Generating electrical energy from bacteria: Harare waste water management case study

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Abstract

The biological nutrient removal waste water treatment process requires large amounts of electrical power mainly for pumping and aeration. This traditional waste treatment processes proves to be expensive mainly because of this huge electricity demand. However, waste water contains 9.3 times more energy than is used to treat an equivalent volume, this is useful energy that is not being tapped into. Herein, an industrial scale Microbial Fuel Cell system is proposed to harness this energy in the form of direct electricity using the bacteria found in the waste water whilst simultaneously treating the waste water from the municipal waste water treatment plants with an assumed Biological Oxygen demand (BOD) and Chemical Oxygen Demand (COD) removal of 75%. Microbial fuel cells directly capture the electrons generated when electrochemically energetic bacteria breakdown organic substrates. Creating electrical energy from Microbial Fuel cells is basically as a result of microbes acting as catalyst in degrading the organic content and the existence of a potential gradient across the microbial cell membrane. This work evaluated the operational parameters of microbial Fuel Cell system and estimated the electricity generation potential of Firle waste water treatment plant (treating a volume of 90ML a day) as 900 kW. A cost analysis showed that Microbial Fuel Cells could be competitive as a sustainable and energy-efficient technology for municipal wastewater treatment.

Keywords
Microbial Fuel Cell, Waste water, Bacteria, Electrical energy.

1. Introduction
Energy is fast becoming the requirement of every individual on Earth, however with the increasing demand for energy mainly electricity, there is need for sustainable sources of energy. The past decades have seen evolution from use of fossil fuels to date were renewables are being adopted to counter the effects of the former in the past years by reducing emission of greenhouse gases. Faced with the challenge of creating more energy in a more sustainable manner this has seen some modifications in our way of living and hence the shift towards renewable energy, the science of Renewable energy is now an important area of research for social, health, environmental and economic reasons (Kumar, 2020).

One interesting approach would be to use waste to generate the much needed energy. Just as the food humans consume contains a lot of energy, so does the waste produced as a result (Hong , 2020). Since the early 1900's scientists have known that bacteria can produce electricity with the first report that bacteria can generate electricity by Potter having appeared almost a hundred years ago (Potter, 1911). Back then this was not fully embraced but the recent years have seen the need to further investigate and embrace the energy that can be generated from bacteria more.

Traditionally, biomass like coal or wood has to be burned or combusted to be converted into electrical energy. In a microbial fuel cell many forms of biomass, including food and sewage wastes, are able to be converted directly into electrical energy by bacteria. This direct conversion reduces the amount of energy lost as heat during the conversion processes. The power microbial fuel cells can generate is limited by the rate at which bacteria can degrade its food sources, but they are very efficient. Almost 90% of the energy in waste streams (sewage, waste water treatment plants) can be converted into electrical current, significantly higher than combustion processes (Hong , 2020).

Over the years Zimbabwe has failed to produce enough electrical energy to meet demands, as demand has increased with the increase in population. The power generation capacity for the country does not meet its demand with an estimated 8.89 billion kWh was produced in 2007, while demand was estimated to 10.89 billion kWh (CIA, 2017). This has led to load shedding, a control measure that has severely affected both the domestic and industrial sector. On the other hand there has been an increase in waste production proportional to the growing population of people, however with the outdated waste disposal and sewer systems the municipal councils are failing to properly dispose and manage waste thus posing health and environmental threats. Evidently there is still a gap in our waste management system. As the number of people increase so should their ability to generate their own power, one effective way is by transforming their waste into energy. Bacteria can be used to generate electrical power in microbial fuel cells, which convert chemical energy into electricity via catalysis by exoelectrogenic microorganisms. The process of bacterial power generation will not only benefit the energy industry but has several other potential applications. Firstly, this will contribute to the energy requirements in the country. Secondly, monitoring of pollutant toxicity will be made possible through the generated electrical signals of the microbial fuel cells such as peak voltage, quantity of electrons and start-up time, behaviours corresponding to certain pollutants and their quantities thus making it possible to note toxic materials and engage proper management of them. Thirdly, the use of microbial fuel cells would also help eliminate pollutants like petrol.

2. Literature Review

A fuel cell is an electrochemical device that continuously converts chemical energy to electrical energy for as long as fuel and oxidant are supplied to it. Fuel cells could be broadly categorized into abiotic fuel cells of which the fuel cell components do not comprise any biological material and biotic or biological fuel cells which comprise living organisms or biological material (such as enzymes or derivatives) (Mahadevan.A, 2014) . Microbial fuel cell can be best defined as a fuel cell where microbes act as catalyst in degrading the organic content to generate electricity. The existence of a potential gradient across the microbial cell membrane forms the basis for the generation of bioelectricity (Mane, 2019)**.**

A microbial fuel cell functions like any other chemical cell, except instead of using chemical redox energy, the electrons reduced are from biological sources instead, (Mane, 2019). In a Microbial fuel cell (MFC), the organic material is oxidized on the anode, and the product of oxidation is CO2 and electrons. For a glucose reaction, we obtain:

