Microbial Fuel Cell Development and Testing for Implementing Environmental Engineering Education in High Schools

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Abstract

Developing nations have limited or non-existent access to reliable electricity and clean water. A reliable electricity source could power valuable devices, like communication or water purification mechanisms. Finding a way to remove harmful pathogens from their wastewater is vital to the health of residents. This paper will focus on a project for the development of a microbial fuel cell (MFC) system for developing communities appropriate for use to demonstrate the principles of scientific and engineering inquiry in advanced high school classroom. The MFC system will utilize a simulated waste stream resulting from existing food processing activities and potentially provide both a modest amount of stable electricity for local use.

High school students have utilized the environmental science and engineering principle that control the MFC system to design, build and test Microbial Fuel Cells made from simple materials. The MFC captures the electrons produced by the bacteria while they break down the waste in the water. The students evaluated MFC designs in the lab to find an affordable design that both efficiently generates power and effectively treats the water. The long-term goal of the project is to implement a MFC at the Songhai Center in Porto-Novo, Benin, which can then help implement the design in other developing nations through its connections with the United Nations (UN) and the Economic Community Of West African States (ECOWAS) countries. The MFC system could produce reliable electricity from waste while simultaneously cleaning water. This paper describes the processes used by students, teachers and faculty to bring environmental engineering design into the high school science classroom.

Introduction to Microbial Fuel Cell (MFC) Technology

The MFC captures the electrons produced by the bacteria while they break down the waste in the water. Many developing communities have unreliable electricity sources and have little access to clean water. MFCs could provide an alternative source of electricity using an essentially free fuel source, which could greatly impact developing communities that have limited access to electricity. The MFC should be easy to use, and the materials should not be cost-effective and readily available to developing communities.

People in the developing communities normally do not have clean water easily accessible to them. Only 30% of communities in Sub-Saharan Africa have access to water sanitation systems. With limited access to sanitary water, there is an increased risk in waterborne diseases; Berman estimates over 4,000 children die each day because of diseases caused by ingestion of contaminated water. The microbial fuel cell may help communities socially by providing wastewater treatment, which will help prevent waterborne diseases. In addition to providing primary wastewater treatment, MFCs generate electricity. The MFC produces small amounts of power, but the resulting source of electricity will be useful for the developing communities where there is limited reliable electricity. More than 95% of...
homes in rural communities in Africa do not have access to electricity so that a MFC may be useful in charging cell phones, LED lights or other small electronics.\textsuperscript{5} A recent application of a microbial fuel cell used in treating brewery wastewater provided a maximum power density of 4.1 W/m\textsuperscript{3}, normalized to the anode chamber volume which is enough to potentially could power LED lights.\textsuperscript{6,7}

The wastewater cleaning potential of the MFC can also help reduce impacts on the environment. The MFC breaks down the organic matter in wastewater [8]. The removal efficiency of pollutants as indicated by the Chemical Oxygen Demand (COD) of the aqueous solution in MFCs has been reported high as 98\%.\textsuperscript{8} Using an MFC could have a positive environmental impact due to its ability to “generate electric power from biomass without a net carbon emission into the ecosystem”\textsuperscript{9}

Economically, developing communities will benefit from the product as well. The microbial fuel cell should be affordable, both for materials and maintenance. One low cost system that can power an LED light is only $44.99.\textsuperscript{10} Another low-cost system that is working on implementation in African communities is hoping to get their cost down to $10.\textsuperscript{11} Since dual system of the microbial fuel cell produces electricity while cleaning water, there will not be a need to have two systems.

A microbial fuel cell (MFC) functions much like a battery, but runs on bacteria and a substrate, such as wastewater.\textsuperscript{13} The bacteria grow on the anode and breakdown the substrate; during this process, the bacteria release electrons and hydrogen ions.\textsuperscript{12} The anode collects the electrons and transfers them to the cathode through wires, creating an electrical current.\textsuperscript{12} The hydrogen ions are also transferred to the aerobic cathode, where the hydrogen reacts with oxygen to form water. Figure 1 below shows an example of an air-cathode MFC with carbon paper electrodes and glucose fuel.\textsuperscript{12} The MFC takes advantage of the electrons generated at the half-reactions occurring as the bacteria break down the glucose; the first half-reaction occurs at the anode, and the second occurs at the aerobic cathode.

