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Investigation of the Potentials of Microbial Fuel Cell for Power Generation and Wastewater Treatment

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Abstract

Wastewater treatment is an essential infrastructure for especially larger cities to improve water quality in water bodies. Many developments are going on to improve the quality of wastewater treatment, but, unfortunately, the more advanced the treatment usually, the more energy required to produce better effluent quality. While the power source such as fossil fuel is very limited and could deplete in near future, alternative source of energy is needed to be developed. Municipal waste water Treatment Plant (WWTP) commonly uses1 to 4% of city electricity that is one of the largest municipalities' energy consumers. The method to recover energy in WWTP using Microbial Fuel Cell (MFC) are reviewed and estimated. This report calculated and analyzed that the percentage contribution of MFCs to the energy considered in the case study is less than 1% of the total electricity by other means. In terms of MWh/year basis, MFC-WWTP could provide total energy of 3,061.72 MWh/year representing 0.23% in Nigeria. Microbial Fuel Cells (MFCs) technology that could have big potential in recovering energy in wastewater, but MFC technology is still marred with challenges that range from insignificant power generation contribution.

Keywords: *Microbial, Fuel cell, Wastewater and power generation*

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Background to the Study

As we are all aware, we don't have as much clean water as we want. The same thing applies to energy. Presently more than One billion people around the world do not have access constant power supply according to Aelteman et al (2006), where countries with sparse population densities have more access to electricity. Likewise, nearly One billion people do not have access to clean water. In both, there is significant overlap between areas of the world where both these necessities are scarce. While development efforts are underway, the methods used to harness these are under much scrutiny due to their potential environment impact.

Despite clean water shortages, the increase in population in developing the world has resulted in so much wastewater from our houses and manufacturing activities than it should be. And we typically don't want this waste incorporating into our food supply system, and hence we need to take care of it and adequately manage its disposal. One of the most widely used methods of treating wastewater is the activated sludge. This technique has many drawbacks among which are, aeration that account for up to 45-75% of wastewater treatment plant (WWTP) energy costs. And high sludge generation that is around 60% of the total operation cost Huggins, et al, (2013). Conventional activated sludge-based treatment plants employ aerobic heterotrophic bacteria to degrade organic matters. Such types of microbes have high metabolic kinetics, so they can metabolize substrates faster than anaerobic bacteria, but they also require an ample supply of oxygen and generate considerable amount biomass.

Therefore, Conventional wastewater treatment is both an energy-intensive and expensive process. Between 3–5% of the total electrical load in developed countries is geared to sustaining the process (Kalago Y., 2008). Given that wastewater contains energy in the form of the organic matter then why don't we recover the energy instead of putting energy into the treatment process? A fantastic idea from the point of view that the proposed method does not require energy. Instead, it even produces a little bit of energy. One such promising technology is the Microbial fuel cell (MFC). Power generation using microbial cultures was first reported early in the last century (Potter, 1911). Although MFCs generate a less amount of Energy than conventional fuel cells, a combination of both electricity generation and wastewater treatment could reduce the cost of treating primary effluent wastewater.

The energy content in wastewater is about 2-4 times the energy required for its treatment. Therefore, it is feasible to make wastewater treatment self-sufficient if new techniques can recover the energy while at the same time achieving treatment objectives Zhang, et al (2012). The idea behind MFC technology in wastewater treatment is not only about retrieving electrical energy but also cleansing of waste. Other applications reported seem even more interesting such as powering remote sensors, Picioreanu, (2010). Apart from its practical use in domestic wastewater treatment plants, MFCs have various other uses e.g. in breweries, desalination plants.Others are hydrogen production, remote sensing, and pollution remediation, and also as a remote power source.The widespread use of MFCs in these areas can take our waste products and transform them into energy.

Problem Statement

The inadequacy of clean water coupled with environmental concern has ignited the quest to develop new processes and techniques that would allow reuse of wastewater and at the same time obtain value added products.A microbial fuel cell is considered to be such a substitute and a readily available alternative to treating of wastewater combined with electricity generation; Durruty et al (2012). Industries that produce wastewaters high in readily degradable organic carbon are suitable candidates for this application. Examples of such industries include the food industry, breweries, dairies, the bio- products industry, and the biofuels industry, such as bio- refineries. Another significant source of waste water is the daily domestic chaos from our houses.