ANODE $C_6H_{12}O_6 + 6H_2O \longrightarrow 6CO_2 + 24H^+ + 24e^-$ Equation 1

CATHODE $24H^+ + 24e^- + 6O_2 \longrightarrow 12H_2O$ Equation2

Summary reaction: $C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2 + 6H_2O$ + electricity Equation 3
(Włodarczyk, 2019)

Bacteria and the organic compound are confined to the anode chamber of a Microbial Fuel Cell where anaerobic conditions are maintained. The cathode is maintained under aerobic conditions (aeration).The anode and cathode chambers are separated by an ion-selective membrane; it provides for the transfer of protons and prevents oxygen from entering the anode chamber (Debabov.V, 2008). Electrons produced by the bacteria from these substrates are transferred to the anode (negative terminal) and flow to the cathode (positive terminal) linked by a conductive material containing a resistor, or operated under a load. The difference in the potential coupled to electron flow produces electricity in this fuel cell thus by convention, a positive current flows from the positive to the negative terminal, a direction opposite to that of electron flow. The device must be capable of having the substrate oxidized at the anode replenished, either continuously or intermittently; otherwise, the system is considered to be a bio battery (Logan.B, 2006).

Electron transfer to the electrode is the key point of Microbial fuel cell technology. These mechanisms for electron transfer are not yet fully understood but they are essential for efficient microbial fuel cell operations. Electrons can be transferred to the anode by electron mediators or shuttles, by direct membrane associated electron transfer, or by so-called nanowires produced by the bacteria, or perhaps by other as yet undiscovered means (Logan.B, 2006).
A typical microbial fuel cell consists of different construction formats for the makeup of their own body. There are three types of microbial fuel cell s on the basis of configurations:

1. Single chamber microbial fuel cells
2. Two-chamber microbial fuel cells
3. Stacked microbial fuel cells

Other than this there are two types on the basis of mediators used:

1. Mediator less microbial fuel cells
2. Mediator microbial fuel cells (Mane, 2019)

A typical MFC consists of an anode and a cathode separated by a proton exchange
membrane to prevent direct oxidation. As to assist the flow of electricity, the presence of salt bridge is crucial as it transports the proton in microbial fuel cell (MFC) (Table 1).

Table 1. Basic components of Microbial Fuel Cells (Mane, 2019)

Materials	**Items**
Anode	Graphite, graphite felt, carbon paper, carbon-cloth, Pt black, RVC
Cathode	Graphite, graphite felt, carbon paper, carbon-cloth, Pt black, RVC
Anodic Chamber	Glass, polycarbonate, Plexiglas
Cathodic Chamber	Glass, polycarbonate, Plexiglas
Proton Exchange system	Proton exchange membrane: Nafion, Ultrex, polyethylene. poly, (styrene- codivinylbenzene); salt bridge, porcelain septum, or solely electrolyte)
Electrode catalyst	Pt black, MnO2, Fe3+, polyaniline, electron mediator immobilized on anode

Along with the understanding of the Microbial Fuel Cell concept, many Microbial Fuel Cell based applications have emerged, such as wastewater treatment, microbial electrolysis cells, sediment Microbial Fuel Cells and bioremediation. Among those Microbial Fuel Cell-based technologies, the most immediate and useful one is as a method of wastewater treatment. The electricity produced by Microbial Fuel Cells can be used for powering other technologies, such as biologically inspired robots, some small devices, or remote devices. In addition, the voltage generated by Microbial Fuel Cells can be used on microbial electrolysis cells (MECs), which is a modified Microbial Fuel Cell-based system to produce Hydrogen gas(H_2) or hydrogen peroxide (H_2O_2) instead of electricity. However, most of the MFCs applications are limited to lab-scale systems because of some practical difficulties, such as economic or environmental feasibilities (Anand, 2016).

MFCs are being constructed using a variety of materials, and in an ever increasing diversity of configurations. These systems are operated under a range of conditions that include differences in temperature, pH, electron acceptor, electrode surface areas, reactor size, and operation time. It has been observed that MFCs operated using mixed cultures currently achieve substantially greater power densities than those with pure cultures (Logan.B, 2006).Currently, several theoretical and practical works connected to increasing the Microbial Fuel Cells' power have been presented, not only in the field of the microorganism selection. The upper limit of the power level that is achievable in Microbial Fuel Cells is not yet known because there are many reasons for power limitations. The reasons limiting the maximum power density may be different, e.g., high internal resistance or low speed of reactions on electrodes. The speed of the process depends on the catalyst used. In a Microbial Fuel Cell, the catalyst at the anode is microbes (on a carbon electrode). Thus, it is important to find a catalyst for the cathode. Due to its excellent catalytic properties, platinum is most commonly used as the catalyst (Włodarczyk, 2019) . However since platinum

is expensive other materials can be used for the cathode if not properly chosen the cathodic process may become the bottleneck of the Microbial Fuel Cell performance. Due to costs, in Microbial Fuel Cells, carbon or carbon cloth with platinum is most often used as the cathode catalyst. It is also possible to use metal catalysts for the cathodes of Microbial Fuel Cells. The theoretical current density is described by the Butler–Volmer exponential function. (Włodarczyk, 2019). Of concern, it is important to note that Potentials are reported with different reference states, and sometimes only under a single load (resistor). The range of conditions, and in some cases a lack of important data like the internal resistance or power densities derived from polarization curves taken using different methods, has made it difficult to interpret and compare results among these systems. The variation in reported data has created a need to clarify methods of data collection and reporting (Logan.B, 2006).

