Effect of cell structure and heat pretreating of the microorganisms on performance of a microbial fuel cell

Milad Kadivarian, Ali A. Dadkhah and Mohsen Nasr Esfahany

ABSTRACT

While microbial fuel cells are being considered as a tool for energy saving in wastewater treatment facilities, such applications in oil refineries pose a challenge due to harder acclimation of microorganisms. In this research, the effect of heat pretreating mixed culture microorganisms (MCM), and cell cross section, on the performance of a novel cell design with two cross sections (single chamber microbial fuel cells, with circular: SCMFC_CC and rectangular: SCMFC_RC cross section) fed batched with refinery wastewater were investigated. First, using original and heat pretreated MCM, the performance of SCMFC_CC in terms of chemical oxygen demand (COD) removal and electricity production was investigated. Then, using only the heat pretreated MCM, the electricity production of SCMFC_RC was measured and compared with that of SCMFC_CC. Heat pretreatment of MCM improved maximum open circuit voltage (OCV) and maximum power density generated by 14% and 16%, respectively. However, heat pretreatment reduced COD removal by about 4%. The performance of SCMFC_CC in terms of maximum OCV and power density compared to SCMFC_RC was improved by 41% and 279%, respectively. Heat treatment of MCM increases the electricity generation of the cell, while reducing the performance of COD reduction due to decreasing the microorganism varieties in the MCM.

Key words | heat pretreating, microbial enrichment, microbial fuel cell, microbial fuel cell structure, refinery wastewater

INTRODUCTION

The wastewaters produced in petroleum refineries include a large number of harmful pollutants such as aliphatics, phenol, benzene, xylenes, nitrogen and sulfide compounds (Guo et al. 2016). The microbial fuel cell (MFC) is a biological reactor that can degrade substrate by bacteria and produce electricity directly. These bacteria oxidize organic matter and produce electrons and protons. Electrons are transferred from anode to cathode via the external circuit. In single chamber cells, protons move to the internal surface of the cathode electrode. In the cathode electrode, the electron acceptor receives the electron and is reduced (Logan 2007a). A considerable amount of literature has been published on the performance of MFCs. These studies have focused mostly on parameters affecting the performance of MFC such as electrode materials (Rabaey & Keller 2008; Pusomjit et al. 2018), operating parameters (Behera et al. 2011) and substrate (Pandey et al. 2016). Organic matters such as synthetic wastewater (Vamshi Krishna & Venkata Mohan 2016) and industrial wastewater (Zhang et al. 2008; Guo et al. 2016; Srikanth et al. 2016; Estrada-Arriaga et al. 2017) etc. have been used as substrate to MFC.

Investigation on the performance of a single chamber microbial fuel cell (SCMFC) in degradation of a pure substrate (glucose) indicated that SCMFC with heat pretreated mixed culture microorganisms (MCM) has higher produced voltage and shorter period of biofilm formation compared to SCMFC with original mixed culture microorganisms (MCM) (Tanikkul & Pisutpaisal 2015). In another research, Krishna and Mohan studied the effect of two different pretreatment methods of MCM (iodopropane and heat-shock pretreatment) on the efficiency of SCMFC in degradation of glucose. They reported improvement of produced voltage and coulombic efficiency, whereas chemical
oxygen demand (COD) removal was decreased in both methods (Vamshi Krishna & Venkata Mohan 2016).

Wastewaters consist of a large number of organic matters, and pure cultures of microorganisms are unable to use all of them in their metabolism. Thus, it is necessary to use MCM for treatment of wastewater (a mixed substrate) and production of electricity when the microbial fuel cell is employed. Moreover, using a single pure microbial culture requires sterilization of the feed, which is not a practical task. MCM contain different microbial clusters such as methanogens and electrogens. Methanogens compete with electrogens for consuming substrate in the course of methane production. Operations with selective enrichment of electrogens such as heat shocking can destroy non-electrogenic microorganisms like methanogens. As a result, electrogens become the dominant microbial group, yielding better efficiency in electrical production. The effect of heat pretreatment of MCM on the performance of wastewater (a mixed substrate) treatment for COD removal and electricity production by the microbial fuel cell has not been studied.

