A performance evaluation of three membrane bioreactor systems: aerobic, anaerobic, and attached-growth
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ABSTRACT
Water sustainability is essential for meeting human needs for drinking water and sanitation in both developing and developed countries. Reuse, decentralization, and low energy consumption are key objectives to achieve sustainability in wastewater treatment. Consideration of these objectives has led to the development of new and tailored technologies in order to balance societal needs with the protection of natural systems. Membrane bioreactors (MBRs) are one such technology. In this investigation, a comparison of MBR performance is presented. Laboratory-scale submerged aerobic MBR (AMBR), anaerobic MBR (AnMBR), and attached-growth aerobic MBR (AtMBR) systems were evaluated for treating domestic wastewater under the same operating conditions. Long-term chemical oxygen demand (COD) and total organic carbon (TOC) monitoring showed greater than 80% removal in the three systems. The AnMBR system required three months of acclimation prior to steady operation, compared to one month for the aerobic systems. The AnMBR system exhibited a constant mixed liquor suspended solids concentration at an infinite solids retention time (i.e. no solids wasting), while the aerobic MBR systems produced ~0.25 g of biomass per gram of COD removed. This suggests a more economical solids management associated with the AnMBR system. Critical flux experiments were performed to evaluate fouling potential of the MBR systems. Results showed similar critical flux values between the AMBR and the AnMBR systems, while the AtMBR system showed relatively higher critical flux value. This result suggests a positive role of the attached-growth media in controlling membrane fouling in MBR systems.

Key words | aerobic treatment, anaerobic treatment, attached-growth, biological treatment, membrane bioreactor, membrane fouling

INTRODUCTION
Water sustainability is essential for meeting human needs for drinking water and sanitation in both developing and developed countries. Reuse, decentralization, and low energy consumption are key objectives to achieve sustainability in wastewater treatment. Consideration of these objectives has led to the development of new and tailored technologies aimed at balancing societal needs with the protection of natural systems. Membrane bioreactors (MBRs) are one such technology (Fane & Fane 2005; Fawehinmi et al. 2005). However, the establishment of MBR technology has been slower than expected because decision makers view MBRs as high risk and costly compared to conventional technology (Judd 2006). MBRs have mostly been used to treat municipal and industrial wastewater where water reuse is desired, a small footprint is required, or stringent discharge standards exist (Yang et al. 2006b; Kang et al. 2007).

One of the main challenges in developing MBR technologies is to control fouling with modest energy input (Le-Clech et al. 2006). Membrane fouling is considered to be one of the major limitations to widespread application of MBR technology and has been investigated from various perspectives, including the causes, characteristics, and mechanisms of fouling and methods to prevent or reduce membrane fouling (Judd 2005; Le-Clech et al. 2006; Meng et al. 2009; Wang & Wu 2009). Fouling markedly affects membrane cleaning and replacement intervals, system productivity, and membrane integrity; all of which are factors that affect energy requirements and costs (Judd 2006; Le-Clech et al. 2006).
The great majority of MBR systems are operated under aerobic conditions (Judd 2008). In recent years there has been growing interest in the use of anaerobic MBR (AnMBR) systems due to their potential advantages over aerobic systems, which include low sludge production and net energy production through methane gas generation (Aquino et al. 2006; Jeison & van Lier 2008). Yet, despite the many advantages, their use is still limited, mainly because of the typical higher membrane fouling than aerobic MBR systems (Le-Clech et al. 2006). Furthermore, the vast majority of literature on AnMBR systems focuses on the treatment of high-strength wastewater, such as landfill leachate, brewery wastewater, and palm oil wastewater (Ince et al. 1995; Choo & Lee 1996; Cho & Fane 2002). In general, anaerobic biological processes have traditionally been favored over aerobic processes for the treatment of high-strength wastewater due to their ability to operate at high loading rates (5–30 kg COD/m³-day compared to less than 1 kg COD/m³-day for aerobic systems). However, anaerobic biological systems have not received much attention for municipal wastewater treatment due in large part to the longer biomass retention times needed to support the slower-growing anaerobic microorganisms. MBRs, however, offer a unique opportunity in anaerobic systems for municipal wastewater treatment due to their ability to retain biological solids for long periods of time independent of the reactor volume or hydraulic retention time.

