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Sustainable organic loading rate and energy recovery potential of mesophilic anaerobic membrane bioreactor for municipal wastewater treatment

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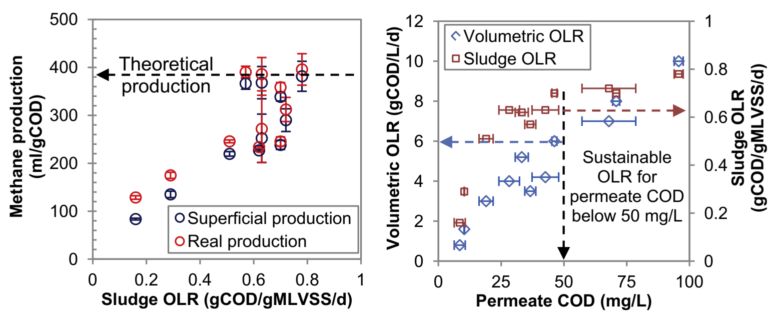
HIGHLIGHTS

- Sustainable volumetric and sludge OLR was 6 gCOD/L/d and 0.63 gCOD/gMLVSS/d.
- Sustainable sludge OLR resulted in high methane production up to theoretical value.
- A very low biomass production of 0.015–0.026 gMLVSS/gCOD was observed.
- A sustainable flux of 6 L/m^2/h maintained stable permeability for over 3 months.
- AnMBR coupling heat pump and forward osmosis was promising in temperate area.

GRAPHICAL ABSTRACT



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ABSTRACT

The overall performance of a mesophilic anaerobic membrane bioreactor (AnMBR) for synthetic municipal wastewater treatment was investigated under a range of organic loading rate (OLR). A very steady and high chemical oxygen demand (COD) removal (around 98%) was achieved over a broad range of volumetric OLR of 0.8–10 gCOD/L/d. The sustainable volumetric and sludge OLR satisfying a permeate COD below 50 mg/L for general reuse was 6 gCOD/L/d and 0.63 gCOD/gMLVSS (mixed liquor volatile suspended solids)/d, respectively. At a high sludge OLR of over 0.6 gCOD/gMLVSS/d, the AnMBR achieved high methane production of over 300 ml/gCOD (even approaching the theoretical value of 382 ml/gCOD). A low biomass production of 0.015–0.026 gMLVSS/gCOD and a sustainable flux of 6 L/m^2/h were observed. The integration of a heat pump and forward osmosis into the mesophilic AnMBR process would be a promising way for net energy recovery from typical municipal wastewater in a temperate area.

1. Introduction

Municipal wastewater can be regarded as a valuable resource rather than a simple waste (Mo and Zhang, 2013). Compared with the widely-used aerobic biological process for municipal wastewater treatment, the anaerobic biological process has some potential benefits including no energy input required for aeration, energy recovery through methane production, lower sludge production and most nutrients (nitrogen and phosphorus) remain in the effluent suitable for agricultural and landscaping irrigation reuse (McCarty et al., 2011). Despite these advantages, the perceived notion is that an anaerobic biological process is inappropriate for municipal wastewater treatment as there is relatively low concentration of organics (in terms of chemical oxygen demand (COD), usually less than 1000 mg/L) with a significant particulate fraction in

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municipal wastewater. This makes it technically challenging to achieve a high organic loading rate (OLR) to sustain a sufficient amount of slow-growing anaerobic biomass in the bioreactor. Furthermore, a conventional anaerobic activated sludge process is generally restricted by the sludge-water separation performance in a gravitational settler (McCarty et al., 2011), and may not be able to achieve high organics removal and good effluent quality.

An anaerobic membrane bioreactor (AnMBR) – a hybrid of anaerobic digestion and membrane separation – may overcome the drawbacks of the conventional anaerobic activated sludge process through the excellent sludge-water separation by a microfiltration (MF) or ultrafiltration (UF) membrane. The coupling of a membrane results in high biomass (and thus high OLR and organics removal), and produces a good quality effluent that has significantly lower amount of particles and pathogens (Liao et al., 2006). Several recent reviews on published AnMBR studies over the past two decades show that AnMBR can achieve high COD removal (more than 85%, up to 99%) with low permeate COD (less than 100 mg/L, down to below 10 mg/L) under a range of hydraulic retention time (HRT) of 3–120 h, sludge retention time (SRT) of 15 d to infinity, volumetric OLR of 0.2–5 gCOD/L/d and operating temperature of 10–37 °C for real and/or synthetic municipal wastewater treatment (Lin et al., 2013; Ozgun et al., 2013; Skouteris et al., 2012; Smith et al., 2012; Stuckey, 2012).

