated sludge thickening and digestion to significantly reduce sludge volume (about 30 g/L thickened sludge was achieved) as well as superior effluent water quality. The main limitations of this process are high energy requirement for operation process and quick membrane fouling. Besides, other physicochemical processes have been used for sludge dewatering, such as microwave irradiation (Yu et al., 2009), ultrasonication process (Feng et al., 2009), electro-dewatering technology (Tuan et al., 2012), combining chemical conditions and filter press (Zhai et al., 2012) and advanced oxidation process (Zhen et al., 2012). Although these methods may have high dewatering potentials, their application has been limited by problems such as high operation cost and secondary environmental pollution.

Recently, FO membrane has attracted much attention in many potential applications such as power generation, food processing and wastewater treatment (Semiat et al., 2010; Garcia-Castello and McCutcheon, 2011; Lutchmiah et al., 2011). Zhu et al. (2012) used FO membrane to conduct simultaneous thickening, digestion, and dewatering of waste activated sludge. After 19 days of operation, the mixed liquor suspended solids (MLSS) concentration reached 39 g/L from an initial amount of 7 g/L, and a dry sludge content of approximately 35% was achieved in 60 min with a sludge depth of 3 mm, indicating a good dewatering efficiency. Nevertheless, it is difficult to evaluate sufficient influence of membrane fouling on dewatering in a small module with initial sludge depth only of 3–5 mm and this study did not investigate nutrient removal ability of FO membrane. Moreover, the combined FO/RO process was conducted to treat the nutrient-rich liquid stream which was produced during the dewatering of digested biomass (Holloway et al., 2007). This method was able to achieve water recovery up to 70% and the final product water met stringent permit limit. However, until now, no research has discussed using FO membrane to simultaneously replace secondary settler and thickening process as well as investigate nutrient removal efficiency on dewatering of activated sludge. Hence, this study focused on evaluating feasibility of applying FO on sludge dewatering for conventional biological treatment to simultaneously improve the water quality. Fundamentally, forward osmosis is a process of water driven by the osmotic pressure difference across the semi-permeable membrane without the aid of external energy. Based on chemical potential gradient, water is spontaneously transported from low concentration solution through the membrane into a solution of higher solute concentration. Therefore, unlike other membrane process with hydraulic pressure requirement such as nanofiltration (NF: 3–20 bar) and reverse osmosis (RO: 5–120 bar), FO has the advantage of low energy consumption (low pressure) which contributed to lower fouling. Theoretical water flux (J_w) across the FO membrane is the product of the membrane permeability coefficient (A_w) and the osmotic pressure driving force:

$$J_w = A_w\,(\pi_{\text{Draw solution}} - \pi_{\text{Feed solution}}) \tag{1}$$

$$\text{with } \pi = \Delta CRT \tag{2}$$

where ΔC is the concentration gradient of solute (mol/L), R is the gas constant (R = 0.082 L atm/(mol K)) and T is the absolute temperature (K).

Consequently, the influences of different biomass and nutrient loadings on activated sludge dewatering are conducted and the objectives are the following: (1) effect of operational conditions on water flux and reverse salt transport; (2) rejection of nutrient and organic compounds; (3) mechanism of FO membrane fouling; (4) the proposed technology fitting on conventional biological treatment.

2. Methods

2.1. Characteristics of forward osmosis membrane and feed solution

In this work, FO membrane was supplied by Hydration Technology Innovations (HTI, ALBANY, OR) in USA with each piece size of 15 × 22 cm and has been determined to be the best available membranes for current FO applications (McCutcheon et al., 2006; Achilli et al., 2009). These flat-sheet cellulose triacetate (CTA) FO membranes, asymmetric structure, were used and classified as cartridge type under membrane orientation of active layer facing feed solution to reduce membrane fouling. Samples of activated sludge were collected at the secondary sedimentation tank of new Taipei wastewater treatment plant in Taiwan with pH value of 7.2. And then these raw sludge samples were added glucose, NH_4Cl and K_2HPO_4 solution to produce synthetic sludge with various MLSS concentrations of 3000–8000 mg/L, NH_4^--N of 100–200 mg/L, PO_4^{3-}-P of 100–200 mg/L and dissolved organic carbon (DOC) of 200 mg/L as presented in Table 1. Nine feed solutions (FS) were used in the work with various MLSS loadings from loading 1 (L_1) to loading 3 (L_3) and various nutrient loadings from loading 4 (L_4) to loading 9 (L_9) according to Eq. (3). Besides, draw solution (DS) was prepared by dissolving NaCl in the deionized (DI) water to achieve DS of NaCl of 36 ± 1 g/L, a concentration of typical seawater.

2.2. Experimental setup

The batch FO experiment setups for sludge dewatering are shown in Fig. 1. The flat sheet was rolled as a tube configuration with total effective membrane surface area of 106 cm^2. The reactor

Table 1
Initial sludge properties with various biomass and nutrient loadings (standard deviation of three replicate experiments).

MLSS loading (g MLSS/m^2 day)	MLSS (mg/L)	SVI (mL/g)	Equivalent NaCl (mg/L)	NH_4^+-N (mg/L)	PO_4^{3-}-P (mg/L)	DOC (mg/L)
L_1 = 360	3000 ± 26	93 ± 3	1455 ± 5	100 ± 4	100 ± 3	200 ± 6
L_2 = 601	5000 ± 39	80 ± 3	1676 ± 9			
L_3 = 961	8000 ± 47	68 ± 2	1790 ± 11			
NH_4^+-N loading (g NH_4^+-N/m^2 day)	NH_4^+-N (mg/L)	SVI (mL/g)	Equivalent NaCl (mg/L)	MLSS (mg/L)	PO_4^{3-}-P (mg/L)	DOC (mg/L)
L_4 = 12	100 ± 4	80 ± 3	1676 ± 9	5000 ± 39	100 ± 3	200 ± 6
L_5 = 18	150 ± 5	80 ± 3	1732 ± 11			
L_6 = 24	200 ± 5	80 ± 3	1785 ± 11			
PO_4^{3-}-P loading (g PO_4^{3-}-P/m^2 day)	PO_4^{3-}-P (mg/L)	SVI (mL/g)	Equivalent NaCl (mg/L)	MLSS (mg/L)	NH_4^+-N (mg/L)	DOC (mg/L)
L_7 = 12	100 ± 3	80 ± 3	1676 ± 9	5000 ± 39	100 ± 4	200 ± 6
L_8 = 18	150 ± 5	80 ± 3	1721 ± 10			
L_9 = 24	200 ± 5	80 ± 3	1757 ± 9			