As microbial fuel cells and microbial electrolysis cells are recently developed technologies, the environmental costs and benefits of Microbial Fuel Cells (MFCs) and microbial electrolysis cell (MECs) have to be verified. This can be done by life cycle assessment (LCA), which is a technique to access the potential environmental impacts caused by a process or a product. The results of life cycle assessment (LCA) reveal the true potential and identify the environmental impacts associated with the evaluated product or process, for example, energy and materials usage, waste discharges, impacts of these wastes on the environment (Anand, 2016).

3. Methods

The research used different research instruments and mainly quantitative research methods are applied in this research project. The experiments were done to get the electrical potential of waste water under given conditions such as, temperature and electrode material and electrode separation distances. Calculations that relate the experimental setup to actual expected estimated projections were done. In so doing there was need to know the factors that affect electricity production and their relationships with one another. The experiments led to determination of optimum operational parameters for the model microbial fuel cell for electricity production and cost effective waste water treatment.
The following instruments were employed in this research project:

1. Literature surveys
2. Data collection
3. Experiments
4. Data analysis

3.1. Materials and Methods

The experiments were investigating the electricity production from bacteria found in waste water; the waste water is from Firle waste water treatment plant.

3.2.1 Microbial Fuel Cell components and assembly

The present set-up consists of the oxygen deprived anode (anaerobic) and the air cathode (aerobic) based on a design used by many laboratories around the world.

3.2.1.1 Electrodes

Carbon of dimension (diameter 1.3 cm) was used as cathode and anode. The electrodes were cleaned with alcohol before use and arranged in a single chamber version that uses an air cathode, which allows air from the outside to enter the chamber and react with the protons travelling from the anode. The microbial fuel cell was arranged as shown in figure 1. Based on this electrode distance was varied (A=0.01m, B=0.05m and c=0.1m)

1. In chamber A, the anode was attached inside wall of glass just near to cathode at about 0,01m distance.
2. In chamber B the anode was hanged with plastic wire inside and in middle of the plastic container with electrode distance of 0.05m.
3. In chamber C the anode and cathode were attached on opposite side of glass with distance of 0.1m.

3.2.1.2 Microbial fuel cell assembly

The anodic chamber with 1000ml effective liquid volume was used (the anode was immersed in the water to a height of 0.08m, whilst the cathode was left outside for natural oxygenation. The waste water obtained from Firle plant was the anolyte without any pre-treatment. Circuit connections were set with the copper wires fixed into the drilled holes of the electrodes and sealed with tape to avoid corrosion of copper wire. Electricity generation was recorded using a multimeter.

3.2.1.3 Anolyte

Figure 1. Sample collection of Raw Sludge at Firle Waste Water Treatment plant.

Wastewater was collected from primary effluent collection tank of Firle sewage treatment plant filtered and analysed. Major characteristics were colour-grey-black, odour-foul, assumed chemical oxygen demand (COD)-500mgL^{-1} (from literature), pH 7.49 and biological oxygen demand (BOD) - 240.2 mgL^{-1}. The plain wastewater (without any modifications such as addition of nutrients, mediator, and any other microbial inoculums or trace metals) was used as the inoculums for all Microbial Fuel Cell tests.

3.2.1.4 Circuit assembly, measurement of potential difference and current

The anode and cathode were connected externally by the circuit that was connected with copper wires which were joined to the two electrodes by a multimeter. The potential difference and current output of MFC were measured using a multimeter.

Current and power generation in the MFC is determined by measuring the voltage (U) across a fixed external resistance (1000 ohm. Current (I) is calculated from Ohm's law:

$$I = U/R \qquad \text{Equation 4}$$

And power (P) is calculated as:

$$P = IU \qquad \text{Equation 5}$$

Power density (mW m^{-2}) was calculated according to:

$$P = IV/A \ldots\ldots\ldots \qquad \text{Equation 6}$$

Where; I is the current

V is the voltage

A is the projected area of the anode.

Electricity potential of the plant was calculated using the ratio of the total volume processed at the plant daily (V_{tot}) to the laboratory scale volume (V_{lab}) used in the experimental set up.

$$Electricity\ potential\ of\ plant = Power\ density\ per\ m^3 \times (V_{tot}\,(m^3)\ ). \qquad \text{Equation 7}$$

3.2.2 Microbial Fuel Cell operations

The electrode chamber and electrodes were surface-sterilized prior to operation of the Microbial Fuel Cell by 70% alcohol. The Microbial Fuel Cell was operated at room temperature, i.e. 24 - 29°C under static condition. The Microbial Fuel Cell was inoculated with 1000 ml of sewage water obtained from the inlet of the primary filter at Firle Sewage Treatment plant (144Ml/day design capacity) with diverse electrochemically active bacteria. After all the attachments and connections were secured in place, the mouth of the anode chamber tightly sealed with cellophane so that it is not exposed to further oxygen. The performance of all MFCs was evaluated by measuring current and potential difference. Constant voltage output was considered as indicators to assess the stable performance of the MFC. The MFC operated by connecting the anode and cathode electrodes through an external

load (1000 Ω) until stable voltage was achieved. The Microbial Fuel Cell set-ups were left undisturbed for 25 days and the voltage was recorded every 24 hours all the cases. The multimeter was connected in series for measuring the potential difference and current. The readings were noted only after the potential difference readings were constant.

