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# Biochemical evaluation of bioelectricity production process from anaerobic wastewater treatment in a single chambered microbial fuel cell (MFC) employing glass wool membrane

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**Abstract**

Biochemical functioning of single chambered microbial fuel cell (MFC) using glass wool as proton exchange membrane (PEM) operated with selectively enriched acidogenic mixed culture was evaluated in terms of bioelectricity production and wastewater treatment. Performance of MFC was studied at two different organic/substrate loading rates (OLR) (2.64 and 3.54 kg COD/m$^3$) and operating pH 6 and 7 using non-coated plain graphite electrodes (mediatorless anode; air cathode). Applied OLR in association with operating pH showed marked influence on the power output and substrate degradation efficiency. Higher current density was observed at acidophilic conditions [pH 6; 98.13 mA/m$^2$ (2.64 kg COD/m$^3$-day; 100 Ω) and 111.29 mA/m$^2$ (3.54 kg COD/m$^3$-day; 100 Ω)] rather than neutral conditions [pH 7; 100.52 mA/m$^2$ (2.64 kg COD/m$^3$-day; 100 Ω) and 98.13 mA/m$^2$ (3.54 kg COD/m$^3$-day; 100 Ω)]. On the contrary, effective substrate degradation was observed at neutral pH. MFC performance was evaluated employing polarization curve, impedance analysis, cell potential, Coulombic efficiency and bioprocess monitoring. Sustainable power yield was calculated at stable cell potential.


*Keywords:* Microbial fuel cell (MFC); Bioelectricity; Single chamber; Anaerobic wastewater treatment; Mixed culture; Sustainable power

## 1. Introduction

Recently considerable attention is being paid to alternative renewable sources of energy through out the world. Harnessing of biohydrogen ($H_2$) by anaerobic fermentation (Das and Veziroglu, 2001; Logan, 2004; Ginkel et al., 2005; Rittmann et al., 2006; Yang et al., 2006; Venkata Mohan et al., 2007a,b,c) and bioelectricity using microbial fuel cells (MFC) (Gil et al., 2003; Rabaey and Verstraete, 2005; Lowy et al., 2006; Logan and Regan, 2006; Lovely, 2006; Davis and Higson, 2007; Du et al., 2007; Biffinger et al., 2007; Kakehi et al., 2007; Prasad et al., 2007; He et al., 2007; Venkata Mohan et al., 2007d,2008) are gaining importance due to their clean, efficient, and renewable nature. Although, fermentative $H_2$ production is considered as a viable alternative energy source of the future, its storage, purification, low-production rates and conversion to energy (electricity) by fuel cells are some of the inherent limitations (Logan, 2004). Alternatively, MFCs facilitate *in situ* conversion of organic substrate to energy (bioelectricity) (Venkata Mohan et al., 2007d,2008).

MFC is a biochemical-catalyzed system which generates electrical energy through the oxidation of organic matter in the presence of fermentative bacteria under mild reaction conditions (ambient temperature and pressure) (Logan and Regan, 2006a). The potential developed between the bacterial metabolic activity [reduction reaction generating electrons ($e^-$) and protons ($H^+$)] and electron acceptor conditions separated by a membrane leads to generation of bioelectricity. Exploiting wastewater as a viable substrate to harness electricity is considered as sustainable approach and is presently in the early stages of research (Rabaey et al., 2003; He et al., 2005; Min and Logan, 2004; Oh and Logan, 2005; Min et al., 2005; Moon et al., 2006; Pham et al., 2006; Ghangrekar and Shinde, 2007; Rodrigo et al., 2007; Venkata Mohan et al., 2007d,2008). MFC design and configuration, characteristics of carbon source, nature and coating of electrodes, membrane electrode assembly, mediators and elec-

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trolytes used, nature of inoculum (biocatalyst) used in the anode chamber, operating conditions such as loading rate, pH, temperature, retention time, etc. are considered to be important factors which govern the overall efficiency of electricity generation. Since microorganisms act as a catalyst in the transfer of electrons from the substrate to the anode, the selection of a high performance microbial consortium (either pure or mixed culture) is crucial (Chaudhuri and Lovley, 2003; Stams et al., 2006).