Another, more unique MBR configuration is the attached-growth MBR (AtMBR). In this configuration, a high density of immobilized microbes allows for a high biomass concentration (Annachhatre 1996; Ng et al. 2010), which can help provide better resistance to changes in operational conditions (e.g. pH, COD, temperature, or water flux) or withstand stress induced by toxic compounds or high shear forces (Liu & Tay 2001; Ye et al. 2005). Additionally, the physiology and gene expression of microorganisms attached to surfaces has been reported to be markedly different than that of microorganisms growing in a suspended culture (Boles et al. 2004), which may allow for a greater range of degradation capabilities. In MBR systems, this could lead to less accumulation of organic foulants on the membrane (Artiga et al. 2005). Furthermore, attached microbial systems can lower membrane fouling by providing a surface other than the membrane for microbial attachment; or by providing a location for soluble microbial products or hydrophobic compounds to adsorb to, thus limiting sorption to the membrane and allowing increased time for degradation. For these reasons, not only does the AtMBR have the potential to improve contaminant degradation, it also may lower the fouling potential of the membrane (Lee et al. 2006). Recently, several researchers have investigated using aerobic attached biomass bioreactors (Sombatsompop et al. 2006; Yang et al. 2006a; Leiknes & Odegaard 2007) and MBR systems operated with powered activated carbon (PAC) (Hu & Stuckey 2007). In these investigations, it was reported that the attachment surface enables fouling reduction in the membrane module and enhancement of the biological process by minimization of floc breakage.

The objective of this investigation is to compare the performance of AMBR, AnMBR, and AtMBR systems for the treatment of domestic wastewater under the same operating conditions. Three identical laboratory-scale MBRs were constructed and operated. Performance was evaluated based on chemical oxygen demand (COD) and total organic carbon (TOC) removal at various stages of the process, as well as net biomass production. Furthermore, critical flux analyses were performed to compare the fouling potential of each of the bioreactor configurations.

MATERIALS AND METHODS

Laboratory-scale MBRs

Three laboratory-scale submerged systems (an AMBR, AnMBR, and AtMBR system) were used to analyze system performance of the three MBR configurations (Figure 1). The acrylic reactors had a volume of 6 L (dimensions of 24 cm (L) × 7.5 cm (W) × 40 cm (H)). Each bioreactor had a permeate withdrawal line that splits into a recycle line and an effluent line through a three-way valve. The three-way valve enabled water flux through the membrane to be controlled independently of the hydraulic retention time (HRT). The trans-membrane pressure (TMP) and permeate flow rate were monitored using high accuracy pressure transducers and flow meters (Cole-Parmer, Vernon Hills, IL, USA) and recorded using a data acquisition module (USB-6009, National Instruments, Austin, TX, USA) and LabVIEW (National Instruments, Austin, TX, USA).

Kubota (Osaka, Japan) polyolefine microfiltration membranes with a pore size of 0.4 μm were used in the reactors. The dimensions of the flat-sheet membranes were 300 mm (W) × 200 mm (H). Each membrane module had 0.1 m² of total membrane surface area. The support media used in the AtMBR system were hollow microspheres with diameters in the range of 300–600 μm (Extendospheres™ 300/600, Sphere One Inc., Chattanooga, TN, USA). The support media concentration was 1.5 g/L.
Operating conditions

The solids retention time (SRT) for the AMBR and AtMBR systems was 30 days and the SRT for the AnMBR system was infinite (i.e. biomass was not wasted). The HRT for all 3 systems was 12 h. The aeration, mixing, and membrane scouring of the AMBR and AtMBR systems were provided by air at a sparging rate of 8 L/min. The AnMBR system was kept airtight; biogas generated by the degradation of organic matter was recycled from the headspace into the bottom of the tank to provide mixing of the biomass and scouring of the membrane at a sparging rate of 8 L/min. Nitrogen gas was also sparged into the reactor at a gas flow rate of 0.2 L/min to ensure a positive pressure inside the tank and thus guarantee that air did not enter the bioreactor. The reactor had a pressure relief valve (set at 5 psi) and a gas overflow line to prevent pressure build-up.

