Improving fermentation industry sludge treatment as well as energy production with constructed dual chamber microbial fuel cell

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Abstract

Microbial fuel cells offer a breakthrough for treatment of waste content coupled with energy generation. However, their applications are mostly limited to laboratories. Present research is focused on conducting the biological conversion of sludge originated from fermentation industry using microbial fuel cell (MFC). The efficiency of MFC was studied at different operating and nutritional conditions including pH, aeration rate and substrate concentration with biocatalyst *Saccharomyces cerevisiae*. The optimized conditions in terms of yielding maximum power density of 610 ± 30 mW/m² were reported at substrate concentration of 60% at 160 ml/min aeration rate and pH of 6, corresponding to a current density of 994 ± 41 mA/m². Results suggested that utilization of fermented sludge in MFC could give direction to handle the problem of fermentation industries and also to overcome a small fraction of energy crisis.

Keywords Fermented industry sludge · Treatment of sludge · Sustainable electricity · Microbial fuel cell

Abbreviations

BOD Biological oxygen demand
COD Chemical oxygen demand
TSS Total suspended solids
VSS Volatile suspended solids

1 Introduction

Due to continuous destruction of fossil fuels as well as uneconomical aspects of other non-renewable energy resources, world is heading towards the energy catastrophe [4–7, 12]. However, fossil fuels' consumption causes pollution which contributes in increasing global warming. Construction of a realistic globe requires the limited

usage of such sources, ultimately to reduce the quantity of pollutants produced. Therefore, there is need to use an alternative energy source which can be regarded as economical, reusable and clean [8, 17, 18]. Microbial fuel cell (MFC) used to decompose organic waste and to generate energy simultaneously, presents the solution of above two problems [18–20, 32]. Potter observed the possibility of using bacteria for production of electrical energy in 1911 [33]. However, adequate study was not conducted to advance this technology during 1911–1967. But in 1967, John Davis patented the first MFC technology, while a formal research in this area was begun later 1990's [1, 3, 11, 21]. Most of the patents were issued in 2000's. The MFC that handles the real fermentation, sludge can produce a power density of about 1884 mW/m² equivalent to about

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51.5% of the power density obtained from MFC (3664 mW/m²) using the same organic loading rate (OLR) of 1.92 g of acetate/L d. With gradual increase of OLR, the power density increased to 2981 mW/m², OLR was 3.84 g/L d [26]. Microbial fuel cells (MFCs) are basically a dual-chamber system consisting of anode and cathode chamber separated by a polymeric proton exchange membrane (PEM). In most MFCs, aqueous cathodes are used, where water is bubbled with air to provide dissolved oxygen to electrode. To increase energy output and reduce the cost of MFCs, we examined power generation in an air–cathode MFC containing carbon electrodes in the presence and absence of a polymeric proton exchange membrane. Power yield was enhanced as glucose concentration was increased according to saturation-type kinetics, with a half saturation constant of 79 mg/L with the PEM-MFC and 103 mg/L in the MFC without a PEM (1000 Ω resistor). Similar observations were reported for the influence of the PEM on power density using wastewater, where 28 ± 3 mW/m² (0.7 ± 0.1 mW/L) (28% Columbic efficiency) was produced with the PEM, and 146 ± 8 mW/m² (3.7 ± 0.2 mW/L) (20% Columbic efficiency) was produced when the PEM was removed [21]. Preliminary tests using a two-chambered MFC with an aqueous cathode indicated that electricity could be generated from swine sludge containing 8320 ± 190 mg/L of soluble chemical oxygen demand (SCOD) (maximum power density of 45 mW/m²). Using a single-chambered air cathode MFC, maximum power density of 261 mW/m² (200 Ω resistor) was yielded from the animal sludge and it was reported to be 79% higher than a previous report involving domestic sludge (146 ± 8 mW/m²) due to the higher concentration of organic matter in the swine sludge [25]. A new highly scalable MFC design, comprising of a series of cassette electrodes (CE), was studied to improve the power generation from organic matter in wastewater. Power production was stable during this period, reaching maximum power densities of 129 W/m² (anode volume) and 899 mW/m² (anode projected area) [31]. Single chamber air–cathode microbial fuel cells (MFCs) are used to ferment the primary fermented sludge. The maximum power density is 0.32 ± 0.01 W/m², and only the primary effluent has a power density of 0.24 ± 0.03 W/m². These results indicate that when fermented, the sludge can be effectively used for power generation and then diluted only with the primary effluent [34].