Therefore, the present work aims to study the feasibility of bioelectricity generation in single chambered MFC (mediatorless (anode); air cathode), using glass wool as proton exchange membrane (PEM) and wastewater as substrate employing selectively enriched acidogenic mixed consortia as anodic inoculum.

## 2. Experimental

### 2.1. Anodic mixed consortia

Acidophilic mixed consortia producing molecular $H_2$ from various types of wastewater treatment in our laboratory was used as parent inoculum (Venkata Mohan et al., 2007b,c). Parent culture was washed thrice in saline buffer (5000 rpm, 20 °C) and enriched in designed synthetic wastewater (glucose—3 g/l; $NH_4Cl$—0.5 g/l, $H_2PO_4$—0.25 g/l, $K_2HPO_4$—0.25 g/l, $MgCl_2$—0.3 g/l, $CoCl_2$—25 mg/l, $ZnCl_2$—11.5 mg/l, $CuC_2$—10.5 mg/l, $CaCl_2$—5 mg/l, $MnCl_2$ —15 mg/l, pH 5.5; COD—3.2 g/l) under aseptic anaerobic microenvironment at pH 5.5 (100 rpm; 48 h). Prior to inoculation mixed culture was subjected to pretreatment to selectively enrich acidogenic microflora employing heat–shock treatment to sustain acidogenic bacterial (AB) activity and to inhibit methanogenic bacteria (MB) as described by Venkata Mohan et al. (2007a,b,c).

### 2.2. MFC configuration and operation

Single chambered MFC was designed and fabricated in our laboratory using 'perplex' (Fig. 1). The fuel cell consists of single anodic compartment with a designed total volume of 0.35 l (working volume 0.32 l). Plain graphite plates (5 cm × 5 cm; 10 mm thick) without any coating were used as electrodes for both anode and cathode. Cathode has projected surface area of 70 cm$^2$. To increase the overall surface area (83.56 cm$^2$), anode was purged with nine uniform sized holes (0.1 cm dia). Prior to use, the electrodes were soaked in deionized water overnight. Glass wool sandwiched between non-absorbent cotton (∼2 mm thickness) was used as PEM between two electrodes in place of normally used Nafion membrane. Copper wires were used for contact with electrodes after carefully sealing with epoxy sealant. Lower side of anode was always in contact with wastewater. Top portion of the cathode was exposed to air. The anode chamber of the fuel cell resembles an anaerobic suspended growth reactor incorporating electrode membrane assembly on the top cover. Provision was made in design for sampling ports, wire input points (top), inlet and outlet ports, gas outlet, etc. Leak proof sealing was provided at joints to maintain anaerobic microenvironment in anode compartment. Prior to

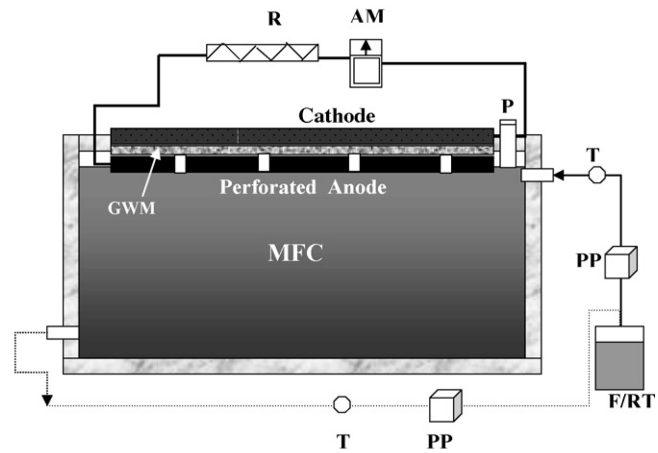


Fig. 1. Schematic details of the experiment setup microbial fuel cell [MFC: single chambered microbial fuel cell; GWM: glass wool membrane T: preprogrammed timer; PP: peristaltic pump; P: sampling/standard electrode port; AM: ammeter; R: resistor (100 Ω); F/RT: feeding and recirculation tank].