In an MFC, some of the microorganisms attach themselves to the surface of the anode, forming a biofilm, and the rest remain in the bulk of the fluid in the form of a suspension (Ren et al. 2008b). In order to facilitate better contact between microorganisms and the anode electrode, mixing by stirrer (Vamshi Krishna & Venkata Mohan 2016) or recirculation of anolyte (Moharir & Tembhurkar 2018) have been employed to prevent the settlement of suspension. However, higher mixing and recirculation increase the total cost (initial and operating) and may result in higher membrane fouling (Moharir & Tembhurkar 2018). Designing an anode chamber that provides more surface for contact between the anode electrode and the settled phase (containing microorganisms), can lead to less mixing requirement, resulting in a decrease in the cost of MFC construction and operation. To the best of our knowledge, the effect of such changes in cell structure on the performance of MFC has not been investigated, and we present the results of such study on two new structures.

This research focused on two objectives. The first target was investigation of the effect of heat pretreatment of MCM on the performance of an SCMFC with circular cross section (SCMFC_CC) with refinery wastewater as the substrate in term of electricity production (in open and closed mode) and COD removal. The second goal was to compare two different cell configurations, namely SCMFC_CC and SCMFC with rectangular cross section (SCMFC_RC). Performance of cells was measured in terms of open circuit voltage (OCV) and power density.

### MATERIALS AND METHODS

#### Fuel cell configuration

Two different configurations of SCMFC were utilized in the present investigation. All of the SCMFCs were made of Plexiglas and had a volume of 500 mL. The SCMFCs have two main parts. According to Figure 1, the first part serves as the holding pole for the entire cell, containing the feed and exit ports for substrate. This part was similar for both cell structures. However, the second part of the first configuration (SCMFC-CC) had a circular cross section (Figure 1(a)) while the second one (SCMFC-RC) had a rectangular cross section (Figure 1(b)). The anode electrode was built from 24 × 6 cm stainless steel mesh 300. Graphite coating was created by spraying graphite paint onto the surface of the stainless steel mesh (Mardanpour et al. 2012). The anode electrode was fixed on the plate located in the middle of the anode chamber. Carbon cloth (E-TEK, USA, 64 cm²) was used as the cathode electrode. The anolyte side of the carbon cloth was modified to achieve about 0.5 mg/cm² platinum content (Cheng et al. 2006), and 30 wt% Nafion 117 loading. That means, all of the SCMFCs used in this research were membrane-less. Nafion solution was used as the binder in the cathode electrode (Cheng et al. 2006). Anode and cathode electrodes were connected electrically by copper wire in open circuit and closed circuit mode (using external resistances of 100 and 500 Ω). With consideration of the general toxic effect of copper on the microbial species in the long term, the copper wires were coated with a graphite layer using the same graphite solution as was used to coat the anode surface. Samples for COD analysis or pH measurements were taken from point 7, as is indicated in Figure 1(a). The total height of the anode chamber was 6 cm, and samples were taken from a height of 2.5 cm from the bottom.

Refinery wastewater was collected from the first stage collection pond of the Isfahan Oil Refining Company waste-water treatment unit, where all wastewater streams of the refinery are collected and mixed before further treatment. Collected samples were stored at 4 °C in 20 L containers till time of use in the MFC. The properties of the refinery wastewater are shown in Table 1. Anaerobic sludge was acquired from the anaerobic digester effluent of North Isfahan Wastewater Treatment Plant, and was used as the microorganism source. Two different MCM were employed:

1. Heat pretreated MCM: MCM was heat pretreated at 80 °C for 15 min to destroy the methanogen bacteria
Changing the substrate source is considered as a stress to microorganisms, and depending on the nature of each feed, adaptation to a new feed may take anything from several days to several months (Rittmann & McCarty 2001). Based on a previous work (Mousavi et al. 2014) with the same source of MCM and feed, the suitable time for adaptation was found to be about 4–6 months. Hence, acclimation of MCM was done for approximately five months in batch mode. In the adaptation period, every 48 h, the MCM were fed with a 40 mL mixture (1:1) of refinery wastewater and cell growth media (Morris & Jin 2007). Stable closed circuit electric current production was taken as an indicator for an acceptable proper acclimation period. VSS of microorganisms at the end of the adaptation process was 20.7 ± 0.7 mg/cm$^3$. Details of the acclimation are provided in the supplementary file (available with the online version of this paper).

