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Wastewater Treatment with Microbial Fuel Cells: A Design and Feasibility Study for Scale-up in Microbreweries

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Abstract

Wastewater treatment has traditionally been an energy intensive process, consuming between 950 and 2850 kJ/m^3 of wastewater treated. By one account, wastewater contains 9.3 times more energy than is used to treat an equivalent volume, thus creating the desire to harness this energy through the use of a Microbial Fuel Cell (MFC). MFCs oxidize organic substrates, allowing simultaneous wastewater treatment and electricity generation. Previous research has primarily focused on the development of MFCs for electricity generation, mainly at the small, laboratory scale. Herein, an industrial-scale MFC process is proposed for the treatment of wastewater from a microbrewery based on a previously published model describing MFC operation. Through optimization and scale-out, a two chamber MFC process is developed for the treatment of 84 L/hr of wastewater with an inlet Chemical Oxygen Demand (COD) of 3000 mg/L. An overall COD conversion of 91.9% is achieved allowing effluent to be discharged directly down a municipal sewer. Electricity generation is 26.4 kWh, 107% of the operational requirement. With a payback period of 5 years, this work shows that there is potential for the implementation of MFC technology in the food and beverage industry.

Keywords: Microbial fuel cell; Scale-up; Economic analysis; Process design; Wastewater treatment; Electricity generation

Introduction

Water and energy security continue to be primary threats to our lifestyle. The United Nations estimates the earth's population at 7.2 billion inhabitants, with a projected population reaching 9.6 billion inhabitants by 2050 [1]. Over 2 billion people currently lack adequate sanitation and one billion do not have dependable access to potable water [2]. Traditional methods of wastewater treatment are energy intensive, often consuming between 950 and 2850 kJ/m^3 of water treated [3]. The United States EPA estimates that water infrastructure consumes 4-5% of all electricity generated with treatment consuming 1.5% [2]. At a traditional wastewater treatment facility in Toronto, it was estimated that there was 9.3 times more energy in the wastewater than was used to treat it [4]. With the high energy potential of wastewater, there is significant benefit in harnessing this power during treatment. Microbial Fuel Cell (MFC) technology allows electricity generation while simultaneously treating wastewater. Microbial fuel cells use electrochemically active bacteria to oxidize substrates and separate protons from electrons. The separated electrons travel through the anode and external circuit to generate a current. The released protons simultaneously travel through a Proton Exchange Membrane (PEM) into the cathode chamber where they combine with the electrons from the completed circuit to form water. When used for wastewater treatment, an effluent stream with a lower organic loading is discharged from the anode, which can be discharged to a municipal sewer or, if required, treated further. MFC technology can be applied as a renewable energy source with applications in power generation, wastewater treatment and water quality monitoring. For power generation, MFCs can provide clean, safe, and quiet performance. Recently, Dhakal and Joshi [5] have shown success in an MFC constructed by using graphite felt immobilized with neutral red as anode and a platinum coated platinum wire as cathode. Logan et al. [2] demonstrated that an MFC installation at a food processing plant had potential to generate 330 kW/day of power on 7,500 kg of waste organics based on 30% efficiency [6]. Previous research has focused primarily on the optimization of electricity generation while neglecting wastewater treatment. Herein, this work presents an industrial-scale MFC suitable for treatment of wastewater from a theoretical craft brewery located in Ontario, Canada. This work has three major parts: first, the implementation and scale-up of a published model describing microbial fuel cell operation and determination of the optimal conditions for operation. Second, based on the results from the first phase, a design for the industrial process is developed. In the final stage, an economic analysis is conducted to draw conclusions about the feasibility of implementing an industrial-scale MFC system. In the development of any modern process, a primary goal should be a net improvement in the overall environmental burden of the process. For the development of an industrial MFC process, this involves the reduction in harmful materials (e.g., cyanide, chlorine) and reduction in power requirements compared to traditional treatment methods. Wastewater treatment with MFC has benefits to the environment, namely decreased stress on wastewater treatment facilities. For the brewery, a "green" product enhances market value and triple bottom line. Operators of MFC technology must be prepared to handle electricity generation equipment and microorganisms, and have a procedure in place to mitigate the risk of spills. Producers of wastewater must ensure effluent from their process meets local discharge requirements. Water that does not meet these requirements may be subject to fines.

