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4 **Microbial Fuel Cells and Osmotic Membrane Bioreactors Have Mutual**
5 **Benefits for Wastewater Treatment and Energy Production**
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Abstract

This study demonstrates that microbial fuel cells (MFCs) and osmotic membrane bioreactors (OMBRs) can be mutually beneficial when integrated together for wastewater treatment. When connecting MFCs with OMBRs, the solute buildup increased conductivity and buffer capacity, which greatly increased MFC power density from 3 W/m³ up to 11.5 W/m³. In turn, the MFCs conditioned and reduced sludge production and therefore reduced forward osmosis (FO) membrane fouling. The MFC-OMBR equipped with new thin-film composite (TFC) membrane showed excellent organic (>95%) and phosphorus removal (>99%) and therefore maintained effluent sCOD below 20 mg/L. However, the nitrogen removal was limited due to the negative surface charge of the thin-film composite membrane and solution chemistry, which led to higher flux of ammonium toward the OMBR draw solution. Further studies are needed to improve nitrogen removal, reduce fouling, and optimize system integration.

Keywords: forward osmosis, microbial fuel cell, thin-film composite membrane, osmotic membrane bioreactor

1. Introduction

Microbial fuel cells (MFCs) and osmotic membrane bioreactors (OMBRs) are two emerging technologies for sustainable wastewater treatment. While most studies focus on individual technology development, we hypothesize that these two processes can be mutually beneficial. MFCs use electrochemically active microorganisms to produce direct current from wastewater with less sludge production, but the current density is low from municipal wastewater due to its low conductivity and buffer capacity.(Nam et al., 2010; Wang and Ren, 2013; Logan et al., 2015; Zhang et al., 2015) Another challenge of MFCs is that the effluent quality (e.g., chemical oxygen demand (COD) and turbidity) generally cannot meet the discharge standard and therefore requires post-treatment.(Logan et al., 2015; Zhang et al., 2015) Membrane processes such as ultrafiltration (UF), microfiltration (MF), and FO have been incorporated into MFCs, and the effluent quality has been significantly improved.(Wang et al., 2011; Ge et al., 2013a; Ren et al., 2014; Tian et al., 2014; Yuan and He, 2015; Zuo et al., 2015) Most previous research focused on this effluent quality aspect with good success, but in this study we hypothesize that the accumulation of FO solute (e.g., NaCl, PO_4^{3-} and HCO_3^-) similar to high contaminants retention improves the solution salinity and buffer capacity and therefore will improve MFC power production.

On the other hand, because MFCs remove organic matters with small biomass accumulation, we anticipate that they may reduce FO membrane fouling as pre-treatment by improving the mixed liquor properties.(Tian et al., 2014) Forward osmosis (FO) is an osmotically-driven membrane process where water flows from a low-salinity

1 feed solution (FS) to a high-salinity draw solution (DS) through a semi-permeable
2 membrane.(Cath et al., 2006; Achilli et al., 2009; Lay et al., 2010; Chen et al., 2014;
3 Holloway et al., 2014; Gu et al., 2015; Holloway et al., 2015) The non-porous FO
4 membrane with lower fouling propensity acts as a barrier to the contaminants so provide
5 a high-level wastewater treatment and reclamation.(Lay et al., 2010; Chen et al., 2014;
6 Holloway et al., 2014; Gu et al., 2015; Holloway et al., 2015) Although OMBRs are likely
7 to have lower fouling propensity compared to the conventional pressure-driven MBRs
8 with MF or UF membranes, fouling is still a major challenge where the concentrations of
9 foulants are high. (Lay et al., 2010; Chen et al., 2014; Holloway et al., 2014; Gu et al.,
10 2015; Holloway et al., 2015) Another unknown factor is the FO membrane materials.
11 Most existing OMBR and/or osmotic microbial fuel cell (OsMFC) studies were
12 performed with cellulose triacetate (CTA) based FO membranes.(Achilli et al., 2009; Lay
13 et al., 2010; Zhang et al., 2011; Ge et al., 2013b; Chen et al., 2014). However, it was
14 shown that CTA membranes are vulnerable to hydrolysis and biological
15 degradation.(Geise et al., 2010; Chen et al., 2014) Thus, in this study we investigated
16 the thin film composite (TFC) polyamide FO membranes, which has higher water flux,
17 better solute rejection, and biodegradation resistance.(Yip et al., 2010; Wei et al., 2011)
18 Despite the great potential of TFC membranes for FO applications, their performance
19 and fouling behavior in MBRs are rarely reported in the literature.

