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Demonstration of an Energy-Neutral, Off-Grid Microbial Fuel Cell System for Decentralized Wastewater Treatment

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Water and energy are becoming important priorities as increasing demands on the world's resources force nations to make sustainable choices. Microbial fuel cells (MFCs) have emerged as a promising technology to provide energy efficient wastewater treatment at significant cost savings compared to conventional aerobic treatment processes. These systems are especially beneficial in areas that are difficult to connect to municipal sewage treatment networks.

Initial laboratory results from MFC tests using swine waste indicated that improvements to power output could be achieved with a carbon-fabric pleats design when compared to a previous packed bed design. An 88-liter pilot scale demonstration system was developed based on these results that allowed for full system operation in an energy neutral configuration. Initial results from the startup phase, showed an 80% decrease in chemical oxygen demand (COD) with a 7-day treatment time (fed-batch mode). During continuous flow operation, an average of 93% COD removal was observed.

Introduction

Energy efficient wastewater treatment and water recycling is a critical need throughout the world. The U.S. EPA estimates that 3-5% of total domestic energy consumption is accounted for by conventional wastewater treatment methods (1). Further, global communities are turning to indirect and direct wastewater recycling to address water demands in the industrial, military and residential sectors (2). New technologies are needed to meet the demand for energy efficient wastewater treatment that can ultimately lead to direct or indirect reuse in areas throughout world – independent of existing infrastructure.

Here we describe results from laboratory and pilot-scale evaluations of a microbial fuel cell (MFC) system that was constructed to efficiently treat wastewater and enable indirect water reuse programs in remote locations. The majority of results reported on MFC systems focus on smaller lab scale system with very few larger pilot scale system results (3). Nevertheless, recent studies have been published at scales approaching 100 liters (4–7). Our pilot-scale system integration also tested the use of low-power DC pumps and solar recharging of battery packs to enable off-grid power and showcase the opportunity for decentralized wastewater treatment without significant power consumption.

Materials and Methods

In this study, cylindrical lab-scale 1-liter MFC reactors were tested with different electrode configurations. Promising electrode designs from the 1-liter results were scaled-up and tested in a set of 22-liter MFC reactors that would be implemented in a field demonstration.

1-liter reactor construction and operation

Cylindrical MFCs were constructed at the 1-liter scale and were constructed with the anode electrode inside a rigid plastic cylindrical frame (RN7480; Industrial Netting, Minneapolis, MN, USA). A nanofiltration membrane (ESNA3J; Hydronautics; Oceanside, CA, USA) was wrapped around the outside of the cylindrical frame and used to separate the anode and cathode. The cathode was then wrapped over the nanofiltration membrane. The carbon fabric cathode for each reactor was constructed from carbon cloth (FG-CF19750; US Composites Inc., West Palm Beach, FL, USA) that was also cleaned with acetone followed by flame treatment with a Bunsen burner after drying to remove residual acetone.

Each 1-liter system featured a different anode electrode configuration, including: standard packed bed granules, carbon pleats, and granule bundles (Figure 1). The graphite used for the reactors plain graphite granules screened to a size of 3/8" (EC-100 3/8"x10; Graphite Sales, Inc., Chagrin Falls, OH, USA). Carbon pleats were constructed from carbon cloth (FG-CF19750; US Composites Inc., West Palm Beach, FL, USA) cleaned with acetone. Bundles were made by taking the same packed bed graphite granules and bundling them with stainless steel wire cloth (9319T127; McMaster-Carr Supply Company, Santa Fe Springs, CA, USA). Average diameter of the granule bundles was approximately 1.5".

