

Brewery wastewater treatment using air-cathode microbial fuel cells

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Abstract Effective wastewater treatment using microbial fuel cells (MFCs) will require a better understanding of how operational parameters and solution chemistry affect treatment efficiency, but few studies have examined power generation using actual wastewaters. The efficiency of wastewater treatment of a beer brewery wastewater was examined here in terms of maximum power densities, Coulombic efficiencies (CEs), and chemical oxygen demand (COD) removal as a function of temperature and wastewater strength. Decreasing the temperature from 30°C to 20°C reduced the maximum power density from 205 mW/m² (5.1 W/m³, 0.76 A/m²; 30°C) to 170 mW/m² (20°C). COD removals (R_{COD}) and CEs decreased only slightly with temperature. The buffering capacity strongly affected reactor performance. The addition of a 50-mM phosphate buffer increased power output by 136% to 438 mW/m², and 200 mM buffer increased power by 158% to 528 mW/m². In the absence of salts (NaCl), maximum power output varied linearly with wastewater strength (84 to 2,240 mg COD/L) from 29 to 205 mW/m². When NaCl was added to increase conductivity, power output followed a Monod-like relationship with wastewater strength. The maximum power (P_{max}) increased in proportion to the solution conductivity, but the half-saturation

constant was relatively unaffected and showed no correlation to solution conductivity. These results show that brewery wastewater can be effectively treated using MFCs, but that achievable power densities will depend on wastewater strength, solution conductivity, and buffering capacity.

Keywords Microbial fuel cell · Beer brewery wastewater · Temperature · Solution conductivity

Introduction

The annual wastewater production from beer breweries in China is about 0.3 billion m³, which is 1.5% to 2.0% of the total wastewater production in the nation (Guo 2005). Brewery wastewaters produced from cooling and washing units have high chemical oxygen demands (CODs) but are nontoxic because much of the organic matter in the water consists of sugar, starch, and protein (Speece 1996). Biological methods usually used for brewery wastewater treatment include: aerobic sequencing batch reactor (Wang et al. 2007), cross-flow ultrafiltration membrane anaerobic reactors (Ince et al. 2000), and up-flow anaerobic sludge blanket reactors (Kida et al. 1994; Parawira et al. 2005). Biological treatment processes are particularly effective for wastewater treatment, but they require a high energy input. Thus, there is a need for reducing the energy demand for wastewater treatment.

Microbial fuel cells (MFCs) have recently drawn worldwide interest as a new method of directly generating electricity from organic matter in wastewater, while simultaneously treating the wastewater. MFCs are devices which use bacteria to directly convert the chemical energy of the organic matter into electrical energy. MFC reactors

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are designed for anaerobic treatment by bacteria in the solution near the anode, with the cathode exposed to oxygen (or an alternative chemical electron acceptor). Electrons released by bacterial oxidation of the organic matter are transferred through the external circuit to the cathode where they combine with oxygen to form water.

Most MFC studies have been conducted using pure compounds, such as acetate (Bond and Lovley 2003), glucose (Rabaey et al. 2003), sucrose (He et al. 2006), an amino acid (cysteine; Logan et al. 2005), or a protein (bovine serum albumin; Heilmann and Logan 2006). Power densities obtained with these substrates vary with MFC architecture, but they are generally higher with pure compounds than tests with actual wastewaters. For example, maximum power densities were 494 mW/m² using glucose compared to 146 mW/m² using domestic wastewater (Liu and Logan 2004), and 354 mW/m² using bovine serum albumin compared to 80 mW/m² using a meat packing wastewater (Heilmann and Logan 2006) in single-chamber, air-cathode MFCs (Table 1). Complex organic matter sources that have been used in MFC tests include domestic wastewater (Liu et al. 2004), swine wastewater (Min et al. 2005), meat packing wastewater (Heilmann and Logan 2006), food processing wastewater (Kim et al. 2004), hydrogen fermentation reactor effluent (Oh and Logan 2005), and corn stover hydrolysates (liquefied corn stover; Zuo et al. 2006; Table 1).

The above studies demonstrate that the power densities cannot be predicted a priori from experiments using pure chemicals. Beer brewery wastewater has not previously been examined as a substrate for power generation in an MFC, although it should be suitable for electricity generation due to the food-derived nature of the organic matter and the lack of high concentrations of inhibitory substances (for example, ammonia in animal wastewaters).

We therefore investigated here the effectiveness of treatment of a full-strength beer brewery wastewater using an air-cathode MFC previously used to examine power generation with several different pure compounds and types of wastewaters (Liu and Logan 2004; Min et al. 2005; Liu et al. 2005a, b). The performance of the MFC for electricity generation was evaluated in terms of maximum power densities and Coulombic efficiencies for reactors operated at two different wastewater temperatures (30°C and 20°C) over a range of wastewater strengths, with the effectiveness of treatment measured in terms of COD removal.