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21 In this study, we investigated the mutual benefits between MFCs and OMBRs with new
22 TFC FO membrane for low strength wastewater treatment. The central hypothesis is
23 that by connecting MFC with OMBR, the accumulated FO solute increases solution

conductivity and alkalinity and therefore improve ion transfer and MFC power output. The MFCs pretreat the wastewater with reduced sludge production, so it reduces membrane fouling in OMBRs. We investigated the MFC-OMBR system performance under different conditions in terms of TFC FO membrane flux level, solute transport, and nutrient removal, as well as organic removal and power production from MFCs. We also characterized TFC membrane fouling behaviors in the MFC-OMBR system and analyzed the potential mechanisms of nutrient transfer.

2. Material and methods

2.1 Membranes and Chemicals

A commercial TFC FO membrane (Hydration Technology Innovations, Albany, OR) was used in this study. The membrane has a water permeability of 7.49×10^{-12} m/s.Pa, a NaCl permeability of 7.40×10^{-8} m/s, and a structure parameter of 0.70 mm.(Coday et al., 2015; Wang et al., 2016) Membrane coupons were soaked in MilliQ water (18.2 MΩ.cm) at room temperature for over 24 h before use.(She et al., 2013a; Zhang et al., 2014) Glucose-based defined medium was used as the synthetic feed wastewater, so degradation and mass transfer mechanisms can be understood. (Huggins et al., 2013; Gu et al., 2015; Lu et al., 2015) The medium contained (mg/L): glucose, 250; yeast extract, 100; NaCl, 400; NaHCO₃, 150; NH₄Cl, 80; KH₂PO₄, 50; MgCl₂•6H₂O, 5; and CaCl₂, 10. The total soluble chemical oxygen demand (sCOD), NH₃-N, PO₄-P, electric conductivity and pH of the feed solution were 400 ± 10 mg/L, 21.6 ± 0.5 mg/L, 13.0 ± 0.2 mg/L, 1.20 ± 0.05 mS/cm and 7.25 ± 0.05 , respectively.

2.2 Reactor Configuration and Operation

The schematic diagram of the two-stage MFC-OMBR system is shown in Figure 1. The system consists of two parallel MFCs and one OMBR, which are hydraulically connected in series. The single-chamber MFCs used carbon-brush anodes and air-cathodes. The volume of the MFCs was 110-120 mL, respectively, due to the size differences of the anode brushes. The MFCs were inoculated with the anaerobic digested sludge collected from Boulder Wastewater Treatment Plant and fed with the synthetic wastewater. In the OMBR, a tubular membrane module (effective membrane area, A_m : 81 cm²) with active layer facing feed orientation was fully submerged into a bioreactor (effective volume, V_R : 1.5 L). A magnetic stirrer bar was used to mix the solution in the OMBR at a speed of 400 rpm. In order to study the performance and fouling behavior of the MFC-OMBR system, different operation practices were conducted (Table 1). In Run 1, fresh medium was used after system inoculation, and no membrane cleaning was performed during the run. In Run 2, the same operation was performed, but the membrane was chemically cleaned each day to investigate the difference in membrane fouling behavior. The chemical cleaning procedure included 30 min alkaline (0.2% NaOH/0.2% EDTA) wash followed by 30 min acid (2% citric acid) wash.(Wang et al., 2015) In Run 3, similar operation was used as Run 1, except 2000 mg total suspended solids (TSS)/L anaerobic sludge was added together with the medium into the MFC-OMBR system to understand if MFCs could serve as a pre-treatment to reduce membrane fouling. The performance under these operations was compared with a control conventional anaerobic OMBR (Run 4, 2000 mgTSS/L anaerobic sludge) without MFCs. Each run was performed three cycles. In Run 1-3, the

same membrane module was used and chemical cleaning was performed to restore the membrane flux after each cycle; however, due to membrane damage in Run 3, a fresh membrane module was employed in Run 4. All reactors were maintained at anaerobic condition and 28 ± 0.5 °C.