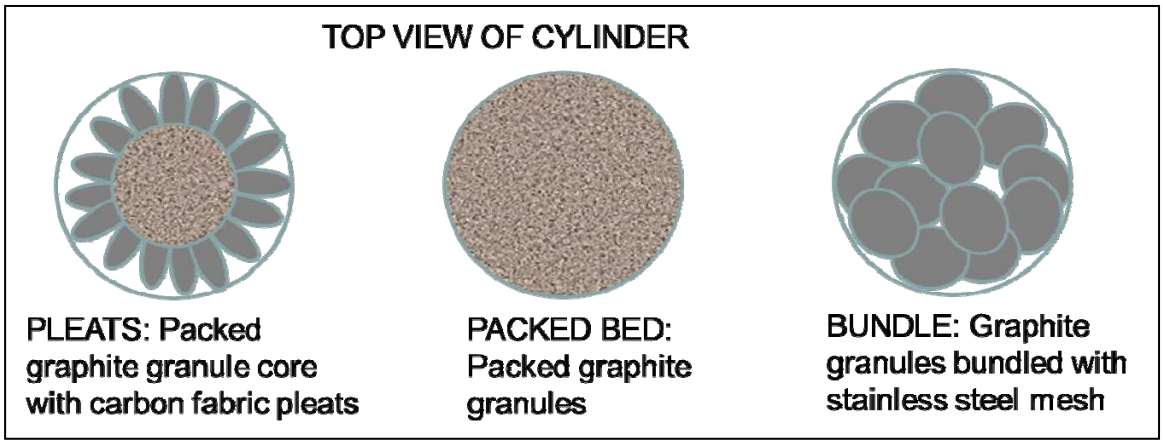

Figure 1. Different MFC anode configurations tested in 1 liter column reactors with recycle

Each reactor was setup in a DI water bath to serve as the catholyte. An aquarium pump was used to sparge air into the water bath to maintain a high dissolved oxygen (DO) concentration (5-8 mg-DO/L at room temperature). Each anode chamber was setup to receive wastewater influent along with a line for recycle flow provided by a peristaltic

pump. For these experiments, the recycle flow rate was 100 mL/min. All experiments were conducted under batch conditions.

Inoculation was performed with swine waste from San Pasqual High School's Agricultural Teaching Center (San Pasqual, CA, USA), sediment from San Elijo Lagoon, and buffered with carbonate (30mM final concentration). Anode and cathode were connected over an external resistor. For start-up, the initial resistance was set to 51 kΩ for 7 days. The resistance was then lowered to 5.6 kΩ for another 17 days. After this, the resistance was set to 330 Ω for performance evaluation. MFC cell voltage was monitored by a digital multimeter (Model 2700; Keithley Instruments, Cleveland, OH, USA).

A total of 7 batch cycles were executed to evaluate COD removal. Average COD removal rates were calculated based on total COD removal divided by the treatment time in batch mode. COD at the beginning and end of each cycle was determined by acid digestion followed by colorimetry (8). Polarization curves were generated on day 94 by loading each MFC with fresh swine waste followed by swapping resistors to change the external resistance until a stable voltage was observed (9). MFC cell voltages were allowed to stabilize under each external load prior to proceeding with the next resistor loading.

Electrochemical impedance measurements were carried out on day 17, using a potentiostat (Model 600, Gamry Instruments, Warminster, PA, USA) with the anode as the working electrode, cathode as the counter electrode, and an Ag/AgCl reference electrode. Voltage was held at open circuit potential of the anode and frequency was scanned from 0.1 – 100,000 Hz with an amplitude of 5 mV.

Pilot reactor construction and operation

Anodes for 4 22-liter reactors (Figure 2) were constructed using perforated PVC pipe (8" diameter, 28" length) with regularly spaced 3/8" holes (S40, 74.6% open area; Bigfoot Manufacturing, Inc., Cadillac, MI, USA). The system was built so that 2 reactors used a scaled-up pleat design and 2 reactors used a scaled-up packed bed design. The anode leads were constructed from wire rope that was woven through the anode backing material (for the pleated anodes), or embedded in the graphite granules (for the packed bed anodes). Each anode design had twelve 0.0625" diameter stainless steel wire rope leads (8908T27, McMaster-Carr Supply Company, Santa Fe Springs, CA, USA) that spanned the length of the electrode (28") and were crimped into 4 hollow 0.25" diameter stainless steel tubes (3" lengths, 89785K825; McMaster-Carr Supply Company, Santa Fe Springs, CA, USA). The tubes were the external electrical terminals that were sealed into the reactors with water-tight cord fittings.

An outer cathode chamber was constructed from slotted 14" diameter PVC pipe. The cathode material had a 12 evenly spaced 0.0625" diameter stainless steel wire ropes (8908T27; McMaster-Carr, Chicago, IL, USA) sewn to the carbon fabric that was also in a pleated configuration. Connection to external load was made by crimping these wires in bundles of 4 with hollow 0.25" diameter stainless steel tubes (3" lengths, 89785K825; McMaster-Carr Supply Company, Santa Fe Springs, CA, USA) that was fed through the top of the reactor assembly as described above for the anodes.

Anodes, cathodes and nanofiltration membranes were constructed in a similar manner to the 1-liter MFC reactors, using the same materials and techniques for materials preparation and construction.

The full system was submerged into a polyethylene primary container (48" x 40" x 48") to accommodate freshwater catholyte and space for piping to and from the MFC. Air was pumped into the catholyte via a linear air pump (HK-25LP; Hakko Air Pumps, Laguna Hills, CA, USA) and a DO of approximately 8 mg/l was measured at ambient temperature.