Objective of Study

The study is intended to evaluate the feasibility and viability of using MFC in generation of renewable energy. This can be achieved through the following;

1. To investigate the feasibility of using MFC for treating waste water and at the same time generating electricity at the same time.
2. To determine the of power-output of MFC systems in wastewater treatment based on the wastewater generated at a particular plant.

Microbial Fuel Cell

Microbial Fuel Cell is a kind bio-electrical battery that use the natural metabolism of microbes in converting organic matter to produce electricity (Allen, (1993); Samrot et al., (2010). These come as a result of the discovery of certain bacteria that lives in soil that swims up to solids metals such as iron and transfer electrons to the metal. This mechanism is similar to aerobic bacteria that move oxygen molecules during respiration. The electron transfer generates electricity and where there is electricity there is power. The bio-electric chemical cell is often employed to harvest the power.Figure 2.1 illustrates how an MFC system works. The bacteria on the MFC anode decompose organic substrate in wastewater, liberating electrons that flow to the cathode through an external circuit and generate electricity. At the cathode, electrons, protons and oxygen from water '(Del Campo, et al (2014). The reactions occurring at the anode and cathode are the following:

Anode: $C_6H_{12}O_6 + 6H_2O \rightarrow 6CO_2 + 24H^+ + 24e^-$

Cathode: $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$

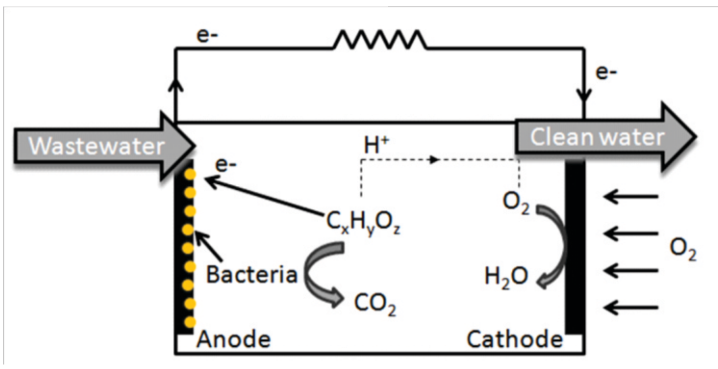

Figure 2.1 Schematic of a Microbial Fuel Cell. Retrieved from "Microbial fuel cell: technology for harvesting energy from biomass," byV. Kiran and B. Gaur, 2013, Reviews in Chemical Engineering, *29*(4), p. 189-203.(Kiran & Gaur, 2013)

Figure 2.1 depicts the basic design of a two-chamber Microbial fuel cell that is mostly used in the laboratory. For electricity generation to occur, bacteria are permitted to feed on organic substrates in the Anode chamber thereby oxidizing it through its natural metabolism to liberate electrons. The Bacteria attach themselves to the anode of the battery, forming a living matrix of protein and sugar known as a biofilm and transfer their electrons to the metal. These electrons then flow to the cathode side, generating useable electricity in the process. As part of their metabolic pathway, the bacteria consumed organic matter as food and need to surrender excess electrons at the end of the process. Other configurations of the device produce hydrogen at the cathode.

The oxidation produces electrons and protons; this half-reaction releases a certain amount of energy, and the electrons are conducted over the wire while the protons move through the membrane to the Cathode to uphold electron neutrality. The electrons being transferred to the Cathode chamber reacts to form water with the protons. This half reaction also releases a certain amount of energy. The theoretical maximum energy gain is determined by combining both half-reactions. However, resistance found in multiple layers of the fuel cell, includes ohm losses present in the electrical wire and the proton transfer from the anode to the cathode. Concentration losses occur when the rate of mass transfers in either the anode or cathode compartments limit the rate of product formation. Others include bacterial metabolic losses. The cycle continues limited only by the availability of nutrients in the feed and oxygen within the air.

