

# Long-Term Performance of Liter-Scale Microbial Fuel Cells Treating Primary Effluent Installed in a Municipal Wastewater Treatment Facility

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## S Supporting Information

**ABSTRACT:** Two 4 L tubular microbial fuel cells (MFCs) were installed in a municipal wastewater treatment facility and operated for more than 400 days on primary effluents. Both MFCs removed 65–70% chemical oxygen demand (COD) at a hydraulic retention time (HRT) of 11 h and reduced about 50% suspended solids. The COD removal rates were about 0.4 (total) or 0.2 (soluble) kg m<sup>-3</sup> day<sup>-1</sup>. They could handle fluctuation, such as emptying the anode for 1–3 days or different HRTs. The preliminary analysis of energy production and consumption indicated that the two MFCs could theoretically achieve a positive energy balance and energy consumption could be reduced using larger tubing connectors. Through linkage to a denitrifying MFC, the MFC system improved the removal of total nitrogen from 27.1 to 76.2%; however, the energy production substantially decreased because of organic consumption in the denitrifying MFC. Establishing a carbon (electron) balance revealed that sulfate reduction was a major electron scavenger (37–64%) and methane production played a very minor role (1.3–3.3%) in electron distribution. These results demonstrate the technical viability of MFC technology outside the laboratory and its potential advantages in low energy consumption, low sludge production, and energy recovery from wastes.



## INTRODUCTION

Microbial fuel cells (MFCs) have been intensively studied in the past decade, and much of the fundamental knowledge in microbiology, electrochemistry, and reactor architecture has been obtained from laboratory investigation.<sup>1,2</sup> The working theory and performance of MFCs (both organic treatment and power production) is well-demonstrated; however, it is mostly in small-scale and batch-operated reactors. Among the studies reported in MFC-related literature, less than 2% reported a reactor larger than 1 L, less than 30% operated continuously, and most studies were conducted with pure substrates under a controlled laboratory condition and for a short period of time, indicating that engineering development of MFC technology lags behind laboratory studies. To further demonstrate the technical viability of MFC technology, it is necessary to examine the long-term performance and stability of larger size MFCs with actual wastewater.

There have been several studies reporting the long-term operation of MFCs. A cubic MFC with an anode working volume of 20 mL was operated for more than 2 years and achieved stable electricity generation from glucose.<sup>3</sup> Using electrochemical impedance spectroscopy, the researchers found that the anode impedance decreased in the first 50 days because of biofilm formation and then became stable in the next few months, resulting in a constant power output in an air-cathode MFC with a working volume of 16 mL.<sup>4</sup> However, the cathode

electrode of the air-cathode MFC could clog over time, and it was observed that the maximum power density decreased by 20–40% after operating a MFC with a working volume of 28 mL for 1 year.<sup>5</sup> Chemical and biological cathodes were evaluated and compared during a 400 day operation of the MFCs fed on glucose with an anode working volume of ~53 mL, and the results showed that the chemical cathodes had deteriorated performance while the biological cathode remained relatively stable.<sup>6</sup> An upflow tubular MFC with an anode working volume of 750 mL was used to treat animal carcass wastewater and continuously produced electricity during more than a 280 day operation.<sup>7</sup> A MFC system consisting of 40 individual tubular MFCs had a total liquid volume of 10 L and was operated for more than 180 days with a maximum power density of 4.1 W/m<sup>3</sup> generated from brewery wastewater.<sup>8</sup> The researchers also operated a 16 L MFC in a municipal wastewater treatment facility and obtained good treatment performance but low electricity production.<sup>9</sup> The first MFC pilot system was constructed in Queensland, Australia, consisting of 12 MFC modules with a total liquid volume of 1000 L; little information is available about its

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performance.<sup>10</sup> Microbial electrolysis cells (MECs), a derivative of MFC technology,<sup>11</sup> have been advanced to a pilot scale in two separated studies treating low-strength domestic or high-strength winery wastewaters.<sup>12,13</sup>

These prior long-term studies are healthy attempts to evaluate MFC performance; however, none of them analyzed energy production/consumption, which is the key parameter of MFC performance,<sup>14</sup> and most of them were conducted in laboratories. Clearly, more work is needed to understand the long-term behavior of MFCs outside of the laboratory. In this study, we installed two tubular MFCs (4 L/each) in a municipal wastewater treatment facility and operated them for more than 400 days without temperature control. We evaluated the stability, treatment performance, and energy production/consumption of the MFCs treating primary effluent by monitoring various parameters, including organic contents, electricity, nutrients (nitrogen and phosphate), suspended solids, pH, turbidity, coliform bacteria, and temperature. The resulting information was expected to help to assess scalability and application niche of MFC technology.

