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Single-stage versus two-stage anaerobic fluidized bed bioreactors in treating municipal wastewater: Performance, foulant characteristics, and microbial community

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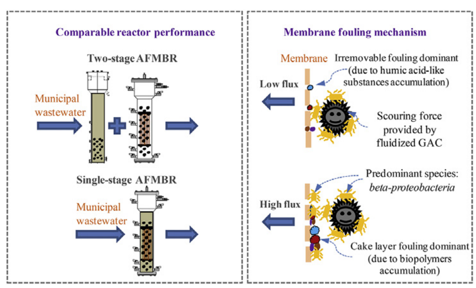
HIGHLIGHTS

- Single and two-stage AFMBRs exhibited comparable reactor performance.
- Different membrane fouling mechanisms were identified in both AFMBRs at a low flux.
- Formation of cake layer was the main cause of membrane fouling in single-stage AFMBR.
- *beta-Proteobacteria* were dominant in both AFMBRs.
- Different abundances of dominant species were developed in both AFMBRs.

GRAPHICAL ABSTRACT



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ABSTRACT

This study examined the receptive performance, membrane foulant characteristics, and microbial community in the single-stage and two-stage anaerobic fluidized membrane bioreactor (AFMBR) treating settled raw municipal wastewater with the aims to explore fouling mechanisms and microbial community structure in both systems. Both AFMBRs exhibited comparable organic removal efficiency and membrane performances. In the single-stage AFMBR, less soluble organic substances were removed through biosorption by GAC and biodegradation than those in the two-stage AFMBR. Compared to the two-stage AFMBR, the formation of cake layer was the main cause of the observed membrane fouling in the single-stage AFMBR at the same employed flux. The accumulation rate of the biopolymers was linearly correlated with the membrane fouling rate. In the chemical-cleaned foulants, humic acid-like substances and silicon were identified as the predominant organic and inorganic fouants respectively. As such, the fluidized GAC particles might not be effective in removing these substances from the membrane surfaces. High-throughout pyrosequencing analysis further revealed that *beta-Proteobacteria* were predominant members in both AFMBRs, which contributed to the development of biofilms on the fluidized GAC and membrane surfaces. However, it was also noted that the abundance of the identified

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dominant in the membrane surface-associated biofilm seemed to be related to the permeate flux and reactor configuration.

1. Introduction

With increasing concerns on the sustainability of wastewater-energy nexus, anaerobic membrane bioreactors (AnMBRs) have received growing attention because of potential energy recovery and sludge reduction compared with conventional aerobic MBRs (Skouteris et al., 2012; Stuckey, 2012). These suggest the possibility to achieve energy self-sufficiency in AnMBRs (McCarty et al., 2011). However, membrane fouling in AnMBRs is still a major challenge for their wide applications, which may lead to high energy consumption and operating cost. Therefore, the effective control strategies of membrane fouling are needed for sustainable operation of AnMBRs. Generally, for pressure-driven cross-flow AnMBRs, a high cross-flow velocity is required to prevent the deposition of foulants on membranes, whereas bubbling through biogas recirculation has been practiced to mitigate membrane fouling in vacuum-driven submerged AnMBRs (Stuckey, 2012; Smith et al., 2012). However, these two methods for fouling control in AnMBRs are energy intensive. For example, the energy demand associated with biogas recirculation for fouling control had been reported to be in the range of 0.69–3.41 kWh/m^3 in submerged AnMBRs (Martin et al., 2011), which was even higher than that the energy consumption incurred in aerobic submerged MBRs (e.g. 0.5–1.0 kWh/m^3) (Krzeminski et al., 2012).

As an alternative, two-stage anaerobic fluidized-bed membrane bioreactor (AFMBR) has been proposed by Kim et al. (2011), in which the first-stage is an anaerobic fluidized bed bioreactor (AFBR) for biosolids reduction and biodegradation of soluble organics by anaerobic bacteria grown on granular activated carbon (GAC), and the second stage is an AFMBR where membrane fouling is expected to be controlled through the scouring created by fluidized GAC. Importantly, the calculated two-stage AFMBR energy requirement was only about 0.028–0.227 kWh/m^3, which was significantly lower than conventional aerobic/anaerobic MBRs and could be offset by the produced methane gas (Kim et al., 2011; Shin et al., 2014).