Industrial or domestic sludge are generally regarded as conductive substrates in the phenomenon of bioconversion in a bioreactor, whereby, highly concentrated organic (Sewage Sludge) contain higher chemical energy per unit volume as compared to that of present in the sludge. Therefore, sewage sludge being enriched with organic content is deemed as a suitable fuel for MFC operation in terms of electricity generation. In addition, domestic or

municipal sludge which contains a multitude of organic compounds could be used as substrate. Adequate level of study is required for reporting the effects of various key parameters including aeration rate, substrate concentration, temperature and pH on performance MFC for voltage output [9, 24, 29, 30, 37]. This study is aimed to achieve the objectives of both the reduction in waste content of Fermentation industries as well as energy generation by using a rectangular dual chamber MFC. The efficiency of MFC is investigated by utilizing different substrate (sludge from fermentation) concentrations coupled with variation in above mentioned parameters.

2 Materials and methods

2.1 Substrate

Substrate utilized in current study is sludge from fermenter, which decanted every hour about 1.5 ± 0.2 l. Sludge from fermenter was collected from a fermentation industry located in district Mirpurkhas Sindh Pakistan. Different concentrations of substrate were used with water addition, which were 30%, 60% and 90% utilized to acquire the best possible results. The pH was varied in the range of 6–9 with step size 1, aeration rate was regulated between 130 and 220 mL/min with step size 30 mL/min, and operating temperature is room temperature. Characteristics of fermented sludge are listed in Table 1.

2.2 Growth medium

Baker's yeast, *Saccharomyces cerevisiae*, has been utilized as a biocatalyst for use in Microbial Fuel Cell because it has many attractive features, i.e., nonpathogenic, inexpensive, easy mass cultivation, and can be maintained for a long time in the dried state. However, there is a little information about the catalytic activity and electron transfer without an exogenous mediator for the *Saccharomyces cerevisiae* yeast cells. Yeast *Saccharomyces cerevisiae* [2, 14, 15] was procured from the market in lyophilized form

Table 1 Sludge from fermenters characteristics

Characteristics	Value
pH	4.5
COD (g/l)	15.5
VSS (g/l)	15.3
TSS (g/l)	16.5
Conductivity ms/cm	4.7
Acetate (g/l)	3.6
Propionate (g/l)	5.5
Butyrate (g/l)	1

(saf-instant dry yeast) and used as biocatalyst to inoculate into the anode chamber of Microbial Fuel Cell for electricity generation from sludge. *Saccharomyces cerevisiae* were grown on growth medium [15] described in Table 2. The medium was sterilizing by autoclaving at 120 °C and 16 psig for 22 min. About 100 ml of inoculums was prepared with different ingredients with the use of shake flask for initially cell growth with incubation temperature is 35 °C. After 24 h of incubation inoculums was inserted in anode chamber and About 4.5 g/l of cell growth achieved after 24 h. The medium pH was initially adjusted to 6 and the inoculums were introduced into the media at ambient temperature.

2.3 Construction and working principle of MFC

The glass (Pyrex) material was used for the fabrication of laboratory scale MFC. The volume of each chamber (anode and cathode chambers) was 1000 ml with a working

volume of 850 ml. The sample port was provided for the anode chamber, wire point input, and inlet port. The anode and cathode electrode each with surface area of 0.0024 m² were used. Two different conditions were maintained such as aerobic in cathode and anaerobic in anode chamber. Figure 1 depicts the typical schematic diagram of microbial fuel cell, in which carbon electrodes made of carbon material were used, these were connected with external resistor of 250 ohm. A Salt bridge was provided to facilitate the proton transfer from anode chamber to cathode chamber. Salt bridge work as membrane for proton exchange. Aerobic condition maintained by air addition through Air pump equipped with controlled flow meter was used for aeration at desirable rate where as anaerobic condition maintained through 80% circulation of N₂. The mechanism of conversion and reaction at anode and cathode chamber is also highlighted in figure. Anode chamber was inoculated with *Saccharomyces cerevisiae* at different operating conditions of pH, aeration rate, and concentration of substrate to maximize energy generation from sludge. Cell growth was observed after 24 h about cell density of 4.5 g/l later than beginning of MFC operation.

Table 2 Growth medium for *Saccharomyces cervisiae*

Ingredients	%(w/v)
Ammonium sulfate	0.055
Potassium di hydrogen phosphate	0.055
Magnesium sulfate	0.055
Yeast extract	0.6
Glucose	2.2
pH	6

2.4 Measurement of electrical parameters

A digital multimeter fixed to a line connecting both electrodes either in closed or open configuration of circuit, was used to measure the electrical power (2700, Keithley, USA) [28]. Timer was used to record the corresponding voltage and power current across the resistor terminals to estimate

Fig. 1 Schematic representation of microbial fuel cell

the electrical output. For the time averaged results, readings were recorded three times at every 2 h, up till 30 h. All experiments were carried out at room temperature. Both the current density and power density were calculated through the equations:

$$\text{Power Density} = \frac{VI}{A} \quad (1)$$

$$\text{Current Density} = \frac{I}{A} \quad (2)$$

where I (mA) is the current, V (mV) is the voltage and A (m^2) is the projected surface area of the anode (25 cm^2) [9].