[Figure 1]

During operation, the solution volume of the MFC-OMBR system was monitored by a water level sensor. The flow was controlled by the volume of permeate extracted from the OMBR. When the water level of the OMBR dropped below the designated value, fresh feed wastewater converged with the same amount of bulk solution from the OMBR (Recycle Ratio = 100%) was firstly transferred into the two MFCs in parallel then into the OMBR using a peristaltic pump. Conductivity, temperature, pH, oxidation–reduction potential (ORP) values in the OMBR were monitored and logged using LabVIEW. In the meanwhile, draw solution (DS, 0.5 M NaCl) was recirculated at a cross flow velocity of 8.3 cm/s (equivalent to a flow rate of 230 mL/min). The concentration of DS was monitored by conductivity measurements and maintained constant through dosing a 5 M NaCl stock solution. The water flux was determined gravimetrically by weighing the mass of permeate water collected at predetermined time intervals with a digital balance (VWR, Radnor, PA). The FO membrane rejection rate (R_m) and the overall removal efficiency (η_R) of the MFC-OMBR system were calculated using Eq. (1) and Eq. (2), respectively.

$$R_m = 1 - \frac{C_P}{C_R} \approx 1 - \frac{C_{DS}}{C_R} f_D \quad \text{Eq. (1)}$$

$$\eta_R = 1 - \frac{C_{DS} V_{DS}}{C_{FS} V_{FS} - V_R \Delta C_R} \quad \text{Eq. (2)}$$

where C_P , C_R , C_{DS} and C_{FS} are the solutes and/or contaminants concentrations in the permeate, bulk reactor, draw solution and feed solution, respectively; and V_{DS} and V_{FS} , are the volume of draw solution and feed solution; ΔC_R is the concentration change of solutes and/or contaminants in the bulk reactor; f_D is the concentration factor, i.e., the ratio of C_{DS}/C_P , ~1.11 in this experiment. Detailed descriptions of R_m and η_R can be found elsewhere. (Gu et al., 2015)

2.3. Water and Solute Flux Modeling

In order to simulate water flux and solute accumulation in OMBR, a water flux model accounting concentration polarization was developed and given by:

$$J_w = K_m \ln \frac{\pi_D + \frac{B}{A}}{\pi_F + \frac{J_w}{A} + \frac{B}{A}} \quad \text{Eq. (3)}$$

where, K_m is the mass transfer coefficient, π_D osmotic pressure of draw solution, π_F feed solution osmotic pressure, A membrane water permeability, and B solute permeability. (She et al., 2012; She et al., 2013a)

Based on classic solution-diffusion theory, the reverse solute flux in FO process can be determined by:

$$\frac{J_{s\_DS}}{J_w} = \frac{B}{A\beta RT} \quad \text{Eq. (4)}$$

where J_{s_DS} is the reverse solute flux from draw solution, β the van Hoff coefficient for NaCl, R the universal gas constant, and T temperature in Kelvin (Phillip et al., 2010; Tang et al., 2010; She et al., 2012; She et al., 2013b). The values of constants and modeling parameters can be found in Table S2 in Supporting Information. Moreover, the accumulated solute flux from wastewater (J_{s_FS}) can be described as:

$$\frac{J_{s,FS}}{J_w} = C_{FS} \quad \text{Eq. (5)}$$

Thus, the theoretical ratio of the accumulated solute flux from wastewater to the total solute accumulation ($\eta_s = 83.3\%$ in this study) can be determined using:

$$\eta_s = \frac{J_{s,FS}}{J_{s,FS} + J_{s,DS}} \quad \text{Eq. (6)}$$

Experimentally, the contributions of solutes from wastewater to the total solute accumulation (η_s') in OMBR can be estimated using:

$$\eta_s' = \frac{EC_0 \left(\frac{\int J_w A_m dt}{V_R} + 1 \right)}{EC_t + \sum_1^t \frac{V_s}{V_R} (EC_t - EC_0)} \quad \text{Eq. (7)}$$

where EC_0 is the solution conductivity of fresh wastewater, $\int J_w A_m dt$ the cumulative volume of water transport to the draw solution from the OMBR bulk solution at time t , V_R the OMBR reactor volume, EC_t the solution conductivity in OMBR at time t , and V_s the sampling volume at time t .

2.4. Analyses

All samples for sCOD, N and P measurements were filtered through 0.45 μm cellulose membranes (Millipore), and the sludge was used for TSS measurements. sCOD and TSS were measured according to standard methods described in detail by American Public Health Association. (APHA, 1998) $\text{NH}_3\text{-N}$ (TNT 832/831/830) and $\text{PO}_4\text{-P}$ (TNT 846) were measured with HACH test tubes (HACH, Loveland, CO). All samples were collected and analyzed in triplicate. It should be noted that the samples collected from the MFC-OMBR system were replaced by the same amount of fresh wastewater.

The voltage across an external resistor (R , $10\ \Omega$) over the MFCs was recorded every 10 minutes using a data acquisition system (Keithley Instruments, Inc., OH). The current was calculated by:

$$I_i = \frac{U_i}{R} \quad \text{Eq. (3)}$$

The overall Coulombic efficiency (CE) (%) of the MFCs was calculated using:

$$CE = \frac{\sum_{i=1}^2 (\sum_{i=1}^n I_i t_i)}{F b \Delta S} M \quad \text{Eq. (4)}$$

where U_i is the output voltage of MFC at time t_i , R the external resistance, F Faraday's constant (96485 C/mole), b the number of moles of electrons produced per mol of COD (4 mol of e^- /mol of COD), ΔS the removed substrate (mg COD), and M the molecular weight of oxygen (32 g/mol). (Luo et al., 2012b) Polarization curves were obtained by linear sweep voltammetry (LSV) using a potentiostat (PC4/300, Gamry Instruments, NJ). The scan rate of LSV was 0.1 mV/s with the anode as working electrode and the cathode as counter and reference electrode. (Wang et al., 2012) Power density and current density were normalized by the effective volume (Ge et al., 2014). Paired two-sample t test was performed to study the significance of fouling mitigation and power production improvement.

3. Results and discussion

3.1. Salt Accumulation and Water Flux Change

Figure 2 shows the time-course change of solution conductivity (Figure 2a) and water flux (Figure 2b) in the OMBR during different operations. Though varied in different conditions, the solution conductivity increased from 1.2 ± 0.05 up to 12.6 ± 1.2 mS/cm, and the corresponding water flux decreased from 12.0 ± 0.7 to 2.0 ± 0.2 LMH in 9 days.

The increase of solution conductivity was due to accumulation of solutes from wastewater (i.e., NaCl, NaHCO₃, KH₂PO₄) as well as the reversely diffused solutes (i.e., NaCl) from DS into the OMBR. Previous modeling on OMBR solute accumulation using CTA membranes showed comparable contributions of these two mechanisms,(Xiao et al., 2011; Chen et al., 2014; Gu et al., 2015) but this study shows that the salts from wastewater influent was the major contributor ($\eta_s' = 82.1 \pm 4.0\%$) of the salinity build-up in the OMBR, indicating better solutes rejection of the TFC membrane than that of CTA membrane (Figure S2 in Supporting Information).