startup, the anodic compartment was inoculated with selectively enriched $H_2$ producing mixed microflora (volatile suspended solids (VSS), 2.0 g/l) dissolved in designed synthetic wastewater (320 ml). MFC was operated in fed batch mode at room temperature (29 ± 2 °C). Anolyte was continuously re-circulated (0.7 l/h) to eliminate concentration gradient. Before every feeding event, inoculum was allowed to settle down (30 min; settling) and exhausted feed (320 ml) was removed (decanted; 15 min) under anaerobic conditions. Settled inoculum (∼30 ml by volume) was used for subsequent operation. Feeding, decanting, and recirculation operations were performed using peristaltic pumps (Gilson, India) controlled by electronic timer (ETTS, Germany). After every feeding event, MFC was sparged with oxygen free $N_2$ for 2 min to maintain anaerobic microenvironment. Prior to feeding, pH of wastewater was adjusted to desired value (6.0/7.0) using concentrated orthophosphoric acid (88%) or 1 N NaOH. MFC performance with respect to power generation and substrate degradation was evaluated at two organic loading rates (OLR) [(2.64 kg COD/m$^3$-day (3 g glucose/l) and 3.54 kg COD/m$^3$-day (6 g glucose/l)] and pH conditions (6.0 and 7.0).

### 2.3. Analysis

Current output and substrate degradation rate (SDR) were considered as two key parameters to evaluate the performance of MFC. Bio-electrochemical calculations were done based on the procedure outlined by Logan et al. (2006). Current (I) was recorded after every 3 h using digital multi-meter (Metravi 901) by connecting 100 Ω as external resistance in the open circuit in series. For polarization, current production during stabilized operation of fuel cell was monitored by connecting to various external resistances (100–30,000 Ω) immediately in parallel. The anodic and cathodic potentials of MFC were measured against a saturated Ag/AgCl electrode (PPC Ltd., Hyderabad) using a pH meter (LI612 model, ELICO Ltd., Hyderabad). A variable resistance box was used to select an applied exter-

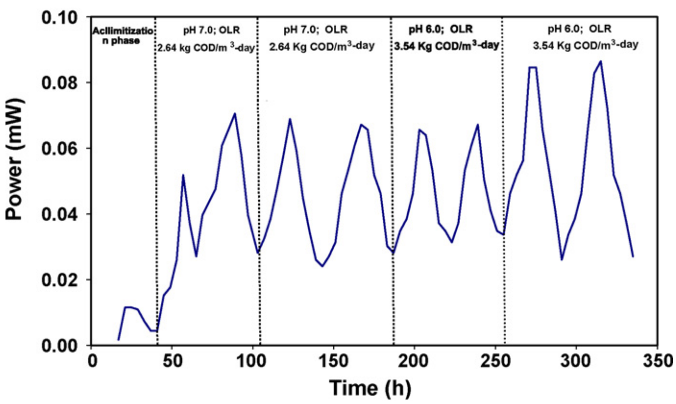


Fig. 2. Power generation during the operation of MFC with the function of time [$r^2$—0.9942].

nal resistance for current measurement. COD (closed refluxing method), alkalinity (total), volatile suspended solids (VSS), total volatile fatty acids (VFA), pH/oxidation-reduction potential (ORP) and biochemical oxygen demand ($BOD_5$) were determined according to the standard methods (APHA, 1998).

## 3. Results and discussion

MFC after inoculation with the selectively enriched acidogenic mixed consortia was initially operated with designed synthetic wastewater at OLR of 2.64 kg COD/m$^3$-day at operating pH of 7.0 for a period of 103 h (including acclimatization phase of 37 h). The acclimatization phase refers to adaptation of inoculated consortia to the anodic microenvironment. During this phase, feed was changed twice after a drop in current was observed. Subsequently, MFC was operated at higher OLR (3.54 kg COD/m$^3$-day) by keeping operating pH at 7.0 for two cycles of feed for a total period of 62 h. Further, the MFC was evaluated at operating pH of 6 with OLRs, 2.64 and 3.54 kg COD/m$^3$-day for a period of 82 and 86 h respectively with two cycles of feed. Constant substrate (COD) removal efficiency and voltage output were considered as indicators to assess the stabilized performance of the MFC and subsequently shifted to new feed.