For the purposes of modeling, discharge requirements for the completed process are based on the required discharge requirements in Waterloo, Ontario, as summarized in Table 1 [7].

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Parameter	Specification
Temperature (°C)	<65
pH	5.5-9.5
Solvent Extractable Matter (mg/L)	<15
BOD (mg/L)	<300

Table 1: Discharge Requirements for City of Waterloo [7].

Substrate	Concentration	Current density at max power (mA/cm²)
Acetate	1 g/L	0.8
Farm Manure	20% w/v	0.004
Pure Glucose	6.7 mM	0.7
Brewery Wastewater	2240 mg/L	0.2
Municipal Wastewater	600 mg/L	0.06

Table 2: Substrates with applications to MFCs [9].

This work serves as a feasibility study for the scale-up of MFC technology. While the proposed design primarily targets the brewery industry, the results can easily be expanded to other industries generating wastewater with high organic content. For example, Parkash et al. [8] have developed mediated salt bridge based dual chamber MFC in which anode solution was batch and cathode was in continuous mode of operation under optimum conditions.

Substrate Selection

It was not until the 1990s when interest and research into MFCs advanced [2]. To date, significant work has been done to improve MFC performance with regards to power generation. MFC technology has benefitted from advances in membrane technology, electrode materials and modelling and simulation. Four major bodies of research influence the scale-up of MFCs: substrates, modelling, electrode materials and membranes. This section presents selection of this work as it pertains to an industrial design. MFCs generate power and treat wastewater by harnessing the oxidizing potential of anaerobic bacteria and the conduction of electrons through an external circuit. The substrate acts as a source of electrons, making the ideal substrate one that is quickly and easy metabolized by a robust species of bacteria. In early MFC research, simple substrates of acetate and glucose were commonly used as these substrates offered easy degradation and high associated electrical system output [9]. Recently, more practical research focuses on the use of practical wastewaters such as food processing waste, municipal wastewater and agricultural wastewater. These results are summarized in Table 2 [9]. Studies on current density demonstrate that brewery wastewaters offer the most promise as they tend to be high in COD and have a high concentration of easily-reduced carbohydrates while being low in inhibitory substances [9]. It should be noted that when fed in similar concentrations, domestic wastewaters have achieved higher power outputs than brewery wastewaters [9]. Due to the primitive nature of the current work, industrial scale-up should be focused around industries that offer the most promise in terms of power generation and wastewater treatment. When compared to other sources such as domestic wastewater, brewery wastes are available in relatively consistent concentrations. Consideration for the availability of a model must also be given at this stage. Brewery wastewater has previously been modelled as simple organic materials such as acetate [10]. In the literature, acetate has been readily modelled, thus providing a solid foundation for the design and scale-up based on brewery wastewaters, however, modeling with more complicated wastewaters has been conducted.

Model Selection

The use of a published model provides a basis by which to describe the operation of the MFC. As a feasibility study, an industrial-scale MFC is proposed based on currently published models. Oliveira et al. provide an in-depth summary of the currently published models describing MFC behavior before developing their own [11]. Published models have varying complexities, assumptions and results. Models may include mass transport models, and pH effects. Table 3 presents a summary of models considered as part of the current work. In Ref. [12], 2-dimensional model of a mediator-less, two-chamber MFC is developed in ANSYS Fluent. This model focuses less on voltage and power optimization and more on developing a model using this software package, which can then be used for further studies on model geometry. The fundamental focus of the work and unfamiliarity with the software in which it was developed meant that this work was not considered for implementation. Picioreanu et al. develops a biofilm-based model of an redox mediated MFC processing a solution of acetate [13]. This model provides a basis for more complicated models by developing equations governing the operation and proving that similar modelling efforts can be used to develop mathematical models for MFCs with feed water and mixed substrates. It is found that acetate is the basis for several models published later, namely those in Ref. [11,14]. Zeng et al. [14] present a one-dimensional model describing a two-chamber microbial fuel cell using the Butler-Volmer expression and mass/charge balances based on an acetate substrate. This model was then fit to experimental results with close agreement. The acetate model was then extended to glucose and glutamic acid (GGA), confirming extension of the model to multiple substrates is indeed possible. Oliveira et al. [11] expanded on the model by Zeng and developed a model that describes the thermodynamic behavior of the MFC. Models describing MFC operation must be selected simultaneously with the substrate, as the two are interdependent: the project relies on the accurate modelling of a reasonable substrate. From substrate selection, brewery wastewater proves to be the most promising for this feasibility study due to high power output and basic composition of simple sugars. The model by Zeng et al. [14] is chosen for this work as it remains relatively easy to implement and provides parameters for all model parameters. The glucose-glutamic acid substrate that it describes is of interest as that is a combination similar to what may be found in brewery waste. As a feasibility study, simulation of the thermodynamic behavior is not of immediate interest, but rather, work that can be studied once a design and operating parameters have been finalized.

