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Bioelectricity production from various wastewaters through microbial fuel cell technology

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Abstract

Microbial fuel cell technology is a new type of renewable and sustainable technology for electricity generation since it recovers energy from renewable materials that can be difficult to dispose of, such as organic wastes and wastewaters. In the present contribution we demonstrated electricity production by beer brewery wastewater, sugar industry wastewater, dairy wastewater, municipal wastewater and paper industry wastewater. Up to 14.92 mA current and 90.23% COD removal was achieved in 10 days of operation.

Keywords: Bioelectricity, COD, Microbial Fuel Cells, wastewater

Introduction

It is evident that humankind is increasingly dependent on energy with the advancement of science and technology. Increased economic growth and social development are leading to a large gap between energy demands and the availability of fossil fuels. Increasing human activities are consuming the natural energy sources leading to depletion of fossil fuels. The present-day energy scenario in India and around the globe is precarious, thus driving to the search of alternative to fossil fuels. Current methods to produce energy are not sustainable, and concerns about climate change and global warming require developing new methods of energy production using renewable and carbon-neutral sources.

In our energy-based society, the value of any energy-rich matters is increasing. Thus, the high organic load in wastewaters is no longer seen as waste, but instead as a valuable energy resource. Finding a way to exploit these biological substrates degradation for the generation of electricity is the driving force for the development of microbial fuel cells (MFCs). Although the concept of electricity production from bacteria was conceived nearly a century ago by Potter (Potter 1910; Potter 1911), only recently the technology has been sufficiently improved to make it useful as a method for energy generation. One near-term application of MFCs will be to produce electricity from wastewater, providing a new way to simultaneously treat wastewater while obtaining a source of clean and renewable energy (Lui et al. 2004; Min and Logan 204; Dental et al. 2004; Tiehm et al. 2001; Ra et al. 2000; Servrin-Reyssac 1998; Van Ginkel et al. 2005; Maekawa et al. 1995).

Microbial fuel cells (MFC) are electrochemical devices that convert the chemical energy contained in organic matter into electricity by means of the catalytic (metabolic) activity of living microorganisms (Mathuriya and Sharma 2009; Allen and Bennetto 1993; Kim et al. 2002; Miriam et al. 2007). An MFC consists of anode and cathode separated by a cation specific membrane. In the anode compartment of an MFC microorganisms oxidize fuel (substrate) generating electrons and protons. Electrons are transferred through an external circuit while the protons diffuse through the solution to the cathode, where electrons combine with protons and oxygen to form water (Jae et al. 2003). Oxygen is superior to other electron acceptors for its unlimited availability and its high redox potential (Zhao et al. 2006).

$$4H^+ + 4e^- + O_2 \rightarrow 2H_2O$$
or
$$4H^+ + 4e^- + 2O_2 \rightarrow 2H_2O_2$$

MFCs have operational and functional advantages over the technologies currently used for generating energy from organic matter. First, the direct conversion of substrate energy to electricity enables high conversion efficiency. Second, MFCs operate efficiently at ambient temperature. Third, an MFC does not require gas treatment because the off-gases of MFCs are enriched in carbon dioxide and normally have no useful energy content. Fourth, MFCs do not need energy input for aeration provided the cathode is passively aerated **(**Lui et al. 2004**)**. Fifth, MFCs have potential for widespread application in locations lacking electrical infrastructures and can also operate with diverse fuels to satisfy our energy requirements.

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Most MFC studies have been demonstrated using pure compounds, such as acetate (Bond and Lovley 2003), glucose (Rabaey et al. 2003), sucrose (He et al. 2006), an amino acid (cysteine; Logan et al. 2005), or a protein (bovine serum albumin; Heilmann and Logan 2006). Waste water sources that have been used in MFC tests include domestic wastewater (Liu et al. 2004), swine wastewater (Min et al. 2005), meat packing wastewater (Heilmann and Logan 2006), food processing wastewater (Kim et al. 2004), hydrogen fermentation reactor effluent (Oh and Logan 2005), Paper Industry wastewater (Mathuriya and Sharma 2009) and corn stover hydrolysates (liquefied corn stover; Zuo et al. 2006). Power densities obtained with these substrates vary with MFC architecture, but they are generally higher with pure compounds than tests with actual wastewaters.