### 3.1. Bioelectricity generation

Experimental data depicted the feasibility of bioelectricity generation by utilizing wastewater as substrate along with wastewater treatment (Fig. 2). However, the performance of MFC with respect to power generation and substrate removal was found to depend on the applied OLR and pH. During acclimatization phase (37 h), a consistent increase in voltage output was observed with time accounting for a maximum voltage output of 212 mV (Sfig I) along with substrate (COD) removal efficiency of 60%. At operating OLR of 2.64 kg COD/m$^3$-day (pH 7.0), during initial phase of fuel cell operation, open circuit voltage of 143 mV (0.21 mA; 100 Ω; series) was observed. A steady increase in voltage with time was observed and registered a maximum of 226 mV. Current measured at 100 Ω external load (series) showed a maximum of 0.84 mA. At operating pH 6 (acidophilic conditions) fuel cell operated at same OLR depicted maximum open circuit voltage of 297 mV and current 0.82 mA (100 Ω; series). At higher OLR (3.54 kg COD/m$^3$-day) studied, during initial phase of operation, potential difference of 203 mV (0.58 mA; 100 Ω) was observed. Voltage increased steadily with time and approached a maximum of 308 and 291 mV at operating pH 6 and 7 respectively prior to decreasing. Maximum current of 0.93 mA (100 Ω; series) and 0.82 mA (100 Ω) was observed at operating pH of 6 and 7 respectively.

Applied OLR in association with pH has shown influence on the power output. Comparatively higher current output (0.93 mA; 8.89 mW/m$^2$) was observed at higher OLR and operating pH 6.0. Higher current density was observed at acidophilic conditions [pH 6; 98.13 mA/m$^2$ (2.64 kg COD/m$^3$-day; 100 Ω) and 111.29 mA/m$^2$ (3.54 kg COD/m$^3$-day; 100 Ω)] rather than neutral conditions [pH 7; 100.52 mA/m$^2$ (2.64 kg COD/m$^3$-day; 100 Ω) and 98.13 mA/m$^2$ (3.54 kg COD/m$^3$-day; 100 Ω)] during fuel cell operation irrespective of OLR applied. Irrespective of the operating pH, higher OLR depicted higher power. With every additional feeding event, a consistent increase in potential difference was observed which might be attributed to the adaptation tendency of the inoculated microflora. Immediately after shifting OLR/pH event, a marked drop in potential difference was noticed for a short period of time.

### 3.2. Substrate degradation

MFC which resembles anaerobic suspended growth contact reactor used for wastewater treatment, documented its capacity to treat wastewater in association with power generation (Fig. 3). During the stable phase of fuel cell operation at pH 7, COD removal efficiency of 43.78% and 43.06% accounting for SDR of 1.15 and 1.52 kg COD/m$^3$-day was observed at OLRs of 2.64 and 3.54 kg COD/m$^3$-day respectively (Stable 1). Similarly, at operating pH of 6, COD removal efficiency of 35.23% and 41.88% accounting for SDR of 0.93 and 1.48 kg COD/m$^3$-day kg COD/m$^3$-day was observed at OLRs of 2.64 and 3.54 kg COD/m$^3$-day respectively. A gradual improvement in the current generation was observed with substrate exhaustion during fuel cell operation. Reduction in substrate (COD) during fuel cell operation enumerates the effective functioning of selectively enriched mixed microflora in metabolizing the