Materials of Construction

MFC performance is influenced by three primary components: the anode, the cathode, and the membrane. MFCs will benefit from advances in electrode and membrane technology, and are affected by similar properties as other fuel cell technologies. A good MFC anode should have the following properties: good electrical conductivity, low resistance, strong bio-compatibility, chemical stability, corrosion resistance, a large surface area, economic sensibility, and should also have an appropriate amount of mechanical strength [15]. Traditionally, anodes in MFCs are composed of carbon cloth, paper or

Date	Paper	Reference
2015	Neutral Red Immobilized Graphite Felt Anodic Microbial Fuel Cell for Wastewater Treatment and Generation of Electricity	[5]
2015	Utilization of Sewage Sludge for Production of Electricity using Mediated Salt Bridge Based Dual Chamber Microbial Fuel Cell	[8]
2013	A 1D mathematical model for a microbial fuel cell	[11]
2010	Modelling and simulation of two-chamber microbial fuel cell	[14]

Table 3: A selection of published MFC models.

felts. Graphite rods have been the most popular type of anode as they provide good electrical conductivity and chemical stability whilst being inexpensive [16]. The main disadvantage to using graphite rods is that the surface area is difficult to increase. An alternative to the graphite rods is a graphite fiber brush, which is comprised of many graphite fibers wrapped around a titanium rod to produce a brush with a greater amount of surface area [16]. Non-carbon anodes have been considered with limited practicality. In an MFC utilizing a stainless steel anode, a maximum power density of 4 mW/m^2 has been achieved, a result that is unacceptably low compared to carbon anodes [17]. Gold anodes have achieved power densities similar to that of carbon anodes, however high material costs and large anode sizes required makes this material unacceptable [18]. Cathodes in the MFC should have high redox potential and easily capture protons [16]. Common cathode materials currently include graphite, carbon cloth and carbon paper. Using a highly active catalyst such as platinum is an effective way to increase the performance of the MFC, however platinum is an expensive metal and is not practical in industrial applications [16]. Morris et al. compared the use of lead dioxide to that of Pt and found that a glucose-fed MFC, was able to produce 2 to 4 times more power than was produced using a platinum catalyst [19]. As lead dioxide is much more attainable in both cost and availability, the scale-up of an MFC for practical applications is much more feasible with this type of cathode. Overall power generation for a platinum/carbon cathode (PtC/Ti) was found to be approximately 45 μW/$, while the lead dioxide (PbO_2/Ti) cathode was found to be 612 μW/$, making it significantly less expensive [19]. When filtering wastewater from a brewery, it is concluded in Ref. [15] that a cloth-cathode assembly is more economical than using a membrane-cathode assembly. The cloth-cathode assembly was made using polytetrafluorethylene (GORE-TEX) cloth coated with an MnO_2 catalyst painted on the surface. This combination achieved a power generation of 96 mW/m^2, equivalent to 1603.6 μW/$. The ideal membrane material permits maximum conductivity with minimum thickness. Dupont Nafion N115 and N117 are common membranes, with thicknesses of 1.27×10^{-4} and 1.83×10^{-4} m respectively Both membranes permit minimum conductivities of 0.10 S/cm. Based on the model in Ref. [14], environmentally-conscious design objectives and the optimal materials presented above, it is intended to design a MFC using graphite brush anodes, cloth cathodes and a Nafion N115 membrane. These materials represent economical choices and closely match the materials used in Ref. [14], thus allowing the scale-up of this model with limited parameter modification.