Overview of Wastewater Treatment

Wastewater treatment is a process to remove pollutants in the wastewater that comes from human activities, so it can be safely disposed ofin awater body. The level of treatment required determines the type wastewater treatment process. Alsoto achieve ascertain degree of effluent quality proper selection of the process is required. Typical wastewater treatment process could be seen in Figure2;

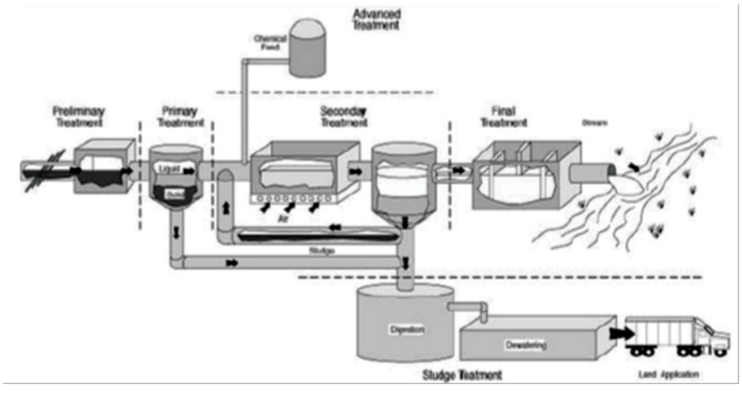

Figure 2. Wastewater Treatment Flow Diagram Reprinted from “Wastewater Treatment Principles and Regulations”, by Hayes, W. Retrieved from; http://ohioline.osu.edu/aexState. Reprinted with permission.(Hayes, 2012)

From the Figure 2 above, WWTP consists of several stages to treat wastewater to clean water are as follows;

a. Preliminary treatment; screening process to remove significant objects (plastic, debris, garbage, etc.) this process is to protect mechanical equipment from such objects that could cause damage.
b. Primary treatment; sedimentation process to settle some suspended solids particle that could be easily removed by gravity.
c. Secondary treatment process in WWTP; use biological process to remove most of the organic matter in wastewater
d. Final treatment; disinfection process or further process to improve the effluent quality so it could be used as recycle or reused water.
e. Sludge treatment; settled solids from primary treatment and secondary treatment contains a considerable amount of organic matter and pathogens which need to be removed before disposal.

Sludgetreatment process is mainly thickening process,stabilization process (digestion) anddewatering process (toremove thewater content and produce dried sludge). Wastewater treatment adopted anaerobic biological process for the secondary treatment. The aerobic biological process utilizes microorganisms by using oxygen to degrade all organic matter in the wastewater, but this process could take days in the natural environment due to the limited oxygen supply in the environment. In the wastewater treatment plant, this biological process is accelerated and controlled by supplying oxygen from the atmosphere using aeration system. This ventilation system is the primary consumer of electricity in WWTP: it needs to be operated 24 hours continuously, and the system will depend on the wastewater flow rate coming into WWTP.

Energy Content of Wastewater

The energy content of wastewater is in four dominant kinds: Kinetic, Thermal, Chemical, and Potential energy. Described briefly below;

a. Thermal Energy

Thermal energy is the heat energy contained in the wastewater and is governed by the specific heat capacity of water. And this is approximately 4.2 KJ/kg/K or 4.2 MJ/m3 per °C of temperature change.

b. Hydraulic (Kinetic and Potential) Energy

Potential energy is the energy due to the water elevation and is calculated by the mass x acceleration due to gravity x head = 9.8 kJ/m^3Per m of the head for the water. Kinetic energy, or the energy due to the momentum of the water, is calculated as 1/2mv2 = 0.18 kJ/m3 for a water velocity of 0.6 m/s (2 feet per second). Most of the WWTP is located on the low elevation and very close to the river body. Thus, the hydraulic head will not be so significant and will provide a small amount of energy.

c. Chemical (Calorific) Energy

This is the energy content stored in the various organic chemicals in the wastewater. The organic strength is typically expressed as a chemical oxygen demand (COD) in mg/L. As shown on Table 1 below, chemical energy content is around 12 - 15 MJ/kg COD (13 MJ/kg COD typical). Electricity required to treat wastewater is around 1000 to 3000 kWh/Mgal per day. Standard COD concentration in wastewater is 430 mg/L, therefore if 1 Mgal

(3,785 m^3) of wastewater is treated per day. Thechemical potential energy that could be recovered is 21,158.15 MJ (5,882 kWh).This means that the energy required to treat wastewater is much less than potential energy could be recovered.