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{mfc_diagram.png}
\caption{Reactions Occurring within a MFC [13]}
\end{figure}
Although the technology seems to have promising potential, researchers are struggling to successfully transition the MFCs from small-scale laboratory studies to scaled-up, useful applications. Microbial fuel cells have shown remarkable wastewater treatment potential. The chemical oxygen demand (COD) reduction efficiencies typically range from 70-90%, with one study showing a COD removal efficiency of 98%. The wastewater treatment capabilities is not the struggle with MFCs, it is their low electricity output. One of the main barriers prohibiting a scalable MFC design are finding low-cost electrode materials that can reach high power densities at a large scale.

To create feasible scaled up designs, the standard lab MFC with carbon cloth electrodes and a platinum catalyst must be replaced with low-cost alternatives, such as graphite, carbon felt or mesh, and stainless steel mesh. A common inexpensive replacement for the precious metal catalyst is MnO₂. Platinum as a catalyst on the cathode has proved to have the highest performances; however, the cost makes this unrealistic when trying to scale the MFC design. A study, comparing a low cost MFC and a Pt-MFC, the platinum outperformed the low-cost MFC; 350 ±25 mV compared to 207 ±30 mV. However, when normalized to the cost of the MFC, the low-cost MFC proved superior, so an effective low-cost design is feasible.

In another study, a scaled-up design using brewery wastewater, PVC pipe and cloth cathodes, a maximum power density of 4.1 W/m³ was achieved, which was enough to power a LED panel. The successful scaled-up designs have consisted of a microbial fuel cell stack, which contain multiple small cells, rather than one large cell. Due to electrode spacing and internal resistances of the fuel cells, it is believed that creating a MFC stack of smaller fuel cells will be more successful than one large volume MFC. While improvements in power densities of scaled-up designs of MFCs will need to continue for practical implementation into common wastewater treatment facilities, studies showing designs providing enough electricity to power simple electronics is promising for an application in a developing community.

One group has even developed a MFC for implementation in Africa. The group, Lebone Solutions, used a dirt powered MFC with a graphite cloth anode and a chicken wire cathode, which could run a cheap LED light for a few hours. The group could recharge a cell phone with approximately one square meter of the graphite sheet in the MFC, which produces one watt. The aim of the project was to replicate similar results in a simple MFC.

Learning Objectives

The following learning objectives were developed for developing a MFC project.

- Describe the bio-chemical mechanisms of MFC operation
- Conduct and write a review of scientific journal articles related to MFCs
- Design, build and test a MFC using appropriate methods for analysis and data collection
In this case the MFC project was used to satisfy degree requirements associated with science and math course at a Virginia High School.

**Concept Selection**

The Pugh Chart contains a comparison of the three potential MFC. Other concepts and other designs found in the literature were too costly or not feasible for the implementation in developing communities. The Pugh Chart in Table 1 compares the final concepts to the MudWatts.\(^\text{19}\) The MudWatt is a simple microbial fuel cell design, used in testing; the team used this as the datum because it is an already established design that is low cost. In theory, the team’s final concept should better suit the needs of the users in Benin than the MudWatt.

This first design is able to be scaled-up in size, but uses more expensive, custom components compared to the MudWatt. The carbon cloth electrodes and custom-made container would be harder and more expensive to manufacture and maintain. The orientation of the electrodes also poses a problem when manufacturing the design, because the cathode must be adhered to the side of the container.