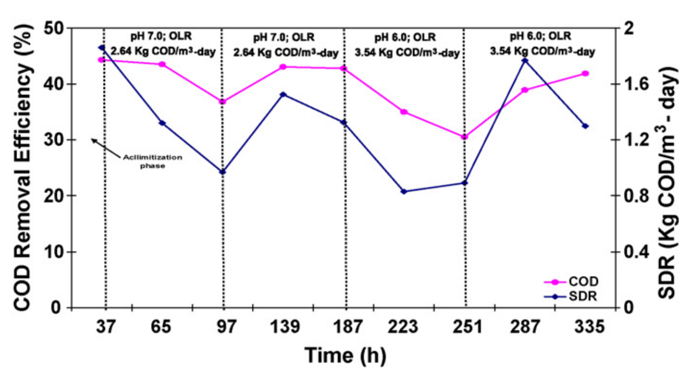


Fig. 3. Substrate degradation rate and efficiency during the operation of MFC [$r^2$—0.9878].

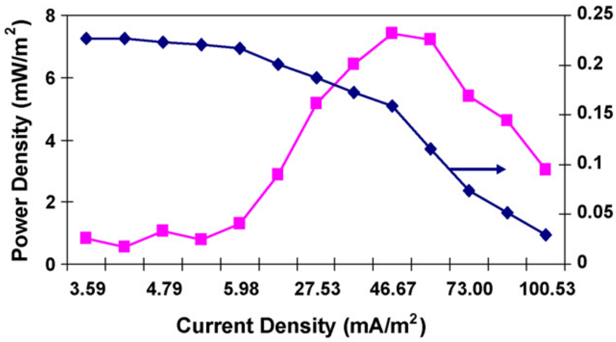


Fig. 4. Polarization curve measured at various resistances generated during stabilized performance of MFC [pH 7.0; 2.64 kg COD/m$^3$-day].

carbon source as electron donors. Operating pH and applied substrate loading rate showed marked influence on the substrate degradation efficiency. Increase in substrate loading rate showed improvement in substrate degradation efficiency. However, at operating pH 6, the increase was significant especially at higher OLR studied. Power output was comparatively higher at acidophilic conditions. Higher substrate degradation efficiency observed at neutral pH condition may be attributed to the effective functioning of MB in metabolizing soluble metabolic intermediates (VFA) produced during the acidogenic process.

Relatively higher specific power yield was observed at acidophilic microenvironment compared to neutral pH irrespective of applied OLR (Stable 1). Specific power yield of 57.17 mW/kg $COD_R$ [pH 6] and 44 mW/kg COD [pH 7] was observed at operating OLR of 2.54 kg COD/m$^3$-day. A good correlation ($R^2$; 0.91–0.87) was observed between power yield and current density during fuel cell operation at studied operating conditions. Comparatively higher power yield was documented at lower OLRs studied irrespective of the operating pH. The lower power yields observed at higher operating OLR may be attributed to the loss in proton transfer mechanism. This observation was reported earlier with chemical wastewater in dual chambered MFC using same culture (Venkata Mohan et al., 2008).

### 3.3. Biochemical analysis

#### 3.3.1. Polarization study

Polarization curve was generated by plotting current density against potential and power density measured at variable resistance points (100–30,000 Ω) during stabilized fuel cell operation at all the experimental variations studied (Fig. 4 and Sfig II). Maximum power density of 7.43 and 7.83 mW/m$^2$ was observed at 500 Ω resistances at operating OLR of 2.64 kg COD/m$^3$-day at pH 7 and 6 respectively. At higher operating OLR (3.54 kg COD/m$^3$-day) maximum power density of 7.69 and 8.89 mW/m$^2$ was registered at 400 Ω resistance for pH 7 and 6 respectively. Operation at peak power density can cause instability due to tendency of oscillation between lower and higher current densities at peak and it is usual practice to operate the cell to the left side of the power density peak and at a high voltage or low current density (Jang et al., 2004). At OLR of 2.64 COD/m$^3$-day, maximum power density was observed at external resistance of 500 Ω and the fuel cell can be operated effectively below 500 Ω resistances. Similarly with OLR of 3.54 COD/m$^3$-day, maximum power density was observed at 400 Ω and the cell can be operated effectively below 400 Ω resistance. Upon variation in operating OLR and pH in concurrence with the external resistance applied, changes in the overall power output and the specific power production (substrate to current conversion efficiency) were observed.