Materials and methods

Beer brewery wastewater

Brewery wastewater was collected from the regulating reservoir of the wastewater treatment system at the Harbin Brewery Co., Ltd. (Harbin, China), and stored at 4°C before being used. The wastewater had a COD of 2,250 ± 418 mg/L, and other characteristics shown in Table 2. In some tests, the wastewater was diluted with ultra-pure water (Milli-Q system; Millipore Corp., New Bedford, MA, USA) or a phosphate buffer (PBS; 50 or 200 mM) and was added to MFCs. The 50-mM PBS solution contained (per liter): KCl, 0.13 g; NaH₂PO₄·2H₂O, 3.32 g; Na₂HPO₄·12H₂O, 10.32 g; NH₄Cl, 0.31 g.

MFC configuration

A single-chamber, air-cathode MFC was constructed as previously described (Liu and Logan 2004). The anode electrode (projected surface area = 7 cm²) was made of carbon cloth (without wet proofing; E-TEK, USA), and the

Table 1 Comparison of power generation from pure and mixed chemicals in MFCs

| MFC configuration | Substrate: single chemical | Power density (W/m ³) | Substrate: wastewater | Power density (W/m ³) | Reference |
|--------------------|----------------------------|-----------------------------------|------------------------------|-----------------------------------|--|
| Single-chamber MFC | Glucose | 12.4 | Domestic wastewater | 3.7 | Liu and Logan (2004) |
| | | | Swine wastewater | 6.5 | Min et al. (2005) |
| | | | Corn stover hydrolysates | 9.3 | Zuo et al. (2006) |
| | Acetate | 12.7 | Biohydrogen reactor effluent | 9.3 | Liu et al. (2005b); Oh and Logan (2005) |
| | | | Butyrate | 7.6 | |
| | | | Propionate | 1.7 | |
| Two-chamber MFC | Cysteine | 0.35 | Meat packing wastewater | 2.0 | Heilmann and Logan (2006) |
| | | | Cereal wastewater | 0.59 | Logan et al. (2005); Oh and Logan (2005) |
| Baffled MFC | Glucose | 37 | Maple syrup with M9 medium | 49 | Rabaey et al. (2005a) |
| Tubular MFC | Acetate | 58 | Digester effluent | 5 | Rabaey et al. (2005b) |

Table 2 Characteristics of beer brewery wastewater

| Parameter | Value |
|------------------------------|-----------|
| pH | 6.5±0.2 |
| COD, mg/L | 2,250±418 |
| BOD, mg/L | 1,340±335 |
| TOC, mg/L | 970±156 |
| NH ₃ -N, mg/L | 54±14 |
| Phosphate, mg/L | 50±35 |
| Total suspended solids, mg/L | 480±70 |

cathode was made of carbon cloth (30% wet proofed, E-TEK, USA) containing a Pt catalyst (0.35 mg/cm², water-facing side; E-TEK). The air-facing side of the cathode was coated with four PTFE diffusion layers as previously described (Cheng et al. 2006a). The electrodes were placed on opposite sides of the cylindrical chamber (4 cm long, 3 cm diameter; 28 mL liquid volume). Titanium wire was used for the connection of the external circuit to the carbon electrodes.

MFC tests

Eight reactors (MFC1–MFC8) were operated in fed-batch mode at a fixed external resistance of 1,000Ω (except as indicated) and refilled each time the voltage decreased below 50 mV. All reactors were inoculated with full-strength brewery wastewater, and initially operated at 30°C (±0.1°C). After four stable cycles of power generation, reactor MFC7 was transferred into a 20°C (±0.1°C) temperature-controlled room (redesignated as MFC20). Another reactor (MFC8) was used to examine the effect of the addition of the PBS (50 or 200 mM) on power generation. The other six reactors (MFC1 to MFC6) were maintained at 30°C but at various wastewater concentrations ranging from 84 to 2,250 mg COD/L (full-strength wastewater). The time for each batch cycle varied with wastewater concentration, with a maximum time of 4 days needed for the full-strength wastewater.

Additional experiments were conducted to specifically investigate the effect of COD concentration on power generation at different solution conductivities. NaCl was added to the wastewater to increase the conductivity from 3.5 to 5 mS/cm (0.96 g/L) or 7 mS/cm (2.33 g/L).

Analyses

Cell voltages were measured every 30 min using a data acquisition system (PISO-813, ICP DAS Co., Ltd). For the MFCs using diluted wastewater, polarization curves were obtained by varying external resistances from 50,000 to 50Ω, with each resistor tested for two complete fed-batch cycles. A reference electrode (saturated calomel electrode,

SCE; 241 mV versus standard hydrogen electrode, SHE) connected to an electrochemical test system (model 263A, AMETEK-AMT, USA) was used to measure anode and cathode potentials.