All COD analysis was performed according to standard method APHA 5220 (APHA 1999). COD removal efficiency

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**Table 1 | Properties of refinery wastewater used as substrate**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>8 ± 0.5</td>
</tr>
<tr>
<td>COD (mg/L)</td>
<td>4,650 ± 150</td>
</tr>
<tr>
<td>BOD$_5$ (mg/L)</td>
<td>2,230 ± 70</td>
</tr>
<tr>
<td>H$_2$S (mg/L)</td>
<td>1</td>
</tr>
<tr>
<td>NH$_4^+$ (mg/L)</td>
<td>27.5</td>
</tr>
<tr>
<td>Conductivity (μs/cm)</td>
<td>3,150 ± 45</td>
</tr>
</tbody>
</table>

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**Figure 1 | Configuration of (a) SCMFC-CC with circular cross section, (b) SCMFC-RC with rectangular cross section, (c) horizontal cross section of both SCMFCs. 1 Cathode electrode, 2 porous protective layer, 3 anode electrode, 4 injection tubes of wastewater, 5 tubes for discharging produced gas, 6 sampling tube, 7 sampling height or sampling point. x and y are the height of the settled microorganisms in the anode chamber.**
was studied only for closed circuit operation of two SCMFCs, one containing the heat-pretreated MCM and the other having original MCM at 500 Ω external resistance. For this purpose, and in order to start with feeds of similar concentration, 400 mL of liquid content from each of these two cells at the end of open circuit operation were extracted and added together. Of this 800 mL liquid, 140 mL was exchanged with refinery wastewater. At this stage, the COD of this 800 mL was measured as 1,150 ± 28 mg/L. Now each of the cells was filled with 400 mL of this liquid (COD 1,150 ± 28 mg/L) and operated with the external loading of 500 Ω, as mentioned above. Then, at 24 h periods, 10 mL samples were taken from each cell and analyzed for COD.

The SCMFCs were filled with MCM, cell growth media and refinery wastewater with a ratio of 2:3:5. When OCV decreased below approximately half of the last maximum OCV, or when the closed circuit voltage dropped to a stable minimum, 70 mL of lighter liquid content from the top of the cells was replaced by 70 mL of refinery wastewater. The only exception was for the last injection in open circuit mode, where the replacement volume for fresh substrate was equal to the wastewater consumption in the previous cycle, which was about 35 mL. pH of feeds was set at 8.5 equal to the wastewater consumption in the previous cycle, mode, where the replacement volume for fresh substrate was only exception was for the last injection in open circuit mode, in which a uniform biofilm formed on the anode electrode (Mardanpour et al. 2014). Figure 2 shows the OCV of SCMFCs with different MCM and cell structures. In the first part of operation, in open circuit mode, the effect of heat pretreating of MCM was investigated. It is seen that for SCMFC_CC, for both heat treated and untreated MCM, initially OCV dropped rapidly, reaching a minimum value (at 8 h), after which it increased to a local maximum, then there was a drop in the voltage, a maximum afterwards, and a slow decrease in voltage until the next feed injection at about 155 h. Then, as described

where I is current (mA), F is Faraday's constant (96,500 C/mole), V_{An} is volume of anolyte (L), Δ(COD) is the overall change in substrate concentration during run duration (mg/L) and t_b is run duration (s).

Internal resistance is one of the most important factors in investigating the performance of MFC. Two different methods were introduced by Logan for calculation of internal resistance. First, in the peak of the polarization curve, internal resistance and external resistance are equal, and in the second method the slope of the polarization curve is used for calculation of internal resistance (Logan 2007b):

$$R_{int} = -\frac{\Delta V}{\Delta I}$$

where ΔV and ΔI are changes of maximum voltage and maximum current in two different external resistances. In the present investigation, the second method was used for calculating the internal resistance.

RESULTS AND DISCUSSION

External resistance has a direct effect on the performance of different microbial species. Higher resistance results in less electron transfer from anode to cathode, resulting in less electrochemical potential between anode and cathode, which in turn reduces the proton migration from the anolyte to the cathode. Accumulation of protons in the anolyte is favorable for methanogens and the overall result is less power generation at higher resistances (Chae et al. 2010). To test this phenomenon, three-difference modes (OCV and two external resistances of 100 and 500 Ω) were used.

