4

Performance evaluation of algae assisted microbial fuel cell under outdoor conditions

In recent years microbial fuel cell (MFC) has emerged as an alternative bio-electrochemical device for wastewater treatment and energy recovery. An MFC produces energy due to the exoelectrogenic activity of anaerobic microbes [Gao et al., 2020]. These microbes oxidize electron donor substrate and reduce anode giving electrical energy [Chen et al., 2019]. Although being a powerful technology, most of the promising MFC studies are limited to the lab scale. Several factors affect the scale-up and outdoor operation of algae assisted MFCs [Gajda et al., 2018]. In particular, the power output decrease with the increase in the scale. This is addressed by stacking multiple small MFCs in series or parallel. However, maintaining multiple stacks of MFCs is a tedious task. It is also necessary to use low-cost materials in a scaled-up system.

The literature cites a few examples of the scale-up MFCs system. For example, A 26 L-MFC constructed to treat anaerobic sludge, produced 17.85 mW of power and removed 78.8% COD [Ghadge and Ghangrekar, 2015]. Similarly, a 45 L MFC fabricated using glass fiber reinforced plastic & ceramic separators gave 14.28 mW power & 84 % COD removal [Ghadge et al., 2016]. Recently, Liang et al. (2018) reported a 1000 L-modularized MFC treating real municipal wastewater. The reactor operated for one year generating power density of 7-60 W/m^3 & COD removal at 70-90% [Liang et al., 2018]. Except for some of the studies, the performance of outdoor MFC is rarely reported and, when reported, is often incomplete. To the best of our knowledge, there are no studies on the outdoor operation of algae assisted MFCs. Therefore, this study was undertaken to assess the performance of algae assisted outdoor MFC. The materials used for MFC were low-cost mainly, the anodic and cathode chambers, which were made of clay and plastic bag, respectively. The clayware chamber served as a separator as well. The study also undertook the blending of clay and rock phosphate (RP) to enhance its performance.

Rock phosphates (RP), also known as phosphorites, are sedimentary depositions of apatites. Apatites are referred to as substances having phosphate and other minerals like carbonates, silicates, quartz, sulfates, etc. [Kumari and Phogat, 2008]. Rock phosphate dissolves gradually in acidic conditions [Basak and Biswas, 2016], enabling the slower release of phosphates for algae growth. In one of the studies, fluorapatite enhanced algal growth by releasing ortho-phosphate. The biomass production showed a linear correlation with the amount of apatite added in the nutrient media [Smith et al., 1977].

Keeping in mind the above mentioned points the fabricated outdoor MFCs were evaluated in terms of power output, algae growth rates, and energy productivity. The bacterial community degrading residual lipid extracted algae (LEA) biomass in the anode chamber was also analyzed. The study also presents cost assessment data.

4.1 MFC CONSTRUCTION, INOCULATION, AND OPERATION

Rock phosphate was obtained from Jhamarkotra mines located at Udaipur (Rajasthan). Rock phosphate was mixed with clay (Black soil) at 5% & 10% loading. Clayware/Clayware blended with rock phosphate served as the anodic chamber (1L). Low-density polythene (LDPE) bags (10 L) having dimensions (L*W*D) as 1 m × 0.2 m × 200 µm served as the cathodic chamber. The anodic inoculum was taken from previously operating MFCs degrading lipid extracted algae

(LEA) biomass. The original source of inoculum was pre-treated cow-manure. The electrode material as an anode (11cm × 11cm) and the cathode (18cm × 36cm) was graphite felt. Copper wire (gauge 2 mm) connected anode and cathode through a 1000 ohm resistor. The MFCs labelled as 5% RP-MFC, 10% RP-MFC, and CW-MFC (Clay only) were operated outdoor (Figure 4.1 b). Synthetic wastewater containing KH_2PO_4 4.4 g/l, K_2HPO_4 3.4 g/l, NaCl 0.5 g/l, $MgSO_4$ 0.2 g/l, $CaCl_2$ 0.014 g/l and KNO_3 1 g/l constituted the anolyte [Vijay et al., 2016]. LEA biomass (2 g/l) served as an electron donor substrate with anodic inoculums acclimatized on it. The anode chamber or the clayware was a closed cylinder with the detachable lid for medium exchange. The lid was closed and sealed properly to enable anaerobic conditions. Catholyte consisted of algae cultivation medium and *Chlorella vulgaris.*

The MFC reactors operated in a fed-batch mode in triplicates. Drop-in voltage & COD after each cycle accompanied LEA addition and medium replenishment.