3.3 Microbial Fuel Cell Scaling up to a practical level

To adapt the microbial fuel cell technology in electricity production and waste water treatment there is need to scale up the reactors to a more practical size. However, challenges arise with scaling up as it inherently decreases the membrane surface area to volume ratio and increases the distance between electrodes, resulting in increased electrolyte resistances, implying a decreased power output. Therefore, the biggest challenge of MFCs designed for wastewater treatment application is how to simultaneously scale up the reactor size and energy output. The specific limitations associated with system scaling up include: high internal resistance, pH buffering, high material cost, and low efficiency of mixed culture bio film on an electrode. Thus there is need to overcome or lessen these limitations. Some factors affecting performance related to reactor design that were considered during scaling up of the microbial fuel cell; materials, electrode spacing, surface area to volume ratio.

3.3.1 Reducing capital investment

High capital cost is one of the major challenges when it comes to Microbial Fuel Cell scaling up; this mainly results from expensive materials. Thus there is need to adopt economically affordable materials that are efficient and scalable. Carbon-based materials, because of a large surface area, good stability, and low cost, are a desirable choice in this respect. Another high-cost component in a Microbial Fuel Cell is the separator, for which an ion exchange membrane is commonly adopted. Not only are they costly but most of them have low mechanical strength, fouling and unstable in large chambers with time. In this design adopted the exchange membrane is eliminated.

3.3.2 Materials

Precious metal catalysts and expensive materials should be avoided for scale-up application, as it is economically not feasible.

3.3.3 Surface area to volume ratio

Scaling-up typically results in an increase in electrode area. Depending on the type of electrode material used, larger electrode area can result in increased internal resistance due to the increased distance electrons travel through the material. It has been shown that although increasing anode surface area can increase power, it does not affect performance as much as increasing cathode surface area (Janicek.A, 2014), In particular, it is important to maintain cathode specific surface area (i.e. Ratio of cathode surface area to the volume of the reactor) when scaling up, as volumetric power density is a function of this parameter. Cathode specific surface areas that are to be used are presented. High specific surface area does not necessarily correspond to higher power densities.

3.3.4 Electrode spacing

Firstly, a close distance between the anode and the cathode electrodes, and an efficient transfer of ions should be ensured to decrease internal resistance, regardless of an increased overall reactor size. However, shortening the electrode spacing would also increase the possibility of oxygen intrusion into the anode and substrate crossover to the cathode, especially in the membrane-less MFCs. To illustrate the importance of electrode spacing, a calculation can be made based on methods outlined by (Janicek.A, 2014).The internal resistance for an MFC can be calculated as:

$$R_{int} = R_c + R_a + R_e + R_m \qquad \text{Equation 8}$$

Where; Rc, *Ra*, *Re* and *Rm* are the resistance of the cathode, anode, electrolyte and membrane, respectively

*Re*is given by:

$$R_e = \frac{La}{S_r C_e} \qquad \text{Equation 9}$$

where *Re* is a function of the distance between anode and cathode (*L*), the cross-sectional area of the reactor(*Sr*) and the concentration of the charge transfer electrolyte (*Ce*), and *a* is a constant (Janicek.A, 2014)

Using Equations 5&6 and assuming an operating voltage of 0.3 V for a membrane-less configuration (Rm = 0), the power can be calculated and compared at different electrode spacing's.

Electrode shape and orientation have the greatest effect on the minimum distance attainable in a given design. The resistance of the electrodes also has to be small so as to not increase total internal resistance. The resistance of the electrode is given by:

$$R_{electrode} = \frac{\rho L}{A} \ldots\ldots\ldots\ldots\ldots\ldots \quad \text{Equation 10}$$

Where; L is the length of the electrode
A is the surface area of the electrode
ρ Is the electrode material resistivity (Ωm)

3.3.5 Microbial Fuel Cell stacks

In some work done on Microbial Fuel cells, it was proven that a serial connection of multiple Microbial Fuel Cells can substantially boost the overall output voltage, and offer high flexibility for Microbial Fuel Cell installation and modularized operation.

3.4 Economic analysis

Financial feasibility analysis is conducted by developing a base case financial plan and assessing the sensitivity of the profitability of the project, and the projected return, on the investor's equity to various contingencies. The economic feasibility aspect of a project plays an important role in implementation of the project; therefore, in this research it was necessary to investigate the following economic parameters for all of the user specifications:

3.4.1 Capital investment

The capital investment consists of the cost of: Building the microbial fuel cell - labour and materials, Power management system, Water flow control system, Oxygen extraction system and Other accessories.

3.4.2 Operational and maintenance costs

Operation of the plant will enquire operating and maintenance costs, these include; daily operating and maintenance costs of devices, labor costs, water quality monitoring costs, and routine maintenance costs.

