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Performance of a submerged anaerobic membrane bioreactor with forward osmosis membrane for low-strength wastewater treatment

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ABSTRACT

A submerged anaerobic membrane bioreactor with forward osmosis membrane (FO-AnMBR) was operated at 25 °C for the treatment of synthetic wastewater. As the experiment progressed, the water flux reduced due to the membrane fouling and the increasing salinity in the reactor, and achieved at around 3.5 LMH in one cycle. It was worth noting that the level of salinity in the reactor was not a concern in terms of inhibition or toxic effects on the biological processes. The FO-AnMBR process exhibited greater than 96% removal of organic carbon, nearly 100% of total phosphorus and 62% of ammonia-nitrogen, respectively, suggesting a better removal efficiency than the conventional anaerobic membrane bioreactor. The methane and carbon dioxide compositions achieved concentrations of around 65%–78% and 22%–35%, respectively; and no obvious difference in the biogas composition was observed with the changes of conductivity. With respect to the methane yield, an average value of 0.21 L CH_4 g^{-1} COD was obtained, exhibiting the feasibility of energy recovery by this FO-AnMBR system. Additionally, an increase in the salinity enhanced the accumulation of soluble microbial products, especially for the proteins with 88.9% increment as the conductivity increased from 1.2 to 17.3 ms cm^{-1}. In contrast, a relatively stable concentration of extracellular polymer substances (EPS) was observed, indicating that the influence of conductivity on EPS cannot be directly correlated.

1. Introduction

In recent years, increasing pressure on designing anaerobic reactors, such as reducing the footprint, separating hydraulic retention time (HRT) from the solids retention time (SRT) and minimizing environmental impacts, led to the development of the anaerobic membrane bioreactor (AnMBR) (Stuckey, 2012). The conventional AnMBR with a long SRT and microfiltration membrane (or ultrafiltration membrane) offered numerous advantages, such as improving effluent quality, reducing waste biosolids production and strengthening methane conversion (Huang et al., 2011). However, small molecular weight substances (e.g. natural organic matter) and trace

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contaminants might escape into the effluent, which would be the major barrier to the reuse extent of AnMBR permeate (such as in the drinking water). Additionally, high energy consumption due to the high pressure pumps used in the filtration was another drawback for the conventional AnMBR system; therefore, to explore other plausible technologies with lower energy requirement was necessary.

Recent achievements in the membrane technology have demonstrated that the emerging forward osmosis (FO) membrane process was a potential and effective alternative to conventional membrane processes in seawater desalination and water reclamation. It was a natural process driven by the osmotic pressure difference that retained solutes but allowed water to permeate through a semi-permeable membrane (Cath et al., 2006). Compared with pressure-driven processes, FO was a relatively low fouling treatment option for the absence of hydraulic pressures, and the foulant compaction might be milder due to the utilization of osmotic pressure to extract water (Achilli et al., 2009). More importantly, FO process demonstrated better water quality because of a double barrier, which exhibited remarkable removal efficiency for salts (e.g., Ca^{2+}, above 95%), ammonia (74%), nitrate (78%), sulfamethoxazole (90%), carbamazepine (83%), trace organics (~80%) and so on (Alturki et al., 2012; Cath et al., 2009; Heo et al., 2013; Jin et al., 2012).

Owing to these advantages, several attempts have been made to the development of forward osmosis membrane bioreactors (FO-MBR) combining the biological and FO processes (Achilli et al., 2009; Cornelissen et al., 2008; Zhang et al., 2012), which have demonstrated acceptable permeate flux and remarkable removal efficiency for organic compounds. The high rejection capacity of the FO membrane can effectively retain small and persistent trace organic contaminants in the reactor, thus significantly prolonging the retention time and subsequently facilitating their biodegradation. However, previous researches only focused on the aspect of aerobic bioreactor, wherein the costs of aeration and sludge handling remained as the major disadvantages. Considering that AnMBR can provide the same benefits as MBR (Smith et al., 2012), it was reasonable to suppose that the anaerobic membrane bioreactor with forward osmosis membrane (FO-AnMBR) retained the inherent advantages of FO-MBR but with reduced energy requirements and lower biomass yield. Nevertheless, to the best of our knowledge no studies have investigated the performance of FO-AnMBR.

