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Performance of a combined system of microbial fuel cell and membrane bioreactor: Wastewater treatment, sludge reduction, energy recovery and membrane fouling

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ABSTRACT

A novel combined system of sludge microbial fuel cell (S-MFC) stack and membrane bioreactor (MBR) was proposed in this study. The non-consumed sludge in the MBR sludge-fed S-MFC was recycled to the MBR. In the combined system, the COD and ammonia treatment efficiencies were more than 90% and the sludge reduction was 5.1% higher than that of the conventional MBR. It's worth noting that the energy recovery and fouling mitigation were observed in the combined system. In the single S-MFC, about 75 mg L^{-1} COD could be translated to electricity during one cycle. The average voltage and maximum power production of the single S-MFC were 430 mV and 51 mW m^{-2}, respectively. Additionally, the combined system was able to mitigate membrane fouling by the sludge modification. Except for the content decrease (22%), S-MFC destroyed simple aromatic proteins and tryptophan protein-like substances in loosely bound extracellular polymeric substances (LB-EPS). These results indicated that effective wastewater treatment, sludge reduction, energy recovery and membrane fouling mitigation could be obtained in the combined system.

1. Introduction

As efficient technology for wastewater treatment, membrane bioreactors (MBRs) have experienced unprecedented growth in recent years (Fan and Zhou, 2007). MBRs offer several advantages over conventional activated sludge system, including stable and high effluent quality, ease of operation, small footprint, and absolute removal of bacteria (Wang et al., 2009b). However, membrane fouling remains as a major obstacle for wider application of MBRs (Kimura et al., 2012). The most common approaches to reduce membrane fouling are supplying an excessive amount of air (high energy con-sumption), cleaning the membrane module (reduction the membrane life-span), optimizing the operating parameters and improving activated sludge characteristics in the reactor (Akamatsu et al., 2010; Bani-Melhem and Elektorowicz, 2010).

Microbial fuel cells (MFCs) have been developed as a promising technology to recover energy from wastewater, marine sediments, sludge etc. (Min et al., 2005). Several systems combining MBR and MFC have been reported previously. A bioelectrochemical membrane reactor, which takes advantage of both MBR and MFC processes, was recently developed (Wang et al., 2011). In this reactor, stainless steel mesh was designed as both the cathode and the membrane. Wang et al., 2012 developed a more practical MFC–MBR integrated process, which used the aeration MBR tank as the cathode chamber and the carbon felt as the cathode. Both systems took MFCs as wastewater treatment units for simultaneously enhancing wastewater treatment and achieving energy recovery. However, for MBR process, stable and high effluent quality is one of the advantages (98% total organic carbon removal and 99% ammonia removal), while membrane fouling is a major obstacle (Pan et al., 2010; Visvanathan et al., 2000). It would be exciting if a combined MBR–MFC system offers the option of membrane fouling mitigation. It has been reported that sludge extracellular polymeric substances (EPS), which have been considered as the major cause of membrane fouling in MBRs (Chang et al., 2001; Drews et al., 2006), could be removed by 36.8% in the form of dissolved organic carbon (DOC) after MFC treatment (Jiang et al., 2010). Therefore, taking MFC as a sludge treatment unit might have benefits for membrane fouling mitigation due to EPS reduction and modification of sludge characteristics.

A novel combined system of MBR and MFC was established in this study. The MFC was operated with a direct feed of activated sludge from the MBR. Then the non-consumed sludge in the MFC was returned to the MBR. MFC could convert the chemical energy in organic matter directly into useful electrical energy by the catalytic reaction of microorganisms; on the other hand, the sludge is hydrolyzed, converted and reduced during electricity production of MFCs (Xiao et al., 2011). 25.1% reduction in total suspended solids

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(TSS) and 22.8% reduction in volatile suspended solids (VSS) were observed in the MFC which used sewage sludge as fuel (Xiao et al., 2011). Consequently, the combined system may also have the potential for both energy recovery and sludge reduction.

Therefore, the objective of this research was undertaken to evaluate the performances of the combination of MBR and MFC: (1) assess the efficiencies of wastewater treatment and sludge reduction; (2) calculate the power generation and COD transformation; and (3) investigate the membrane fouling mitigation and potential mechanisms. On this basis, a new combination approach for effective wastewater treatment, sludge reduction, energy recovery and membrane fouling mitigation is proposed.

2. Materials and methods

2.1. Microbial fuel cell (MFC)

Single-chamber air cathode MFC with a cube anodic chamber (7.5 cm × 7.5 cm × 4 cm) was used in this study. The MFC was fitted with carbon cloth anode (projected surface area = 40 cm^2, without wet proofing; E-TEK, USA) and cathode (projected surface area = 40 cm^2, contained 10% platinum as catalyst and four-coating poly tetra fluoro ethylene (PTFE) diffusion layers; E-TEK, USA). The distance between two electrodes was 4 cm. An external resistance of 1000 Ω was connected across the anode and cathode electrodes. The working volume of the anodic chamber was 200 mL.

The anodic compartment of the MFC directly used MBR sludge as anodic inoculum and substrate. The sludge in MFC was retained for 5 days. The MFC was inoculated with MBR sludge mentioned above repeatedly until the constant electric power was produced. After approximately 30 days culture (6 cycles), constant electrical power was obtained with MBR sludge added as fuels. Experiments were conducted in batch mode at room temperature (22 ± 3 °C). Sludge-MFC (S-MFC) contained anaerobic digestion as well as electricity generation process. Simultaneously, a control MFC with no applied load (C-MFC) was adopted in this study.