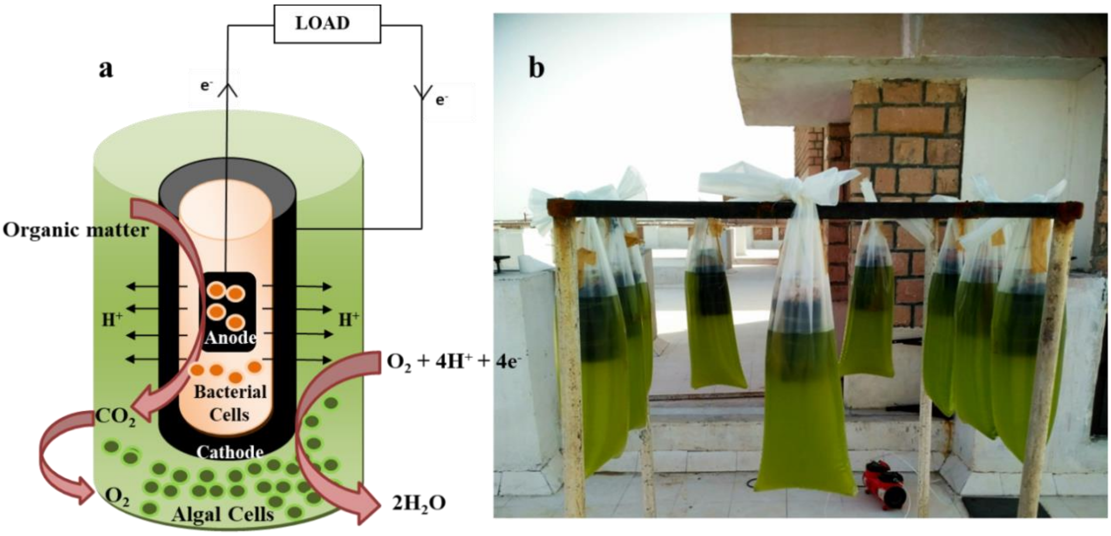

Figure 4.1: a) Schematic depicting the design and function of a MFC used in the study. b) Photograph showing the real experimental MFCs operating outdoors.

4.2. RESULTS AND DISCUSSIONS

4.2.1 Physical characterization

The XRD analysis determined the composition of Clay, RP and RP blended clay. The XRD for clay revealed the presence of several hygroscopic oxides like SiO_2, Al_2SiO_3, ZrO_2, and Al_2O_3. Among these, the significant peaks were associated with SiO_2 and Al_2SiO_3. The presence of high mineral contents results in enhanced ion exchange capacity. XRD obtained for the RP showed peaks corresponding to fluorapatite ($Ca_5(PO_4)_3F$) & calcium fluoride (CaF_2). The diffractogram obtained for RP blended clay showed peaks of aluminum phosphate and aluminum silicate. In the blends, fluorapatite and quartz were also detected (Figure 4.2).

