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Effect of pressure relaxation and membrane backwash on adenovirus removal in a membrane bioreactor

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ABSTRACT

Pressure relaxation and permeate backwash are two commonly used physical methods for membrane fouling mitigation in membrane bioreactor (MBR) systems. In order to assess the impact of these methods on virus removal by MBRs, experiments were conducted in a bench-scale submerged MBR treating synthetic wastewater. The membranes employed were hollow fibers with the nominal pore size of 0.45 μm. The experimental variables included durations of the filtration ($t_{TMP>0}$), pressure relaxation ($t_{TMP=0}$) and backwash ($t_{TMP<0}$) steps. Both pressure relaxation and permeate backwash led to significant reductions in removal of human adenovirus (HAdV). For the same value of $t_{TMP>0}/t_{TMP=0}$, longer filtration/relaxation cycles (i.e. larger $t_{TMP} + t_{TMP=0}$) led to higher transmembrane pressure (*TMP*) but did not have a significant impact on HAdV removal. A shorter backwash ($t_{TMP<0} = 10$ min) at a higher flow rate ($Q = 40$ mL/min) resulted in more substantial decreases in *TMP* and HAdV removal than a longer backwash ($t_{TMP<0} = 20$ min) at a lower flow rate ($Q = 20$ mL/min) even though the backwash volume ($Qt_{TMP<0}$) was the same. HAdV removal returned to pre-cleaning levels within 16 h after backwash was applied. Moderate to strong correlations ($R^2 = 0.63$ to 0.94) were found between *TMP* and HAdV removal.

1. Introduction

Membrane bioreactors, a combination of activated sludge process and membrane filtration, have developed into a staple technology for municipal and industrial wastewater treatment and a particularly attractive treatment choice for water reuse (Judd 2010, Hoinkis et al. 2012, Andrade et al. 2014, Yin and Xagoraraki 2015).

Compared to conventional activated sludge wastewater treatment systems, MBRs are more compact and, generally, afford more stable performance (Choi et al. 2002). With proper design and optimized operational conditions MBRs can remove a wide range of pollutants (Vaid et al. 1991, Pankhania et al. 1994, Beaubien et al. 1996, Kishino et al. 1996, Gujer et al. 1999, Van der Roest et al. 2005, Phan et al. 2014, Sun et al. 2015, 2013, Boonnorat et al. 2014, Malaeb et al. 2013).

Membrane fouling in MBRs remains a major technical challenge (Bouhabila et al. 2001, Judd 2008, Cornel and Krause 2008). During MBR operation, biosolids as well as colloidal and macromolecular species may deposit and accumulate on membrane surfaces resulting in a decline in permeate flux. A number of membrane fouling mitigation methods have been developed including pressure relaxation, air sparging and membrane cleaning by hydraulic or chemical means. Hydraulically reversible fouling is defined as fouling that can be removed by a hydraulic wash, while hydraulically irreversible fouling refers may only be removed by chemical cleaning (Chang et al. 2002) and is typically due to intrapore fouling. Air sparging mainly targets external fouling, such as a loosely attached cake layer on membrane surface while backwash can also remove internal fouling (Bouhabila et al. 2001, Psoch and Schiewer 2006).

Air sparging is very commonly applied, especially in submerged aerobic MBRs with ultrafiltration and microfiltration membranes, where aeration serves a dual purpose of providing oxygen to bacteria and mitigating membrane fouling. Coarse air bubbles create shear at membrane surfaces, and partially remove loosely attached fouling layers. It has been well documented that air sparging can enhance hydraulic permeability of MBR membranes with strong positive correlations found between air sparging rate and fouling reduction (Chang and Judd 2002, Yu et al. 2003, Ghosh 2006, Fan and Zhou 2007, Delgado et al. 2008). To further reduce membrane fouling, air sparging is often coupled with pressure

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relaxation. (Hong et al. 2002) clearly demonstrated that permeate flux decreased slower when periodical pressure relaxation was applied. (Wu et al. 2008) reached a qualitatively similar conclusion reporting that the extent of fouling was related to the duration and frequency of pressure relaxation.

Membrane backwash is another method that is widely used to reduce membrane fouling in MBRs. (Hwang et al. 2009) suggested that backwash by deionized water can completely remove membrane cake and alleviate intrapore fouling. (Yigit et al. 2009) reported that membrane resistance was reduced ~160% after backwash and concluded that backwash effectively diminished reversible fouling due to pore blocking and cake layer formation. Backwash parameters such as duration, interval and backwash flow rate can significantly affect fouling (Wu et al. 2008, Hwang et al. 2009). (Delgado et al. 2008) reported that backwash time had a strong impact on residual fouling. (Kim and DiGiano 2006) showed that higher backwash frequency could reduce long-term fouling rate. With the same backwash volume, higher backwash flux was more effective in fouling reduction than a longer duration of the backwash (Zsirai et al. 2012).

Enteric viruses, as a type of infectious pathogens in wastewater, pose a significant threat to public safety. Most published studies on virus removal by MBRs focused on *bench- and pilot-scale* MBR systems and bacteriophages such as MS2, T4 and F-specific and somatic coliphage (Cicek et al. 1998, Hu et al. 2003, Shang et al. 2005, Comerton et al. 2005, Fiksdal and Leiknes 2006, Lv et al. 2006, Zhang and Farahbakhsh 2007, Zheng and Liu 2007, Tam et al. 2007, Ravindran et al. 2009, Hirani et al. 2010, Chaudhry et al. 2015a, Fox and Stuckey 2015, Hmaied et al. 2015, van den Akker et al. 2014). Two bench-scale studies employed human viruses; (Madaeni et al. 1995) reported that the removal of poliovirus ranged from 1.3 to 1.8 logs while (Ottoson et al. 2006) showed that the log reduction value (LRV) for enterovirus and norovirus ranged from 0.5 to 1.8 logs.