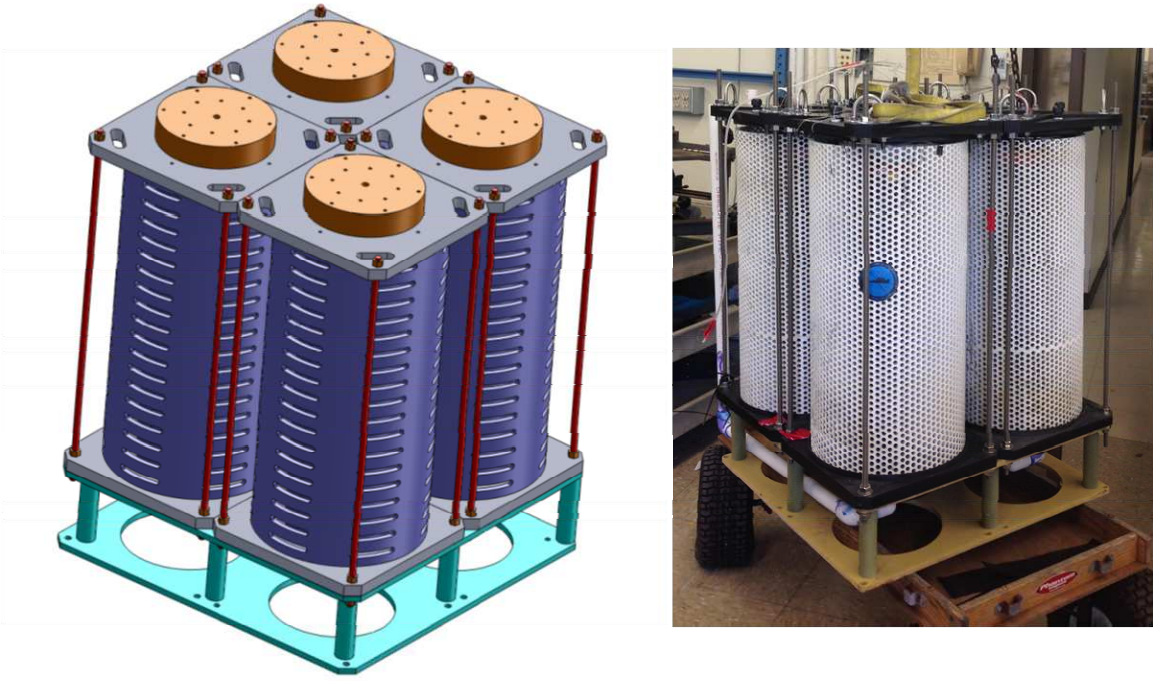

Figure 2. Computer rendering and image of assembled reactor consisting of 4 22-liter downflow MFC reactors.

The anode caps were plumbed with 1" PVC piping and fittings to enable fluid inflow at the top and outflow at the bottom. A liquid equalization (EQ) tank was periodically filled with wastewater by a transfer pump (FRX 75-SP; MP Pumps, Fraser, MI, USA) from a settling tank located at Warner Springs, CA. Each individual MFC was setup with a recirculation pump (RD-40X; Iwaki America, Inc.; Holliston, MA, USA) set to provide recirculation flow at 11.2 gallons per minute (gpm). MFC effluent was then directed to activated carbon filtration barrels that would act as a final purification step (Figure 3).