3.5 Designing the tool to determine Microbial Fuel Cell size

The factors that affect operation of a Microbial Fuel Cell include; Anolyte (waste water), Electrode material, Salt bridge/ permeable membrane, Resistance, Electrode spacing.
Different waste water treatment plants process different volumes of waste per day. An Excel spreadsheet was prepared in which a user enters the volume of waste water available. The bacteria necessary for a comprehensive electricity production are assumed to be contained in the waste from industries, domestic, hospital e.tc that are processed in waste treatment plants in Zimbabwe.

4 Results and Discussion

Many parameters determine the electricity production in Microbial Fuel Cell, however in this study, only one was varied while the other parameters were fixed as follows.
Fixed parameters:

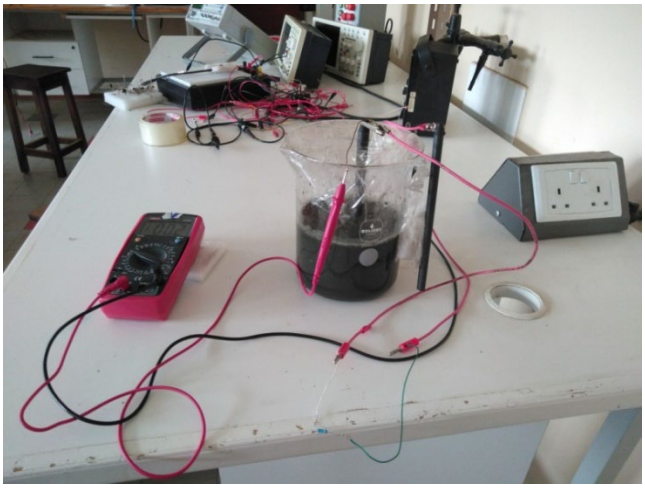
1. Electrode material
2. Electrode area (anode: cathode): 1:1
3. Substrate concentration (the same substrate type was used that is waste water from Firle waste water treatment plant)

Variable parameter:

1. Electrode spacing

Experiments were carried out with three different chambers of different electrode spacing. The potential difference between the electrodes was considered as the performance indicator. In all arrangements, the cathode was attached outside the glass wall exposed to oxygen and in all arrangements no technique was adopted to remove oxygen from

anolyte. The electrodes (both anode and cathode) were connected using copper wire. Figure 2a shows the microbial fuel cell set up at day 3 and figure 2b shows the microbial fuel cell set up at day 25.



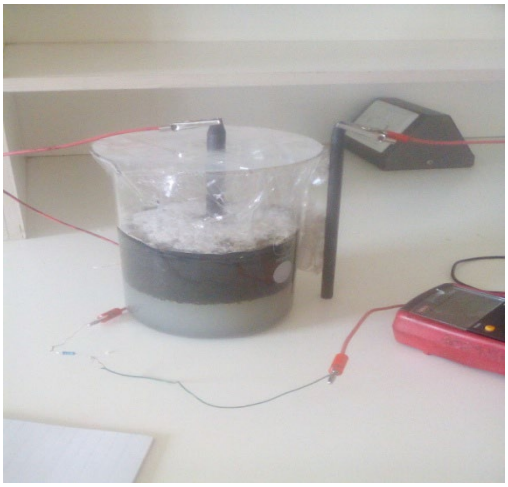


Figure 2a. The Microbial Fuel Cell experimental setup (day 3). Figure 2b The Microbial Fuel Cell experimental setup (day 25).

The Microbial Fuel Cells setup was able to utilize the sewage water for electricity production as recorded in table 3. When the Microbial Fuel Cells were inoculated with the sewage-water, there was about a 24-hour lag phase followed by an increase in the current output for all three electrode spacing arrangements. The initial increase of current here can be attributed to the presence of components that are easily utilized by microbes present in sewage water. When these easily degradable substrates were exhausted, the current output began to decrease. From the results recorded in table 3 the electrode spacing of 0,01m in MFC-A was generally lower than that of MFC-B this can be attributed to some oxygen crossover from the aerobic cathode to the anaerobic anode due to the shorter distance. Electrode spacing of 0,05m in MFC-B produced a reasonable constant supply of electrical energy, however more experimental setup is necessary in order to determine an optimum electrical current producing distance. As shown in table 3 the trends of electrical current in MFC-C at 1m distance is similar to the other MFC chambers only producing lower values, this can be attributed to the larger distance of separations were as a result the electrons have to travel a greater distance thus reducing the electrical current output. From the electrical current and voltage recorded power was determined and the respective power density per unit volume for all Microbial Fuel Cell setups was calculated since they had a uniform volume of 1000ml.