Model Implementation and Optimization

The glucose and glutamic acid model presented in Ref. [14] was implemented in MATLAB. There are three primary sections to this model: chemical reactions and their associated rates, anode material balances and cathode material balances. The operation of the MFC is simplified to three chemical reactions describing the oxidation of glucose and glutamic acid in the anode and the reduction of oxygen in the cathode. Governing equations are reproduced in this section and explained further in Ref. [14].

$$C_6H_{12}O_6 + 6H_2O \rightarrow 6CO_2 + 24H^+ + 24e^- \quad (1)$$

$$C_5H_9NO_4 + 6H_2O \rightarrow 5CO_2 + NH_4^+ + 17H^+ + 18e^- \quad (2)$$

$$O_2 + 4e^- + 2H_2O \rightarrow 4OH^- \quad (3)$$

The above reactions are characterized by reaction rates based on Monod kinetics as governed by (4) – (6).

$$r_1 = k_1^0 \exp\left(\frac{\alpha_1 F}{RT}\eta_a\right)\frac{C_6}{K_6 + C_6}X \quad (4)$$

$$r_2 = k_2^0 \exp\left(\frac{\alpha_2 F}{RT}\eta_a\right)\frac{C_5}{K_5 + C_5}X \quad (5)$$

$$r_3 = -k_3^0 \frac{C_{O_2}}{K_{O_2} + C_{O_2}}\exp\left[(\beta - 1)\frac{F}{RT}\eta_c\right] \quad (6)$$

For each species, a mass balance is developed. A single species exists exclusively in the anode or the cathode, and it is assumed that there is no transfer of species across the PEM. In the anode, glucose, glutamic acid, carbon dioxide, hydrogen and the biomass are present as described in (7) – (11).

$$V_a\frac{dC_6}{dt} = Q_a(C_6^{in} - C_6) - A_m r_1 \quad (7)$$

$$V_a\frac{dC_5}{dt} = Q_a(C_5^{in} - C_5) - A_m r_2 \quad (8)$$

$$V_a\frac{dC_{CO_2}}{dt} = Q_a(C_{CO_2}^{in} - C_{CO_2}) + 6A_m r_1 + 5A_m r_2 \quad (9)$$

$$V_a\frac{dC_H}{dt} = Q_a(C_H^{in} - C_H) + 24A_m r_1 + 17A_m r_2 \quad (10)$$

$$V_a\frac{dX}{dt} = \frac{Q_a(X^{in} - X)}{f_x} + A_m Y_{AW}(r_1 + r_2) - V_a K_{dAW} X \quad (11)$$

Mass balances in the cathode involve dissolved oxygen, hydroxide and protons that have been transported across the PEM as described in (12)-(14).

$$V_c\frac{dC_{O_2}}{dt} = Q_c(C_{O_2}^{in} - C_{O_2}) + r_3 A_m \quad (12)$$

$$V_c\frac{dC_{OH}}{dt} = Q_c(C_{OH}^{in} - C_{OH}) - 4r_3 A_m \quad (13)$$

$$V_c\frac{dC_M}{dt} = Q_c(C_M^{in} - C_M) + N_M A_m \quad (14)$$

Protons produced due to the oxidation of organic material permeate across the membrane. This flux is given by (15).

$$N_M = \frac{3600 i_{cell}}{F} \quad (15)$$

Charge must be conserved – the balance given by (16) and (17) below. Lastly, the cell voltage is given as described in (18).

$$C_a\frac{d\eta_a}{dt} = 3600 i_{cell} - 24F r_1 \quad (16)$$

$$C_c\frac{d\eta_c}{dt} = -3600 i_{cell} - 4F r_2 \quad (17)$$

$$U_{cell} = U^0 - \eta_a + \eta_c - \left(\frac{d^m}{k^m} + \frac{d_{cell}}{k^{aq}}\right) i_{cell} \quad (18)$$