Wastewater characteristics

The seed biomass used in the MBR systems was taken from the Truckee Meadows Water Reclamation Facility (Reno, NV, USA). The AMBR and the AtMBR systems were seeded with biomass taken from the aeration tank, while the AnMBR system was seeded with biomass from the anaerobic digester. The seed biomass was screened through a 1-mm sieve before inoculation to remove coarse matter. The bioreactors were fed with a balanced synthetic wastewater containing 170 mg/L glucose and 140 mg/L peptone to mimic a medium-strength domestic wastewater influent (Metcalf & Eddy 2003). The feed solution was made 100 times concentrated and the concentrated feed solution was sterilized and stored in a refrigerator at 4 °C. The concentrated solution was pumped to a holding tank by a peristaltic pump and once in the holding tank, the concentrated feed solution was diluted with tap water before being gravity fed to the bioreactors.

Analytical methods

Effluent samples from the MBR systems were either filtered through a 0.45 μm filter or tested unfiltered. COD and mixed liquor suspended solids (MLSS) concentrations were measured according to Standard Methods (APHA/AWWA/...
Critical flux experiments

In order to determine the fouling potential for each of the bioreactor configurations, critical flux analyses were performed on the bioreactors after they reached a steady-state condition. Critical flux was determined via the flux-step method (Le-Clech et al. 2005) where the flux was incrementally increased by 2 L/m²/h every 15 min and two TMP values were determined: the first (TMP₁) was the average TMP value obtained between the 0.5 and 1.5 min of the step (tave1), and the second (TMP₂) was the average value obtained during the last minute of the step (tave2). For each step, the rate of TMP increase is determined by $\frac{dTMP}{dt} = \frac{TMP₂ - TMP₁}{tave2 - tave1}$. Each value is then plotted on a graph of $\frac{dTMP}{dt}$ as a function of flux. The point on the graph where a clear discontinuity occurs in the trend indicates the critical flux as defined by the flux-step method and is an important characteristic of the fouling potential of each bioreactor condition.

This test was performed with a new membrane and the same membrane was used in all the bioreactors and cleaned manually after each run. The physical membrane cleaning procedure consisted of a 30-min soak in tap water, then cleaning with flowing water on the membrane surface, and then a second 30-min soak in tap water. The membrane fouling test sequence was as follows: first, the new membrane was tested in the AMBR system and pressure data were collected (AMBR first run), the membrane was then cleaned and tested in the AnMBR system, the membrane was then cleaned and tested in the AtMBR system, and finally, the membrane was re-tested in the AMBR system (AMBR second run) as a control to verify that the membrane had similar performance to the first run.

RESULTS AND DISCUSSION

Data recording and analysis started 30 days after biomass inoculation. Therefore, the 30-day point is referred to as time 0 throughout the analysis.

COD and TOC removal performance

The data in Figure 2 show COD concentration inside the bioreactors (mixed liquor) and in the effluent water (permeate) of the three MBR systems over a 5-month period. Figure 2 also shows the average feed solution concentration (322 ± 94 mg/L COD). For the AMBR and AtMBR systems (Figures 2(a) and (c)), steady-state operation was reached by time 0 and the mixed liquor COD concentrations after time 0 were relatively similar for the two systems (92 ± 37 and 90 ± 40 mg/L for the AMBR and AtMBR systems, respectively) over the test duration. For the AnMBR system (Figure 2(b)), steady-state operation was reached ~60 days after time 0 (90 days total from inoculation) and the mixed liquor COD concentration was 121 ± 34 mg/L thereafter. The relatively lengthy acclimation time is likely caused by exposure of the biomass to a new feed composition; similar acclimation times for AnMBR systems are reported elsewhere (Huang et al. 2008). The high value of the mixed liquor COD in the AnMBR system in the first 60 days likely resulted from cell lysis and decay of the inoculated biomass during the acclimation period (Baek & Pagilla 2006). For the AMBR and AtMBR systems, the permeate COD concentrations were relatively similar (54 ± 14 and 38 ± 20 mg/L for the AMBR and AtMBR systems, respectively) over the entire test duration. For the AnMBR system, the permeate COD concentration was 54 ± 34 mg/L.