Table 3. the current, voltage, power and power density recorded using carbon electrodes at different electrode spacing A, B and C

	Current (mA)			Voltage (V)			Power (W)			Power density (W/m2)			Power density (W/m3)		
Day	MFC-A	MFC-B	MFC-C	MFC-A	MFC-B	MFC-C	MFC-A	MFC-B	MFC-C	MFC-A	MFC-B	MFC-C	MFC-A	MFC-B	MFC-C
1	0,00	**0,00**	0,00	0,00	**0,00**	0,00	0,00000	**0,00000**	0,00000	0,00000	**0,00000**	0,00000	0,000	**0,000**	0,000
2	0,01	**0,01**	0,00	0,01	**0,01**	0,00	0,00000	**0,00000**	0,00000	0,00000	**0,00000**	0,00000	0,000	**0,002**	0,000
3	0,11	**0,16**	0,01	0,11	**0,16**	0,01	0,00001	**0,00003**	0,00000	0,00021	**0,00044**	0,00000	0,012	**0,444**	0,002
4	0,12	**0,19**	0,10	0,12	**0,19**	0,10	0,00001	**0,00004**	0,00001	0,00025	**0,00063**	0,00017	0,014	**0,627**	0,174
5	0,13	**0,19**	0,11	0,13	**0,19**	0,11	0,00002	**0,00004**	0,00001	0,00029	**0,00063**	0,00021	0,017	**0,627**	0,210
6	0,15	**0,20**	0,13	0,15	**0,20**	0,13	0,00002	**0,00004**	0,00002	0,00039	**0,00069**	0,00029	0,023	**0,694**	0,293
7	0,17	**0,22**	0,13	0,17	**0,22**	0,13	0,00003	**0,00005**	0,00002	0,00050	**0,00084**	0,00029	0,029	**0,840**	0,293
8	0,17	**0,23**	0,15	0,17	**0,23**	0,15	0,00003	**0,00005**	0,00002	0,00050	**0,00092**	0,00039	0,029	**0,918**	0,391
9	0,21	**0,25**	0,17	0,21	**0,25**	0,17	0,00004	**0,00006**	0,00003	0,00077	**0,00109**	0,00050	0,044	**1,085**	0,502
10	0,22	**0,26**	0,18	0,22	**0,26**	0,18	0,00005	**0,00007**	0,00003	0,00084	**0,00117**	0,00056	0,048	**1,174**	0,563
11	0,25	**0,26**	0,18	0,25	**0,26**	0,18	0,00006	**0,00007**	0,00003	0,00109	**0,00117**	0,00056	0,063	**1,174**	0,563
12	0,25	**0,28**	0,19	0,25	**0,28**	0,19	0,00006	**0,00008**	0,00004	0,00109	**0,00136**	0,00063	0,063	**1,361**	0,627
13	0,27	**0,31**	0,20	0,27	**0,31**	0,20	0,00007	**0,00010**	0,00004	0,00127	**0,00167**	0,00069	0,073	**1,668**	0,694
14	0,29	**0,34**	0,22	0,29	**0,34**	0,22	0,00008	**0,00012**	0,00005	0,00146	**0,00201**	0,00084	0,084	**2,007**	0,840
15	0,32	**0,35**	0,23	0,32	**0,35**	0,23	0,00010	**0,00012**	0,00005	0,00178	**0,00213**	0,00092	0,102	**2,127**	0,918
16	0,33	**0,38**	0,25	0,33	**0,38**	0,25	0,00011	**0,00014**	0,00006	0,00189	**0,00251**	0,00109	0,109	**2,507**	1,085
17	0,35	**0,39**	0,26	0,35	**0,39**	0,26	0,00012	**0,00015**	0,00007	0,00213	**0,00264**	0,00117	0,123	**2,641**	1,174
18	0,37	**0,41**	0,28	0,37	**0,41**	0,28	0,00014	**0,00017**	0,00008	0,00238	**0,00292**	0,00136	0,137	**2,918**	1,361
19	0,36	**0,42**	0,29	0,36	**0,42**	0,29	0,00013	**0,00018**	0,00008	0,00225	**0,00306**	0,00146	0,130	**3,063**	1,460
20	0,36	**0,42**	0,30	0,36	**0,42**	0,30	0,00013	**0,00018**	0,00009	0,00225	**0,00306**	0,00156	0,130	**3,063**	1,563
21	0,33	**0,40**	0,28	0,33	**0,40**	0,28	0,00011	**0,00016**	0,00008	0,00189	**0,00278**	0,00136	0,109	**2,778**	1,361
22	0,31	**0,37**	0,28	0,31	**0,37**	0,28	0,00010	**0,00014**	0,00008	0,00167	**0,00238**	0,00136	0,096	**2,377**	1,361
23	0,31	**0,37**	0,25	0,31	**0,37**	0,25	0,00010	**0,00014**	0,00006	0,00167	**0,00238**	0,00109	0,096	**2,377**	1,085
24	0,29	**0,36**	0,25	0,29	**0,36**	0,25	0,00008	**0,00013**	0,00006	0,00146	**0,00225**	0,00109	0,084	**2,250**	1,085
25	0,27	**0,35**	0,23	0,27	**0,35**	0,23	0,00007	**0,00012**	0,00005	0,00127	**0,00213**	0,00092	0,073	**2,127**	0,918

Figure 3 highlights the difference in electrical current produced from the different microbial Fuel Cell electrode spacing setups. It took around 24hours to record a significant amount of electrical current in all setups reaching their peaks at around day 25 were the anaerobic were more prevailing since most of the oxygen in the anode chamber had been used up, therefore encouraging more anaerobic respiration for the microbes to produce electricity. Depletion of the microbes found in sewer water resulted in the decrease in electrical current production as shown in Figure 3 on day 25.