The model variables and parameters are shown in Table 4. These governing equations, as developed by Zeng et al. [14] allow the simulation of a two-chamber MFC. This model was implemented in MATLAB and results were verified against the results published in Ref. [14]. The model was further verified against those published in Ref. [20] to compare the model to similar experimental results. As shown in Figure 1 the model implemented in MATLAB very closely reproduces experimental results published in Ref. [14] and Ref. [19]. Optimization of wastewater treatment was conducted by determining the critical model parameters that affect wastewater treatment

Parameter	Description
F	Faraday's constant (96485.4 C mol^{-1})
R	Gas constant (8.3144 J mol^{-1} K^{-1})
T	Temperature (K)
k^m	Electrical conductivity of membrane (Ohm^{-1} m^{-1})
d^m	Thickness of membrane (m)
k^{aq}	Electrical conductivity of aqueous solution (Ohm^{-1} m^{-1})
d^{cell}	Distance between anode and cathode in the cell (m)
C_a	Capacitance of anode (F m^{-2})
C_c	Capacitance of cathode (F m^{-2})
V_a	Volume of anode (m^3)
V_c	Volume of cathode compartment (m^3)
A_m	Area of membrane (m^2)
Y_{AW}	Bacterial yield (dimensionless)
K_{dec}	Decay constant (h^{-1})
f_x	Reciprocal of wash-out fraction (dimensionless)
Q_a	Flow rate of wastewater feed to anode (m^3 h^{-1})
Q_c	Flow rate of oxygen rich water to cathode (m^3 h^{-1})
C^{in}_{Ac}	Concentration of acetate in wastewater (mol m^{-3})
C^{in}_{CO2}	Concentration of CO_2 in the wastewater (mol m^{-3})
X^{in}	Concentration of bacteria in the wastewater (mol m^{-3})
C^{in}_{H}	Concentration of H^+ in the wastewater (mol m^{-3})
C^{in}_{O2}	Concentration of O_2 in the influent of cathode compartment (mol m^{-3})
C^{in}_{M}	Concentration of M^+ in the influent of the cathode compartment (mol m^{-3})
C^{in}_{OH}	Concentration of OH^- in the influent of the cathode compartment (mol m^{-3})
U^0	Cell open circuit potential (V)
k_1^0	Forward reaction rate constant for glucose (mol m^{-2} h^{-1})
k_2^0	Forward reaction rate constant for glutamic acid (mol $m^{-2}h^{-1}$)
K_6	Half velocity rate constant for glucose (mol m^{-3})
K_5	Half velocity rate constant for glutamic acid (mol m^{-3})
K_{O2}	Half velocity rate constant for dissolved oxygen (mol m^{-3})
α_1	Charge transfer coefficient for glucose oxidation (dimensionless)
α_2	Charge transfer coefficient for glutamic acid oxidation (dimensionless)
β	Charge transfer coefficient of cathode (dimensionless)

Table 4: MFC model parameters.

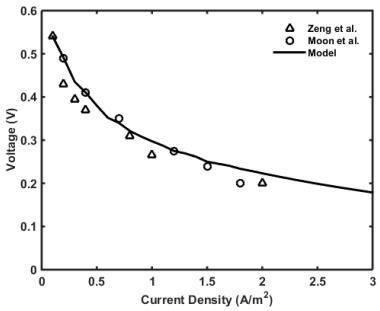

Figure 1: Model implementation and verification.

performance. A nominal approach, achieved by running the base case model and comparing the exit concentration of same model with the one parameter 10% above and 10% below the base value was conducted, similar to the genetic algorithm. All other parameters were held constant when comparing the results. From this analysis, it is found that anode wastewater flow rate, anode and cathode volumes, membrane area and cathode flow rate significantly affect treatment performance. Through optimization, it was found that decreasing the flow rate into the fuel cell had the smallest impact on the overall conversion of organic material. As inlet flow rates are only 21 mL/h in the base case, it is not feasible to decrease this any further in order to increase the overall conversion. Through sensitivity analysis it was determined that increasing the area of the PEM membrane had a significant impact impact on the conversion, however, increasing the membrane too quickly made the model unstable. Increasing the size of the anode and cathode chambers also provided a minor improvement in the conversion of the organic material.