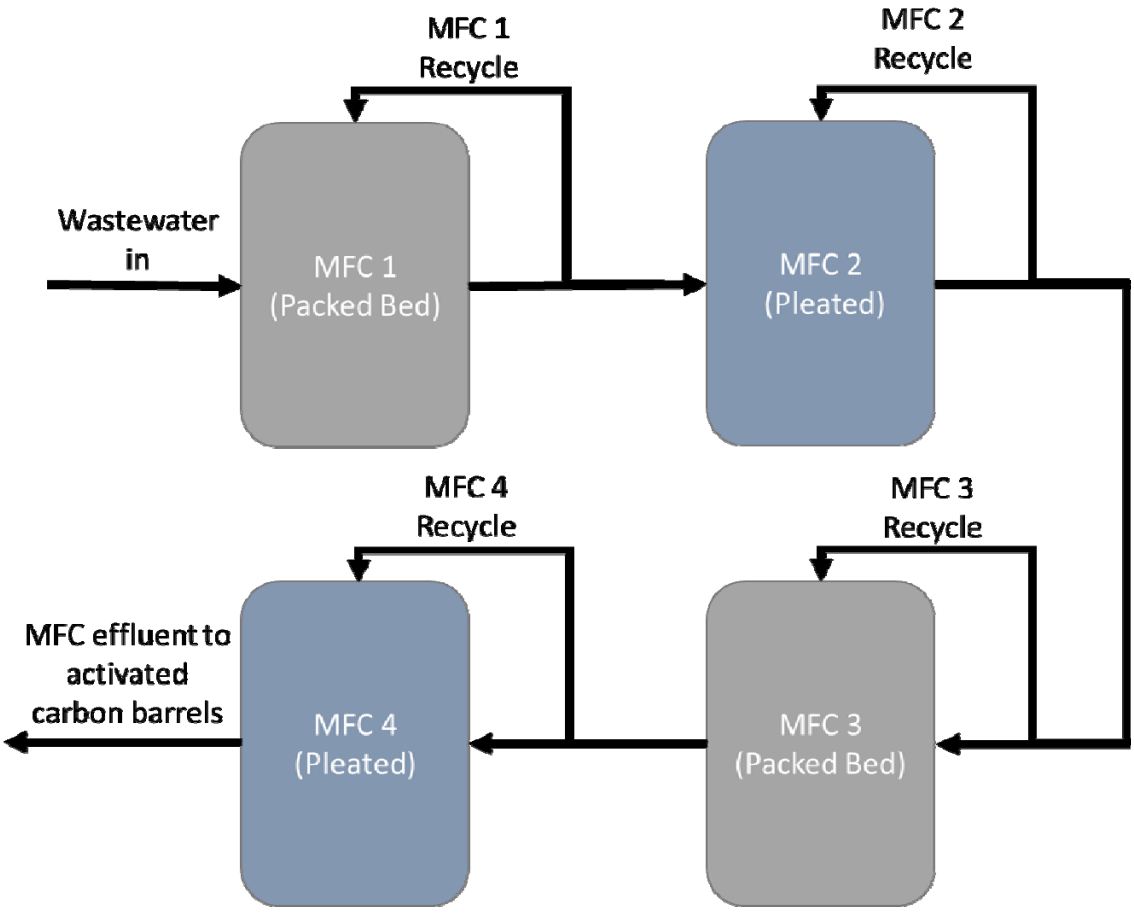

Figure 3. Intended flow path for pilot scale MFC reactors. MFC2 was bypassed during operation due to failure during pre-operation validation testing.

The MFCs and supporting equipment (pumps, control electronics, safety implementations) were located on an 18' trailer for easy, drop-in-place installation (Figure 4). MFC cell voltage and electrode potentials (in reference to an Ag/AgCl electrode) were collected with stand-alone dataloggers (MCR-4V; T&D Corporation, Matsumoto, Nagano, Japan). Power was provided via a semi-portable solar panel system (8 x 100W monocrystalline bendable panels and 26.4 kWh deep-cycle lead-acid battery storage). All power for system operation was provided via this power system for fully off-grid operation.