3.2. Membrane Fouling Behavior and the Benefits of MFCs

Figure 2b shows the water flux changes under different conditions. It can be seen that Run 2 with daily membrane cleaning showed almost the same profile as the modeled water flux, which simulated the flux under solute conductivity build-up without considering membrane fouling. This reveals that the water flux of the fouled membrane was almost fully recovered after chemical cleaning, and the water flux decline in Run 2 was mainly caused by the decrease of driving force across the membrane due to the salinity build-up in the bioreactor.

When no chemical cleaning was performed, as shown in Run 1, Run 3, and Run 4, membrane fouling led to more significant flux salvage, suggesting fouling mitigation is needed. This is different from the OMBRs with CTA membranes, where salt accumulation was the major contributor to flux decline other than membrane fouling (Chen et al., 2014; Gu et al., 2015). The high fouling property of TFC membrane might

be due to the rougher surface and surface charge, which may promote divalent cation (e.g., Ca^{2+} , Mg^{2+}) enhanced fouling.(Vrijenhoek et al., 2001; Mi and Elimelech, 2008; Mi and Elimelech, 2010; Liu and Mi, 2012; Gu et al., 2013) Interestingly, although similar flux declines were observed during the first 4 days, further flux drops in Run 1, 3, and 4 behaved differently. The flux of Run 1 stabilized around 4.0 ± 0.5 LMH, but the flux of Run 3 kept decrease till 3.0 ± 0.2 LMH, while the flux of Run 4 dropped even lower to 2.0 ± 0.2 LMH in Day 9. These results indicate that lower sludge accumulation alleviated membrane fouling, because Run 1 was not amended with extra sludge, and the TSS in Run 1 was all below 350 mg/L. In comparison, both Run 3 and Run 4 showed greater flux decline and more severe fouling due to addition of external sludge (TSS = 2000 mg/L) (Figure S3 in Supporting Information). The less fouling property of Run 1 and Run 2 was also supported by the fact that almost full flux recovery ($97.3\pm0.7\%$) was obtained each time after chemical cleaning. This recovery was much higher than the water flux recovery ratio after Run 3 and Run 4, which were $86.1\pm0.5\%$ and $84.4\pm0.8\%$, respectively. It should be noted that the flux drop of Run 3 was lower than Run 4 ($P < 0.05$), which suggested that the MFCs served as a pre-treatment to improve sludge property and reduced fouling potential. (Tian et al., 2014) It is acknowledged that the benefit of MFCs to OMBR is not as substantial (though statistically significant, $P < 0.05$) as hypothesized, partially due to the separate designs and operation of the two reactors. Previous studies have used also MFCs for sludge reduction and power generation, and results were positive in both MFC-alone operations and MFC-MBR combinations. (Su et al., 2013; Tian et al., 2014)

[Figure 2]

3.3. MFC Power Production and the Benefits of OMBR

Figure 3 compares the power production from the two MFCs operated in parallel in Run 1 (without cleaning) and Run 2 (with cleaning). For both MFCs, the power outputs increased in the first 4 days, which directly correlated with increase in solution conductivity shown in Figure 2a as well as buffer capacity due to solute build-up (Figure S4 in Supporting Information). Moreover, because Run 2 showed higher conductivity and pH increase, the power outputs from both MFCs in Run 2 were also higher than the outputs from Run 1 ($P < 0.05$). The highest power density accomplished by the MFC 1 and MFC 2 were $11.5 \pm 0.9 \text{ W/m}^3$ and $9.6 \pm 0.3 \text{ W/m}^3$, respectively. This demonstrates that the OMBR maybe a better integration option than MF/UF membranes for MFCs as it helps condition the solution for higher power output. Most MFC power outputs dropped after 6 days especially for Run 2 with higher flux. This is mainly caused by the depletion of substrates. As shown in Figure 4, the sCOD reading dropped to $\sim 100 \text{ mg/L}$ after 4 days, which was a level reported not enough to support sustainable power production. (Zhang et al., 2015)