Current generation showed consistent decreasing trend with increase in the resistance which is in concurrence with literature reported earlier (Jang et al., 2004; Oh and Logan, 2005; Venkata Mohan et al., 2007a,d,2008). Voltage stabilization was rapid at higher resistance (30,000 Ω) compared to lower resistances (100 Ω) studied. Relatively effective electron discharge observed at lower resistances may be probable reason for higher potential drop and slow stabilization of the voltage at lower resistors. Substrates metabolism was observed to be more at lower resistance than at higher resistance, where microbes donate electrons to the anode which are discharged in closed circuit (Jang et al., 2004). At operating pH of 6, the fuel cell documented relatively effective electron discharge at external resistances of 10 and 15 kΩ at lower and higher OLRs studied respectively. On the contrary, at neutral operation (pH 7), the fuel cell responded at lower external resistance (5 kΩ) at both the OLRs studied.

#### 3.3.2. Measurement of cell potential

The relative decrease in anode potential against the external resistance was depicted in Fig. 5. Variation in potentials of the cathode, anode, and cell against the external resistance are presented in Sfig III. The cathodic potential was almost constant at each external resistance, showing that the current is limited by the anode (Menicucci et al., 2006). The cell potential decreased significantly when resistance applied was less than 1 and 0.75 kΩ at higher and lower OLRs applied.

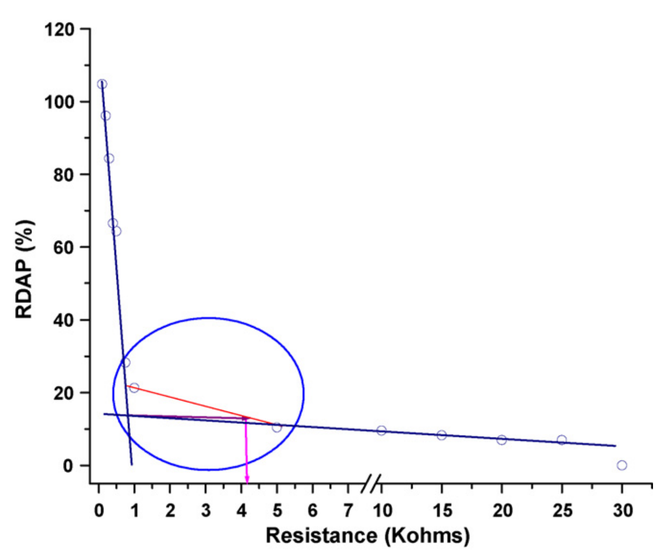


Fig. 5. Effect of external resistance on the variation of percent deviation of anodic potential with respect to applied external resistance and evaluating sustainable power [3.54 kg COD/m$^3$-day; pH 6].

### 3.3.3. Sustainable power evaluation

Power generated by MFCs can be computed as the product of the cell potential and the current in the external circuitry (Menicucci et al., 2006). The fuel cell and the external circuit will be in steady state if the power generated by the MFC equals the power consumption for an extended time and at steady state conditions the power production is sustainable. Because many steady states are possible, it is important to define conditions at which the sustainable current reaches a maximum by a MFC (Menicucci et al., 2006). Decreasing resistance was measured to evaluate the sustainable power, current and cell potentials by changing external resistance stepwise in equal time intervals (Fig. 5). Sustainable power calculations were made considering the initial anodic potential ($E_{o,\text{anodic}}$) and relative decrease in anodic potential (RDAP) at each applied external resistance as shown in Eq. (1) (Menicucci et al., 2006) after the MFC reached a stable cell potential at respective experimental conditions.

$$\text{RDAP}(\%) = \left[\frac{(E_{o,\text{anodic}} - E_{\text{anodic}})}{E_{o,\text{anodic}}}\right] \times 100 \quad (1)$$