## MATERIALS AND METHODS

**MFC Setup.** Two identical tubular MFCs (except different cathode catalysts) were made of cation exchange membrane (CEM, Ultrex CMI7000, Membranes International, Inc., Glen Rock, NJ) according to a previous study.<sup>15</sup> Each MFC consisted of two CEM tubes connected on the bottom to form a “U” shape (see Figure S1 of the Supporting Information). Each CEM tube had a diameter of 5 cm and a length of 100 cm containing a carbon brush as an anode electrode and carbon cloth as cathode electrode. The total anode liquid volume of a “U”-shape MFC was about 4 L. One MFC used activated carbon powder (5 mg/cm<sup>2</sup>) as cathode catalysts (designated as MFC-AC), and the other had both activated carbon powder (4 mg/cm<sup>2</sup>) and 10% platinum in carbon black (0.1 mg of Pt/m<sup>2</sup>) as cathode catalysts (named “MFC-Pt”). The catalysts were coated to the carbon cloth (cathode electrode) by mixing with 5% polytetrafluoroethylene (PTFE) and then applied to the surface of the carbon cloth. The coated carbon cloth was heat-treated at 370 °C for 30 min. The anode and cathode electrodes were connected to an external circuit containing a resistance decade box via titanium wire.

**Operating Conditions.** The MFCs were installed in a small room without any temperature control at the South Shore Water Reclamation Facility (Milwaukee, WI). During the operation period, the temperature varied between −10 and 36 °C (see Figure S2 of the Supporting Information). The MFCs were fed with the effluent from the primary settling tanks by pumps without any further pretreatment, and the anode effluent was used as a catholyte to rinse the cathodes of the MFCs, as described in a previous study.<sup>16</sup> The final effluent was collected in a tank under the MFCs and then returned to the flow channel of the primary effluent that was about 3 m under the room. The hydraulic retention time (HRT) of the wastewater in the anodes was 11 h or otherwise adjusted by the feeding pump. The anolyte was recirculated at ~165 mL/min, and the catholyte was recirculated at 21 mL/min. The external resistors of the MFC-Pt and MFC-AC were (individually) set as day 0–57, 5 Ω; day 58–104, 10 Ω (in each of the two separated circuits of one MFC); and the remaining period, 10 Ω. To study the effect of inhibiting sulfate

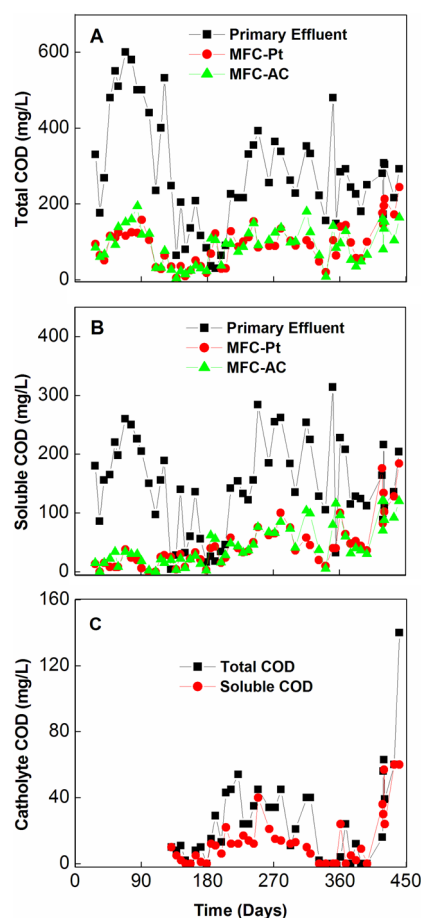
reduction, we added 3.25 mM sodium molybdate to the anode feeding wastewater of the MFC-Pt for 2 weeks.