The second concept in the Pugh Chart is a MFC made of PVC pipes. The PVC-based MFC is not as user friendly as the MudWatt. While this design is possible, it is less intuitive. Although the materials would be inexpensive, the manufacturing of the PVC-based design with the cloth cathode is more difficult since the cloth cathode will need special pretreatment to paint, waterproof, and adhere it in the proposed system. Maintenance is also more difficult if the system gets clogged or broken, the sealed end-caps are not easy to remove. The PVC pipe MFC would likely produce more power density because the electrode pretreatment and the smaller spacing between the electrodes.

The 5-gallon bucket MFC with stainless steel mesh electrodes is the final concept evaluated in the Pugh Chart. The 5-gallon bucket MFC consists of low-cost, off-the-shelf materials. The design is more user friendly than the MudWatt due to the valve that allows for easy extraction of the fuel for testing or removal. Also, the larger volume of the 5-gallon bucket will allow for easier scaling up than the MudWatts or the PVC-based design; multiple buckets can be used to handle larger volumes, and they can be placed in series and parallel to increase the voltage output. Overall, this concept best meets the design criteria compared to the other concepts.
Table 1: Pugh Chart Used for Concept Selection

<table>
<thead>
<tr>
<th>Criteria</th>
<th>MudWatts</th>
<th>Flow-System Design with Carbon Cloth Electrodes</th>
<th>PVC Pipe MFC with Cloth Cathode</th>
<th>5-Gallon Bucket MFC with Stainless Steel Mesh Electrodes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Cost</td>
<td>0</td>
<td>-1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Power Density</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Availability</td>
<td>0</td>
<td>-1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>COD removal</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Durability</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Scalability</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>User Friendly</td>
<td>0</td>
<td>-1</td>
<td>-1</td>
<td>1</td>
</tr>
<tr>
<td>Easily Manufactured</td>
<td>0</td>
<td>-1</td>
<td>-1</td>
<td>0</td>
</tr>
<tr>
<td>Low Maintenance</td>
<td>0</td>
<td>-1</td>
<td>-1</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total +</strong></td>
<td>0</td>
<td>1</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td><strong>Total -</strong></td>
<td>0</td>
<td>-5</td>
<td>-3</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>0</td>
<td>-4</td>
<td>0</td>
<td>3</td>
</tr>
</tbody>
</table>

Design and Analysis

Off-the-shelf MudWatts microbial fuel cells are available to demonstrate the basic technology. Figure 2 below shows a schematic of how the MudWatt is structured. The MudWatt is a small scale system that is self-contained, operates in small batches of approximately 100ml and provides an LED light as proof of the concept of microorganisms creating an electrical current that may be used to power a small light.

![Figure 2: Schematic of MudWatt Microbial Fuel Cell [12]](image)

The human factors allowed the team to make sure the concept would fully meet the needs of the user. Since the fuel cell needs to be as simple as possible, the fuel cell will have only one chamber and no exchange membrane because it simplifies the physical structure making construction and use easier. In addition, a bucket will be the container for the fuel cell since it is inexpensive and readily accessible. Users can easily move the five-gallon
bucket MFC to convenient locations, and users can stack the fuel cells to handle more waste output if necessary. The wastewater fuel should be able to enter and exit the fuel cell with ease; so, the design will have a valve to allow easy extraction of the water from the fuel cell. The material for the anode and cathode will need to be non-corrosive and need no pre-treatment; a steel mesh anode and cathode satisfies these needs.

A five-gallon bucket was selected for the container for the MFC. The two electrodes, the anode and cathode, will be made of stainless steel mesh. The anode will be at the bottom of the bucket laying on a small amount of gravel and mud. The cathode suspend on top of the fuel by sitting on floats. The aluminum wire will attach directly to the electrodes. The insulated aluminum wire will then connect to a 150kΩ resistive load. A spigot will be at the bottom of the bucket, just above the anode, so that water can exit from the MFC. Figure 3 below shows a schematic of the final concept.