Current density was calculated as $i = E / RA$, where E (mV) is cell-measured voltage, R (Ω) the external resistance, and A (cm²) the projected surface area of the anode. Power density in MFC tests was calculated according to P (mW/m²) = $10iE$, where 10 is needed for the given units. The Coulombic efficiency (CE) was obtained by $CE = Q_R / Q_{th} \times 100\%$, where Q_R (C) is the total Coulombs through external circuit in a complete cycle, and Q_{th} (C) is the theoretical amount of Coulombs that can be calculated based on COD removal. The internal resistance, R_{int} , was calculated from the slope of the polarization curve according to $V = E_{cell} - IR_{int}$, where E_{cell} was electromotive force of the cell (Liu et al. 2005a).

COD measurements were conducted using standard methods (closed reflux method; American Public Health Association et al. 1998). Wastewater conductivities were measured using a conductivity meter (DDS-307, Spsic-Rex Instrument Factory, China) and probe (JS-1C, Spsic-Rex Instrument Factory, China), calibrated using a KCl solution.

Results

Effect of temperature (30°C and 20°C)

Voltage was rapidly generated from beer brewery wastewater (full strength, no amendments) from the eight different MFCs. While there were large differences in voltages produced in the first two cycles, the voltage was stable and reproducible after the reactors were refilled three times (after 230 ± 30 h). In the fourth fed-batch cycle, a stable maximum cell voltage of 362 ± 8 mV ($n = 8$) was produced (260 to 420 h), which is equivalent to a power density of 187 ± 8 mW/m² (4.7 W/m³; $n = 8$, 1,000Ω, 30°C).

The maximum power density of the reactors at 30°C, determined from polarization and power density data, was 205 mW/m² (5.1 W/m³; Fig. 1a). This is less than 494 mW/m² generated with glucose (0.6 g/L), but more than the 146 mW/m² achieved using domestic wastewater (200–300 mg COD/L) in the same reactor (Liu and Logan 2004). The maximum power is not only affected by the type of substrate, however, but also the concentration of the substrate and the solution conductivity as further explored below.

When an MFC acclimated at 30°C was transferred into 20°C, the maximum voltage decreased only by 4.6% (329 mV, 155 mW/m²) at a fixed resistance of 1,000Ω. The maximum power density, determined using polarization data, was reduced by 17.1% to 170 mW/m² (Fig. 1a). This reduction was slightly larger than that previously

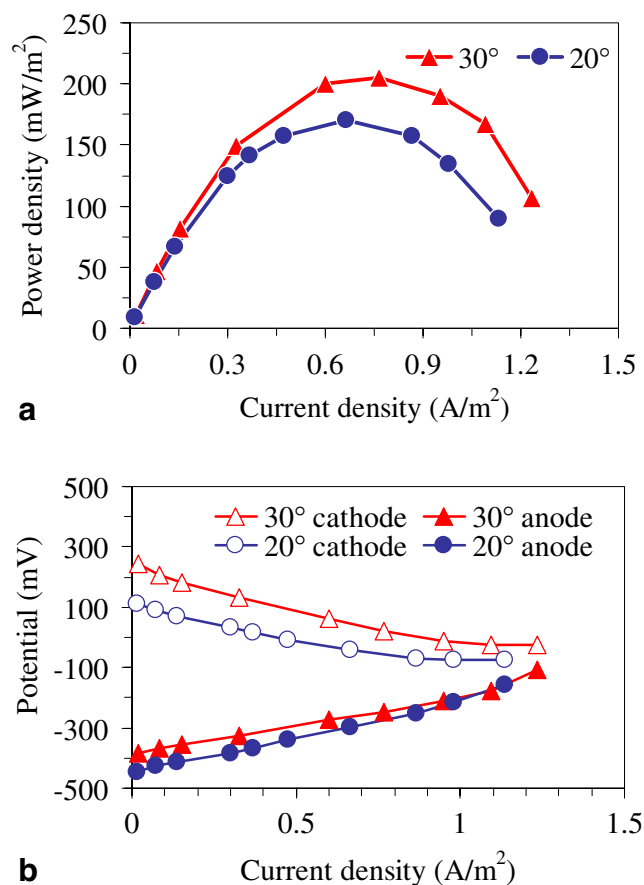


Fig. 1 Effects of temperature on **a** power density and **b** electrode potential (using SCE as reference electrode; 241 mV versus SHE) on the basis of current density using full-strength beer brewery wastewater (COD: 2,240 mg/L)

obtained (9%) using glucose on maximum power for an MFC transferred from 32°C to 20°C (Liu et al. 2005a).

Decreasing the temperature from 30°C to 20°C resulted in a greater change in the cathode potentials than the anode potentials (Fig. 1b). At the point of maximum power output, for example, the cathode potential was reduced by 315% (from 20 to -43 mV, versus SCE reference electrode), while the anode potential was reduced by only 21% (from -248 to -299 mV, versus SCE reference electrode). These data suggested that the decreased performance of the MFC with temperature was primarily a result of the reduced performance of the cathodic reaction, rather than microbiological effects at the anode.

