Enhanced energy recovery from anaerobically digested distillery wastewater through microbial fuel cell connected in series

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Abstract
Two biggest environmental concerns of waste management and energy demand can be handled by microbial fuel cell (MFC). Two chambered MFC was used to generate electricity from anaerobically digested distillery wastewater. The stacking of MFCs connected in series was employed to enhance the voltage generated by MFC. The voltage generated and total power production by 4 MFCs connected in series was 0.817 ± 0.07 V and 349.7 ± 59.38 mW respectively.
Keywords: Microbial fuel cell, series, distillery wastewater, power, voltage

1. Introduction
Energy saving programs are the need of the current situation considering the fact of constant increase in the global energy demand (Ragauskas et al., 2006). The world is also progressing towards the carbon-neutral development of energy sources. Biomass is considered as the green source of energy production (Deval and Dikshit 2013). Microbial Fuel Cell (MFC) is defined as a system in which microorganisms function as catalysts to convert chemical energy directly into electrical energy (Choi and Chae 2012). The advances in the conversion processes will improve the sustainability of biofuels, while higher efficiencies will reduce the environmental impacts (Deval and Dikshit 2013). MFC offer solutions to all these problems by taking nature’s solutions to energy generation and tailoring them to our own needs. The main advantages of MFCs include direct generation of electricity and removal of organic load without additional conversion step as well as its operating temperature could be even below 200°C and substrate concentration levels could be low (Pant et al., 2010).

MFCs are stacked in series or in parallel in order to increase the voltages and currents produced by the system (Aelterman et al., 2006). In this study, two chambered microbial fuel cells fed with anaerobically digested distillery wastewater were connected in series in order to amplify the voltage. The voltage generated by single MFC was compared and analyzed with 2 MFCs, 3 MFCs and 4 MFCs in series.
2. Materials and methods

2.1. Materials
For construction of MFC, customized Scott Duran glass bottles of 500 mL capacity used as reservoir in the preparation of MFC were acquired from Omega Glass Works, Mumbai, India. Graphite rods removed from exhausted Eveready AA batteries were used as electrodes. Electrical hardware like resistance and copper wires was bought from local vendor, Mumbai, India. Voltages for all experiments were recorded by Picolog 1216, bought from Picotech, UK. Anaerobically digested distillery wastewater used as feed throughout the experiments was procured from a distillery near Nasik, India. All chemicals used were of ExelaR grade, used without further purification and obtained from Qualigens (Fisher Scientific), India.

2.2. Wastewater sampling and analysis
Wastewater was immediately stored at 4°C. Characterization of the wastewater was carried out using APHA standard methods. The wastewater characteristics are shown in Table 1.

Table 1. Characteristic of anaerobically digested distillery wastewater.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>7.96 ± 0.1a</td>
</tr>
<tr>
<td>BOD (mg/L)</td>
<td>2330 ± 108a</td>
</tr>
<tr>
<td>COD (mg/L)</td>
<td>18560 ± 640a</td>
</tr>
<tr>
<td>TOC (mg/L)</td>
<td>6519 ± 89a</td>
</tr>
<tr>
<td>Total solids (mg/L)</td>
<td>34658 ± 38.7a</td>
</tr>
<tr>
<td>Total dissolved solids (mg/L)</td>
<td>21914 ± 390.2a</td>
</tr>
<tr>
<td>Total suspended solids (mg/L)</td>
<td>12744 ± 135a</td>
</tr>
</tbody>
</table>

*values expressed as the mean ± the standard deviation (n=3).

2.3. Preparation of feed
Two hundred and fifty milliliters of wastewater was diluted to 1 L with distilled water. 2% Dextrose along with 1 mL each of 0.1 M phosphate buffer of pH 7.2, 0.1 M MgSO₄·7H₂O, 0.2 M CaCl₂·2H₂O and 0.01 M FeCl₃·6H₂O was added to 1 L diluted anaerobically digested distillery wastewater to induce the growth of endogenous bacteria. This modified wastewater was used as feed throughout the experiments.