In this study, the performance of a laboratory-scale FO-AnMBR system fed with synthetic wastewater and operated at 25 °C was evaluated to report on water flux, reverse salt transport, nutrient removal, volatile fatty acids (VFAs) production and gas composition. Simultaneously, the characteristics of soluble microbial products (SMP) and extracellular polymer substances (EPS) with the increase of conductivity were investigated.

2. Materials and methods

2.1. FO-AnMBR configuration and operating conditions

A laboratory-scale anaerobic membrane bioreactor with 3.6 L of working volume was run at 25 °C (Fig. 1), which was equipped with pH, conductivity, pressure and oxidation-reduction potential (ORP) monitoring units (Mettler-Toledo M200 system). A flat-sheet membrane module made of cellulose triacetate (CTA) membranes (Hydration Technologies Inc.) with 0.025 m^2 was submerged in the tank. The membranes were oriented with active side facing the reactor and support sides facing the draw solution. A synthetic wastewater simulating municipal wastewater was used as feed water (see Table S1). The influent pump was controlled by a water level sensor to maintain a constant water level in the reactor. Produced biogas was recycled through gas diffuser both to mix the biomass and scour the membrane surface for fouling control, and the recirculation rate was controlled at 2 L min^{-1}. A 0.5 M NaCl solution was used as the draw solution (with the conductivity in a range of 45.0–45.5 ms cm^{-1}), which was maintained by conductivity control connected to a 5 M NaCl solution tank. The flow rate of draw solution was kept at 0.4 L min^{-1} to minimize the effect of internal concentration polarization. The permeate flux was derived by mass balance to account for the mass of 5M NaCl dosed into the draw solution tank, and then normalized for the membrane area. During the entire FO-AnMBR operation, the sludge retention time (SRT) was kept at 90 days, and the hydraulic retention time (HRT) was in a range of 15–40 h depending on the membrane flux.

2.2. Analytical methods

Mixed liquor suspended solids (MLSS), volatile suspended solids (VSS) and total phosphorus (TP) were determined using Standard Methods (APHA., 1998). Chemical oxygen demand (COD), total nitrogen (TN), and ammonia concentration (NH_4^+–N) were analyzed using HACH USEPA reactor digestion method (HACH 2125815/2415815), persulfate digestion method (HACH 2714100/2672245) and salicylate method (HACH 2606945), respectively. The gas production rate was measured by the liquid displacement method; additionally, the composition of gas was determined using a Agilent GC-TCD fitted with J&W 113-4362 column (0.32 mm × 60 m, 0 μm) and Agilent 19095P-MS6 column (0.53 mm × 30m, 50 μm). VFAs were analyzed by Perkin–Elmer HPLC system with H^+ cation exchange column (HAMILTON, 305 × 7.8 mm, 8–10 μm) and UV–Vis detection at 210 nm.

The sludge from the bulk phase was harvested by centrifugation (4000 rpm, 10 min), washed with water and then resuspended in sterilized deionized water for analysis of EPS using heat treatment (Morgan et al., 1990). The proteins and carbohydrates were determined using the modified Lowry method (Frolund et al., 1995) and the phenol-sulphuric acid method (Dubois et al., 1956), respectively. The three-dimensional excitation-emission matrix (EEM) spectroscopy (LS55, Perkin–Elmer Co.) was applied to characterize the SMP under different conductivities. Particle size distribution of the anaerobic mixed liquor was measured by laser scattering with a detection range of 0.02–2000 μm (Mastersizer 2000, Malvern).

3. Results and discussion

3.1. Flux performance and salt accumulation

Changes of membrane flux and conductivity against operation time are illustrated in Fig. 2. In general, the membrane