To investigate the feasibility of nitrogen removal from the wastewater, a denitrifying MFC was linked to the MFC-AC for reducing nitrate that was produced from the cathode of the MFC-AC. The details of the denitrifying MFC can be found in the Supporting Information. In such a system, the primary effluent was first fed into the anode of the denitrifying MFC and then the anode of the MFC-AC; the anode effluent of the MFC-AC rinsed its cathode and flowed into the cathode of the denitrifying MFC for nitrate reduction (the inset of Figure 5A).

**Measurement and Analysis.** The cell voltage was recorded every 10 min by a HOBO U12 outdoor/industrial data logger. The concentrations of total chemical oxygen demand (TCOD), soluble chemical oxygen demand (SCOD), ammonium, nitrite, nitrate, phosphate, and sulfate were measured using a colorimeter according to the instructions of the manufacturer (Hach Company, Loveland, CO). The concentrations of total suspended solids (TSS) and volatile suspended solids (VSS) were measured according to the standard methods.<sup>17</sup> The coliform bacteria were determined using the membrane filter technique for members of the coliform group approved by the Standard Methods Committee.<sup>17</sup> The concentration of total Kjeldahl nitrogen (TKN) was measured by a Digesdahl digestion apparatus (Hach Company) according to the instructions of the manufacturer. Turbidity was measured with a turbidimeter (Scientific, Inc., Fort Myers, FL). The pH, temperature, and dissolved oxygen (DO) were measured using a 556 MPS multiparameter instrument (YSI Incorporated, Yellow Spring, OH). Biogas was analyzed using gas chromatography (Thermo Fisher Scientific, Inc.), and the dissolved methane was determined according to a previous publication.<sup>18</sup> The calculations of Coulombic efficiency (CE), Coulombic recovery (CR), energy consumption, and oxygen flux through the CEM are shown in the Supporting Information.

## RESULTS AND DISCUSSION

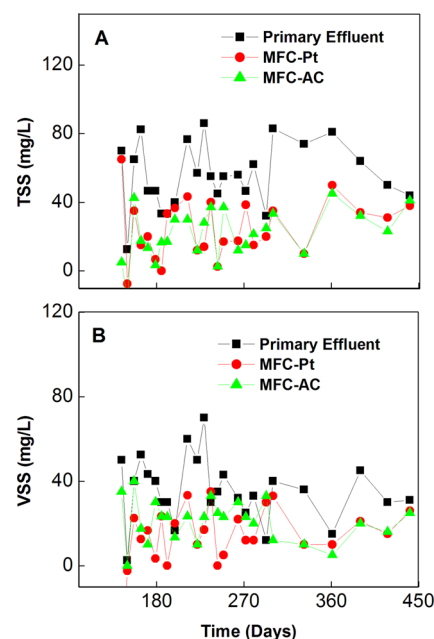
**Treatment Performance.** The organic concentration in the primary effluent (feeding solution) was highly variable (279.7 ± 144.4 mg of TCOD/L and 146.2 ± 77.1 mg of SCOD/L) and could reach a very low level after a major storm (panels A and B of Figure 1). In general, both MFCs achieved similar COD removal efficiency of 65–70% or COD removal rate of ~0.40 kg of TCOD m<sup>−3</sup> day<sup>−1</sup> or ~0.22 kg of SCOD m<sup>−3</sup> day<sup>−1</sup> in their anodes at a HRT of 11 h. The anode effluent of the MFC-AC contained 90.3 ± 48.3 mg of TCOD/L and 45.0 ± 35.0 mg of SCOD/L, while the MFC-Pt produced 93.2 ± 53.2 mg of TCOD/L and 44.6 ± 41.1 mg of SCOD/L (see Table S1 of the Supporting Information). The COD removal efficiencies of both MFCs started to decrease after day 400 (panels A and B of Figure 1) because of a significantly decreased temperature, and the experiments were stopped on day 450 because the MFCs were completely frozen at a room temperature of ~−10 °C (see Figure S2 of the Supporting Information). We observed further reduction of the organic concentration after the anode effluent flowed over the cathode surface; the water in the tank under the MFCs that collected the catholytes (see Figure S1 of the Supporting Information) contained low concentrations of both TCOD and SCOD (Figure 1C), resulting in an overall organic removal >90%. This improved organic removal was likely due to aerobic treatment (without active aeration), confirming that the quality of the



**Figure 1.** Organic concentrations in the primary effluent and the MFC anode effluents: (A) TCOD, (B) SCOD, and (C) organic concentrations in the catholyte.

effluent from anaerobic treatment (MFC anode) can be further improved through aerobic polishing.<sup>19</sup> This post-aerobic treatment was also important to the pH of the solution, because we observed that the anolyte pH varied between 4.0 and 6.5 and the pH of the catholyte was about 7.5–8.5 (see Figure S3 of the Supporting Information).