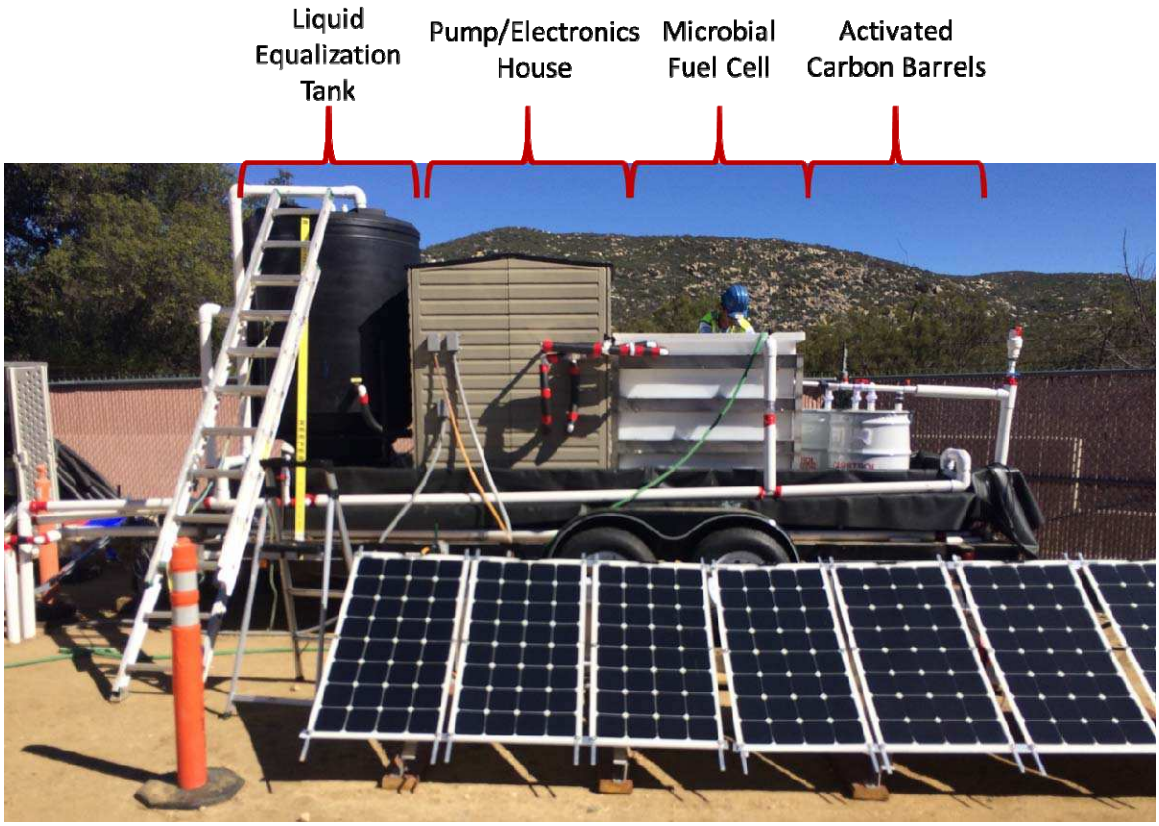

Figure 4. Installed off-grid wastewater treatment system centered around pilot scale MFC reactors.

During pre-startup checks, 1 of the 2 "pleated" reactors (MFC 2, Figure 3) developed a catastrophic leak and was bypassed. The other MFC reactors passed start-up checks and were inoculated with a mix of sediment from San Elijo Lagoon and domestic wastewater provided on-site at Warner Spring, CA. Startup was carried out by operating in recycle-batch mode with this inoculum in the anode for approximately 13 days with an external load of 47 kΩ. External resistance was then switched to 4.7 kΩ and the anodes flushed with domestic wastewater.

The reactors were operated with a 4.7 kΩ external load and periodic flushing of new wastewater periodically for an additional 21 days. After 34 days of batch operation, a polarization curve for each operating MFC was generated and the whole system was set to continuous mode. In this mode, a 0.32 gpm wastewater flow from a liquid equalization tank was provided by a centrifugal pump (RD-40; Iwaki America, Inc.; Holliston, M, USA). The external load was then set to 680 Ω after 14 days of operation in continuous mode. COD samples were collected periodically during operation and analyzed via standard colorimetric methods (8). BOD samples were also collected for analysis (10).

Results and Discussion

1-liter reactor construction and operation

Polarization curves (Figure 5) indicate that there was no significant difference between the packed bed and the bundled anode configurations since both had a maximum

power point of about 1 mW. The pleated configuration showed a two-fold increase in power production. This increase in power production could have resulted from the different architecture and materials. Both factors have the potential to both increase the available active surface area in the reactor system and/or provide a material better suited for interaction with electrically active microbes.