3 Results and discussion

All experiments were carried out with the variation in each parameter repeatedly three times shown in Table 3. Electricity generation by treating waste water in MFC has many environmental advantages over conventional treatment technologies. MFC technology is the most appropriate method regarding waste water treatment and simultaneously generation of electricity. Detailed operational and nutritional parametric effect on the performance of MFC is given in this section. Figure 2 shows the voltage generation from microbial fuel cell with different time using fermented sludge as substrate. Maximum voltage 735 mV was obtained at about 20th hour. The decline trend indicates that reduction in organic content from anode chamber via reduction multiple electron generation. Potassium ferrioxalate 50 mM was used as an electron acceptor in all experiments.

3.1 Effect of air rate on cathode performance

The current generation is dominated by the efficiency of cathode. The Cathode performance can be optimized by allowing passive airflow. Air flow rate has significant effect on performance of microbial fuel cell as discussed by Mateo et al. [23]. When there is increase or decrease in air flow rate there will be effect on current density. It

Fig. 2 Timely variation in the voltage

must be about 10% mole fraction of oxygen supplement needed for cathode chamber as described by Mateo et al. [23]. Thus, in relation to power generation, the effect of increasing the air flow rate of the cathode ranging from 130 to 190 mL/min with step size of 30 mL/min was investigated. As shown in Fig. 3, the trend of increasing in voltage generation was due to increase in aeration rate up to 160 mL, but further increase in aeration rate disturbed the anaerobic condition of anode chamber, thus the voltage generation was decreased. The maximum voltage found at 160 mL/min about 745 mV, because that maintained the condition of cathode chamber which got the electron from external circuit and proton from the membrane. While 190 mL/min gave the minimum amount of voltage about 430 mV. This indicates that at higher air flow rates, the power generation of MFC is greatly reduced by the proportion of higher oxygen that diffuses into the air near the anode, which may disrupt the anaerobic microorganisms living on the anode surface.

3.2 Anodic pH impact on MFC performance

In MFC, the anodic reaction produces a proton that flows towards the cathode chamber and reacts with

Table 3 Detailed analysis of different experiments

	Aeration rate (ml/min)			pH			Substrate (w/v)		
	130	160	190	6	7	8	30	60	90
Current (mA)	0.81	0.88	0.95	0.82	0.84	0.86	0.79	0.83	0.81
Voltage (volts)	0.78	0.96	0.94	0.78	0.81	0.84	0.74	0.77	0.75
Power (mW)	0.63	0.86	0.85	0.65	0.65	0.765	0.58	0.6391	0.5431
Power density (mW/m^2)	514	610	625	610	585	602	487	609	512
Current density (mA/m^2)	683	949	779	692	715	746	748	994	634

Fig. 3 Voltage generation at different aeration rate

Fig. 4 Effect of pH on voltage generation

oxygen (or other reducing compound) to produces water. On the other hand, since the proton is continuously consumed by the oxygen, reduction reaction and the proton substitution due to the cationic oxidation reaction is lacking, alkalization is observed on the cathode side. Such phenomenon leads to a membrane pH concentration gradient that produces electrochemical/thermodynamic limitations of overall performance. Increased pH in the cathode chamber can immensely reduce the current generation because the potential of the oxygen reduction reaction increases with decreasing pH. In addition, the bacteria usually require a pH close to neutral to achieve their optimal growth, and the bacteria responds to changes in internal and external pH by adjusting their activity. Depending on the bacteria and growth conditions, variation in pH can causes to change several major physiological parameters such as ion concentration, membrane potential, proton motility and biofilm formation [16, 27].

pH is a major factor affecting the activity of most prokaryotes. It has been reported that a change in pH will result in a change in the ionic form of the active site, which will further alter the enzyme activity, resulting in a change in the reaction rate [35]. pH was maintained with different ranges with the addition of different buffer solution. Figure 4 depicts the highest voltage of around 710 mV yield at pH 6 when the microbial secreted enzyme may have a potent ionic group at its active site to function normally. This value is very close to the one obtained at pH 7, significantly reduced voltage nearly equal to 420 mV was observed with pH 8.