Table 1 Typical Constituent Concentrations and Energy Content of Untreated Domestic Wastewater

Constituent	Unit	Value (typical)[a)]
Constituent concentrations		
Total Solids (TS)	mg/L	390 - 1230 (720)
Dissolved Solids (TDS)	mg/L	270 - 860 (500)
Total Suspended Solids (TSS)	mg/L	120 - 400 (210)
Biochemical Oxygen Demand (BOD) 5-d, 20°C	mg/L	110 - 350 (190)
Total Organic Carbon (TOC)	mg/L	80 - 260 (140)
Chemical Oxygen Demand (COD)	mg/L	250 - 800 (430)
Oil and Grease	mg/L	30 - 90 (60)
Energy Content[b)]		

Source: (Metcalf, 2003)

Plant Energy Requirement

WWTP consumed energy in the form of electricity for the treatment processes. The power is used to operate pumps and other mechanical equipment. For example, to treat one Mgal of wastewater the energy requirement depending on the kind of treatment used could range from about 1,800 kWh/Mgal and above –EPRI, (2005). The energy employed in the biological treatment and disinfection process such as UV system could also be huge. One of the activated sludge process to treat 11.5 MGD would require average total plant operation of 1,690kWh/Mgal. This means that the total energy required is 19,435 kWh/day or 7,093 MWh/year.

Wastewater Energy Recovery

Currently, there were many research and development going on to recover energy in wastewater treatment. It was found out that the possibility of energy recovery is indeed quite high, and WWTP could become net energy producer and help to supply power for cities in the future. Even though the potential is reasonably high, the conventional technology still cannot sufficiently recover the energy in wastewater with high efficiency. And the cost to install the energy recovery system was still quite high. One of the promising technologies to recover energy from wastewater other than the traditional energy recovery systems is the microbial fuel cells. Besides energy recovery, societies demand increasingly intensive treatment to remove organic and inorganic pollutants from the wastewater produced by our households and industrial activities before it is discharge or reuse. Some wastewater sources such as sanitary wastes, food processing wastewater, and swine wastewater are exceptionally rich in organic matter that itself feed a broad range of microbes used in Microbial Fuel Cells. Such sources of substrates have massive content of growth promoters that can enhance the growth of bio-electrochemically active bacteria during wastewater treatment. Microbial Fuel Cells using such substrates have an exceptional ability to remove sulfides and other pollutants as required in wastewater treatment.

MFC Feed Materials
Although, the feed for past prototypes of microbial fuel cells has been a complicated matrix of laboratory chemicals in highly precise dose. In developing nations, however, the feed must be materials that are readily obtainable. As such, the choice of wastewater as the feed material for the microbial fuel cell will bring down the cost of the fuel cell among other things. Wastewater is heterogeneous and will vary in organic content from location to another. Also, the micro-organisms' environment will differ depending on where the MFC system operates and so it may transpire that microbial consortia need to be customised to reflect the conditions they work in and organic components they encounter.

Energy Feasibility Study
Preliminary verification is needed to show the feasibility of the project at the technical level. So far, several experiments were conducted on microbial fuel cells to determine the voltage and power output from the system at laboratory scale. Power density i.e. the amount of power or rate of energy transfer per unit volume, were deduced for the different substrate. But the actual power density of MFCs using real wastewater in lab-scale could be seen in the Table 2 below, this is based on several research. MFC, which is fed from effluent of anaerobic digester, showed the highest result with Power Density at 42 W/m^3 of reactor and showed the highest substrate removal at 2.99 kg COD/m^3/day. The experiment also indicated there is a decline of power after 12 hr and decrease of pH (Aelterman, et al (2006).

Table 2 Power Outputs in lab-scale MFCs during the Treatment of Several Wastewaters using Pt/Cand Hexacyanoferrate (HCF) as a cathode

Substrate	Power Density (W/m^3)*	Substrate removal (kg COD/m^3/day)	CE (%)	Cathode
Domestic wastewater	1.7	0.43 – 0.6	3 – 12	Pt/C
Domestic wastewater	3.7 ± 0.2	-	20	Pt/C
Hospital wastewater	8 ± 5	0.71 ± 0.06	22	HCF
Hospital wastewater	14 ± 1	0.67	13	HCF
Influent from AD	25 ± 2	1.23	20	HCF
Effluent from AD	42 ± 8	2.99	29	HCF

CE: Coulombic Efficiency; AD: Anaerobic Digester; *Expressed as NAC: Netto Anode Compartment. **Source:** (Aelterman, et al (2006)

Determining MFC volume
Assumed:
Quantity of dry volatile solids = 0.15 kg/m^3, Sludge moisture content = approx. 95%, Specific gravity of 1.02

Thus, sludge volume V could be calculated:

$$V = \frac{(0.15\ kg/m^3)(5.80 \times 10^5 m^3/d)}{1.02(10^3\ kg/m^3)(0.05)} = 1{,}703.78\ m^3/\text{d}$$