The percent variation of RDAP with respect to applied external resistance is shown in Fig. 5 (3.64 kg COD/m$^3$-day: pH 6). The linear fit at high external resistances represents a region in which the external resistance controls the power, while, the linear fit at low external resistances represents a region in which the power is limited by kinetics, mass transfer, or internal resistance (Menicucci et al., 2006). When external resistance is high, the RDAP increases linearly with decreasing external resistance because the electron delivery to the cathode is limited by external resistance. However, when a low external resistance is applied, the electron delivery to the cathode is limited by kinetic and/or mass transfer (or internal resistance). The RDAP increases linearly with decreased external resistance, with different slopes, for external resistance or internal resistance limited conditions. The conditions where external and internal resistance limitations are equal must be somewhere between these two lines, which is presented as a dotted line. When both lines intersect, a horizontal line from the intersection was drawn to estimate the external resistor that allows us to measure sustainable power. From the graphical procedure we found an external resistor value between 4.25 and 6.15 kΩ for the experimental variations studied with the MFC that corresponds to sustainable power generation (Table 1).

### 3.3.4. Coulombic efficiency

Coulombic efficiency ($\epsilon_{cb}$) is defined as the ratio of total coulombs actually transferred to the anode from the substrate, to maximum possible coulombs if total substrate removal produces current (Logan et al., 2006). Coulombic efficiency ($\epsilon_{cb}$) over a period of time ($t_b$) is calculated as shown in Eq. (2) (Cheng et al., 2006; Logan et al., 2006; Rabaey et al., 2005].

$$\epsilon_{cb} \frac{M \int_0^{tb} I \, dt}{F b v_{An} \, \Delta \text{COD}} \quad (2)$$

Table 1
Effect of the rate of change of external resistance on the change in sustainable power yield and impedance analysis in association with experimental variations studied

| Experimental condition | Maximum sustainable power (mW) | Maximum sustainable power yield (mW/kg $COD_R$) | Corresponding resistor (kΩ) | $Z_T$ variation (kΩ) | Specific power production at max $Z_T$ (mW/kg $COD_R$) | Specific power production (mW/kg $COD_R$) and $Z_{load}$ (Ω) | $Z_T$ at max specific power production (Ω) |
|---|---|---|---|---|---|---|---|
| pH 6; 2.64 kg COD/m$^3$-day | 16 | 14 | 4.55 | 0.060 to 27.94 | 7 | 57.17 (500) | 451.87 |
| pH 6; 3.54 kg COD/m$^3$-day | 38 | 14 | 4.50 | 0.049 to 27.87 | 3 | 26.00 (400) | 333.33 |
| pH 7; 2.64 kg COD/m$^3$-day | 21 | 15 | 6.15 | 0.051 to 28.40 | 5 | 44.00 (500) | 462.26 |
| pH 7; 3.54 kg COD/m$^3$-day | 24 | 11 | 4.25 | 0.061 to 28.04 | 3 | 23.63 (400) | 339.68 |

$Z_T$—total impedance.

Where, $M$ is the molecular weight of oxygen (32), $F$ is Faraday's constant (96,485 °C), $b$ represents number of electrons exchanged per mole of oxygen (4), $\nu_{An}$ is the volume of liquid in the anode compartment (0.65 l), and ΔCOD depicts change in COD concentration over a period of time (tb). Maximum $\epsilon_{cb}$ of 8.2% was observed at lower OLR (2.64 kg COD/m$^3$-day) studied irrespective of applied pH (Sfig IV; Stable 1). At higher OLR relatively lower $\epsilon_{cb}$ [(7.5% (pH 7); 7.1% (pH 6)] was observed.