3.3 Substrate concentration impact on electricity generation

Different substrate concentration was under investigation with mutational increase or decrease in power generation. As from pervious study it was observed that microbes degrade substrate into electron and proton [13, 22]. Previously, different substrates have been analyzed and studied by different researchers on behalf that current study was focused at using fermented sludge with different concentration in the range of 30–90% with step increment of 30% with the help of *Saccharomyces cerevisiae* which served to achieve the degradation of fermented sludge into electron and proton. Different concentration of substrate was maintained through addition of water 70%, 40% and 10% with ferementated sludge 30%, 60% and 90% respectively. Profiles of voltage generation with respect to concentration of substrate are presented in Fig. 5 which clearly signposts that by increasing or decreasing concentration of substrate energy generation also influenced due to limiting organic load in substrate. Enhancement in the electricity generation was observed as the substrate concentration increased up to 60%, further increase in concentration up to 90% caused the voltage generation to decrease, due to decrease in enzyme activity. The voltage obtained is written as 420 mV (90%) < 610 mV (30%) < 630 (60%). It was observed that higher concentrations of the substrate may actually affect the performance of the anode, resulting in a significant generation of low voltage.

Fig. 5 Effect of time of fermented sludge on voltage generation

Fig. 6 Power density and voltage as function of current density

3.4 Effect of current and power density on performance of microbial fuel cell

Profiles of power density and voltage obtained at different conditions of current density are given in Fig. 6. Polarization curves describe the voltage as a function of current and are a powerful tool for MFC analysis and characterization. A maximum power can be produced when the internal and external resistances are equal. Maximum power density of 610 mW/m^2 at external resistance of 250Ω was obtained in MFC. The power density observed in this study is greater than a previously reported for MFC inoculated with fermented sludge [34]. The dissimilarity between the results obtained in this study and the previously reported studies of MFC inoculated with fermented sludge could be attributed to the difference in abiotic parameters including but not limited to the quality of organic content

concentration, type of wastewater, electrodes material, the applied resistance, and membrane type. However, for this study results revealed that MFCs inoculated with mixed and single cultures and fueled with actual fermented achieved different maximum power indicated the dissimilarity of electrochemical activity of the inoculums species. This is due to the fact that the existence of electrochemically inactive species in the mixed cultures may compete with the active species for the available substrate that's why their activity is restricted and electrons are subsequently released.

3.5 COD and BOD removal in MFC couple with current generation

The two-chamber microbial fuel cell was operated at initial COD concentration range from 310–350 mg/l. Volumetric flow rate couple with COD loading to microbial fuel cell was $0.18 \text{ kg COD/m}^3\text{-d}$. After 18 days operation under unchanged condition, 88% COD and 87% BOD removal were achieved. The unsettled BOD and COD values observed in the effluent were 20.9 and 29.14 mg/l, respectively. BOD removal efficiency was higher than 78% removal reported by Gude [10] and Liu and Logan [21]. The COD removal percentage in anode chamber was 46.3% and remaining COD was getting removed in the cathode chamber. For single chamber MFC, operated at HRT of 33 h, COD removal efficiency of 50–70% was reported by Liu and Logan [21]. By comparing above discussion with Fig. 4. Figure 4 shows the BOD and COD removal with respect to time couple with current generation. Trend of COD and BOD decreasing as time passes couple with increasing in current generation, due to microorganism decomposing organic matter into electron and proton.

COD removal proceeded in two stages. Fast COD removal in first stage with high current production was followed by a slower COD removal in second stage with little current production. While using MFCs increased COD removal rate due to current generation, secondary processes will be needed to reduce COD to levels suitable for discharge [36]. During running of MFC different process parameter effect on power production and performance. COD and BOD show how much organic load present in substrate and show the value for treatment. Figure 7 shows time dependent removal of COD and BOD for current generation. As time passed the variation in COD removal and increase in current generation the initial amount of 1336 mg/l with current generation 1.2 mA. As time, processed decreasing in percentage of COD and increasing in amount of current up to 3.3 mA. This leads to sustainable development regarding treatment of distillery effluent couple with energy generation.

Fig. 7 COD and BOD reduction with respect to time simultaneously current generation

4 Conclusion

The sludge as a substrate was subjected into MFC in the presence of *Saccharomyce cerevisiae* biocatalyst. The maximum voltage obtained was 750 mV per liter of sludge when the anode and cathode chamber were maintained in batch and continuous mode respectively. These results have demonstrated the specificity of the mediator-microbial combination as well as the importance of developing a dual chamber MFC. This potential substrate was proved to produce a stable voltage in the feed batch at different initial sludge concentrations couple with aeration rate of 160 ml/min, pH 6 and 60% substrate concentration.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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