Suspended solids (SS) in biological treatment are related to the production of secondary sludge. In this study, we monitored the concentrations of both TSS and VSS (Figure 2) and found that the anodes of the MFCs reduced about 50% TSS and VSS. In the tank that collected the catholyte (which possibly acted as a sedimentation tank), the SS concentrations became even lower at  $14 \pm 18$  mg of TSS/L and  $4 \pm 10$  mg of VSS/L (see Table S1 of the Supporting Information). Similarly, the MFC anodes decreased turbidity, another indicator of the particle concentration in water, which was also further reduced in the catholyte (see Figure S4 of the Supporting Information). For comparison, the SS concentrations in the aeration tanks of the South Shore Water Reclamation Facility were  $2214 \pm 314$  mg of TSS/L and  $1642 \pm 242$  mg of VSS/L. Although the post-aerobic polishing would accumulate sludge via aerobic activities (unfortunately, we did not quantify biosolid accumulation in the tank collecting the catholyte), in general, the MFC + post-aerobic treatment is expected to produce much less sludge than an activated sludge process, because of significant reduction of organic compounds in the MFC anodes (65–70%, while the cathode removed another 20–25%). The low biomass yield in



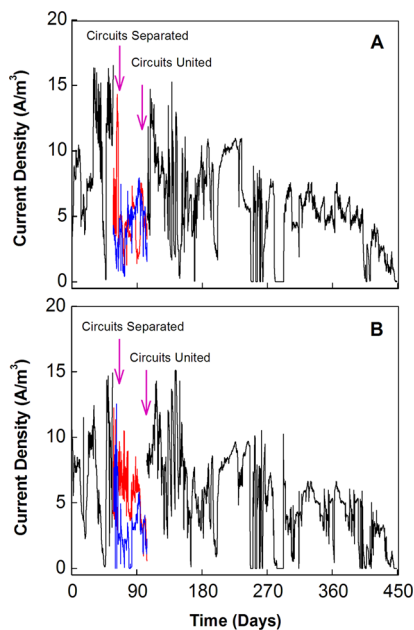
**Figure 2.** Concentrations of suspended solids in the primary effluents and the MFC anode effluents: (A) TSS and (B) VSS.

the MFCs was also observed in the prior studies of laboratory systems.<sup>20,21</sup> As a result, the use of a secondary clarifier will be greatly reduced, thereby saving a tremendous amount of energy and effort for sludge disposal.

As expected, the anodes of the MFCs did not achieve any obvious removal of nitrogen and phosphorus. The concentrations of ammonium, nitrite, and nitrate are shown in Figures S5–S7 of the Supporting Information, respectively, and the phosphate concentration is shown in Figure S8 of the Supporting Information. However, the catholyte showed a significantly lower concentration of ammonium (see Figure S5 of the Supporting Information) and accumulation of nitrate (see Figure S7 of the Supporting Information), indicating the presence of nitrification. We have investigated nitrogen removal in greater detail by linking a denitrifying MFC to the MFC-AC, which is introduced in the following section. The MFC anodes did not achieve any significant removal of coliform bacteria, which were mainly affected by season and temperature (see Figure S9 of the Supporting Information).

**Electricity Generation.** Electric current was used as a parameter to monitor the long-term performance of electricity generation in the MFCs; power and energy were also analyzed. Both MFCs exhibited high current generation in the first 180 days (Figure 3), likely because of high organic concentrations in the primary effluent during that period (panels A and B of Figure 1). For most of the time, two tubes of a MFC (see Figure S1 of the Supporting Information) were connected by one electric circuit, in which two anode carbon brushes were connected together as one anode and two cathodes were linked as one cathode. Between days 57 and 104, we separated the circuit into two to examine whether power and energy production could be higher; that is, each tube functioned as an independent MFC. The results did not support our idea; therefore, the two individual circuits were combined back to one after day 104. The large variation in current generation was possibly because of the varied organic concentrations and conductivity in the primary effluent; the sharp decreasing lines, especially those that decreased to a level close to zero in a short