The Coulombic efficiency increased from $3.3 \pm 0.8\%$ up to $22.6 \pm 2.1\%$ in Run 1 and from $6.4 \pm 1.1\%$ up to $15.7 \pm 2.2\%$ in Run 2. Run 2 showed higher power production but lower Coulombic efficiency than Run 1, which is believed due to the flux difference. Despite of higher solutes accumulation and carbon source input, the higher shear stress caused by higher flow rate in Run 2 may promote mass transfer in the MFCs thus improving

current production.(Aaron et al., 2010) However, the carbon source competition between the biomass in the OMBR (Figure S5 and S6 in Supporting Information) and the anode biofilm may lead to reduction of Coulombic efficiency.(Zhang et al., 2015) Moreover, it is expected that the recirculation ratio may play an important role through controlling the balance between solution conductivity, buffer capacity and substrate availability for the reactors. Research and modeling works on the effects of different operational parameters are needed in future studies.

[Figure 3]

3.4. Organics and Nutrients Removal

Figure 4 shows the sCOD concentration changes in the MFC effluent, OMBR bulk solution, and draw solution in Run 1 without membrane cleaning. It can be seen that the sCOD in the MFC effluents as well as the bulk solution dropped very quickly from 400 to ~100 mg/L in 4 days, presumably due to the biological degradation in the MFC and OMBR reactors. The biomass accumulation in the OMBR supports the hypothesis, and the total suspended solid (TSS) production rates were $0.078 \pm 0.008 \text{ g/gCOD}$ and $0.074 \pm 0.010 \text{ g/gCOD}$ for Run 1 and Run 2, respectively, which was in the similar level of previous studies.(Brown et al., 2015) No further sCOD degradation was observed in MFCs, confirming with previous findings that MFCs couldn't remove organics to a lower level. However, the sCOD in the OMBR draw solution maintained below 20 mg/L, indicating very good rejection (>90%) and organic removal (>95%) by the TFC membrane OMBR reactor, which guaranteed effluent quality.

[Figure 4]

The changes of nutrients ($\text{NH}_3\text{-N}$ and $\text{PO}_4\text{-P}$) in the OMBR bulk solution and draw solution are shown in Figure 5. With an inflow of 13.0 ± 0.5 mg/L, the OMBR showed perfect rejection ($> 99\%$) of $\text{PO}_4\text{-P}$ (Figure 5b), leaving an accumulation of $\text{PO}_4\text{-P}$ in the reactor and very low $\text{PO}_4\text{-P}$ in the DS. The concentration of $\text{PO}_4\text{-P}$ increased from 13.0 to 61.6 ± 9.5 and 119 ± 19 mg/L for Run 1 and Run 2 in 8 days, respectively. The high rejection of $\text{PO}_4\text{-P}$ is believed due to the electro-repulsion by the negatively charged TFC membrane surface. Moreover, the reverse salt flux of Na^+ (0.36 nm) and Cl^- (0.33 nm) could block the membrane pores (0.42 nm) thus hinder the forward diffusion of PO_4 as well.(Xie et al., 2014) However, it should be noted that the accumulation in the bioreactor might contribute to membrane fouling since PO_4^{3-} may react with Ca^{2+} to form $\text{Ca}_3(\text{PO}_4)_2$ precipitation.(Gu et al., 2015) Therefore, $\text{PO}_4\text{-P}$ recovery from the bioreactor is needed in future studies.(Lu and He, 2015)

[Figure 5]

In contrast with almost perfect rejection of $\text{PO}_4\text{-P}$, TFC membrane showed poor rejection of $\text{NH}_3\text{-N}$ (Figure 5a), which was likely due to membrane properties and solution chemistry. The surface of TFC membrane is negatively charged due to deprotonation of carboxylic groups.(Lu et al., 2014; Xue et al., 2015) In FO, water passed through the membrane from low-salinity FS to high-salinity DS. In the meanwhile, portions of draw solutes (i.e., NaCl) could reverse diffuse from DS to FS against the concentration gradient, while the feed solutes (i.e., NH_4^+ , K^+) may also