To our knowledge, there have been only seven studies on the removal of viruses in *full-scale* systems. Norovirus removal in a full-scale MBR utilities was reported to cover a very wide range from 0 (i. e. no removal) to 5.5 logs (da Silva et al. 2007) LRVs of ~5.1 logs for enteroviruses, 3.9 logs for norovirus, and 5.5 logs for adenoviruses were reported (Kuo et al. 2010, Simmons et al. 2011, Simmons and Xagoraraki 2011). (Zanetti et al. 2010) measured LRVs for F-specific coliphage and somatic coliphage to be 6 logs and 4 logs, respectively. Two recent studies investigated virus removal in full-scale MBRs equipped with 0.04 μm membranes: the reductions of adenovirus, norovirus and F+ coliphage were 3.9–5.5 logs, 4.6–5.7 logs and 5.4–7.1 logs, respectively after MBR treatment (Chaudhry et al. 2015b), while removals of somatic, F-RNA, GB124, MS2 and B14 coliphages were 5.3 logs, 3.5 logs, 3.8 logs, 2.2 logs and 2.3 logs. All the studies indicated that MBR systems were not able to serve as an absolute barrier against viruses, even though high virus removals were achieved in many cases.

The role of biofilm in virus removal by MBRs has been studied by (Wu et al. 2010) who found that the clean membrane (d_{pore} = 0.4 μm) contributed only ~0.5 logs removal of somatic coliphages; in contrast, when covered with a biofilm the same membrane could remove 1.8 to 2.6 logs of the virus. Similarly, (Shang et al. 2005) observed that an MBR with the nominal pore size of 0.4 μm could initially (i.e. prior to significant membrane fouling) only remove 0.4 logs of MS-2 coliphage. After 21 days of operation, the removal efficiency increased to 2.3 logs; it was concluded that membrane biofilm played an important role in removing the virus. Despite the fact that one or several fouling mitigation methods are routinely applied in MBR plants, little is known about the impact that these practices have on virus removal (Table 1). Most of the published work on the subject focused on chemical cleaning and employed bacteriophages.

It has been reported that chemical cleaning that completely removed the membrane biofilm greatly affected the removal of viruses and it could take more than 24 h for the removal to recover to pre-cleaning levels (Lv et al. 2006, Tam et al. 2007). Only two studies (Lv et al. 2006, Zheng et al. 2005) evaluated the effect of hydraulic flushing (not backwash) by cleaning the membrane surface with tap water, using the same bench scale MBR system and T4 coliphage.

One recently published paper (Fox and Stuckey, 2015) evaluated the impact of air sparging on virus removal in an anaerobic MBR, and indicated that higher sparging rates led to greater removal of MS-2 and T4 coliphage. To our knowledge, the impacts of pressure relaxation and permeate backwash on virus removal in MBR systems have not been investigated. The effect of these fouling mitigation methods on the removal of human adenovirus 40 (HAdV 40), an infectious enteric virus is at the focus on the present work.

2. Materials and methods

2.1. Cell culture experiment and virus incubation

A549 cell line has been suggested as an efficient cell line for HAdV-40 (ATCC, VR 931) (Witt and Bousquet 1988, Lee et al. 2004) and it was used to grow HAdV in this study. Details of virus incubation were described in (Yin et al. 2015).

2.2. Membrane preparation

The polyvinylidene fluoride (PVDF) hollow fiber membrane used in this work had the nominal pore size of 0.45 μm and the outer diameter of 1.3 mm. Membrane units were made by looping and potting 14 hollow fiber segments (effective length: 70 cm each) in a short (~10 cm) piece of 1/2″ ID PFTE tubing with an adhesive (Loctite). Each membrane unit had an effective surface area of ~400 cm^2, and 4 such units were used in each experiment giving a total effective surface area of ~1600 cm^2. Prior to each test, membrane was soaked in deionized (DI) water for at least 24 h, and then compacted by filtering DI water for 12 h.

2.3. Bench-scale submerged MBR

A schematic of the bench–scale MBR system is shown in Fig 1. The MBR could accommodate 25 L of activated sludge and the working volume was 20 L. A peristaltic digital pump (model 07523-80, MasterFlex L/S) served as the permeate pump. The system was running in a constant flux regime (Q = 31.3 mL/min; $j = 3.26 \cdot 10^{-6}$ m/s). Transmembrane pressure (*TMP*) and permeate flow rate were measured by a digital pressure sensor (Cole–Parmer, 68075-00) and digital flow meter (model 106-4-C-T4-C10, McMillan), respectively. A LabView program was developed to (1) maintain the constant permeate flow using a *proportional-integral-derivative (PID) algorithm; (2) conduct periodical pressure relaxation by turning the* permeate pump on and off; (3) record data from the flow meter and the pressure sensor.

Activated sludge from East Lansing wastewater treatment plant was incubated in a 25 L glass cylinder tank with synthetic wastewater (Table 2) for over three months. Membranes were then placed in the activated sludge and the MBR system was run for over three months. The hydraulic retention time (HRT) was 0.5 day, and mixed liquor suspended solids (MLSS) concentration was kept at 4.5 g/L based on daily MLSS measurements. Aeration was continuously applied throughout the experiment at the rate of 0.57 m^3/h. A preliminary test indicated that the MBR was able to remove ~97% of total organic carbon (data not shown).