Table 2 shows the expected bill of material for the containers to create two MFC prototypes. The electrodes were made of stainless steel mesh with a 100X100-mesh size. The anode was a 10” diameter mesh at the bottom of the bucket, and the cathode was a 12” diameter mesh. There is an automatic potential difference due to the electrons released by the bacteria directly onto the anode. Since the cathode needs to sit on top of the fuel, off-the-shelf fishing bobbers were attached to the cathode so that it can float at the top of the bucket. Aluminum wire connected the mesh anode and cathode in each bucket. A spigot allow for water extraction from the bucket.

![Figure 3: Schematic of Final MFC Design](image-url)
Table 2: Expected Bill of Materials for 1 MFC

<table>
<thead>
<tr>
<th>Material</th>
<th>Price</th>
<th>Supplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bucket (5 gallons)</td>
<td>$2.60</td>
<td>Home Depot</td>
</tr>
<tr>
<td>Bucket Lids</td>
<td>$1.28</td>
<td>Home Depot</td>
</tr>
<tr>
<td>2 Stainless Steel Rods</td>
<td>$0.40</td>
<td>Airgas</td>
</tr>
<tr>
<td>4 Floats</td>
<td>$1.21</td>
<td>Wal-Mart</td>
</tr>
<tr>
<td>Spigot</td>
<td>$3.00</td>
<td>Home Depot</td>
</tr>
<tr>
<td>Electrodes + Shipping (Stainless steel mesh, 10’’ Dia.)</td>
<td>$20.30</td>
<td>McMaster Carr</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$28.79</strong></td>
<td></td>
</tr>
</tbody>
</table>

Results

The first test performed with the MudWatts was a proof a concept to use inexpensive material and waste to create electricity. One MudWatt was filled with sterilized sand, which served as a control. Since no bacteria or food was present in the fuel cell, nothing occurred, as expected. The second MudWatt was built as instructed by the MudWatt manufacturers. The team placed a manure-based compost and water mixture into the fuel cell. Since the team is using food-processing waste rather than mud, the team developed a second experiment with a MudWatt that had sterilized sand and sugar water. The MudWatt was seeded with bacteria from the compost-seeded MudWatt. This provided a more realistic testing scenario where the only food available for the bacteria was the sugar water that simulates the wastewater.

Table 3 shows the results of the COD tests. The team collected COD concentration from each MudWatt after 14 days and calculated the average COD concentration.

Table 3: COD Removal Efficiency Results for 200 mg/L Glucose Water

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total Initial Substrate COD</strong></td>
<td><strong>215 mg/L</strong></td>
</tr>
<tr>
<td><strong>Average Substrate COD after 14 days</strong></td>
<td><strong>69 mg/L</strong></td>
</tr>
<tr>
<td><strong>Percent Removal Efficiency</strong></td>
<td><strong>68%</strong></td>
</tr>
</tbody>
</table>

Figure 4 shows the power output of MudWatt A, which had a 150kΩ resistive load, and MudWatt B, which had a 1 MΩ resistive load. The power output was calculated using Ohm’s Law in Equation 1.

$$P = \frac{V^2}{R}$$  \hspace{1cm} (1)
The power data from the MudWatts followed the same pattern as bacteria growth in a batch reactor. This implies there is a direct correlation between the bacteria present and the electrical output. Typical bacterial growth stages are illustrated by the plot of the voltage output of the MFCs in Figure 4.

As seen in Figure 4, MudWatt A had a peak voltage output of approximately 0.75 V. According to those results, ideally two MudWatts performing at that level could generate the 1.5 V specified in the requirements. The MudWatts met the 70 mg COD/L effluent concentration requirement with an effluent of 69 mg COD/L. One way to possibly increase this value is to leave the wastewater in the fuel cell longer, even past the point of readable power output, to allow the bacteria to continue breaking down the substrate.