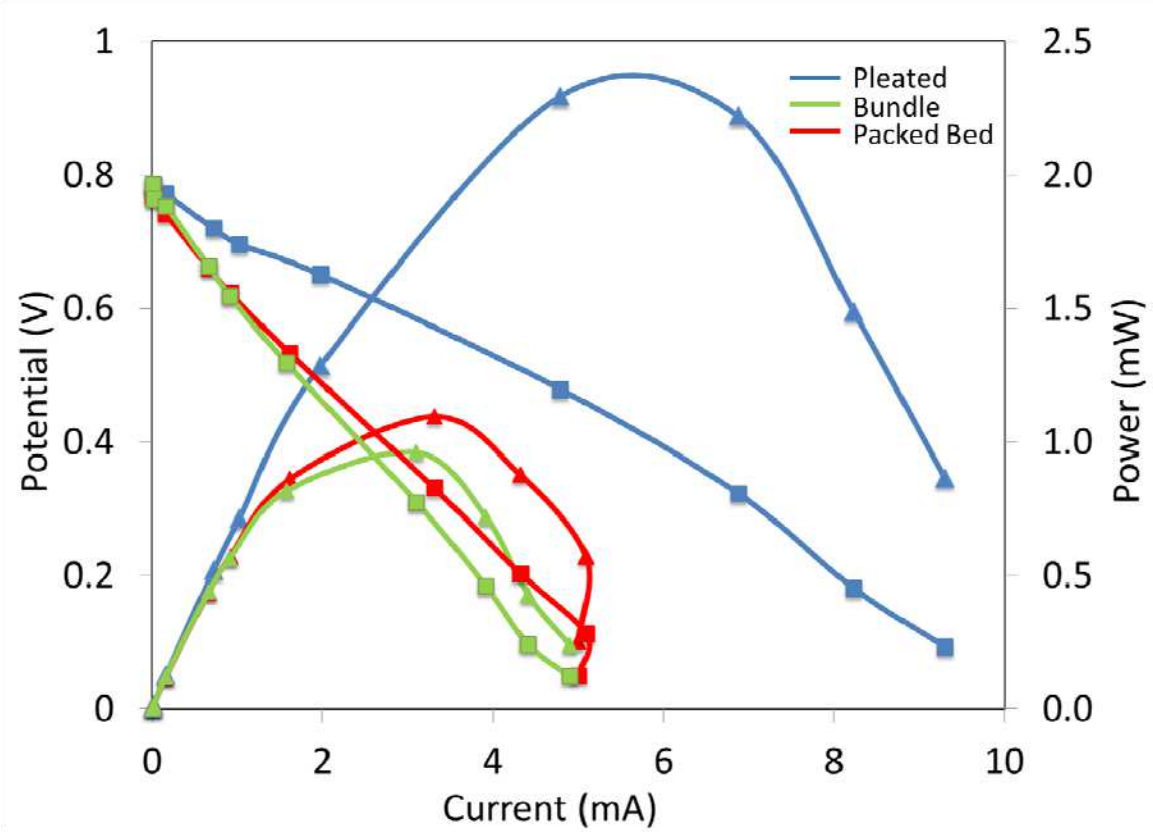

Figure 5. Polarization curves for 1-liter reactor systems.

Impedance data shows that the overall internal resistance was approximately the same for all the cells tested. However, the pleated electrodes had a lower charge transfer resistance than the other two anode configurations and a higher diffusion related resistance (Figure 6). COD removal during the 7 batch events were also approximately equivalent for each anode configuration (Table 1).

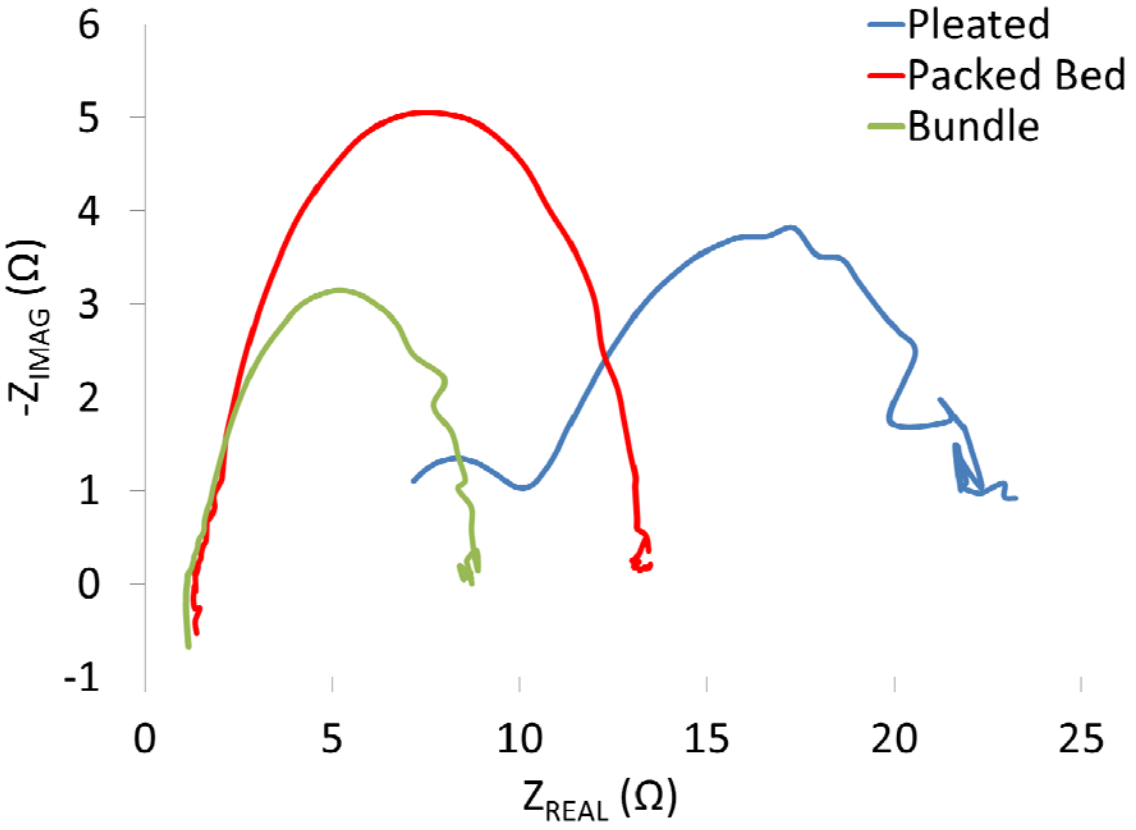

Figure 6. Nyquist plots of impedance data gathered from 1-liter reactors.