The COD removal efficiency at 20°C (85%) was similar to that obtained at 30°C (87%). The CE similarly decreased by a small amount, with a CE = 10% at 30°C compared to CE = 8.9% at 20°C.

Effect of buffer concentration

To examine the effects of buffer concentration on MFC performance, MFC8 was inoculated with 50 or 200 mM

PBS and examined for power production at 30°C. When stable voltage of 363 ± 5 mV (188 ± 5 mW/m²) was obtained, the MFC was refilled with beer brewery wastewater (2,240 mg COD/L) amended with 50 or 200 mM PBS. Voltages increased in MFC8, producing 465 mV (50 mM PBS) and 491 mV (200 mM PBS) at a fixed external resistance of 1,000Ω (Fig. 2a). These increases in voltage represent increases in maximum power densities of 136% (483 mW/m²) for 50 mM PBS, and 158% (528 mW/m²) for 200 mM PBS added (Fig. 2b). The pH was constant throughout the power generation cycle at both buffer concentrations (pH 6.9 ± 0.1). The solution conductivity of the full-strength beer brewery wastewater was 3.23 mS/cm, which was lower than that of other tests using complex waste sources such as corn stover hydrolysates (8.0–9.4 mS/cm; Zuo et al. 2006). When PBS was added, conductivities increased to 7.65 (50 mM) and 14.6 (200 mM) mS/cm, indicating that PBS addition can substantially increase the solution conductivity and the reactor performance.

PBS addition can also be helpful in increasing CE. Compared with the case where PBS was not added (CE = 10%), the value of CE was improved to CE = 16% with 50 mM PBS, and CE = 20% with 200 mM PBS. COD removal efficiency (87%) was also slightly increased to 90% (50 mM PBS) and 86% (200 mM PBS).

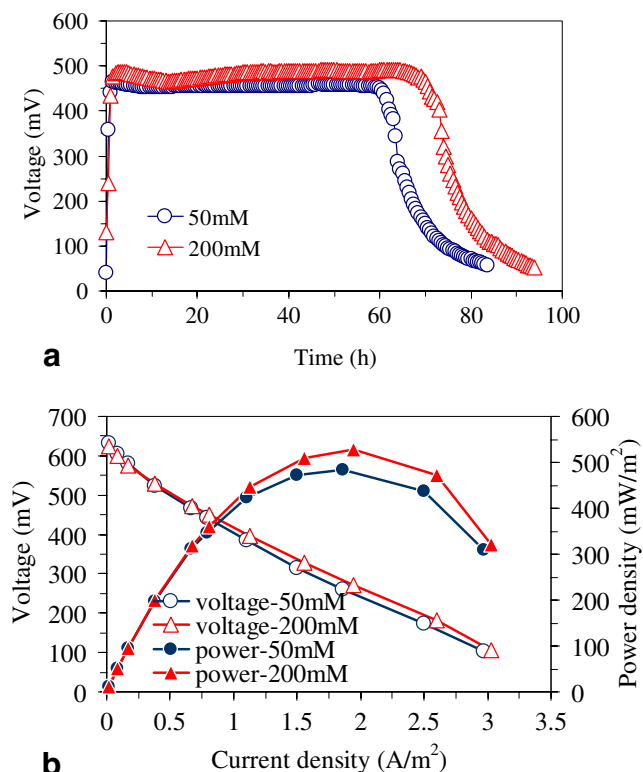


Fig. 2 **a** Voltage generation (1,000 Ω) and **b** power output of MFCs using full-strength beer brewery wastewater (2,240 mg COD/L) containing 50 or 200 mM PBS

Effect of COD concentration

Six parallel MFCs were operated using beer brewery wastewater diluted to COD concentrations of 84 to 2,240 mg/L using deionized water. The polarization curves were obtained and maximum power densities were varied from 29 to 205 mW/m² (Fig. 3a).

COD removals increased from 54% to 98% when wastewater strength was increased from 84 to 1,600 mg/L ($R = 1,000\Omega$). However, COD removal decreased slightly to 87% removal at the highest wastewater strength of 2,240 mg/L (Fig. 4). A general trend of decreasing CEs was also observed, with CEs ranging from 27% to 10% as substrate concentration was increased. Higher substrate concentrations also required longer cycle times, with 14 h needed at 84 mg COD/L, and 94 h for 2,240 mg COD/L. The longer cycle time can affect CE, as the longer cycle time can increase the amount of oxygen diffusing into the reactor, and thus the amount of COD removed aerobically.

