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Biomass viability: An experimental study and the development of an empirical mathematical model for submerged membrane bioreactor

M.F.R. Zuthi [a], H.H. Ngo [a,*], W.S. Guo [a], L.D. Nghiem [b], F.I. Hai [b], S.Q. Xia [c], Z.Q. Zhang [c], J.X. Li [d]

[a] Centre for Technology in Water and Wastewater, School of Civil and Environmental Engineering, University of Technology Sydney, Sydney, NSW 2007, Australia
[b] Strategic Water Infrastructure Laboratory, School of Civil Mining and Environmental Engineering, University of Wollongong, Wollongong, NSW 2522, Australia
[c] College of Environmental Science and Engineering, Tongji University, Shanghai 200092, PR China
[d] State Key Laboratory of Hollow Fiber Membrane Materials and Processes, School of Materials Science and Engineering, Tianjin Polytechnic University, Tianjin 300387, PR China

HIGHLIGHTS

- Sustainable operation of MBR greatly depends on biomass viability.
- Among biomass parameters, EPS has highest correlation with biomass viability.
- Proposed models correlate SOUR with characteristic biomass parameters.
- Mathematical model simulations agree well with the experimental results.

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ABSTRACT

This study investigates the influence of key biomass parameters on specific oxygen uptake rate (SOUR) in a sponge submerged membrane bioreactor (SSMBR) to develop mathematical models of biomass viability. Extra-cellular polymeric substances (EPS) were considered as a lumped parameter of bound EPS (bEPS) and soluble microbial products (SMP). Statistical analyses of experimental results indicate that the bEPS, SMP, mixed liquor suspended solids and volatile suspended solids (MLSS and MLVSS) have functional relationships with SOUR and their relative influence on SOUR was in the order of EPS > bEPS > SMP > MLVSS/MLSS. Based on correlations among biomass parameters and SOUR, two independent empirical models of biomass viability were developed. The models were validated using results of the SSMBR. However, further validation of the models for different operating conditions is suggested.

1. Introduction

Membrane bioreactor (MBR) has been increasingly used in wastewater treatment industries around the world. Indeed, MBR has emerged as a viable wastewater treatment system for superior effluent quality with a much smaller physical footprint and less sludge production when compared to that of other conventional activated sludge (CAS) treatment systems. However, the removal of organic contaminants in an MBR, like that of other CAS systems, largely depends on the oxidative process where microorganisms utilize oxygen as the terminal acceptor (Silvan et al., 2013). Therefore, it is a major concern to maintain a desired rate of oxygen transfer for microbial activity to help track instability in the operation of any biological wastewater treatment system and the MBR systems as well.

The microbial culture in biological wastewater treatment processes can undergo changes due to the continuous changes of microbial communities in structure, population and activity with time (Chipasha and Medrzycka, 2008). Although a significant number of studies were performed on MBR systems to identify factors of treatment efficiency or of membrane fouling (Başaran et al., 2014), only limited studies (Clouzot et al., 2011; Germain et al., 2007; Han et al., 2005; Hasar et al., 2002; Lee et al., 2003; Malamis et al., 2011) were aimed at assessing the factors affecting the oxygen transfer rate and the viability of the microbial culture in MBR. Among the MBR plant characteristics and operating conditions, the influence of membrane configuration (Germain et al., 2007) and sludge retention time (SRT) (Han et al., 2005) on biomass viability has been investigated. It has been acknowledged in many studies that different types of organic polymeric compounds such as bound extra-polymeric substances (bEPS) and soluble microbial products (SMP) are released to the bioreactor due to the metabolism of microorganisms present in the bioreactor, and

* Corresponding author. Tel.: +61 2 95142745; fax: +61 2 95142633.
E-mail address: h.ngo@uts.edu.au (H.H. Ngo).

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their influence on membrane fouling has already been identified in MBR studies done during the past few years. The inhibitory effects of the above mentioned microbial products on microbial activities have been acknowledged in few studies (Chuboda, 1984; Germain et al., 2007; Huang et al., 2000; Malamis et al., 2011; Rojas et al., 2005; Zuthi et al., 2014). A strong negative correlation between microbial activity and concentration of EPS was observed in previous studies (Lee et al., 2003; Rojas et al., 2005). Germain et al. (2007) identified solids concentration and carbohydrate fraction of the extra polymeric substances (EPS) and the chemical oxygen demand (COD) concentration of the SMP as the factors affecting the oxygen transfer efficiency (Germain et al., 2007).

The specific oxygen uptake rate (SOUR) was used as an indicator of biomass viability in many MBR studies (Ngo et al., 2008; Nguyen et al., 2012; Villain and Marrot, 2013). The SOUR reflects the oxygen uptake by different biological processes such as microbial growth, endogenous respiration, substrate storage etc. with these individual or coupled process rates dynamically influencing the SOUR in a complex manner. The process rates for microbial growth, respiration or storage etc. may also become significantly dependent on selected experimental conditions of a treatment system. In this backdrop, it becomes almost impossible to identify active biomass affecting the biomass viability. Nevertheless, it is important to identify or characterize the functional relationships between the key factors affecting SOUR and microbial viability.