2.2. MBR

Two 8 L MBRs used in this study were operated in parallel. Each MBR was installed with a submerged hollow fiber microfiltration (MF) membrane module. The membrane modules were made of polyvinylidene fluoride (PVDF) with a nominal pore size of 0.1 μm and an effective surface area of 0.1 m^2 (Motian, China).

The MBR was fed with synthetic wastewater (glucose 227 mg L^{-1}; starch 227 mg L^{-1}; $NaHCO_3$ 254 mg L^{-1}; urea 33 mg L^{-1}; $(NH_4)_2SO_4$ 121 mg L^{-1}; KH_2PO_4 15.4 mg L^{-1}; K_2HPO_4 19.6 mg L^{-1}; $MgSO_4 \cdot 7H_2O$ 51 mg · L^{-1}; $CaCl_2$ 12 mg L^{-1}; $ZnCl_2$ 0.13 mg L^{-1}; $FeSO_4 \cdot 7H_2O$ 17.48 mg L^{-1}; $Pb(NO_3)_2$ 0.27 mg L^{-1} and $MnSO_4 \cdot 4H_2O$ 0.13 mg L^{-1}) from a wastewater tank. All the membrane modules were operated at the constant flux of 10 L m^{-2} h^{-1} with an intermittent suction of 8-min on and 2-min off. The mixed liquid suspended solids (MLSS) concentrations of these MBRs were maintained at almost the same level. During the experiments, chemical cleaning (soaking for 2–8 h in 0.5% sodium hypochlorite solution) was provided when the transmembrane pressure (TMP) reached 30 kPa.

2.3. Combined system

In this study, a combined system of a MBR (combined MBR) and a MFC stack was set up. The stacked MFC was obtained by connecting five single S-MFCs in parallel. Every day, 200 mL raw sludge discharged from the combined MBR was pumped into the settle pool to remove the residual dissolved oxygen (DO). Then, the sludge in the settle pool was pumped into S-MFC for sludge degradation and energy recovery. At the same time, about 200 mL mixed sludge liquor was discharged from the S-MFC and recycled to the combined MBR. A parallelly operated conventional MBR system was running simultaneously as a control experiment. Both systems were performed schematically as shown in Fig. S1 lasting for 6 months. The physicochemical properties of the mixed liquid in the combined MBR, conventional MBR and MFC were monitored every two days.

2.4. Analytical methods

2.4.1. Electrical parameters

Cell voltages (V) were monitored at 1 min intervals using a data acquisition system (VX5100R/C2/U, Hangzhou, China) connected to a personal computer. The maximum power densities were determined from polarization curves by varying the external resistor ranged 5000–50 Ω. Current (I), power ($P=IV$) and coulomb efficiency (CE) were calculated as previously described (Liu et al., 2004), and normalized by the cathode surface area.

2.4.2. Other analysis

The concentrations of TSS, VSS, ammonia and Chemical Oxygen Demand (COD) were determined according to Standard Methods (APHA, 1995). The preparation of the supernatant was made according to the following procedures. The mixed liquor samples were firstly centrifuged at 4000 rpm for 5 min, and then the extracted supernatant was filtered through a 0.45 μm membrane filter. The filtrate was regarded as soluble microbial products (SMP). The loosely bound EPS (LB-EPS) and tightly bound EPS (TB-EPS) were extracted by two-step heating methods and analyzed for the contents of proteins and carbohydrates (Li and Yang, 2007). The calculation method of sludge yield is listed in supporting information. Excitation-emission matrix (EEM) spectra (FP 6500, JASCO, Japan) were collected with corresponding scanning emission spectra from 220 nm to 550 nm at 2 nm increments by varying the excitation wavelength from 220 nm to 400 nm at 5 nm sampling intervals. The molecular weight (MW) distribution of the organic matters in SMP was determined using a GPC (Gel Permeation Chromatography) (Agilent 1100, Agilent, USA). The number-average molecular weight (Mn) and weight-average molecular weight (Mw) were calculated. The morphological properties of the mixed liquid were described by the floc size distribution and distribution spread index (DSI) of sludge flocs. At the end of the continuous experiments, membrane resistance analyses of the fouling layer were also investigated by resistance-in-series model

$$J = \Delta P_T/(\mu R_t) \tag{1}$$

$$R_t = R_m + R_c + R_f \tag{2}$$

where ΔP_T is the transmembrane pressure (Pa), μ is the viscosity of the permeate (Pa s), R_c is the cake resistance formed by the cake layer deposited over the membrane surface, (m^{-1}); R_f is the resistance caused by pore plugging and/or solute adsorption onto the membrane surface and pores (m^{-1}); R_m is the intrinsic membrane resistance (m^{-1}) and R_t is the total resistance (m^{-1}).

3. Results and discussions

3.1. The performance of S-MFC, combined system and conventional MBR

For new wastewater treatment systems, it is necessary to evaluate their nutrient removal efficiencies. After 5 days retention, the COD and NH_4^+-N concentrations of sludge supernatant within S-MFC were increased from 57 mg L^{-1} and 2.27 mg L^{-1} to 616 mg L^{-1} and 8.22 mg L^{-1} respectively (Table 1). When the treated sludge was recycled to the combined MBR, the COD and NH_4^+-N loads were increased by 1.49% and 0.3%, respectively. The averages of permeate