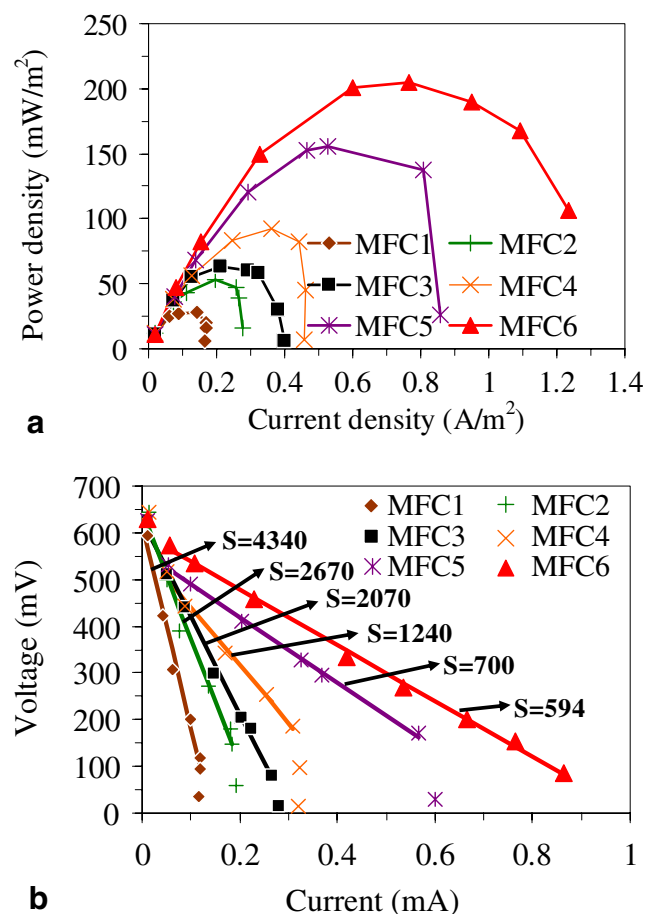


Fig. 3 Power outputs (a) and polarization curves (b) of MFCs operated at different initial COD concentrations using diluted wastewater: S (Ω) indicates the slope. COD concentrations of MFCs: MFC1: 84 mg/L, MFC2: 200 mg/L, MFC3: 350 mg/L, MFC4: 770 mg/L, MFC5: 1,600 mg/L, and MFC6: 2,240 mg/L

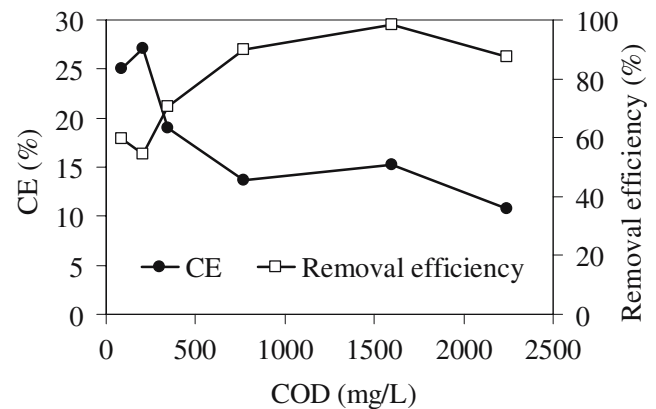


Fig. 4 Effects of wastewater COD concentration on CE and COD removal efficiency

Discussion

The maximum power produced by the brewery wastewater was lower than that achieved using domestic wastewater, when both wastewaters are compared at similar wastewater strengths. At COD concentrations of 200 and 350 mg/L, the maximum power densities with the brewery wastewater were 53 and 63 mW/m², respectively. This is less than the 146 mW/m² achieved with domestic wastewater at COD concentrations of 200–300 mg/L. This comparison, however, is likely not made on the basis of identical solution conductivities. Diluting the brewery wastewater to 200 mg COD/L using deionized water decreased the solution conductivity from 3.23 to 0.31 mS/cm. An exact comparison to the previous study using domestic wastewater cannot be made, however, as the solution conductivity was not reported by Liu and Logan (2004).