Although MFCs operating on wastewaters generate a lower amount of energy than on pure compounds, a combination of both electricity production and wastewater treatment would reduce the cost of treating primary effluent wastewater.

In the present demonstration, we compared the electricity production capacity of beer brewery waste water, sugar industry waste water, dairy waste water, municipal waste water and paper industry waste water through microbial fuel cell technology.

Materials and Methods

Waste water samples

Beer brewery wastewater was collected from the Central Distilleries and Breweries Ltd. Meerut, India. Sugar industry wastewater was collected from Daurala Sugar Works, Meerut. Dairy Industry wastewater was collected from New Kailash Dairy, Meerut. Municipal wastewater was collected from nearby Municipal waste tank; Meerut and Paper Industry wastewater was collected from Star paper Mills Ltd. Saharanpur, India. Table 1 shows general characteristics of all wastewaters. All wastewater samples were named as:

Beer brewery wastewater: BW
Sugar industry wastewater: SW
Dairy wastewater: DW
Municipal wastewater: MW
Paper industry wastewater: PW

All five wastewater samples were kept in a refrigerator at 4^{o}C before use. The wastewaters were used as the inoculum for all MFC tests without any modifications such as pH adjustments or addition of nutrients, mediator or trace metals. Experiments were conducted using full-strength wastewater, at 35^{o}C and stagnant condition except as indicated.

MFC Construction

The MFCs were constructed from glass (16x16x10 cm) with a total volume of 1000 ml, and working volume of 700 ml. Both anode and cathode were separated by a glass, containing hole (6x6 cm) which was covered with a proton exchange membrane (Nafion ^{TM} 117, DuPont Co. USA). Three electrode arrangements consisting of plain carbon paper (7x7cm) as anode and graphite (7x7 cm) as cathode were used in this study. The electrodes were attached using copper wire with all exposed metal surfaces sealed with a nonconductive epoxy. The anode chamber was filled (600 mL) with various mediums respectively for separate study. The anode was continuously flushed with N_2/CO_2 (80:20) to maintain anaerobic conditions. Cathode chamber (aerobic chamber where oxygen was used as the electron acceptor for the electrode) was filled with 100mM phosphate buffer and pH adjusted to 7 by 0.5 N NaOH. The cathode chamber was provided with air that was passed through a 0.45μm pore size filter.

MFC operation

Initially MFCs were inoculated with artificial wastewater containing glucose as carbon source. The composition of wastewater was (g l^{-1}): 1.0 g glucose, 450.0 mg $NaHCO_3$, 100 mg NH_4Cl, 10.5 mg K_2HPO_4, 6.0 mg KH_2PO_4, 64.3 mg $CaCl_2.2H_2O$, 18.9 mg $MgSO_4.7H_2O$, 10.0 mg $FeSO_4.7H_2O$, 6 mg $MnSO_4$, 0.5 mg $ZnSO_4.7H_2O$, 20 mg $CoCl_2.6H_2O$, 0.65 mg $CuSO_4.5H_2O$. After two cycles, feed solution containing 50% artificial wastewater and 50% different wastewater samples, separately inoculated into MFCs. After four cycles, feed solution was switched to various wastewater samples.

Table 1: Characteristics of different waste waters

S No	Wastewater	pH	BOD (mg/L)	COD (mg/L)	TSS (mg/L)
1	Beer brewery wastewater	6.4	429	1778	405
2	Sugar industry wastewater	6.1	539	1229	287
3	Dairy wastewater	5.5	654	1487	329
4	Municipal wastewater	7.6	234	1235	256
5	Paper industry wastewater	8.3	267	1581	395

Monitoring Electricity and COD

Current (*I*) measurements were recorded using a Digital Multimeter (Kusam electrical industries, India, Model – 108) by connecting with 10Ω external circuit. COD measurements were conducted using standard methods (Greenberg A et al. 1992). All samples were filtered through a 0.22 μm (pore diameter) membrane filter prior to COD measurements. COD removal was calculated as E_{COD}= $[COD_{in}–COD_{out}/COD_{in}]$ x 100%, where COD_{in} is the influent COD and COD_{out} is the effluent COD.