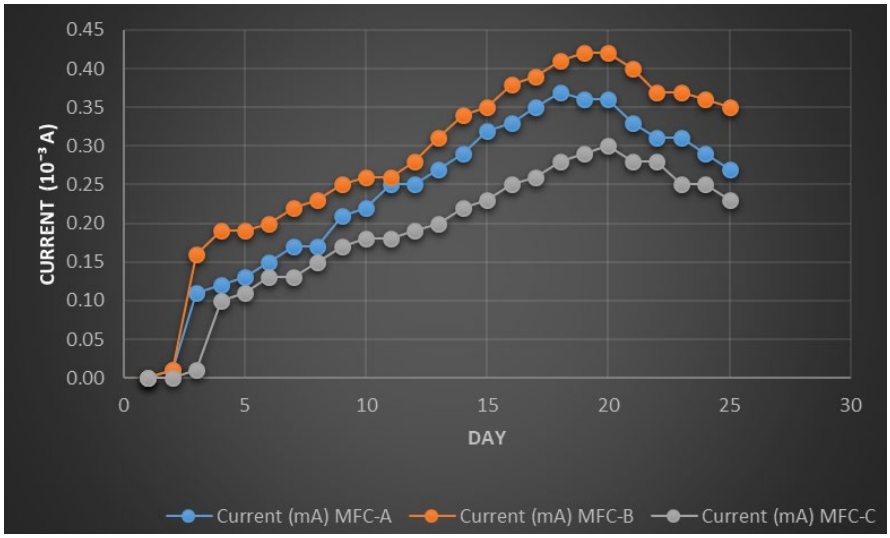


Figure 3. A plot of current (mA) in a microbial fuel cell A, B and C versus time (days) with raw sewage water as substrate indicating the effect of electrode spacing.

The results obtained showed the potential of waste water to generate electricity, with a maximum electric current of 0.65mA recorded. This maximum current was obtained at electrode spacing of 0,05m. Reducing electrode spacing from 0,1m to 0,05m showed that there is more electrical potential with reduced electrode separation as the electrons had to travel shorter distances. However further reduction in electrode spacing was not favourable and thus produced less electricity, this could be attributed to oxygen crossover from the cathode to anode chamber thus affecting the anaerobic anode reactions resulting in less electrical output.

Considering the mean power density for Microbial Fuel Cell B, further calculations can be done to determine the:
Electricity potential of the plant (Firle waste water treatment plant at 90ML capacity) using equation 3.4 and average power density per m^3.

$$Electricity\ potential\ of\ plant = Power\ density\ per\ m^3\ of\ the\ laboratory\ model\ \times (V_{tot})$$

$$\therefore P_p = 1.637388 \times \left[\frac{(90\times10^6)}{(1000)}\right]$$

$$\therefore P_p = 147364.92\text{W}$$

$$\therefore P_p = 147.4K\text{W}$$

This gives an approximation of a Microbial Fuel cell electrical potential using the setup microbial fuel cell, however this potential can differ positively or negatively due differentfactors like; reactor efficiency, system losses when scaling up, materials, electrode spacing and microbial fuel cell stacking.
To eliminate high costs of separators or membrane a reactor without a separator or membrane is adapted with an up flow feeding where the substrate is fed from the bottom. The electrode materials favoured are carbon or graphite without or with minimal metal catalysts.

4.3 Materials

Anode and cathode material was determined from recorded reactors set up before.
Anode material: Granular activated carbon
Cathode material: carbon cloth with Manganese oxide as catalyst

4.4 Surface area to volume ratio

Cathode specific surface areas to volume ratio are used. A reactor of volume 20L of 0, $3m^2$

4.5 Electrode spacing

Since the volume of the cylindrical reactor is 20L or 0, $02m^3$
The approximate radius of the chamber can be determined using:

if $V_r = 0{,}02m^3$ and assuming a reactor of unit length 1m, the diameter of the anode can be determined

$$V_r = \pi r^2 h$$

$$\therefore V_r = \pi r^2$$

$$\therefore r = \sqrt{(V_r/\pi)}$$

$$\therefore r = \sqrt{(0.02/\pi)}$$

$$\therefore r = 0{,}79788456$$

$$\therefore D = 0{,}15957m$$

Surface area of the anode electrode:

$$A_S = 2\pi r(h + r)$$

$$\therefore A_S = 2\pi r(h + r)$$

$$\therefore A_S = 2\pi 0{,}79788456(1 + 0{,}79788456)$$

$$\therefore A_S = 0{,}614812339$$

Using equation 3.7 Resistance of the anode becomes:

$$R_{anode} = \frac{\rho L}{A}$$

$$R_{anode} = \frac{5 \times 10^{-4} \times 1}{0{,}614812339}$$

$$R_{anode} = 0{,}000813256$$

Table 4. Results obtained of internal resistance from iterative calculation and their respective power densities at assumed operational voltage of 0,3V