Through optimization, it was found by increasing flow rate from 8.4 L/h to 84 L/h, COD conversion decreases from 64% to 49%. This decrease is due to a sizeable increase in vessel size. In order achieve the desired conversion while keeping equipment sizes practical, it was selected to run two MFCs in series, allowing a 64% COD conversion required in each MFC. Table 5 presents the final parameters for wastewater conversion. A similar optimization was completed to determine the optimal case for power generation. Through significance testing, membrane conductivity, membrane thickness and the distance between anode and cathode in cell are found to be significant. Final parameters for power generation are presented in Table 6.

The optimized parameters were then used to develop an industrial process to treat wastewater and generate electricity as shown in Figure 2. The final design consists of two MFC systems in series. Each MFC unit has an anode and cathode chamber separated by a semi-permeable membrane of Nafion N115. A surge tank to accommodate the difference between wastewater production and treatment capacity is also specified. This process design does not address the potential of solids in the brewery waste stream. The presence of solids would have to be addressed prior to the treatment with a microbial fuel cell, likely through the incorporation of MFCs as part of another wastewater treatment process train. For the brewery industry, solids are not expected to be a significant concern compared to other wastewater sources such as municipal wastewater. The proposed industrial process design is based on a theoretical microbrewery producing 5000 bottles of beer per week, a production equivalent to 1705 L/week. Previous research indicates that the brewing process produces three liters of wastewater for every liter of beer [21] and thus is assumed that this theoretical brewery produces 5115 L of wastewater per week. For the purposes of simulation, this inlet composition was simulated at 3000 mg/L COD.

It is approximated that the brewery brews 4 batches of beer per week with each batch generating 1278.75 L of wastewater. Waste production occurs over 5 hours and thus the total waste generation rate is roughly 256 L/hr. Based on a waste generation rate of 256 L/hr and treatment capacity of 84 L/hr, a net accumulation of 172 L/

Parameter	Base Case	Optimum Case
Flow Rate (L/h)	0.021	84
Volume of Anode (L)	0.2	1000
Volume of Cathode (L)	0.2	1000
Area of Membrane (cm^2)	24	1000
Flow Rate into Cathode (L/h)	0.57	2
COD of outlet (mg/L)	229.8	108.9
Conversion (%)	23	64

Table 5: Optimized MFC parameters (Wastewater Treatment).

Parameter	Base Case	Optimum Case
Membrane Conductivity (ohm^{-1} m^{-1})	17	25.00
Membrane Thickness (m)	0.0001778	0.0001270
Anode-Cathode Spacing (m)	0.022	0.0001510

Table 6: Optimized MFC Parameters (Power Generation).

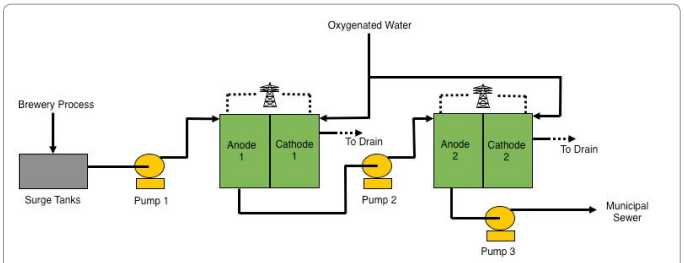

Figure 2: Proposed Process Design Consisting of Two MFCs in Series.