**Figure 3.** Profiles of current generation during the operating period: (A) MFC-AC and (B) MFC-Pt.

period of time, were mostly because the tubing clogging stopped the supply of the primary effluent (or the anode emptiness test). We expect that the tube clogging can be overcome in a larger scale MFC system, which will have a much faster feeding flow rate. The gradual decrease in the current after day 400 was due to the decreasing temperature (see Figure S2 of the Supporting Information). Biofouling of both membrane and cathode electrode over time might also contribute to the decreasing current. In general, there was not an obvious difference in current generation between the two MFCs, both of which achieved similar CEs and CRs (see Table S1 of the Supporting Information), suggesting that activated carbon (AC) powder can be an effective catalyst in a MFC.<sup>22</sup> However, we do not think that AC powder is good enough to replace platinum in any other oxygen-reduction processes, such as conventional hydrogen fuel cells. The relatively comparable performance that AC powder achieved in a MFC is likely due to the low demand of oxygen reduction; that is, platinum is “overqualified” to be a catalyst for MFCs. The low Pt loading rate on the cathode electrode might also be one of the reasons why the MFC-Pt did not outperform the MFC-AC. Nevertheless, the cathode catalyst is not the focus of this study, and our results show that AC powder could be an alternative catalyst for further MFC development.

Energy production is a key parameter to properly evaluate the benefits of MFC technology for wastewater treatment.<sup>14</sup> We analyzed energy production and consumption and established a preliminary energy balance (Table 1). Energy production was expressed as kilowatt hours per cubic meter of treated wastewater or kilogram of removed COD (either TCOD or SCOD). Energy consumption included the consumption by pumps for feeding and recirculation; the feeding energy could be neglected in comparison to the recirculation energy. The two MFCs produced comparable electric energy but had different energy consumption, mainly because of the difference in hydraulic head loss, which is a key element in estimating energy consumption (details in the Supporting Information). The measured hydraulic head loss of

**Table 1. Summary of Energy Production and Consumption in the MFCs<sup>a</sup>**

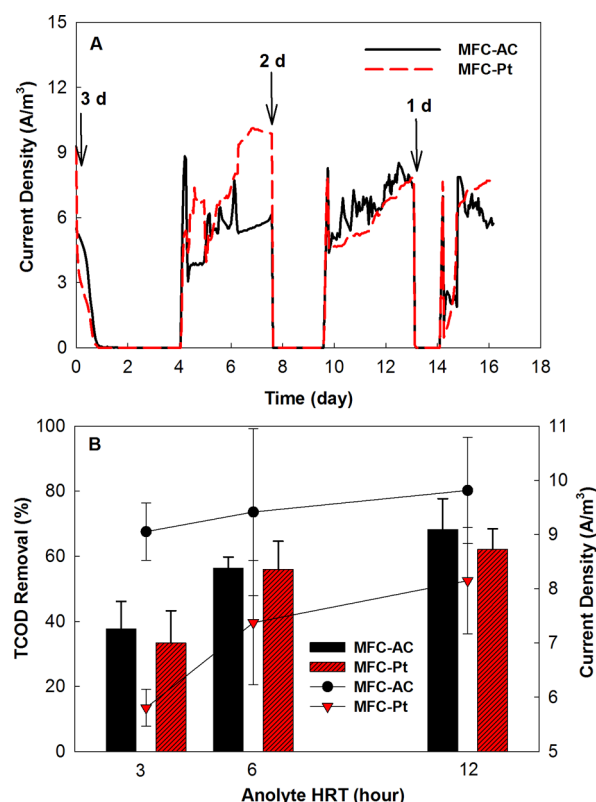
	energy production		energy consumption		energy balance	
	kWh/m <sup>3</sup>	kWh/kg of TCOD	kWh/m <sup>3</sup>	kWh/kg of TCOD	kWh/m <sup>3</sup>	kWh/kg of SCOD
MFC-AC	0.0255 (0.0204)	0.0794 (0.1015)	0.0238 (0.0045)	0.1698 (0.1915)	0.0017 (0.0248)	0.0004 (0.4348)
MFC-Pt	0.0239 (0.0186)	0.0739 (0.0653)	0.0147 (0.0004)	0.1462 (0.2206)	0.0092 (0.0190)	0.0181 (0.3998)
N-MFC <sup>b</sup>	0.0078 (0.0059)	0.0236 (0.0195)	0.0238 (0.0045)	0.1746 (0.1442)	−0.0160 (0.0104)	−0.1356 (0.1729)