Statistical analyses

All experiments were conducted using 3 separate microbial fuel cells. When a single MFC was used, the experiments were repeated at least 3 times and results were presented as average values or a typical result. We found that the all data presented were statistically significant.

Results and Discussion

Current generation

After setting the experiment, all two chambered Mediator Less MFCs were operated with different wastewater samples at different conditions, as feed to support the formation of biomass and subsequent generation of electricity. The MFCs were continuously monitored during experiment and readings were taken after each 24 hr, inoculation time was considered as time 0. Fuel Cells were operated for 15 days and readings were taken up to 10 days. Preliminary experiments conducted using MFCs showed that electricity could be generated using different wastewaters. Stable current output was achieved after two to three cycles.

When MFCs were inoculated with different wastewater samples, there was about 24 h Lag phase followed by an increase in cell current. The initial increase of current here can be attributed to the presence of components that are easily utilized by mixed microorganisms present in the wastewaters. When these easily degradable substrates were exhausted, the current outputs began to decrease. Meanwhile, degradation of complex components was taken place by which a lower current was still obtained.

Fresh feed was supplemented when a drop in current was observed. A steady increase in current generation was observed with additional feed and might be attributed to the adaptation, phenomenon and development of the biofilm on the surface of the anode. Electrode fouling was not observed and the electrodes could be used in further experiments without remarkable activity loss.

Effect of temperature

To evaluate the effect of temperature on current generation, five MFCs were operated with different wastewater samples. Initially all the samples were operated at 35°C, after 5 days temperature was increased up to 45°C. Figure 1 show the current generation by all wastewater samples at both temperatures.

Experimental data indicate that performances of MFCs were slightly decreased with increase of temperature from 35 to 45°C. All wastewater samples started fermentation and current generation after about 24 hrs. SW (Sugar industry wastewater) showed best result at both the temperatures, this sample started current generation after 24 hrs. and reached its maximum value of 11.39 mA after 5th day of operation. As the temperature increased to 45°C, a major current fall observed which continued in the sample. Similarly, BW (Beer brewery wastewater) started current generation after 24 hrs and reached its maximum value of 10.92 mA after 5 days. This sample also showed decreased current at 45°C, yet current recovered after 7 days and maintained up to 8th day. Same pattern was followed by DW (Dairy wastewater), MW (Municipal wastewater) and PW (Paper Industry wastewater) these samples generated 8.39 mA, 9.01 mA and 7.82 mA current after 5 days of operation at 35°C. These results were not unexpected as the ambient temperature for most of the microorganisms is 30-35°C. Higher temperature might resulted in less cell multiplication and growth so less availability of catalysts leading to electron release by oxidation of wastewater and ultimately less current generation.

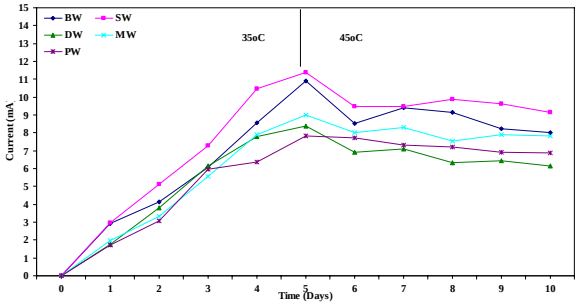

Figure 1: Current Generation by all wastewaters at different temperatures

Effect of agitation

All MFCs were operated with different wastewater samples initially for 5 days at stagnant condition and later at agitated conditions to check their electricity generation capacity. Experimental data (Figure 2) showed an increase in current generation by all wastewaters when a stagnant solution is agitated. All samples started fermentation and current generation after 24 hrs. The best results were showed by SW, which generated 14.92 mA current on 9th day of operation. BW, DW, MW and PW scored 14.33 mA, 10.89 mA, 12.23 mA and 10.48 mA after 9 days of operation. As current generation is diffusion limited since it is a function of the proximity of the microbes to the electrodes and ultimately controlled by the diffusion of electrons to the electrodes. Even under stagnant conditions, some self mixing occurs due to CO_2 evolution by microbes. Agitation or stirring of the solution eliminates this diffusion-limited condition.