Open circuit mode

Initially, in the startup period, the MFC was operated in open circuit mode, in which a uniform biofilm formed on the anode electrode (Mardanpour et al. 2014).
earlier, fresh feed was added at indicated points in Figure 2. In refinery wastewater, a part of the organic matter converts to electricity directly (simple organic matter); however, complex compounds are broken into simpler compounds and then consumed by electrogenesis microorganisms. The first local minimum after start-up may be due to the change in condition of microorganisms from anaerobic acclimation bottles to MFCs. However, the cause of the second local minimum (around 76–78 h, clearly shown for SCMFC_CC and less visible, but present, for SCMFC_RC) may be attributed to the two-step mechanism of converting complex compounds to electricity.

For SCMFC_CC, heat pretreated MCM produced higher OCV values in comparison with original MCM. Moreover, OCV produced by SCMFC_RC using heat pretreated MCM showed almost a similar trend to that of SCMFC_CC using the same type of MCM, but with lower voltage values.

As is shown in Figure 2, after each feed injection the maximum value of OCV regularly increased until uniform biofilm formed on the anode electrode surface (Mardanpour et al. 2012). Maximum OCV generated by SCMFC_CC with heat-pretreated MCM, SCMFC_CC with original MCM, and SCMFC_RC were 780, 683, and 550 mV, respectively. These results showed that heat pretreated MCM increased the cell efficiency in voltage production. Furthermore, in the same context, it is seen that the SCMFC_CC structure was more efficient than SCMFC_RC in producing OCV.

Comparison of performance of SCMFCs in closed circuit mode

Closed circuit performance of all three previously described cells was measured under 100 and 500 Ω external resistances and results in terms of power and current densities are shown in Figure 3. Moreover, the maximum values of power and current densities for all cases are summarized in Table 2.

These results indicated that heat pretreatment of MCM had a positive effect on the conversion of the chemical energy stored in the substrate to electricity. Methanogenic microorganisms influence the performance of MFC in two ways. They compete with electrogenic microorganisms in consumption of substrate, and also consume protons in their metabolism for methane production (Ren et al. 2008a). Heat pretreatment destroys methanogenics and most other microorganisms. However, microorganisms that can resist stress, such as Proteobacteria (like

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**Table 2** Maximum value of power and current densities

<table>
<thead>
<tr>
<th>External resistance</th>
<th>Power density (mW/m²)</th>
<th>Current density (mA/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 Ω</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SCMFC_RC with pretreated MCM</td>
<td>10.4</td>
<td>56.3</td>
</tr>
<tr>
<td>SCMFC_CC with original MCM</td>
<td>32.3</td>
<td>100.3</td>
</tr>
<tr>
<td>SCMFC_CC with pretreated MCM</td>
<td>38.1</td>
<td>109.3</td>
</tr>
<tr>
<td>100 Ω</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power density (mW/m²)</td>
<td>16.8</td>
<td>157.8</td>
</tr>
<tr>
<td>Current density (mA/m²)</td>
<td>55.1</td>
<td>289.1</td>
</tr>
<tr>
<td>Power density (mW/m²)</td>
<td>63.8</td>
<td>315.6</td>
</tr>
</tbody>
</table>

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**Figure 2** OCV generated in SCMFC_CC with original MCM (dashed line); SCMFC_CC with heat pretreated MCM (solid line), and SCMFC_RC with heat pretreated MCM (dotted line). Feed injection times are shown by □, ○ and △ in the same order as above.

**Figure 3** Power density produced in SCMFC_CC with heat pretreated MCM (solid line), SCMFC_CC with original MCM (dashed black line), and SCMFC_RC with heat pretreated MCM (dashed grey line) using (a) 500 and (b) 100 Ω external resistance.
**Xanthomonas** and *Pseudomonas*, Firmicutes (bacilli and clostridia) and *Bacteroidetes*, were enriched. Proteobacteria and Firmicutes can act as electrogenic microorganisms (Ren et al. 2008a; Goud & Mohan 2015; Vamshi Krishna & Venkata Mohan 2016; Saratale et al. 2017).