<sup>a</sup>The values in parentheses are standard deviations. <sup>b</sup>The MFC system for nitrogen removal consisted of the MFC-AC and a denitrifying MFC.

the anode recirculation pump for the MFC-AC was  $19.0 \pm 6.1$  cm, significantly higher than  $6.7 \pm 0.6$  cm with the MFC-Pt. We found that this difference was related to the size of tubing connectors; we accidentally used smaller size connectors in the MFC-AC, which resulted in a higher hydraulic head loss. This indicates that, in designing future MFC systems, the size of connector/port should be large enough to reduce hydraulic head loss and, thus, energy consumption. Overall, both MFCs achieved positive energy balances with large standard deviations (Table 1); the MFC-Pt had a more positive balance because of less energy consumption.

For practical application, it is important to have durable and stable treatment technology, which is related to the maintenance and operating expense. A potential concern with using the anode effluent as a catholyte is the overgrowth of biofilm on the cathode electrode stimulated by the remaining organics/nitrogen in the anode effluent. During the operation, biofilm formed on the cathode electrode and possibly functioned as post-treatment of organics and nitrogen; however, we did not clean the cathode electrode during the entire experimental period. This suggests that biofilm formation was not as serious as expected and did not significantly affect electricity generation. We also examined the response of the MFCs to fluctuation under two conditions. The first condition was to mimic a situation in which the anode compartments were emptied for repair or other maintenance; in this case, oxygen enters the anode compartment after the water was emptied. The emptiness was held for 3, 2, and 1 day, and we observed that the current generation in the two MFCs recovered from oxygen intrusion in a few days, depending upon the length of the exposure (Figure 4A). This demonstrates that the MFCs could successfully handle oxygen flux for a short period of time, likely benefiting from facultative microorganisms in the anode community. The second condition was to simulate a larger water flux for a short period in the case of rain or storm. The large water flux alters the anolyte HRT, and thus, we examined three HRTs: 12 h, 6 h, and 3 h. The amount of the wastewater at a HRT of 3 h was 4 times greater than at 12 h, higher than common ratios of the treatment capacities between dry and wet weather. TCOD removal decreased with the decreasing HRTs in both MFCs, because of a higher organic loading rate at a smaller HRT (Figure 4B). The current generation in the MFC-AC slightly decreased, but the MFC-Pt had a more significant drop in its current at shorter HRTs (the inset of Figure 4B), which might be attributed to Pt catalyst contamination by serious biofouling from more organic input, but the exact reason is not clear at this moment. Both MFCs recovered to regular performance after the HRT was adjusted back to 12 h. We are more optimistic about the COD removal during shorter HRTs and expect much higher removal efficiencies than those shown in Figure 4B, because rainwater will greatly dilute the COD and the actual organic loading rate may not increase significantly.

**Nitrogen Removal.** Nitrogen removal is of great interest in wastewater treatment because of the tightened regulations on nitrogen discharge. Ammonia cannot be effectively oxidized under the anaerobic condition of the anode of a MFC;<sup>23</sup> however, it was found that nitrate can be bioelectrochemically reduced on the cathode by accepting electrons from a cathode electrode.<sup>24</sup> In the cathode of the present MFCs, nitrate was produced and accumulated and ammonium was reduced to a very low level (see Figures S5 and S7 of the Supporting Information), indicating the occurrence of nitrification. The