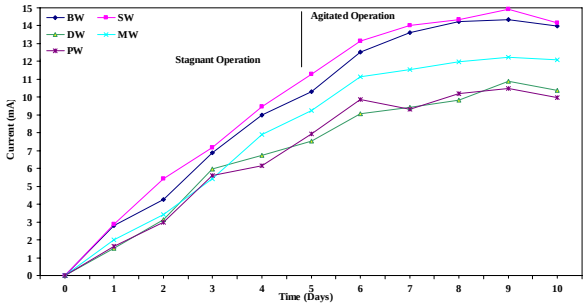

Figure 2: Current Generation by all wastewaters at stagnant and agitated condition

Effect of wastewater concentration

To evaluate the effect of wastewater concentration on electricity production, all MFCs were operated with different wastewater samples. Initially full strength wastewater was used in the anodic chamber, after 5 days 50% part of wastewater was replaced by Ultra pure water. The effect of wastewater concentrations on current response is shown in Figure 3. Experimental data indicated that, current generation was decreased with decrease of waste water concentration from 100% to 50%. Current fall was not observed in DW, it might be due to presence of some bacteria, which faced substrate inhibition at higher waste water concentration. BW, SW, DW, MW and PW achieved maximum 10.29 mA, 11.37 mA, 7.49 mA, 8.98 mA and 7.83 mA current in full strength waste water while 9.76 mA, 9.48 mA, 8.96 mA, 8.56 mA and 7.39 mA respectively in 50% waste water. This variation in current generation may be due to availability of less oxidizable substrates in 50% wastewater samples.

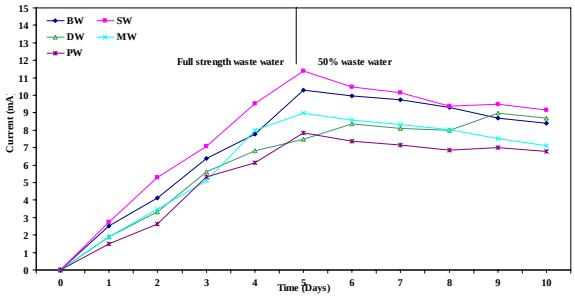

Figure 3: Current Generation by all wastewaters at different waste concentration

COD removal efficiency

During operation, all MFCs were continuously monitored for waste (as COD) removal to enumerate the potential of fuel cell to act as

wastewater treatment unit. All wastewater samples showed their potential for COD removal indicating the function of microbes, present in wastewaters in metabolizing the carbon source as electron donors**.** It is evident from experimental data that current generation and COD removal showed relative compatibility. Continuous COD removal was observed in all MFCs.

Effect of temperature

To observe the effect of temperature on COD removal, all five MFCs were operated with different wastewater samples. Initially all the samples were operated at 35°C, after 5 days temperature was increased up to 45°C. Figure 4 shows the COD removal efficiency of all wastewater samples at both temperatures. BW, SW, DW, MW, PW achieved 51.17%, 53.79%, 53.54%, 51.32% and 48.34% COD removal at 35°C after 5 days of operation. While these samples scored 73.34%, 78.71%, 72.54%, 71.38% and 67.31% COD removal at 45°C after 10th day. These data clearly indicating that COD removal rate was less at 45°C. This may be due to less metabolic activities of microorganisms at relatively higher temperatures.