Part of the MCM gradually settle down in the anode chamber and act like biofilm in consuming substrate with simultaneous production of protons and electrons. The contact surface between the anode electrode and the settled MCM plays an important role in the performance of the MFC. The lower performance of the SCMFC_RC with respect to the SCMFC_CC may be attributed to the fact that changes in the structure of a cell affect the contact surface between the settled MCM and the anode electrode. In Figure 1, x and y indicate the height of the settled MCM in the SCMFC_RC and SCMFC_CC, respectively. When using these two cells with the same volume and under the same conditions, as long as the volume of the settled MCM is less than half of the total volume of the anode chamber, y would be higher than x. This means that surface contact between the anode electrode and settled MCM in the SCMFC_CC is greater than in the SCMFC_RC (in this case, about 27%; detailed calculations are presented in the supplementary file, available with the online version of this paper). The current density produced in the SCMFC_CC was 94% higher compared to the SCMFC_RC. The reason for the lower current density of SCMFC_RC may be explained as follows. Due to the lower contact surface in the SCMFC_RC, the produced protons remained in the settled MCM, resulting in a gradual decrease of local pH, leading to a drop in activity of the MCM.

The response of SCMFC to refinery wastewater injection has three phases. In the first phase, the voltage output of SCMFC rapidly increased. The value of the voltage depends on the performance of SCMFC relative to some of the limiting factors. The limiting factor can be either the amount of substrate loaded or the maximum ability of MCM to convert substrate to electricity. The second phase of the feedback of SCMFC is the stationary phase. The voltage output of SCMFC in the stationary phase is almost constant. The duration of the second phase depends on several parameters, such as the amount of loaded substrate and pH. When the limiting factor in the first phase was the amount of loaded substrate, the second phase disappeared. Voltage output decreases in the third phase. Figure 4 shows the polarization curve of three SCMFCs. It can be seen from Figure 4 that the electricity produced by SCMFC_CC with heat-pretreated MCM was the highest in comparison with the other two SCMFCs. Based on the data from Figure 4 and according to Equation (4), the internal resistance of SCMFC_CCs with heat-pretreated MCM or original MCM was 111.3 and 110.5 Ω, respectively.

**pH** is a very important factor in biological systems. At each cycle, when 70 mL of cell liquid was replaced with refinery wastewater, pHs were measured as in Table 3. The decrease in pH may be attributed to the production of protons and volatile fatty acids by microbial metabolism (Mohan & Chandrasekhar 2011; Srikanth et al. 2016).

**COD removal efficiency**

COD removal efficiency was used to investigate the effect of heat pretreating of MCM on the removal of organic pollutants from oily wastewater. COD concentration changes for a period of 72 h, at an external resistance 500 Ω, using two cells, of which one contained heat pretreated MCM and the other original MCM, are presented in Figure 5. High COD removal efficiency, especially in two days, was due to the special adaptation procedure (using refinery wastewater as the feed of MCM in batch mode for more than 5 months) (Mardanpour et al. 2012; Srikanth et al. 2016). As is shown, the efficiencies of COD removal in SCMFC_CC with original MCM and SCMFC_CC with heat pretreated MCM are 91 ± 1.1% and 87 ± 1.2%, respectively. A possible explanation is that heat pretreating removes non-electrogenic microorganisms, leaving electrogenic microorganisms which are unable to employ all of the compounds in the mixed substrate for

<table>
<thead>
<tr>
<th>Sample</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed pH</td>
<td>8.50 ± 0.10</td>
</tr>
<tr>
<td>Cell content with heat treated MCM</td>
<td>7.03 ± 0.10</td>
</tr>
<tr>
<td>Cell content with untreated MCM</td>
<td>7.36 ± 0.11</td>
</tr>
</tbody>
</table>
their metabolism (Vamshi Krishna & Venkata Mohan 2016). In comparing the COD removal efficiency values reported by this work and those of Vamshi Krishna & Venkata Mohan, it should be noted that for better understanding of the effect of heat pretreatment, pretreated microorganisms should be batch fed for a certain time after heat shock, and then be used in MFCs to avoid feeding on the carcasses of destroyed microorganisms. However, they used MCM in MFC instantly after pretreatment. To investigate the effect of heat pretreating on the performance of SCMFC, coulombic efficiencies of two cells with different MCM were also calculated. The coulombic efficiency of SCMFC_CC with original MCM and SCMFC_CC with heat pretreated MCM were 1.85% and 2.2%, respectively which indicates more than 1/6 improvement. It implies that coulombic efficiency of SCMFC enhanced by heat pretreating of MCM.