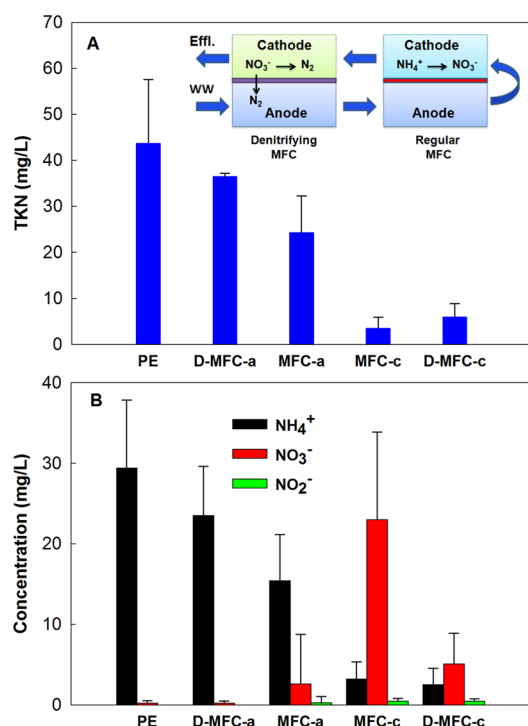


**Figure 4.** MFC performance in response to fluctuation: (A) emptying the anode for different periods and (B) different HRTs (bars represent TCOD removal and dots/lines represent current density).

concentration of total nitrogen in the final effluent (from the cathode) was dominated by the nitrate concentration; therefore, to improve the removal of total nitrogen, we connected a denitrifying MFC for nitrate reduction to the MFC-AC on day 301.

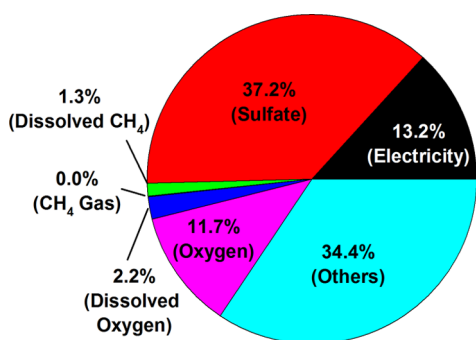
Such a cooperative system between a denitrifying MFC and a regular MFC (as shown by the inset of Figure 5A) significantly improved the nitrogen removal. The concentration of nitrate was reduced from  $21.4 \pm 10.2$  mg/L in the cathode effluent of the MFC-AC to  $4.9 \pm 3.8$  mg/L in the cathode effluent of the denitrifying MFC (also the final effluent of the MFC treatment), about a 77% reduction (Figure 5B). The average current of the denitrifying MFC was about 8.6 mA, resulting in a CE of 14.3% based on nitrate removal, which was lower than those obtained in our previous studies.<sup>25,26</sup> The total nitrogen (sum of TKN, nitrate, and nitrite) was reduced by 76.2%, much higher than 27.1% without the denitrifying MFC. As expected, the ammonium or TKN concentrations were not obviously affected by the denitrifying cathode (panels A and B of Figure 5), and some loss of ammonium or TKN in the anodes of the MFCs was likely due to ammonium ion movement through CEM<sup>27</sup> and microbial synthesis. The denitrifying MFC also removed  $31.8 \pm 23.2\%$  TCOD or  $38.3 \pm 15.3\%$  SCOD. Excessive consumption of organic compounds in the anode of the denitrifying MFC was not desired, because it would reduce energy production in the MFC-AC and result in a negative energy balance (Table 1); the denitrifying MFC was operated under a high-current mode, and thus, little electric power/energy was produced.

**Carbon Balance.** A mass balance of carbon compounds based on either TCOD or SCOD was established with the



**Figure 5.** Concentrations of nitrogen compounds in the MFCs designed for nitrogen removal: (A) TKN and (B) ammonium, nitrate, and nitrite. (Inset) Schematic of the MFC system consisting of a denitrifying MFC and the MFC-AC. PE, primary effluent; D-MFC-a, anode of the denitrifying MFC; MFC-a, anode of the MFC-AC; MFC-c, cathode of the MFC-AC; and D-MFC-c, cathode of the denitrifying MFC.

MFC-Pt by analyzing the contributions from different sources, including electricity, methane, oxygen, sulfate, and other unknown factors (Figure 6 and Table S2 of the Supporting



**Figure 6.** Carbon balance based on TCOD obtained from the MFC-Pt.

Information). Because carbon is an electron donor, this balance could also represent an electron balance. Derived from CE, the carbon distribution to electricity production was 13.2% (on the basis of TCOD) or 22.8% (on the basis of SCOD). Surprisingly, sulfate consumed much more carbon than electricity production (37.2% TCOD or 64.0% SCOD). The primary effluent contained a sulfate concentration of  $119.6 \pm 69.7$  mg of  $\text{SO}_4^{2-}/\text{L}$ , and the anode removed  $81.2 \pm 17.2\%$  sulfate, indicating an active sulfate reduction in the MFC anode. The primary effluent contained dissolved oxygen of  $3.3 \pm 1.3$  mg/L, which could consume 2.2% TCOD or 3.8% SCOD.