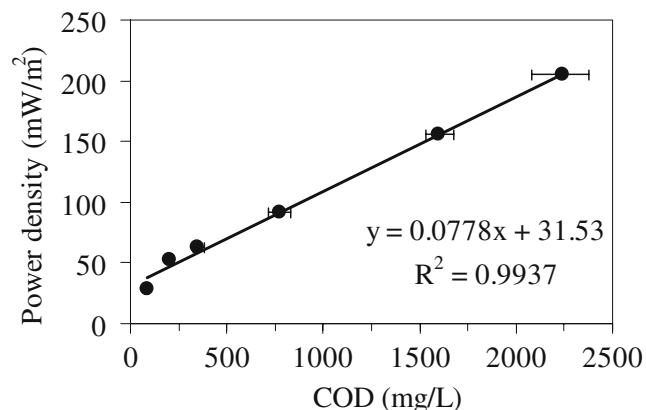
The CE obtained at 30°C is comparable with a range of CE = 9–12% obtained for glucose (Liu and Logan 2004) and CE = 10% for swine wastewater (Min et al. 2005), but less than that achieved with domestic wastewater in the same system (CE = 20%; Liu and Logan 2004). Assuming the same oxygen diffusion rate through the cathode that was calculated by Liu and Logan (2004), COD could be removed at a rate of 0.187 mg/h. Thus, aerobic removal of COD could be sustained by oxygen diffusion, and this could account for a change in 32% of the COD over the time needed here for a batch cycle using full-strength wastewater (94 h, 30°C). So, the low CEs result in part due to substrate depletion by aerobic bacteria sustained by oxygen transfer through the cathode. When a PEM was attached to the cathode in a previous study, the CE was 40–55% compared to only 9–12% in the system lacking a PEM (Liu and Logan 2004). The CE could be increased in future studies by adding two layers of cloth to the cathode surface, as shown by Fan et al. (2007) in a similar reactor where the CE was increased to 71%.

Table 3 Internal resistance of MFCs operated at different COD concentrations, obtained from the slope of the polarization curves

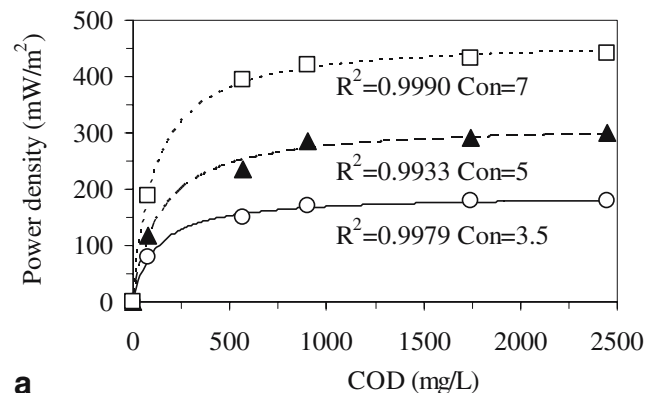
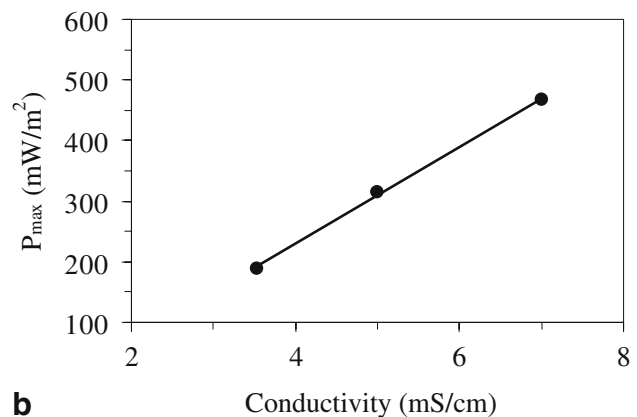
| COD (mg/L) | E_{cell} (mV) | R_{int} (Ω) | R^2 | R_{ext} for maximum power density | P_{max} (mW/m^2) | Conductivities (mS/cm) |
|------------|------------------------|-------------------------------|-------|--|---|--|
| 84 | 594 | 4,340 | 0.982 | 5,000 | 29 | 0.12 |
| 200 | 643 | 2,670 | 0.979 | 2,000 | 53 | 0.31 |
| 350 | 625 | 2,070 | 0.993 | 2,000 | 63 | 0.54 |
| 770 | 643 | 1,240 | 0.992 | 1,000 | 92 | 1.23 |
| 1,600 | 627 | 700 | 0.997 | 800 | 155 | 2.22 |
| 2,240 | 628 | 595 | 0.998 | 500 | 205 | 3.23 |

The effect of temperature on reactor performance appears overall to be relatively minor compared to its effect on more traditional anaerobic wastewater treatment processes where COD removal efficiency is substantially reduced by temperature, especially at temperatures below 30°C (Pham et al. 2006). In addition, the main factor appears to be the performance of the cathode, and thus improving the MFC architecture or using other catalysts (Zhao et al. 2005; Cheng et al. 2006b; Zuo et al. 2007) may help to improve the performance of the system at lower temperatures.

The primary effect of the increased buffer concentration is the resulting increase in solution conductivity as this lowers ohmic resistance, improves proton fluxes between the electrodes, and buffers pH near the electrodes (Gil et al. 2003; Liu et al. 2005a; Cheng and Logan 2007). Compared to the MFC without additional PBS, the ohmic losses (part of internal resistance) are reduced with increasing solution conductivity, as shown by the reduction in the internal resistance (R_{int}) from 594 to 160 Ω ($R^2 = 0.9946$) and an increase in power density (Logan et al. 2006). When the PBS concentration was 200 mM, the power output was increased only 9% (528 mW/m^2), and the R_{int} was nearly the same as that obtained with the 50 mM buffer (159 Ω , $R^2 = 0.9963$). This implies that the solution conductivity was no longer the main limiting factor affecting the MFC performance.