The MudWatt with the 150 kΩ resistive load not only had a slightly higher voltage output, but also had a noticeably higher power output. MudWatt A had a peak power output of approximate 3.75 μW, compared to a 0.3844 μW peak power output from MudWatt B. The internal resistance of the MudWatt appears to be closer to 150 kΩ, since there is a significantly higher power output with that size of a resistive load. In future tests, the team will perform a power sweep to determine the internal resistance of the MudWatt. Since maximum power output occurs when the load matches the internal resistance of the MFC, this information would be important in maximizing power output of a particular design.

The five-gallon-scale fuel cell was also evaluated. The five gallon fuel cell had an electrode-spacing equal to the MudWatts (approximately 1.5”). The influent also had the same 2000 mg COD/L concentration as the MudWatt tests. This allowed a more direct comparison between the small-scale MudWatts and the large prototype. The prototype has approximately 13 times the liquid volume and 7 times the electrode size compared to the MudWatts. The initial testing shows that the prototype has a similar steady-state maximum voltage of around 0.7 V. Although they have a similar voltage output, the five-
gallon prototype produced voltage nearly three times longer than the MudWatts. The COD removal for the 5-gallon prototype was approximately 97%. Figure 5, below, shows the voltage results of the first large prototype compared to the MudWatt with the same electrode spacing and influent concentration.

![Voltage Output of Prototype and MudWatt with 1.5” Electrode Spacing and 2000 mg COD/L](image)

**Assessment of student outcomes**

- Describe the bio-chemical mechanisms of MFC operation

Cartoon based drawings created during student interviews were utilized to assess and improve the understanding of the bio-chemical mechanisms of MFC operation. These drawings began with simple sketches and evolved as learning progress. An example of the concept inventory drawing is shown in Figure 6.

![Concept inventory sketch illustrating the operating principles of a Microbial Fuel Cell](image)
• Conduct and write a review of scientific journal articles related to MFCs

Students were required to write a synopsis of several journal articles related to MFCs. The synopsis was collected and graded by the instructor.

• Design, build and test a MFC using appropriate methods for analysis and data collection

The student designed the MFC test cells on paper prior to fabrication. The electrodes were assembled from locally available materials and spot welded with the assistance of the schools technology instructor. The student constructed the MFC units in the classroom with assistance from the instructional team. Each MFC test unit was connected to a LabVIEW voltage measurement chassis and data collection was done via LabVIEW on a connected computer. COD analysis was conducted at the JMU sustainability laboratory using Hach COD test cells. The test apparatus used for a portion of the experiments in the classroom is shown in Figure 7.

Figure 7: Student MFCs connected to the LabVIEW voltage analysis system.

• Determine the independent and dependent variables in the experimental study

The independent and dependent variables were determined by the student and presented in a related assignment and the final presentation.

• Use statistical concepts to interpret the data collected

The student evaluated voltage response under three scenarios (copper electrodes, solid stainless steel electrodes and mesh stainless steel electrodes). The student reported the Median value for the period of study along with the median value, first and third quartile values, and the minimum and maximum-recorded values. The collection of data via the LabVIEW voltage recorder allowed for significant data collection and interpretation. The student had a significant data set to work with and the contextual application of the study allowed the student to relate the findings to everyday activities – like charging a cell phone.
• Complete a formal presentation of the work including conclusions, limitations, and future directions for MFC study

The student completed a formal presentation to the instructional team, classmates and the public during the school’s design presentation days. Draft presentations were reviewed and edited by the instructional team. The final presentation was graded by the primary classroom instructor at the high-school.

Student feedback showed this was a valuable project that provided an inquiry-based model for learning about environmental systems, experimental design, prototype development and testing, data analysis and technical communications. The project has been expanded to a second year, which is in progress.

Outcomes and applications for student projects

Students designed a microbial fuel cell to treat wastewater and generate electricity. The MFCs can be demonstrated using off-the-self MudWatts™ reactors to demonstrate the principles of biological conversion of a substrate to usable energy. Students were also able to demonstrate the skills associated with describing microbial processes, collecting data via a computer interface and describing experimental results. The availability and cost of materials and information associated with fuel cell development make the MFC technology and excellent fit for student related projects.

References