Oxygen flux through the CEM was estimated to contribute to 11.7% TCOD or 20.2% SCOD. Methane production was observed in MFCs,<sup>28</sup> and thus, we examined both methane gas and the dissolved methane in the anode effluent. The average concentration of the dissolved methane was about 1 mg/L, and methane gas production was  $\sim 0.5$  mL/g of SCOD, resulting in carbon consumption of 1.3% TCOD (or 2.2% SCOD) and 0.04% TCOD (or 0.1% SCOD), respectively.

There was 34.4% TCOD unaccounted for by these calculations, while there was 13.1% SCOD overly accounted (see Table S2 of the Supporting Information). The possible measurement/analytic errors (e.g., collection of methane gas) might also lead to unknown carbon flow in the TCOD calculation. For the balance of SCOD, the total input coulombs could have been underestimated, because additional SCOD could be produced from the degradation of TCOD. Because sulfate reduction was found to be a major contributor to COD removal, it would be interesting to know whether inhibiting sulfate reduction could improve electricity production. We have conducted the tests on inhibiting sulfate reduction, which can be found in the Supporting Information. Because of the significant variation of wastewater quality and testing conditions in the field that could strongly disturb the experimental results, we cannot draw any definitive conclusions on the effect of sulfate reduction on electricity generation, and more laboratory tests under controlled conditions will be needed to further our understanding of this issue.

**Perspectives.** A proper understanding of the application niche and the benefits of the MFC technology is very important to its development. It is critical to acknowledge that the primary function of MFCs is wastewater treatment instead of energy production (which is an added benefit). MFCs are advantageous in several aspects. (1) Low energy consumption: A MFC system avoids the use of aeration, which consumes about 50% of the electric energy of an aerobic wastewater treatment process. (2) Low sludge production: the anaerobic process in the anodes of a MFC system accumulates little secondary sludge. This result has two potential benefits: minimizing the use of a secondary clarifier to save both operation and infrastructure expense and reducing the treatment of secondary sludge, which requires significant effort and energy. (3) Energy recovery from wastewater: the electric energy produced by a MFC system could be used to offset the energy requirement by the pumping system, thereby further reducing the energy consumption of the wastewater treatment process.

We have not observed satisfactory energy production from high-strength/high-solid wastes in MFCs;<sup>29</sup> therefore, we believe that MFCs cannot compete with anaerobic digestion for the treatment of high-strength/high-solid wastes,<sup>30</sup> and MFCs are more suitable for medium- and low-strength wastewater that is currently treated by aerobic processes. However, with the increased attention to anaerobic treatment [e.g., anaerobic membrane bioreactor (AnMBR)] of domestic wastewater,<sup>31,32</sup> there will be competition between conventional anaerobic treatment and MFC technologies (if proven applicable in the future). In comparison to conventional anaerobic treatment of low-strength wastewater, the potential advantages of MFC technology may exist in several aspects: (1) better ability to handle temperature variation, especially at low temperatures, (2) no need of gas collection, treatment, and converting system (for energy production) because of direct electricity production, (3) low dissolved methane in the treated effluent to avoid the release of greenhouse gas, and (4) nitrogen



removal with linking to specially designed MFC systems. Integrating membrane technology into MFCs can also produce high-quality effluent,<sup>33</sup> such as that in AnMBRs. Those advantages need to be further verified and demonstrated with more work of larger scale MFCs treating actual wastewater.

Although energy production may not be the most important feature of MFC technology, it is still beneficial to further improve electricity production by optimizing MFC configuration, materials, and operation. For instance, we recently used spiral spacers to double energy production in tubular MFCs.<sup>34</sup> Nitrogen removal is certainly possible in the present MFC system, and carbon distribution should be carefully coordinated for the purpose of energy production.

## ■ ASSOCIATED CONTENT

### ■ Supporting Information

Calculation of CE, energy consumption, and oxygen flux, details of the sulfate-reduction inhibition test, summary of the treatment performance in Table S1, data of carbon balance in Table S2, and MFC schematic and data of the temperature, nutrients, coliform bacteria, and sulfate in Figures S1–S10. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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### Notes

The authors declare no competing financial interest.

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