hr exists. Assuming that the proposed wastewater treatment system runs 4 days per week (to account for downtime and maintenance) the system must operate 15.2 hours per day. With these operating times, surge capacity of 1717.5 L is required. In the proposed design surge capacity is addressed through the use of two 1000 L polypropylene tanks. The model proposed in Ref. [14] requires a stream of oxygen-rich water to be fed to the cathode. Oxygen rich water is generated using a small tank and aeration pump. All wastewater pumps are 1 hp positive displacement pumps capable of processing 105 L/h of wastewater. A Masterflex L/S Digital Drive with L/S Easy-Load II Head and L/S 25 piping is used to feed each cathode a 2 L/h feed of oxygen rich water. The optimized design uses anode and cathode volumes of 1 m^3. Custom-molded polypropylene tanks with a height: diameter ratio of 5:2 is selected. Brewery wastewater is fed to the first anode chamber where bacteria oxidize the organic material, producing a stream lower in organic material can be fed to the second MFC in series. The PEM constructed of Nafion N115 separates the anode and cathode chamber of each MFC. Water leaving the second anode has a composition lower than the municipal discharge requirements (Table 1) making it suitable for discharge directly down a sanitary sewer.

Analysis of the model by Zeng et al. [14] concludes that total power generation is a function of the anode surface area. Based on estimated total power consumption of 24.7 kW during a four-hour treatment cycle, an equivalent of 26.4 kW of electricity is generated with an anode surface area of 4574.16 m^2 in each MFC. Based on a fiber density of 18,200 m^2/m^3 [22] an anode volume of 0.628 m^3 is required. To ensure that the anode chambers are well mixed and thus have uniform concentration, it is proposed that the anodes be rotated within the anode chamber using electric motors. Water is discharged from the cathode chamber at 2 L/hr and is discharged down the drain. This water is more basic, allowing it to be used to neutralize the acidic water from the anode.

Results and Discussion

The final discharge from the second anode chamber has a COD of 243.67 mg/L at a flow rate of 84 L/hr, representing a wastewater conversion of 91.88%. By definition, total COD will always be higher than BOD, thus, achieving a COD limit of 300 mg/L ensures that the total BOD will meet municipal guidelines. As noted previously, this stream will be acidic, and with a pH of 4.09, must be neutralized prior to discharge to a municipal sewer. There are two potential solutions to address the pH of this stream: mixing and neutralization. The discharge from the cathode will be basic and can be used to neutralize the anode effluent, or alternatively, the anode effluent can be neutralized with NaOH or lime as required. Capital costs were determined using a combination of empirical cost correlations (CAPCOST as available in Ref. [23]) and actual equipment costs determined through supplier resources. For costs determined through correlation, a Chemical Engineering Plant Cost Index (CEPCI) of 580.1 is used. A total capital cost of $289,000 is determined as shown in Table 7. Historically, a major concern for operators of microbial fuel cells is the cost of replacement and maintenance components, chiefly the membranes that are subject to fouling and electrodes susceptible to the formation of biofilms. A study based on the operation of acetate MFC determined that after 90 days of continual use, membrane fouling will decrease the maximum power output by 33% while increasing the internal resistance of the cell by 20% [24]. For the purposes of analysis, monthly membrane replacement has been specified with no appreciable loss in power output between membrane replacements. While the MFC process is capable of generating enough electricity of offset its own consumption, it is not possible to recognize the benefits of this capability directly, thus resulting in utility costs for both electricity, as well as the fresh water required for the cathode. There are additional costs associated with obtaining nitrogen to purge the anode; however this is expected to carry minimal cost. Not within the scope of this project was securing a reliable source of wastewater for inoculation. It is approximated that an operator of this technology would purchase bacteria directly as opposed to inoculation. As shown in Table 8 total operating costs are $16,847 per year.

One brewery located in the Waterloo, Ontario region incurred estimated costs of $0.30 per litre for the disposal of out-of-specification wastewater. Based on this, adaptation of MFC technology allows for a potential revenue source of nearly $80,000. In the Province of Ontario, organizations are compensated at a rate of $0.13/kWh for power returned to the grid. Overall, total revenues (or cost savings) from the operation of the proposed MFC technology is $82,430/year based on deferral of 265.98 m^3 in disposal costs and generation of 20280 kWh of electricity. Based on the capital and operating costs, and any potential revenue sources, a payback period of 5.02 years is calculated. Discounting future cash flows at 6.4% per annum results in a Net Present Value (NPV) of $113,001. Internal rate of return (IRR) is found to be 16%. For a small business, waiting five years to realize positive cash flow may be prohibitive. The current financial analysis does not incorporate any jurisdiction-specific financial incentives that

Component(s)	Complete bare module cost ($)
Positive Displacement Pumps	96800
Surge Tanks	1100
MFC Process Vessels	28000
Peristaltic Pumps	4000
Membranes	400
Anode Motors	2000
Anode Materials	78000
Cathode Materials	800
Aeration Equipment	200
Bare Module Total	211300
Total with Piping (30% of Bare Module Cost)	238769
Total with Contingency (21% of total cost)	**288910**

Table 7: MFC system capital costs.