**Fig. 5** Maximum power densities as a function of COD concentration of beer brewery wastewater with the external resistance range of 50,000 to 50 Ω

The power densities obtained under different COD concentrations of beer brewery wastewater (no change in conductivity) likely were limited primarily by high internal resistances produced with this wastewater (Fig. 3b). The electromotive force of the six cells was approximately the same (619 ± 24 mV), but the internal resistances, R_{int} , varied substantially among reactors, decreasing from 4,340 Ω to 594 Ω with substrate concentrations ranging from 84 to 2,240 mg/L (Table 3). When the response of the system is examined relative to maximum power density obtained from power density curves (i.e., at different and optimal external resistances), however, the power was found to be a linear function of substrate concentration ($y = 0.0778x + 31.53$; $R^2 = 0.9937$; Fig. 5). The changes in

**a****b****Fig. 6** Power output (1,000 Ω external resistance) with various COD concentrations at different conductivities (Con, mS/cm ; **a**), and **b** derived from (**a**)

R_{int} 's, and the linear response of power to substrate concentration, likely resulted from different solution conductivities among the reactors. It is well known that solution ionic strength affects the ohmic resistance and thus power production (Logan et al. 2006). Diluting the brewery wastewater with deionized water decreased the solution conductivity from 3.23 to 0.12 mS/cm, and thus increased ohmic losses. This decrease in solution conductivity thus accounts for the decreased power densities from 205 to 29 mW/m² (Fig. 3a and Table 3).

In the above tests, either the solution conductivity changed (due to dilution with deionized water) or PBS was added that changed both the buffer concentration and the solution conductivity. To examine the effect of COD concentration on power generation separately from the effect of solution conductivity, all solutions were set at the same conductivity using NaCl (Zuo et al. 2006). As shown in Fig. 6a, power densities increased with substrate concentration in a manner consistent with Monod kinetics, according to the relationship:

$$P = P_{\max} \frac{S}{K_s + S} \quad (1)$$

where P_{\max} (mW/m²) is the maximum power output at a fixed external resistance (1,000 Ω), S the concentration of wastewater (mg COD/L), and K_s the half-saturation constant (mg COD/L). P_{\max} increased with solution conductivity from 189 mW/m² (3.5 mS/cm) to 315 mW/m² (5 mS/cm) and 467 mW/m² (7 mS/cm; Fig. 6b). This Monod-like response of power with substrate concentration is similar to that reported in other studies using acetate and glucose at fixed external resistances (Liu et al. 2005b; Liu and Logan 2004). Furthermore, the K_s values for different conductivities varied slightly and not in a systematic manner with solution conductivities, with values of K_s = 117 mg/L (3.5 mS/cm), 144 mg/L (5 mS/cm), and 115 mg/L (7 mS/cm). This suggests that the use of NaCl to adjust solution conductivity did not adversely affect the microbial performance of the anode. This observation of increased power with higher solution conductivity is consistent with previous results using acetate by Liu et al. (2005a, b).

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References

American Public Health Association, American Water Works Association, Water Pollution Control Federation (1998) Standard