The results of present work and those found in the literature for production of electricity by MFCs using petroleum wastewater as substrate are summarized in Table 4. It can be seen that maximum OCVs achieved in present research are higher than maximum OCVs reported in the literature. Moreover, maximum OCV of SCMFC_CC with heat pretreated MCM obtained in this work, is more than 1.5 times of maximum OCVs reported by other researchers.

### CONCLUSION

In this paper, effects of heat pretreating of MCM and cell configuration on the performance of SCMFCs for treatment of an oily refinery wastewater in the batch fed mode were investigated. In the case of the effect of heat pretreating, results showed that maximum OCV of SCMFC_CC with heat pretreated MCM, increased by 14% compared to Maximum OCV of SCMFC_CC with original MCM. Also, the maximum power density of the electricity from SCMFC_CC with heat pretreated MCM is raised by 16% relative to the maximum power density of the electricity from SCMFC_CC with original MCM. However, heat pretreating has a negative influence on COD removal. The COD removal efficiency of the heat pretreated MCM was about 4% less than original MCM. In addition, the coulombic efficiency of SCMFC_CC with heat-pretreated MCM (2.2%) is 0.35% more than the coulombic efficiency in SCMFC_CC with original MCM. It was deduced that the maximum OCV of SCMFC_CC is 1.4-times the maximum OCV of SCMFC_RC.

### Table 4 | Comparison results of present study and literature

<table>
<thead>
<tr>
<th>Cell configuration (Vanode (mL))</th>
<th>Type of microorganism</th>
<th>Max. OCV (mV)</th>
<th>Max. power density (mW/m²)</th>
<th>COD removal %</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC (5)</td>
<td>Anaerobic sludge</td>
<td>343</td>
<td>53.11</td>
<td>41.08²</td>
<td>Mohan &amp; Chandrasekhar (2011)</td>
</tr>
<tr>
<td>SC (500)</td>
<td>Pseudomonas putida</td>
<td>409</td>
<td>50</td>
<td>30</td>
<td>Majumder et al. (2014)</td>
</tr>
<tr>
<td>SC (13)</td>
<td>Anaerobic sludge</td>
<td>–</td>
<td>280</td>
<td>86</td>
<td>Zhang et al. (2014)</td>
</tr>
<tr>
<td>DC (400)</td>
<td>Paenibacillus sp. and Deinococcus sp.</td>
<td>–</td>
<td>102.93⁴</td>
<td>87</td>
<td>Guo et al. (2014)</td>
</tr>
<tr>
<td>DC (400)</td>
<td>Activated sludge</td>
<td>–</td>
<td>310.08⁴</td>
<td>61.92</td>
<td>Guo et al. (2015)</td>
</tr>
<tr>
<td>DC (400)</td>
<td>Activated sludge</td>
<td>–</td>
<td>330.4⁴</td>
<td>64</td>
<td>Guo et al. (2016)</td>
</tr>
<tr>
<td>SC (250)</td>
<td>Anaerobic sludge</td>
<td>–</td>
<td>54.11</td>
<td>82.88</td>
<td>Srikanth et al. (2016)</td>
</tr>
<tr>
<td>SC (300)</td>
<td>domestic wastewater</td>
<td>–</td>
<td>132</td>
<td>47</td>
<td>Mohanakrishna et al. (2018b)</td>
</tr>
<tr>
<td>SC (50)</td>
<td>sewage water</td>
<td>–</td>
<td>28.27⁵</td>
<td>45</td>
<td>Mohanakrishna et al. (2018a)</td>
</tr>
<tr>
<td>SCMFC-CC (500)</td>
<td>Anaerobic and original</td>
<td>683</td>
<td>55.1</td>
<td>91</td>
<td>Present study</td>
</tr>
<tr>
<td>SCMFC-RC (500)</td>
<td>Anaerobic and heat shocked</td>
<td>550</td>
<td>16.8</td>
<td>–</td>
<td>Present study</td>
</tr>
<tr>
<td>SCMFC-CC (500)</td>
<td>Anaerobic and heat shocked</td>
<td>780</td>
<td>63.8</td>
<td>87</td>
<td>Present study</td>
</tr>
</tbody>
</table>

1: Single chamber, 2: Total petroleum hydrocarbons, 3: Dual chamber, 4: mW/m², 5: W/m³.
Furthermore, the maximum power density of the electricity in SCMFC_CC is about 279% more than that of SCMFC_RC. These results indicated that changing the cell structure is more effective than heat pretreatment of MCM.

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