For the energy recovery (expressed as methane production) from municipal wastewater through an AnMBR, the observed methane production in terms of millilitres methane (at the standard conditions of 25 °C and 1 atm) per gram of removed COD (ml/gCOD) has been reported to be in the range of 110–320 ml/gCOD (Gimenez et al., 2011; Ho and Sung, 2009; Hu and Stuckey, 2006; Huang et al., 2013; Kim et al., 2011; Lin et al., 2011; Martinez-Sosa et al., 2011; Saddoud et al., 2007; Wen et al., 1999; Yoo et al., 2012). However, it is still substantially lower than the theoretical value of 382 ml/gCOD, even considering the maximum methane production of 320 ml/gCOD reported which was achieved under optimal conditions for a mesophilic AnMBR using synthetic municipal wastewater (Hu and Stuckey, 2006). Most of these mentioned studies have maintained the optimal conditions including mesophilic temperature, neutral pH, long SRT and strict anaerobic environment to favor methane production. In order to enhance methane production further, increasing the food to microorganism ratio (F/M), and thus the sludge OLR, may be a possible way as high sludge OLR would promote more microorganisms to convert more substrate into methane. However, due to both high biomass concentration in terms of mixed liquor (volatile) suspended solids (ML(V)SS) and low volumetric OLR in these studies, sludge OLR is generally in the low range of 0.03–0.5 gCOD/gMLVSS/d, which may limit the observed methane production. There are only a few studies (Saddoud et al., 2007) that showed increasing biogas production with OLR. Therefore, the comprehensive effects of OLR on methane production as well as organics removal and biomass production still need further investigation to optimize AnMBR operation.

The overall performance (COD removal, permeate COD, methane/biomass production, membrane permeability) of a mesophilic AnMBR treating synthetic municipal wastewater at different OLR levels was intensively investigated to explore the sustainable OLR in this study. The energy recovery potential from typical municipal wastewater through AnMBR was also analyzed.

2. Methods

2.1. AnMBR set-up

A schematic diagram of the lab-scale AnMBR set-up used in this study is shown in Fig. 1. The set-up consisted of an commercial anaerobic completely stirred tank reactor (CSTR, Applikon Biotechnology, Netherland) with an effective volume of 2 L and integrated control functions (including temperature, pH, level, mixing), a side-stream hollow fiber polyvinylidene fluoride (PVDF) UF membrane module with a nominal pore size of 30 nm and effective filtration area of 310 cm^2, pumps (for feeding influent, sludge recirculation, membrane permeation, biogas recirculation), influent/permeate tank, biogas collection system, pressure sensors, and connection tubing.

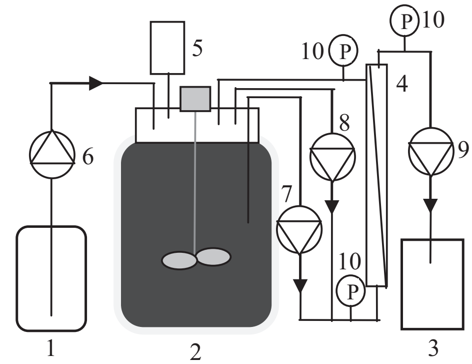

Fig. 1. Schematic diagram of the lab-scale AnMBR set-up.

The synthetic municipal wastewater in the influent tank was pumped into the well-mixed anaerobic CSTR under the control of a level sensor to maintain the stable effective volume. The sludge mixture in the anaerobic CSTR was pumped at a pre-set flow (corresponding to superficial crossflow velocity (CFV) of 0.1–0.3 m/s along the membrane surface) into the membrane module, where one part passed through the membrane into the permeate tank while the other part was recycled back into the anaerobic CSTR (i.e., sludge recirculation). The pre-set permeate flow was controlled by the permeate pump with intermittent operating mode (on/off of 9/1 min) to achieve constant-flux operation. The biogas in the anaerobic CSTR was also continuously pumped at a pre-set flow (corresponding to superficial CFV of 0.1–0.2 m/s along the membrane surface) into the membrane module to enhance gas–liquid diphase crossflow scouring along the membrane surface for membrane fouling control. The pressure sensors connected in recirculation and permeate tubing were used to monitor the trans-membrane pressure (TMP) as the indicator for membrane fouling. A gas bag was connected to the headspace of the anaerobic CSTR to collect biogas.

2.2. AnMBR operational conditions

A synthetic recipe simulating municipal wastewater (COD 400 mg/L) in Table 1 was used in this study. It contained COD of 400 ± 10 mg/L and total organic carbon (TOC) of 115 ± 5 mg/L, which resulted in a mean oxidation number (MON) of −1.2 according to the equation (MON = 4–1.5 × COD/TOC). In order to explore the maximum sustainable OLR, concentrated wastewater (COD 750–5000 mg/L) from the original recipe was also used due to the limit of reducing HRT caused by the small membrane area. A concentrated stock (20 times) was prepared weekly using tap water and stored in a refrigerator (4 °C), which was diluted to the target concentration for daily use as influent.