2.4. Microbial fuel cell set-up and operational conditions
Two chambered MFC was constructed appropriate for the batch operation which is explained in details in previous study (APHA 1995). In brief, the anodic and cathodic chambers of MFC of 500 mL each, which were joined by a salt bridge (15 mL) containing 10% KCl. Two identical cylindrical graphite rods (removed from exhausted Eveready AA batteries) were used as electrodes. Anode and cathode were connected to the copper wires, which in turn were connected to 1000 Ω external resistance. The anodic chamber was filled with 200 mL of standardized anaerobically digested distillery wastewater, while cathodic chamber was filled with 200 mL of 100 mM potassium ferricyanide prepared in 100 mM phosphate buffer of pH 7. Endogenous microflora from anaerobically digested distillery wastewater was used as a source of microorganisms. All the experiments were carried out at room temperature (25°C to 30°C).
2.5. Amplification of voltage generation
In order to increase power generation, two to four individual microbial fuel cells were stacked together in series. Generally, anode of 1st MFC was connected to the resistance while cathode of 1st MFC was connected to the anode of 2nd MFC. Similarly, cathode of 2nd MFC was connected to the anode of 3rd MFC, so on and so forth. The cathode of the last MFC was connected to the resistance and voltage was measured across the resistance.

2.6. Electrical measurements
All experiments were performed using Picolog data logger (1216, Picotech, UK) to determine the electricity generation. The voltage was recorded every 5 minutes. The current was calculated using Ohm’s law $V=I \times R$, where $V$ is the voltage across resistance, $I$ is the current generated and $R$ is the external resistance. The power generated by the system was calculated as $P = V \times I$ where, $V$ is the voltage and $I$ is the current generated by the system. Total power generation was calculated as area under curve with the formula given by Pruessner et al. (2003).

2.7. Statistical analysis
Results are expressed as Mean ± S.D. with experiments being conducted in triplicate. The statistical significance was determined by one-way analysis of variance (ANOVA) to determine if the data obtained is significantly different from each other using Graph Pad Prism software version 5.0 (GraphPad Software, San Diego, CA, USA).

3. Results and discussion
MFCs stacked in series are required to enhance the voltages produced. Connecting several fuel cells in series adds the voltages, while one common current flows through all fuel cells (Aelterman et al., 2006). Besides, the MFC units in an arrangement may not work independently and could be affected by the power generation of different MFCs. The first MFC stack is developed by Aelterman et al. (2006). Their MFC stack consists of six individual units. In other studies, to disclose the cause of voltage reversal in stacked MFCs, Oh and Logan (2007) constructed a two cell air-cathode MFC stack which produced a working voltage of 0.9V at 500Ω.

In another configuration of stacked MFCs bridged internally through an extra CEM was assembled from two single MFCs. To minimize the limitations that non-uniform potential distribution on the electrode surface and lower output voltage due to the potential drop, a bipolar plate stacked MFC consisting of five single cells connected in series was developed. In another study, stack configuration was developed, which produced high voltage from lake sediments (Zhang and Angelidaki 2012).

In this study, two chambered MFC was used in the study with two chambers separated by salt bridge (10 % KCl). Modified anaerobically digested distillery wastewater was used as feed as well as source of bacteria for generation of electricity as in earlier studies. Figure 1 showed increase in voltage generation along with the power production as the number of MFC connected in series was increased. The working voltage generated by single MFC was $0.126 \pm 0.005$ V while total power generated by the system was found to be $7.94 \pm 0.14$ mW. The working voltage was increased to $0.167 \pm 0.01$ V, $0.419 \pm 0.05$ V and $0.817 \pm 0.07$ V when 2 MFCs, 3 MFCs and 4 MFCs were connected in series. Similarly, total power increased from $7.94 \pm 0.14$ mW to $349.7 \pm 59.38$ mW when 4 MFCs were connected in series. Hence, MFCs connected in series was successfully used to increase the voltage output and hence the power output when fed with anaerobically digested distillery wastewater. Because of the limitation of data logger, more than 4 MFCs in series could not be connected.
4. Conclusion
Stacking individual MFCs successfully increased voltage of the system. The power output could increase to 349 mW when 4 MFCs are connected in series. Future studies should examine the current as MFCs when connected in parallel increase current in the system and compare with MFCs in series.

Conflict of interest statement
We declare that we have no conflict of interest.

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