TABLE I. Average COD Removal (mg L^{-1} d^{-1}) for batch fed operation of 1-liter MFCs

Batch Cycle	Pleated	Packed Bed	Bundle
1	92.1	97.9	118.6
2	101.7	121.7	141.2
3	94.6	99.1	100.2
4	43.9	38.5	37.1
5	142.6	144.6	143.0
6	171.6	170.2	169.5
7	142.8	146.1	139.7

Pilot reactor construction and operation

Batch operation (4 feed cycles) of the pilot system was conducted for 35 days with a 47 kΩ or 4.7 kΩ resistor applied to each circuit to establish a stable anodic biofilm in all of the MFC reactors. The COD removal observed during the 4 cycles was only approximately 12 mg/l/day and the maximum current observed under the 4.7 kΩ resistor was 0.17 mA. Polarization curves (Figure 7) taken on Day 34, just before continuous mode was started, show maximum power from each of the MFC units was approximately the same, about 12 mW. Total power that could be recovered from the cells was 35.9 mW, suggesting that 50 mW of power could be recoverable if all 4 reactors were operational. COD removal during continuous mode (Figure 8) showed an average of 93% removal over 18 days of operation. BOD removal measured at Day 52 showed 84% removal (117.5 mg/L to 18.3 mg/L).

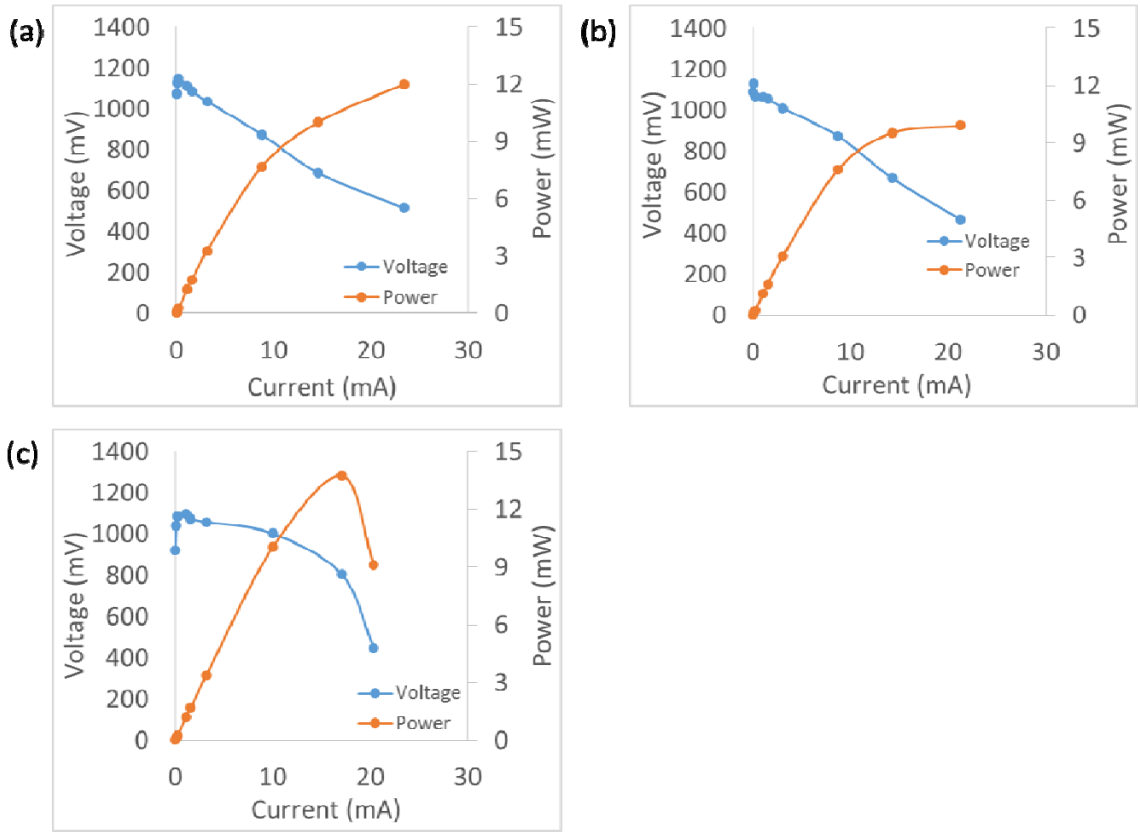

Figure 7. Polarization curves for (a) MFC1 (packed bed); (b) MFC3 (pleated); and (c) MFC4 (packed bed).