forward diffuse to the DS. However, because more Na^+ diffuses to FS than Cl^- , (Coday et al., 2013) a charge inequivalence in DS can be formed. (Lu et al., 2014) To maintain charge neutrality, cations from FS may be exchanged to the DS side through the negatively charged TFC membrane. As a highly diffusive cation, NH_4^+ is likely be the one balancing the charge (Figure S7 in Supporting Information), resulting lower rejection level. (Xue et al., 2015) Moreover, since the $\text{NH}_4^+/\text{NH}_3$ distribution is affected by the solution pH, more $\text{NH}_3\text{-N}$ was in the form of NH_3 under high pH (>8.0 , Figure S4 in Supporting Information), leading to higher flux of $\text{NH}_3\text{-N}$ toward the draw solution. To reduce $\text{NH}_3\text{-N}$ permeation, draw solutes with higher diffusive anion but lower diffusive cation may be a better choice than NaCl , such as MgCl_2 . (Devia et al., 2015) Also, nitrogen removal in bulk solution may be applied using nitrification and denitrification and/or annomox processes, (Li et al., 2015) and alkalinity management may be introduced into the OMBR system to remove $\text{NH}_3\text{-N}$ from the bioreactor. (Lu and He, 2015)

3.5 Implications and Perspectives

While this study demonstrates the feasibility and benefits of connecting MFCs with OMBRs, many more works are required to optimize the performance of the individual reactors and/or combined MFC-OMBR systems. Fouling mitigation strategies need to be further developed for the TFC membranes, and the poor rejection of $\text{NH}_3\text{-N}$ needs to be addressed. (Lu et al., 2014; Xue et al., 2015) Novel TFC membranes with lower fouling and better $\text{NH}_3\text{-N}$ rejection (e.g, surface modifications) (Lu et al., 2014) should be developed, and better draw solutes can be used. (Devia et al., 2015) Future studies may also consider integrated nutrients and/or salts recovery. For example, MFCs in this

study might be modified to microbial desalination cell (Luo et al., 2012a; Luo et al., 2012b) or microbial recovery cell (Chen et al., 2015) to recover salts and nutrients from the bioreactor. Operational optimizations can be investigated by modeling membrane flux or hydraulic retention time (HRT), solute accumulation, and the recirculation ratio of the MFC-OMBR system, all of which are key factors affecting membrane fouling, treatment performance and energy production.

4. Conclusions

This study reveals synergy between MFCs and OMBRs for sustainable wastewater treatment and energy production. The MFC-OMBR system effectively removed organics and phosphorus at mesophilic condition, producing a high quality effluent, accompanied with increased power production (up to 11.5 W/m^3) and less membrane fouling. The MFCs were benefited from the accumulation of buffer capacity and solution conductivity by the OMBR, leading to reduced internal resistance and increased power generation. The pre-treatment from MFCs reduced membrane fouling for the OMBR, credit to low sludge production ($0.076 \pm 0.008 \text{ gTSS/gCOD}$), low sludge load ($< 350 \text{ mg/L TSS}$), and conditioned sludge property. While the study demonstrates the feasibility and potential, more research is needed to improve nitrogen removal, reduce fouling, and optimize system integration.

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Table 1. Summary of operation conditions of the two-stage MFC-OMBR system; each run was performed three cycles.

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Name	Operation regime	Sludge Dose (mg TSS/L)	Membrane Cleaning	Condition
Run 1	MFC-OMBR	-	after run	Anaerobic
Run 2	MFC-OMBR	-	daily	Anaerobic
Run 3	MFC-OMBR	2000	after run	Anaerobic
Run 4	OMBR	2000	after run	Anaerobic

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Figure 4. Time-course changes of sCOD concentrations in the MFC effluent, OMBR bulk solution, and draw solution, as well as the COD removal during Run 1. Run 1: no sludge dose and without daily membrane cleaning. The error bars represent the standard deviations based on three independent experiments.

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Graphical Abstract

Boosted Power Density & Lower Fouling