Item	Quantity (year)	Yearly Cost ($)
Membrane Replacement (2 units)	12	4668
Water Feed	3120	5179
Electricity Cost	20000	1600
Nitrogen Cost	1	400
Bacteria Cost	100	1000
Routine Maintenance Labor	4	4000
Total Cost		**16847**

Table 8: MFC operating costs.

may be available to installations of green-energy and environmentally conscious processes. A positive NPV indicates that this project is worth consideration and further development.

This work has proven that it is realistic to develop an industrial-scale MFC for the treatment of wastewater in the brewing industry. This current work is cash-positive within 5 years and has a positive net present value. Due to the rapid advances in MFC and associated technology, an operating lifespan of 10 years is expected. After 10 years full replacement with a more modern unit is anticipated. While a feasible design for an industrial-scale MFC is demonstrated, the technology still has several limitations, assumptions and challenges that must be addressed before broad adaptation is possible. The primary limitation to this technology is the anode size required to achieve appreciable power generation. Each anode cell currently has four anode units with a total mass of 432 kg. MFC technology will benefit from advanced electrode technologies to reduce the size and weight of anodes. A critical step during the scale-up will be to source a consistent supply of bacteria for the oxidation of organic material. Several organizations specialize in providing bacteria for the wastewater treatment industry, so this is not expected to be a significant concern. The current work is based on the bacteria properties part of the original study in Ref. [14] which had a bacteria-specific growth constant (Y_{AW}) of 0.05. If it is not possible to locate a specific bacterium with these properties, modification of the model against specific experimental results with actual bacteria is required. Current work assumes that residual alcohol or cleaners in the wastewater stream do not adversely affect bacteria selected. While the presence of these compounds will affect the operation of the anaerobic process, previous studies such as Ref. [10] have demonstrated the potential for anaerobic digestion of brewery wastewater. The current work also anticipates a true brewery wastewater containing numerous organic substrates. Modelling of complicated wastewaters is a challenge. Numerous works focusing on anaerobic digestion modelling based on acetate and glucose-glutamic acid substrates confirms the applicability of this model to the brewery industry. Concerns related to complex wastewaters and the effect of wastewater composition on the bacteria will be addressed during operation of a pilot plant.

Concluding Remarks

Herein a design for an industrial-scale MFC capable of treating wastewater with an inlet COD of 3000 mg/L is presented. Using a process based on a model by Zeng et al. [14] it is demonstrated that by using a set of two-chamber MFCs in series, it is possible to reduce the outlet concentration to 243.67 mg/L COD, sufficient for discharge to a municipal sanitary sewer. Based on revenues from the resale of the generated electricity and savings eliminated from paying fines, the $289,000 capital cost has a payback period of 5 years and NPV of $113,001. Based on payback period and NPV, the scale-up of MFC to an industrial process appears feasible. Even with the current contribution, MFC technology remains in a developmental stage, and this current work is based on several assumptions. As this current work has demonstrated economic feasibility, it is recommended that several next steps be taken. Most importantly, the development of a pilot-plant based on this design. A pilot plant, operating in the 10 L/hr range on actual brewery wastewater is required in order to verify that the scale-up of this MFC model is possible. Running the pilot plant on brewery wastewater from an industrial source will also permit the verification of the model operation while treating complicated substrates. During the development of the pilot plant, various bacterial sources should be identified and verified for tolerance against alcohol and cleaner-containing wastewaters. For industrial operation, a consistent source of bacteria must be identified. Based on the successful operation of a pilot plant treating brewery wastewater, this current work and process can be adapted to other industries producing wastewaters with high organic content.

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