Total average current from all 3 operational cells on Day 52 was 2.39 mA under continuous flow, giving a coulombic efficiency (based on BOD removal) of much less than 1%. The low coulombic efficiency suggests that that most of the oxygen demand removed from the effluent during the monitored period was due to anaerobic processes such as fermentation, instead of through current generation. The low produced current also suggests that the operating potential of the MFC's had not yet been set to its maximum power point, as indicated by the initial polarization tests. The low coulombic efficiency and high organic removal is similar to results reported by others for large pilot-scale MFC systems (5,6,11). Thus, further improvements in architecture and operation are needed to ensure MFC systems can be optimized for energy recovery in addition to removal of oxygen demand.

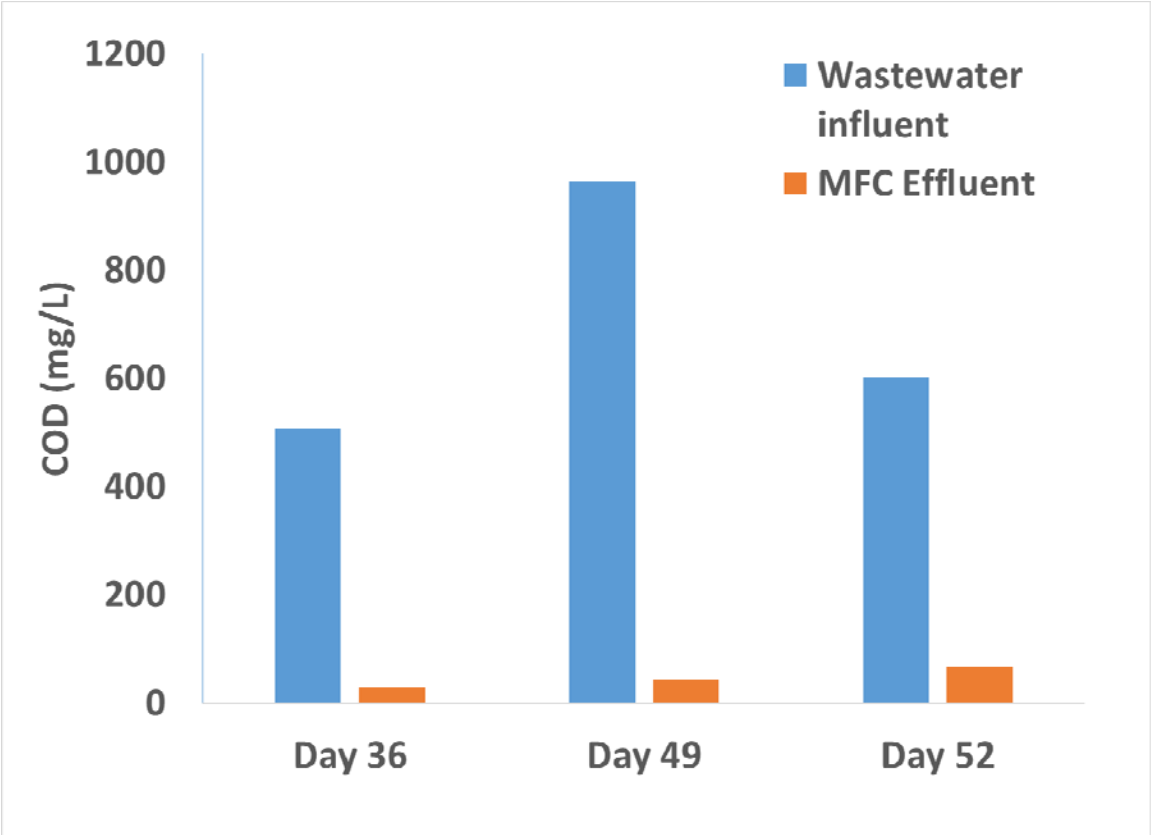

Figure 8. Removal of COD during continuous flow. Continuous flow started on Day 34 with a flow rate of 430 gallons per day and recycle ratio of 35.

Conclusions

The studies presented here show a methodology for scaling and implementing MFC systems at the pilot scale. It is important to not only consider the design of the MFC, but also the requirements for installation and operation at a real-world treatment site. The work here shows the integration of a pilot scale (88 liters total) into an existing wastewater collection system that is suitable for off-grid operation. Furthermore, the technology here is demonstrated to be capable of treating domestic wastewater, although more work is needed to ensure more efficient energy recovery and optimized treatment rates.

Acknowledgements

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