Retention time of wastewater in MFC tank = 12 hr
Thus, volume of MFC = (1,703.78 m^3/d) (12/24 d) = 851.89 m^3

Electric generation
Based on Table 2; Power density for MFC which is fed by anaerobic digester influent was 42 W/ m^3.
Thus; Electricity generated from MFC = (851.89 m^3) x (42 W/ m^3) = 35.78 kW
Electricity generation per day = 35.78 kW x 24 hr = 0.86 MWh/day

Power Generated by MFC Discussions of Results
Conventionally, the best method to recover energy from WWTP is through anaerobic digestion to recover biogas and biosolids that could potentially satisfy some portion of the energy requirement of the WWTP itself. But there are limitations to this process as anaerobic digestion fails to function at temperatures below 20 degree Celsius.This restriction of the anaerobic digestion method makes Microbial Fuel Cell (MFC) to play acomplimentaryrole in recovering energy from the treatment facility, if incorporated in the process. Microbial Fuel Cell (MFC) works best atlow temperature below 20 degrees Celsius and low concentration thereby complement theanaerobic digestion method in the process.In thestudy presented in this report, the power generation with and without the contribution of MFC cell is presented in Figure 2, the calculated percentage contribution of MFCs to the energy mix of thecountries considered in the case study, is less than 1% to the current power generation potentials of these countries; the contribution is insignificant.This is probably the reason why this viable option is not entirelyembraced by the power generations companies despite being a cleaner source of energy.

Organic Carbon removal by MFC results
Generally effective wastewater treatment using microbial fuel cells (MFCs) will require a better understanding of how operational parameters and solution chemistry affect treatment efficiency, but few studies have examined power generation using actual wastewaters. The efficiency of wastewater treatment can be examined either in terms of maximum power densities, Coulombic efficiencies (CEs), or chemical oxygen demand (COD) removal as a function of temperature and wastewater concentration strength Feng, (2008) However, chemical oxygen demand (COD) test is standard method often employed to measure indirectly the amount of pollution (that cannot be oxidised biologically) in a sample of water. It is a standard wastewater variable that is a measure of the chemical potential energy in the wastewater analyte. To determine the efficiency of the treatment process, an acceptable level of COD indicators has to be established. The chemical oxygen demand (COD) removal is a function of temperature and wastewater concentration strength. Therefore, in this investigation COD removal have been determined based on the strength of the concentration of the wastewater in a particular location. In this investigation since there is going to bevariationsin strength of the concentration of wastewater indices from country to country, the study adopt COD minima and maxima range of between 84 – 2240 mg/l. Because such adaptation is solely based on the established relation of these two concentrate parameters in the refereed

literature. About the source, the author establishes using a typical 6 MFC cell at the concentration above as follows:

1. a) COD removal @ 84 mg/l →84% COD removal
   b) COD removal @ 2,240 mg/l →87% COD removal
2. a) Time required for removal @ 84 mg/l =14 hrs
   b) Time required for removal @ 2,240 mg/l =94 hrs

This report also adopts for the purpose of comparison the relationship for power density estimation by Feng et.al. (2008), as 0.0778 (COD value) + 31.53mv/m^2

The result above illustrate the influences of the two concentrate as defined before. It is evident that as the concentrations increases volumetric changes occurs. This may not be unconnected with the number of population because apparently the higher the population, the higher the COD removal volume, and requires much greater time for removal.

Conclusion

This study shows a rough picture of the amount of energy that MFCs can recover from the domestic wate water generated country wise based on the countries selected. But the result indicates that insignificant amount of energy could be recovered when compared with other established technologies for electricity generation. MFC technology could become one of the potential candidates to produce a large amount of energy, but due to limitation in technology it could not have high efficiency. Therefore, MFC technology cannot serve alone in energy recovery in the WWTP in these contries, but it can be viable means of extracting energy in combination with other established energy recovery technologies in the Waste Water Treatment Industries in general. Moreover, with the rising nonrenewable energy prices, and more strict federal regulations being imposed on the wastewater treatment industry in most countries, the cost of maintaining a WWTP is on the incline. Therefore, it is a good idea to invest more in MFC research and development to increase the power densities and to find more efficient alternative materials to lower the cost of MFC production. And with better materials and cheaper installation cost the future of MFC is still promising.

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