### *3.3.5. Bioprocess monitoring*

VFA (represented as the total of all acids generated during acidogenic fermentation) concentration along with pH was monitored during the fuel cell operation to evaluate the bioprocess mechanism of bioelectricty production (Sfig V). Anaerobic process was always associated with conversion of organic fraction to acid intermediates with the help of specific group of bacteria, and acidic intermediates formed will help to enumerate changes in the metabolic pathway. Stabilization in VFA generation was not observed up to the end of the cycle period at OLR 2.64 COD/m$^3$-day. However, at OLR 3.54 COD/m$^3$-day a gradual raise in VFA concentration was noticed. During stable phase of operation, maximum VFA concentration of 577 mg/l was observed at OLR of 2.64 COD/m$^3$-day. In the case of higher OLR studied, maximum VFA concentration of 640 mg/l was observed. Accumulation of high concentration of VFA at the end of cycle operation resulted in lower voltage production. However, VFA concentration cannot be considered to directly influence potential difference created in the given system as the voltage generation depends on number of other factors such as mass transfer, temperature and internal resistance. At lower OLR studied, VFA correlates well with power production and SDR. At higher OLR, VFA either with SDR or power yield did not exhibit good correlation. A consistently decreasing trend in pH values was observed during the fuel cell operation (Sfig 5b). Persistent acidogenic metabolism encountered in the anode chamber due to VFA formation presumably provides congenial microenvironment for the proliferation of AB (Venkata Mohan et al., 2007b,c).

The effective power yield observed at acidophilic pH condition may be attributed to the microenvironment which permits functioning of AB and at the same time inhibiting the MB creating susceptible conditions for $H_2$ production. The optimum range for all MB was between 6.0 and 8.0, with an optimum near pH 7.0, while AB had lower pH optimum around 6.0 and are insensitive to acidic conditions (Dinopoulou et al., 1998; Hawkes et al., 2002; Venkata Mohan et al., 2007a,b,c). Using selectively enriched acidogenic culture improves the generation of protons and electrons by oxidation of organic substrate. Fuel cell utilizes theses protons and electrons to develop a potential gradient which results in higher power generation.

### *3.3.6. Impedance analysis*

Total impedance has an effect on the current generation and voltage output in MFC operation (Ouitrakul et al., 2007). An attempt was made to evaluate the impedance of MFC during operation keeping electrode material and electrode-membrane assembly constant. Current and power distributed to the external resistance/load ($Z_L$) was determined from the generated voltage based on the Thevenin equivalent circuit containing a single voltage source ($V_{MFC}$) and total impedance ($Z_T$). Total impedance ($Z_T$) was calculated by estimating loading effect from the voltage obtained ($V_L$) at the external resistance ($Z_L$; 30 kΩ to 100 Ω) and the open circuit voltage ($V_{MFC} = V_L$) as per the Eq. (3).

$$V_L = Z_L \times \left[\frac{V_{MFC}}{(Z_T + Z_L)}\right] \qquad (3)$$

Table 1 also depicts impedance analysis data generated during the MFC operation in concurrence with the experimental variations studied. Experimental variation did not show significant influence on the impedance values (Sfig VI). However, acidophilic pH showed comparatively lower impedance values than the neutral conditions which is an evidence for effective electron discharge. Higher specific power yield was observed at lower OLR where relatively higher impedance values were recorded. Impedance should be generally low to prevent the loading effect in connection with an external load and also to reduce the power loss inside the electrode itself (Ouitrakul et al., 2007).

## 4. Conclusion

Experimental data showed the feasibility of single chambered MFC fabricated with glass wool membrane employing selectively enriched acidogenic mixed consortia in terms of power generation and substrate degradation. The major advantages of the designed fuel cell evaluated in this study are its single chambered configuration (visualizes anaerobic contact reactor), mediatorless anode chamber, plain/non-coated graphite electrodes, mixed consortia and replacing glass wool as proton exchange membrane depicts cost effectiveness and utilizing wastewater as substrate for *in situ* power generation apart from treatment reveals its sustainable nature. Performance of MFC was found to depend on the applied organic loading rate and pH. Acidophilic conditions showed feasible microenvironment for effective power generation. Biochemical evaluation of experimental data revealed the fuel cell behavior with respect to power generation. The substrate degradation observed in the anode chamber enumerates the functioning of MFC as an alternative wastewater treatment unit process in addition to renewable energy generation. The described system can be directly integrated with the existing anaerobic treatment units with minor modifications.

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## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.bios.2007.11.016.

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