- methods for the examination of water and wastewater, 20th edn. American Public Health Association, Washington DC
- Bond DR, Lovley DR (2003) Electricity production by *Geobacter sulfurreducens* attached to electrodes. *Appl Environ Microb* 69 (3):1548–1555
- Cheng S, Logan BE (2007) Ammonia treatment of carbon cloth anodes to enhance power generation of microbial fuel cells. *Electrochem Commun* 9(3):492–496
- Cheng S, Liu H, Logan BE (2006a) Increased performance of single chamber microbial fuel cells using an improved cathode structure. *Electrochem Commun* 8(3):489–494
- Cheng S, Liu H, Logan BE (2006b) Power densities using different cathode catalysts (Pt and CoTMPP) and polymer binders (Nafion and PTFE) in single chamber microbial fuel cells. *Environ Sci Technol* 40(1):364–369
- Fan Y, Hu H, Liu H (2007) Enhanced coulombic efficiency and power density of air-cathode microbial fuel cells with an improved cell configuration. *J Power Sources* 171(2):348–354
- Gil GC, Chang IS, Kim BH, Kim M, Jang JK, Park HS, Kim HJ (2003) Operational parameters affecting the performance of a mediator-less microbial fuel cell. *Biosens Bioelectron* 18(4):327–334
- Guo W (2005) Compulsory discharge standard of pollutants for beer industry is to be published. *China Environment Daily*: 2005-12-6
- He Z, Wagner N, Minter SD, Angenent LT (2006) An upflow microbial fuel cell with an internal resistance by impedance spectroscopy. *Environ Sci Technol* 40:5212–5217
- Heilmann J, Logan BE (2006) Production of electricity from proteins using a single chamber microbial fuel cell. *Water Environ Res* 78 (5):531–537
- Ince BK, Ince O, Sallis PJ, Anderson GK (2000) Inert COD production in a membrane anaerobic reactor treating brewery wastewater. *Water Res* 34(16):3943–3948
- Kida K, Tanemura K, Sonoda Y, Hikami S (1994) Anaerobic treatment of distillery waste-water from barley-shochu making by UASB. *J Ferment Bioeng* 77(1):90–93
- Kim BH, Park HS, Kim HJ, Kim GT, Chang IS, Lee J, Phung NT (2004) Enrichment of microbial community generating electricity using a fuel cell type electrochemical cell. *Appl Microbiol Biotechnol* 63(6):672–681
- Kim JR, Jung SH, Regan JM, Logan BE (2007) Electricity generation and microbial community analysis of alcohol powered microbial fuel cells. *Bioresour Technol* 98(13):2568–2577
- Liu H, Logan BE (2004) Electricity generation using an air-cathode single chamber microbial fuel cell in the presence and absence of a proton exchange membrane. *Environ Sci Technol* 38(14):4040–4046
- Liu H, Ramnarayanan R, Logan BE (2004) Production of electricity during wastewater treatment using a single chamber microbial fuel cell. *Environ Sci Technol* 38(7):2281–2285
- Liu H, Cheng S, Logan BE (2005a) Power generation in fed-batch microbial fuel cells as a function of ionic strength, temperature, and reactor configuration. *Environ Sci Technol* 39(14):5488–5493
- Liu H, Cheng S, Logan BE (2005b) Production of electricity from acetate or butyrate in a single chamber microbial fuel cell. *Environ Sci Technol* 39(2):658–662
- Logan BE, Murano C, Scott K, Gray ND, Head IM (2005) Electricity generation from cysteine in a microbial fuel cell. *Water Res* 39 (5):942–952
- Logan BE, Hamelers B, Rozendal R, Schröder U, Keller J, Freguia S, Aelterman P, Verstraete W, Rabaey K (2006) Microbial fuel cells: methodology and technology. *Environ Sci Technol* 40(17):5181–5192
- Min B, Kim JR, Oh SE, Regan JM, Logan BE (2005) Electricity generation from swine wastewater using microbial fuel cells. *Water Res* 39(20):4961–4968

- Oh S, Logan BE (2005) Hydrogen and electricity production from a food processing wastewater using fermentation and microbial fuel cell technologies. *Water Res* 39(19):4673–4682
- Parawira W, Kudita I, Nyandoroh MG, Zvauya R (2005) A study of industrial anaerobic treatment of opaque beer brewery wastewater in a tropical climate using a full-scale UASB reactor seeded with activated sludge. *Process Biochem* 40(2):593–599
- Pham TH, Rabaey K, Aeltermann P, Clauwaert P, De Schampelaire L, Boon N, Verstraete W (2006) Microbial fuel cells in relation to conventional anaerobic digestion technology. *Eng Life Sci* 6(3):285–292
- Rabaey K, Lissens G, Siciliano SD, Verstraete W (2003) A microbial fuel cell capable of converting glucose to electricity at high rate and efficiency. *Biotechnol Lett* 25:1531–1535
- Rabaey K, Ossieur W, Verhaege M, Verstraete W (2005a) Continuous microbial fuel cells convert carbohydrates to electricity. *Water Sci Technol* 52(1–2):515–523
- Rabaey K, Clauwaert P, Aeltermann P, Verstraete W (2005b) Tubular microbial fuel cells for efficient electricity generation. *Environ Sci Technol* 39(20):8077–8082
- Speece RE (1996) *Anaerobic biotechnology for industrial wastewater*. Archae, Nashville, TN
- Vijayaraghavan K, Ahmad D, Lesa R (2006) Electrolytic treatment of beer brewery wastewater. *Ind Eng Chem Res* 45(20):6854–6859
- Wang SG, Liu XW, Gong WX, Gao BY, Zhang DH, Yu HQ (2007) Aerobic granulation with brewery wastewater in a sequencing batch reactor. *Bioresour Technol* 98(11):2142–2147
- Zhao F, Harnisch F, Schröder U, Scholz F, Bogdanoff P, Herrmann I (2005) Application of pyrolysed iron(II) phthalocyanine and CoTMPP based oxygen reduction catalysts as cathode materials in microbial fuel cells. *Electrochem Commun* 7(12):1405–1410
- Zuo Y, Maness PC, Logan BE (2006) Electricity production from steam-exploded corn stover biomass. *Energy Fuels* 20(4):1716–1721
- Zuo Y, Cheng S, Call D, Logan BE (2007) Tubular membrane cathodes for scalable power generation in microbial fuel cells. *Environ Sci Technol* 41(9):3347–3353