From the average feed and permeate COD concentration lines in Figure 2, it can be calculated that COD removal was ~89% in both the AMBR and AtMBR systems and ~83% in the AnMBR system. Similar trends in TOC removal (97, 97, and 93% removal in the AMBR, AtMBR, and AnMBR systems, respectively) were observed (data not shown). Slightly lower COD and TOC removals in anaerobic MBRs compared to aerobic MBRs are reported elsewhere and are most likely caused by MLSS hydrolysis in the AnMBR system causing higher COD and TOC concentrations in the mixed liquor (Baek & Pagilla 2006).

Biomass production

MLSS concentrations for the AMBR and AtMBR systems were relatively constant at 5.6 ± 0.5 and 4.9 ± 0.5 g/L, respectively, with a 30 day SRT. The MLSS concentration difference between the two bioreactors is due to the 1.5 g/L of support media in the AtMBR system. Therefore, the biological MLSS concentration in the AtMBR system was 3.4 g/L (4.9 g/L minus 1.5 g/L). At ~60 days after time 0, the AnMBR system MLSS concentration was relatively constant at 4.6 ± 0.5 g/L. The fact that the MLSS remained constant even when biomass was not wasted is likely due to the balance between biomass growth and decay that occurs in anaerobic systems (Baek & Pagilla 2006). Biomass production for the AMBR system was
0.21 g MLSS/g COD removed and for the AtMBR system was 0.28 g MLSS/g COD removed.

**Process fouling potential**

In order to determine the critical flux, dTMP/dt was calculated and plotted as a function of flux for each time step (Figure 3). For the AMBR system, the critical flux was ∼11.5 L/m²/h. The critical flux for the AnMBR system (10.5 L/m²/h) was similar to the value for the AMBR system, suggesting that even though MLSS and COD concentrations were generally higher in the anaerobic system, the AnMBR system didn’t have a higher fouling propensity than the AMBR system. For the AtMBR system, the critical flux (15.0 L/m²/h) was more than 30% higher than the critical flux for both the AMBR and AnMBR systems, suggesting that the attached-growth media may be beneficial in reducing membrane fouling. Similar behavior was previously reported in the literature and was attributed to the reduced soluble microbial products concentration in the AtMBR system compared to AMBR systems (Yang et al. 2006a; Ng et al. 2010).

In Table 1, the critical flux values reported in this investigation are compared to those from investigations previously reported in the literature. The critical flux values from the literature span the range of 4.9–21 L/m²/h for all three types of MBRs; this range encompasses the values obtained in the current investigation. In the only other study that compared critical flux in AMBR and AtMBR systems (Yang et al. 2006a), the AtMBR had a slightly higher critical flux than the AMBR.
Laboratory-scale submerged aerobic, anaerobic and attached-growth MBR systems were evaluated for treating domestic wastewater. COD removal for the three systems was in the range of 85% and TOC removal in the range of 95%. The AnMBR system required three months of acclimation prior to stable operation, compared to one month for the aerobic (AMBR and AtMBR) systems. With regard to biomass production, the AnMBR system did not produce excess biomass while the AMBR and AtMBR systems produced 0.21 and 0.28 g MLSS/g COD removed, respectively. Excess biomass produced within the process must be disposed of and may contribute to up to 60% of the total treatment facility operating costs (Horan 1990; Low & Chase 1999). Therefore, operating costs of an AnMBR system could be significantly lower and AnMBRs could contribute towards a more sustainable treatment scheme; whereas the higher excess biomass produced by the AtMBR system (because of the attached-growth media) would result in higher operating costs. On the other hand, the AtMBR system had a 30% higher critical flux value than the AMBR and the AnMBR systems. This suggests that the attached-growth media had a positive role in controlling membrane fouling in MBR systems. This would make it possible to operate AtMBR systems at higher water fluxes, which could result in reduced membrane area requirements and lower subsequent capital costs. Overall, the three systems evaluated have their tradeoffs and system selection would depend on the weighting of capital and operating costs for a specific application. Compared to AMBR systems (today’s standard in terms of MBRs), AnMBR systems are likely to have comparable water flux values and lower biomass production but require longer acclimation time, while AtMBR systems are likely to have higher water flux values but also higher biomass production.

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