To further reduce costs and footprint associated with the construction and the maintenance of AFMBR, combining the two stages into a single reactor configuration has been examined, e.g. Gao et al. (2014a, 2014b) proposed an integrated reactor in which the outer loop of the reactor served as an AFBR and the inner loop was considered as an AFMBR, both with GAC as carriers. Moreover, Bae et al. (2014) also evaluated the performance of a single-stage AFMBR in treating synthetic wastewater, and found that its performance was comparable with the two-stage AFMBR in terms of organic removal and membrane performance. It has been believed that in the two-stage AFMBR, the first-stage reactor can retain organic solids and degrade soluble organic substances, leading to reduced potential foulants going into the second-stage AFMBR. However, such observations should be further verified with real municipal wastewater containing more refractory organic substances and biosolids. In addition, little information is currently available for transport of organic substances, characterization of membrane foulants and microbial community structure in the single-stage and two-stage AFMBR systems.

In this study, a series of experiments were concurrently conducted in the single-stage and two-stage AFMBR systems fed with settled municipal wastewater, with the focus on better understanding of membrane fouling mechanisms and membrane foulants characterization at different permeate fluxes. The profiles of microbial communities developed on the membrane and GAC surfaces, and in the suspension were also determined. It is expected that this study can shed lights on the ways to further reduce energy consumption of AFMBRs by integrating two-stage reactors into a single-stage AFMBR for treating real municipal wastewater.

2. Materials and methods

2.1. Operating conditions of single-stage and two-stage AFMBRs

Fig. 1 describes a schematic diagram of single-stage and two-stage AFMBRs. Raw sewage (24 m^3/day) from Ulu Pandan Water Reclamation Plant, Singapore flew through a pilot clarifier before feeding to the single-stage and two-stage AFMBRs. The two-stage AFMBR consisted of a pilot-scale AFBR installed at the Ulu Pandan Water Reclamation Plant, Singapore and a lab-scale AFMBR. The pilot AFBR had a reactor volume of 2 m^3 and contained 250 kg of 10 × 30 mesh GAC (Calgon Carbon, USA). Anaerobic digested sludge (equivalent to ~850 g dry weight) from the Ulu Pandan Water Reclamation Plant digester was inoculated into the AFBR. The GAC and sludge were kept fluidized by recycling reactor effluent at an upflow velocity of 0.009 m/s. The HRT of the pilot AFBR was 2 h. The biogas production rate was 0.14 ± 0.08 L/min. After 240 days of operation, the AFBR effluent was fed to the lab-scale second-stage AFMBR. The second-stage AFMBR had an effective reactor volume of 2.7 L, containing 450 g GAC at a size of 1–1.4 mm (Calgon Carbon, USA). A polyvinylidene fluoride (PVDF) hollow fiber membrane module (pore size at 0.1 μm, GE, USA) with an area of 0.022 m^2 was submerged into the reactor. The liquid upflow velocity was fixed at 0.018 m/s to ensure that the fluidized GAC particles fully scoured the membrane surface. The reactor was operated at a HRT of 2 h (i.e., 32.4 L/day of feed, a total HRT of the two-stage AFMBR was 4 h) and a flux of 10, 20, and 30 L/m^2 h, which was correspondent to the volumetric flowrate ratio of discharge effluent to permeate at 5, 2, and 1 respectively. At each tested permeate flux, a new membrane module was employed.

The lab-scale single stage AFMBR had the same reactor volume, GAC packing amount, membrane configuration, and liquid upflow velocity as the second-stage AFMBR in the two-stage system except it was inoculated with 1.5 g (dry weight) of anaerobic digested sludge from the Ulu Pandan Water Reclamation Plant digester. The single-stage AFMBR was operated at a HRT of 3 h (i.e., 21.6 L/day) and a flux of 5, 10, 20, and 30 L/m^2 h, which was correspondent to the volumetric flowrate ratio of discharge effluent to permeate at 7, 3, 1, and 0.4, respectively. The permeate suction pressure and permeate flow rate were recorded via Labview (National Instruments, USA) installed on a computer. Both systems were operated at infinity SRT (i.e., no sludge removal except sampling) and a room temperature at 23 ± 1 °C. The difference of HRT for the two membrane reactors (2 h vs. 3 h) ensured that the both reactors received similar soluble organic loading (Table S1) for a fair comparison. In addition, as this study focused on membrane fouling mechanisms, thus, biogas production of both lab-scale AFMBRs were not examined.