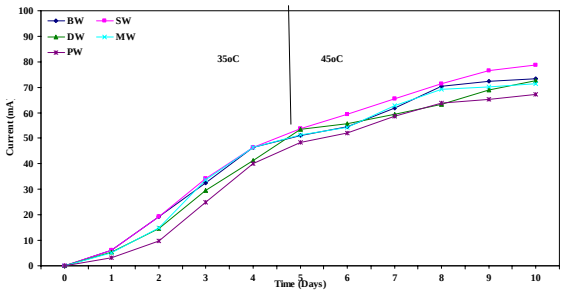

Figure 4: COD removal of all wastewater samples at different temperatures

Effect of agitation

Figure 5 shows the COD removal efficiency of all wastewater samples at stagnant and agitated conditions. Different wastewater samples operated initially for 5 days at stagnant condition and later at agitated conditions. All samples showed increased COD removal efficiency in agitated conditions. BW, SW, DW, MW, PW achieved 49.58%, 54.23%, 50.39%, 48.35% and 41.11% COD removal in stagnant conditions after 5 days of operation. While these samples scored 86.73%, 90.23%, 81.29%, 84.72% and 76.32% COD removal in agitated conditions after 10th day. Data sowed that time taken for carbon exhaustion was relatively less in the agitated conditions. This may be due to more diffusion and mixing of substrate and microorganisms which ultimately helped in COD removal efficiency enhancement of the MFCs.

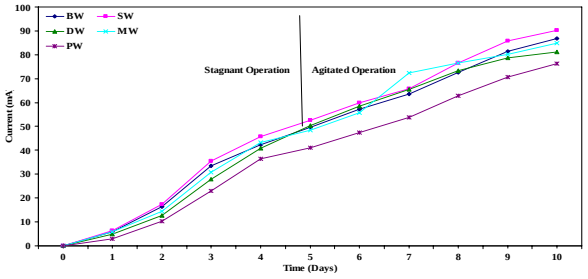

Figure 5: COD removal of all wastewater samples at stagnant and agitated conditions

Effect of waste water concentration

To observe the effect of wastewater concentration on COD removal, all five MFCs were operated with different waste water samples initially in full wastewater strength (first 5 days) and then 50% part of wastewater was replaced by Ultra pure water. Comparatively decreased COD removal efficiency was observed when wastewater concentration was decreased from 100% to 50% (Figure 6). BW, SW, DW, MW, PW obtained 50.41%, 54.83%, 59.16%, 55.78% and 49.43% COD removal in full strength waste water, after 5 days of operation. While these samples scored 73.42%, 80.96%, 73.14%, 72.46% and 70.42% COD removal in 50% wastewater after 10th day. This relatively slow COD removal was possibly due to less availability of biodegradable substrate in 50% waste water samples than that of full strength wastewater leading to competitive inhibition in microorganisms.

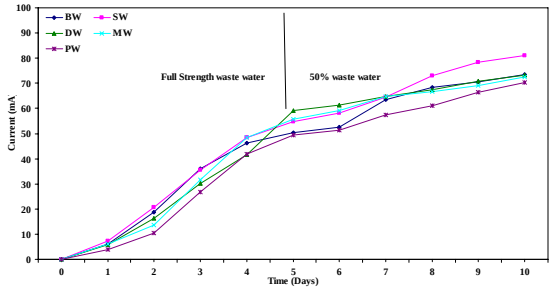

Figure 6: COD removal of all wastewater samples at different wastewater concentrations

The above results indicating the best performance of sugar industry wastewater, which may be due to the availability of waste sugar in the wastewater, which is readily oxidizable and can generate good current in less time. As the insolubility and chemical stability of cellulose limits the rate of microbial substrate decomposition and thus the current output that can be achieved, so Paper Industry wastewater was showed poorest results, which may also be due to presence of cellulose in the wastewater sample.

Conclusion

Under present investigation, electricity was successfully generated with waste (as COD) removal from all different wastewaters using Microbial Fuel Cell technology, and the microorganisms responsible for electricity generation and COD removal were already present in the wastewater. The microbial electricity technology is still in an early stage of development, but shows great promise as a new method to accomplish both wastewater treatment and electricity generation. Major issues to be solved for practical application are to overcome the activity loss, cost factor and incomplete utilization of wastewater. If power generation in these systems can be increased, MFC technology may provide a new method to offset wastewater treatment plant operating cost, making wastewater treatment more affordable for developing and developed nations. Thus, the combination of wastewater treatment along with electricity production may help in saving money as a cost of wastewater treatment at present.

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