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Low energy anaerobic membrane bioreactor for municipal wastewater treatment

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ABSTRACT

Achieving low effluent BOD_5 concentrations and stable performance while treating municipal wastewater at ambient temperature has been difficult for anaerobic biotechnology without using membranes. Membrane operation has typically required energy inputs greater than traditionally needed for activated sludge aeration, thus defeating one main objective of utilizing anaerobic biotechnology. However, new low-energy membrane operational strategies are being evaluated to make anaerobic membrane bioreactors (AnMBR) more energy efficient. In this study, four 3.3 L bench-scale AnMBRs using external crossflow tubular membranes were fed synthetic and real municipal wastewater at 10 and 25 °C and evaluated on the basis of energy demand and organic removal. The membranes were operated at atypically low crossflow velocities of 0.018–0.3 m/s, and with or without fluidized GAC, to reduce AnMBR energy demand. Use of GAC in membranes allowed for significant reduction in crossflow velocity without reducing membrane run-time between cleanings and resulted in energy demands of 0.05–0.13 kWh/m^3. The AnMBRs were able to produce permeate $BOD_5 \leq 10$ mg/L at bioreactor HRTs of 4.2–9.8 h, even at 10 °C. When factoring in theoretical energy production, the AnMBR described herein is estimated to require 70–100% less energy compared to activated sludge, indicating net neutral energy demand may be feasible for BOD_5 and nutrient removal from municipal wastewater.

1. Introduction

New scenarios for municipal wastewater recovery focus on replacing aerobic processes such as activated sludge with anaerobic biotechnology [1,2]. Recently, anaerobic membrane bioreactors (AnMBRs) have become a focal point because of distinct advantages membrane separation offers for biomass retention and low effluent chemical oxygen demand (COD) concentrations, especially at low temperature [3–6]. Anaerobic biotechnology also offers advantages including reduced biosolids production, reduced energy requirements due to aeration elimination, and methane production for energy generation [1,2,7,8]. Additionally, AnMBRs can provide footprint savings due to higher organic loading rate and greater reactor depth compared to standard activated sludge, although deep tank aerobic systems do exist. AnMBR permeate is free of suspended solids and lends itself to post-treatment such as ion exchange for nutrient (nitrogen, phosphorous, and potassium) concentration and recovery [9].

Previous studies have shown AnMBRs are capable of producing effluent with very low five-day biochemical oxygen demand (BOD_5) concentration, even at temperatures less than 10 °C [10–12]. Additionally, recent AnMBR feasibility studies have indicated that AnMBRs employed as mainline treatment options for municipal wastewater reclamation have the potential to operate with net neutral energy consumption [13–15]. However, these feasibility studies make simplifying assumptions such as AnMBR permeate can be used as agricultural irrigation water to avoid nutrient removal/recovery steps or that high energy use for gas sparging submerged membranes will eventually be reduced with technological advances. In both examples these assumptions may be difficult to realize in broad application of AnMBR technology.

In order for the AnMBR energy requirement to be less than that of activated sludge, the energy demand for membrane operation and maintenance must be below the typical activated sludge demand of between 0.3 and 0.6 kWh/m^3 [16]. However, existing membrane operational techniques that help decrease membrane fouling, such as gas sparging or high crossflow velocity (CFV), are more energy intensive than aeration for activated sludge. For submerged AnMBR configurations using biogas sparging, Liao et al. [17] reported energy demands of 0.25–1.0 kWh/m^3, whereas estimates from other studies range from 0.69 to 3.41 kWh/m^3 [18].

External crossflow membrane configurations typically require much more energy than submerged membranes due to high CFV required to maintain flux. Liao et al. [17] reported external

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crossflow energy demands of 3–7.3 kWh/m^3 and Le-Clech et al. [19] indicated demands as high as 10 kWh/m^3. However, lower CFV external membrane examples were found with estimated CFV energy demands ranging from 0.23 to 0.48 kWh/m^3 [18]. Submerged membrane energy demands can also be higher than activated sludge due to the biogas sparging required to prevent membrane fouling. Actual energy demand is highly dependent on membrane selection and operating strategy as indicated by the wide ranges reported for each configuration.

In the past, several fouling mitigation strategies have been evaluated, but only two reports have been found that describe the addition of fluidized granular activated carbon (GAC) as a method to reduce membrane fouling and eliminate the energy demand of gas sparging to maintain operation for wastewater treatment [12,20]. These important reports were limited to a submerged configuration and employed only one membrane material/configuration. Other strategies to improve membrane efficiency and reduce membrane energy demands have centered on methods to minimize membrane fouling through membrane surface modification [5,21], use of adsorbents such as activated carbon [20,22,23], physical scouring mechanisms via fluidization of plastic media [24,25], as well as backflushing and relaxation [17,26,27].

In this study we evaluated the impact of greatly reducing CFV in polymeric and ceramic external crossflow anaerobic membrane bioreactors treating synthetic and actual municipal wastewater in order to reduce energy demands below typical values required for conventional activated sludge. In addition, fluidized GAC was used successfully as a fouling control strategy for both polymeric and ceramic external crossflow membranes.