Following the changes in biological and operational conditions in MBR, modification in biomass viability is very likely (Trapani et al., 2011) especially because of its compact configuration and its operation under higher MLSS concentration. As biodegradation potential of microbial culture and filtration performance play critical roles for the sustainable operation of MBR (Başaran et al., 2014), assessment of biomass viability is always a concern for better management and operational control of MBR. To date, only Hasar et al. (2002), Hasar and Kinaci (2004) have attempted to characterize the biomass viability of the MBR system. Hasar and Kinaci (2004) presented an empirical model of the biomass viability of a submerged MBR (SMBR) taking into account the mixed liquor suspended solids (MLSS), mixed liquor volatile suspended solids (MLVSS), and inert COD in the influent and effluent. The change of inert COD in the effluent was ascribed to the inert compounds that were produced due to microbial activity within the bioreactor. The inert COD was represented in the model mainly as an indicator parameter of SMP in bioreactor, whereas larger microbial aggregates such as bEPS and colloids were not included in the model. Although the parameters presented in the model are useful indicators of the biomass viability, these cannot be linked to the physical sub-model of the membrane fouling as the rejection efficiency of the membrane was not considered (Zuthi et al., 2013).

In an earlier research, the authors (Zuthi et al., 2013) proposed modifications of the above mentioned model and proposed a new conceptual model of microbial viability which correlated SOUR with MLVSS/MLSS, and soluble/colloidal inert COD in the effluent as indicator parameters of SMP/bEPS in the bioreactor. The modified model considers the colloidal COD in the effluent as a representative parameter of bEPS in the bioreactor. With small membrane pore size, smaller colloidal particles may be retained within the bioreactor leaving no traces of colloidal COD in the effluent. Therefore, improvements of the mathematical model of biomass viability has been proposed in this paper based on the experimental results of the biomass viability in a sponge submerged membrane bioreactor (SSMBR). Since the identification of biomass parameters that affect microbial activity is critically important for monitoring the performance of an MBR, key biomass parameters such as MLSS, MLVSS, EPS, bEPS and SMP were investigated for their relative influence on SOUR in a continuously aerated SSMBR that was operated for 50 days. Based on correlations, empirical models of biomass viability were developed based on statistical correlations between SOUR and different biomass parameters. The empirical models are subsequently validated by experimental results of the SSMBR.

2. Methods

2.1. Experimental set-up

The experiment was performed on a continuously aerated lab-scale SSMBR system. The SSMBR system has been preferred for the assessment of biomass viability since the SSMBR offers operational advantages over the CMBR (conventional MBR) system in many aspects. The fundamental difference between the operation of CMBR and SSMBR is that the sponges in the bioreactor of a SSMBR act as a mobile carrier of biomass especially by carrying the components (e.g. SMP, bEPS etc.) of biomass that affects the biomass viability most. Since the sponges consistently move around in the bioreactor of the SSMBR system, the biomass components has more consistent effects on the oxygen transfer and hence on the biomass viability. On the other hand, the effects of biomass components on the biomass viability is erratic in the CMBR when compared to that in the CMBR system.

A schematic diagram of the experimental set-up of the SSMBR system is shown in Fig. 1. The membrane module used in the SSMBR was Polyethylene with hydrophilic coating (Manufacturer: Mitsubishi-Rayon, Tokyo, Japan) with membrane pore size of 0.1 μm and surface area of 0.195 m^2. The SSMBR system was operated for 50 days with a 1-min physical cleaning frequency after every 1 h of filtration. The volume of the bioreactor of the SSMBR was 10 liter (L) in which a constant aeration rate of 2.2 rate L/m^2 (of membrane surface area)/h was maintained providing dissolved oxygen (DO) concentration in the bioreactor in the range between 7.5 and 8.5 mg/L. During the operating period of the SSMBR, the concentration of MLSS varied in the range between 5 and 18 g/L. The volumetric loading rate was maintained at approximately 2 gCOD/L/day. The temperature during the operation of the SSMBR varied in the range between 21 and 24.5 °C. With a hydraulic retention time (HRT) of 4 h, the constant flux of the SSMBR was maintained at 12 $L/m^2/h$.

The influent wastewater characteristics for the SSMBR were COD of 350–380 mg/L, the concentration of PO_4-P of 3.1–4 mg/L and the concentration of NH_4-N of 9–15 mg/L. Due to the innovative application of sponges in the SSMBR system, the overall removal efficiency of the SSMBR was high with COD removal efficiency varying in the range between 95% and 98%, PO_4-P removal efficiency in the range between 85% and 100% and NH_4-N removal efficiency in the range between 70% and 90%. Both the influent and effluent flow rates were controlled by a two-channel pump, and a separate pump was used for membrane backwashing. The developed trans-membrane pressure (TMP) was used as an indicator parameter of unstable operation of the MBR and a pressure gauge was used to measure TMP. A hose air diffuser was used to provide air from the bottom of the reactor and an airflow meter was used to maintain a constant air flow rate at approximately 7 L/min. The sponges used in the SSMBR were reticulated porous polyester-urethane sponge having density of 28–30 kg/m^3 with 90 cells per 25 mm (Joyce Foam Products, Australia). Before starting the operation of the MBR, the sponges were acclimatized with the synthetic wastewater to be treated for at least 30 days. The volume of sponge cube (1 × 1 × 1 cm) was 10% of bioreactor volume which was selected based on optimum operational condition and critical flux experiments done by Guo et al. (2008). The substrate used in the study contained glucose, ammonium sulfate, potassium