L	Anode radius	Cathode radius	Cathode suface area	Ra	Rc	Re	Rint	Power assuming (V=0,3V) (W)	Power density(W/m2)
0,1	0,798	0,898	10,707	0,000077	0,000047	0,213	0,213	0,422	0,686
0,095	0,798	0,893	10,619	0,000077	0,000047	0,203	0,203	0,444	0,722
0,09	0,798	0,888	10,532	0,000077	0,000047	0,192	0,192	0,469	0,762
0,085	0,798	0,883	10,445	0,000077	0,000048	0,181	0,181	0,496	0,807
0,08	0,798	0,878	10,358	0,000077	0,000048	0,171	0,171	0,527	0,857
0,075	0,798	0,873	10,272	0,000077	0,000049	0,160	0,160	0,562	0,914
0,07	0,798	0,868	10,186	0,000077	0,000049	0,149	0,149	0,602	0,980
0,065	0,798	0,863	10,100	0,000077	0,000050	0,139	0,139	0,649	1,055
0,06	0,798	0,858	10,014	0,000077	0,000050	0,128	0,128	0,703	1,143
0,055	0,798	0,853	9,929	0,000077	0,000050	0,117	0,117	0,766	1,247
0,05	0,798	0,848	9,844	0,000077	0,000051	0,107	0,107	0,843	1,371
0,045	0,798	0,843	9,760	0,000077	0,000051	0,096	0,096	0,936	1,523
0,04	0,798	0,838	9,676	0,000077	0,000052	0,085	0,085	1,053	1,713
0,035	0,798	0,833	9,592	0,000077	0,000052	0,075	0,075	1,204	1,958
0,03	0,798	0,828	9,508	0,000077	0,000053	0,064	0,064	1,404	2,283
0,025	0,798	0,823	9,425	0,000077	0,000053	0,053	0,053	1,684	2,739
0,02	0,798	0,818	9,342	0,000077	0,000054	0,043	0,043	2,103	3,421

4.4 Power potential using the scaled up reactor

A reactor operating continuously on municipal primary effluent has a power density of 10 Wm^{-3}. Considering Firle waste water treatment plant:

The power potential of Firle plant treating 90×10^{6}L a day continuously is approximately:

Power potential of plant, $P = 10 \times 90000$

$$P = 900000\ \text{W}$$

P = 900 kW

4.5 Microbial Fuel Cell stacks

The total number of microbial fuel cells possible

$$n = \frac{V_{tot}}{V_{single\ reactor}}$$

Thus for Firle plant, $n = \frac{90000000}{20}$

$$n = 4500000$$

When a connection of a large number of Microbial Fuel Cells is intended, three main scenarios are conceivable: serial or parallel association, or a combination of both. While parallel connection adds currents serial connection adds voltages. To increase the total power output the Microbial Fuel Cell stacks are connected both in series and in parallel. (Asensio.Y) concluded that connecting in series does not show any relevant influence on the performance of the microbial fuel cell (except for an increase in the Open Circuit Voltage) but connecting in parallel allows the bio electrochemical device to produce higher amounts of electricity than the single system, and they also allow the device to get a higher removal of Chemical Oxygen Demand. To achieve more voltage output and at the same time effective waste treatment by removal Chemical Oxygen Demand, the microbial fuel cells are connected in stacks of 3600 parallel connected reactors which are then connected in series making ,5400 serially connected.

4.6 Effect of stacking

Voltage reversal is a common occurrence in stacked Microbial Fuel Cell systems. Voltage reversal may be controlled and prevented using various electrical circuit configurations like incorporating diodes and ensuring that all the connected Microbial Fuel Cells are in good working condition.

4.7 External circuit design

A capacitor-based circuit is used to harvest the electrical energy from the Microbial Fuel Cell system. The circuit was made up of capacitors and relays controlled by a programmable microcontroller. The Microbial Fuel Cells charge the capacitors, when charged the capacitors are connected to power the pump, aerator, electric motors used in the waste treatment plant.

5 Conclusions and Future Research

This current work assumes that alcohol, chemical, disinfectant, bleaches or cleaners in the wastewater stream do not adversely affect the electricity producing bacteria found in the waste water, rather this work anticipates that the waste water contains many electricity producing bacteria. From this work it has been shown that it is feasible to adopt Microbial Fuel Cell system at an industrial scale but the technology still has several limitations, assumptions and challenges that must be addressed before broad adaptation is possible. One critical problem hindering the large scale application of Microbial Fuel Cell system is its high capital cost, which mainly arises from the expensive construction materials. Reducing the capital cost can be achieved by using highly efficient, scalable and less-expensive anode, cathode and reactor materials. Carbonaceous materials are more favourable because they are cheaper, they have a big surface area that maintains a large ratio of electrode surface against reactor volume and is compatible with the exoelectrogens bacterial growth in the anode making a good cost-effective option. Managing power output is another critical issue in the scaling up of Microbial Fuel Cells as to date there is no way to efficiently harvest the electrical energy produced in the microbial fuel cell. Electrodes that contain current collectors can be considered for effective current collection. It is difficult for an MFC to directly support a practical load, even at the maximum power generating point, due to the low voltage and current level. Thus, a power management system is needed to be incorporated into MFCs to make the energy feasible for powering electrical devices.

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