2. Experimental

2.1. AnMBR configurations

Two different lab-scale AnMBR configurations having different biofilm and membrane types were employed as previously described [28]. Briefly, the first configuration consisted of a downflow floating media filter (DFF) bioreactor (2.3 L working volume) coupled to a polymeric tubular membrane module (1 L working volume) (Fig. 1). The polymeric module contained two, 750 mm long, 12.5 mm diameter polyvinylidene fluoride (PVDF) membranes (total surface area = 0.059 m^2) with nominal molecular weight cutoff of 100 kDa (~0.018 μm nominal pore size) (FP100, PCI Membranes, Fareham, UK). The second configuration was a fluidized bed (FBR) bioreactor (2.3 L working volume) coupled to a ceramic tubular membrane module (1 L working volume) (Fig. 1). The ceramic module was a 100 cm long, 16 mm diameter aluminum oxide tube (surface area = 0.05 m^2) with a 0.05 μm nominal pore size (Type 1/16, Atech Innovations, Gladbeck, Germany). Membranes were mounted vertically and operated in inside-out mode. Transmembrane pressure (TMP) was monitored at the top and bottom of modules using gauges (NOSHOK Inc., Berea, OH). All fluid transfer was done with peristaltic pumps (Masterflex, Vernon Hills, IL).

2.2. Bioreactor operation

Both the DFF and FBR configurations were evaluated at 10 and 25 °C, for a total of four systems (FBR25, FBR10, DFF25, DFF10). Each bioreactor was inoculated with methanogenic biomass and fed synthetic primary effluent wastewater (SPE) modeled after primary effluent at the South Shore Water Reclamation Facility (SSWRF) (Oak Creek, WI) for the first 320 days of operation as previously described [28]. After day 320, all systems were fed real primary effluent (PE) from SSWRF that was collected weekly and stored at 4 °C. Average parameters for the SPE and PE influent are summarized in Table 1. From day 80–145, the total system hydraulic residence time (HRT) in all AnMBRs was 9 h. After day 145, the total system HRT was adjusted to the minimum needed to achieve BOD$_5$ < 10 mg/L in permeate from each AnMBR as previously described [28]. Influent and effluent BOD$_5$, COD, NH$_3$-N,

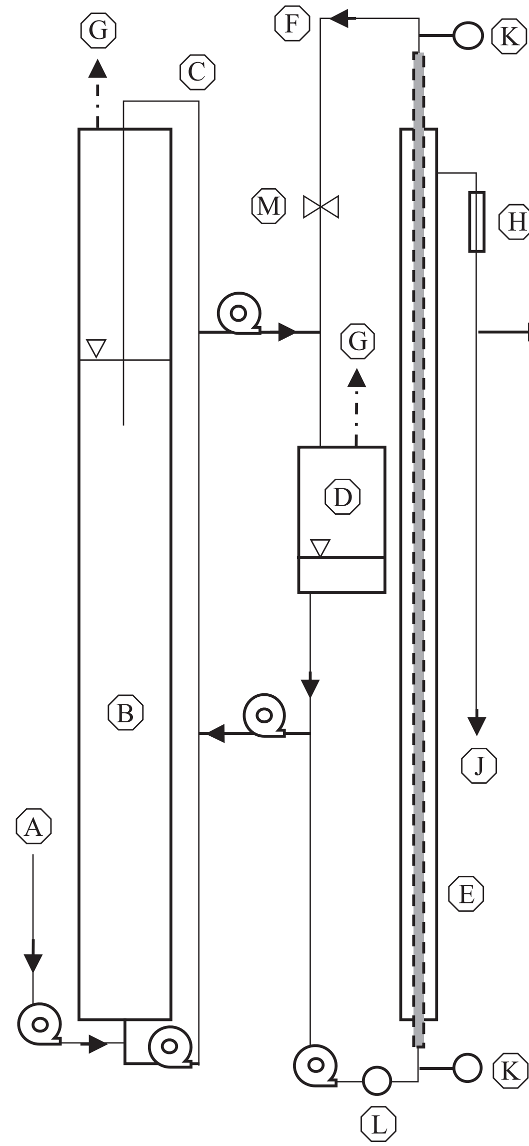

Fig. 1. Schematic of individual AnMBR setup. A. Influent wastewater, B. Bioreactor (FBR or DFF), C. Bioreactor recycle line, D. Equalization tank, E. Membrane module (ceramic or polymeric), F. Membrane recycle line, G. Biogas collection, H. Permeate flow meter, I. Excess permeate return to equalization tank, J. Final permeate, K. Pressure meter, L. Pulse dampener, M. Pressure control.

Table 1.
Average parameters for the influent SPE and PE.

Parameter	SPE	PE
BOD$_5$	235 ± 35	160 ± 60
COD	480 ± 50	310 ± 110
NH$_3$-N	17 ± 1.5	21 ± 7.6
TKN	43 ± 2.8	34 ± 6.7
PO_4^{-3}-P	2.3 ± 0.3	3.8 ± 1.7
Total P	5.0 ± 0.4	5.1 ± 1.7
TSS	120 ± 40	106 ± 40
VSS	115 ± 40	77 ± 25