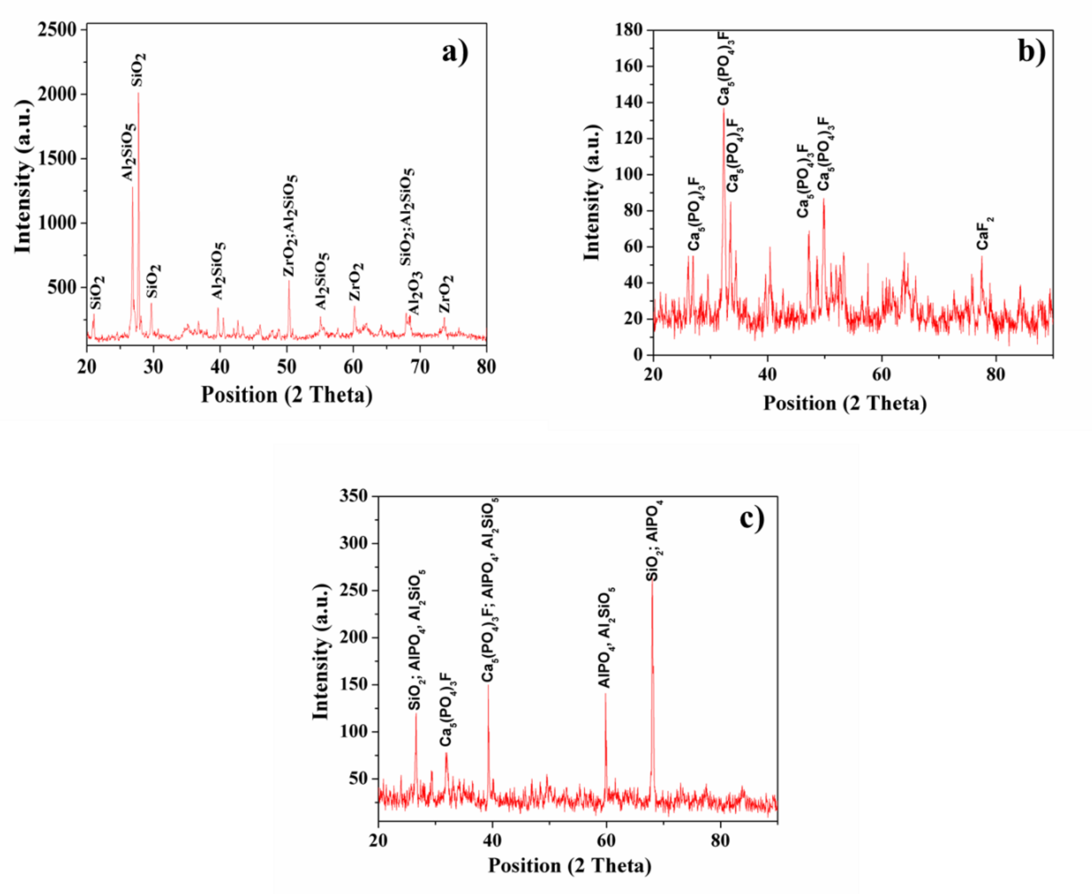

Figure 4.2: X-ray diffractograms obtained for a) clay, b) rock phosphate, and c) rock phosphate blended clay.

Table 4.1 shows the physical characterization of clay and RP blended clay separators. There was no significant difference in the value of the proton diffusion coefficient (K_D – cm^2/sec) and proton mass transfer coefficient (K_H – cm/sec) for both clay and RP blended separators. This suggests that blending RP had no beneficial effect on the proton exchange capacity of clay. Similarly, all the separators exhibited the oxygen diffusion coefficient (K_O – cm/sec) in the same range. The 10% RP blended separator showed slightly higher water holding capacity (WHC) compared to 5% RP blended separator and Clay separator. This may be due to the higher content of phosphates in the 10% RP blended clay membrane. It has been reported in an earlier study that excess phosphate adds negative charge in the soil and lead to formation of iron or aluminium phosphate, which results in enhanced WHC of soils [Lutz et al., 1966].

Table 4.1 : Physical characterization of different separators used in this study.

Parameters	5% RP	10% RP	Clay membrane
Water holding capacity (%)	13.67	14.11	12.21
Proton mass transfer coefficient (K_H – cm/sec)	2.1×10^{-6}	2.8×10^{-6}	5.34×10^{-6}
Proton diffusion coefficient (K_D – cm^2/sec)	0.84×10^{-6}	1.12×10^{-6}	2.73×10^{-6}
Oxygen mass diffusion coefficient (K_O – cm/sec)	1.3×10^{-4}	1.6×10^{-4}	11.26×10^{-5}
Oxygen diffusion coefficient (D_O – cm^2/sec)	5.2×10^{-5}	6.4×10^{-5}	5.63×10^{-5}
Acetate diffusion coefficient (D_a – cm^2/sec)	25.79×10^{-6}	19.08×10^{-6}	15.11×10^{-6}

The diffusion of organic acids from anode to cathode chamber through the porous separator is inevitable, even though, it can adversely affect the MFC performance by lowering the columbic efficiency. In order to assess the organic acid diffusion, acetate diffusion coefficients were determined. Blending 5% RP with clayware increased the acetate diffusion coefficient (D_a at 25.79×10^{-6} cm^2/sec) by 1.7 times that of clay alone. This further points to the fact that 5% RP MFC realized lower power output but higher algae growth as the diffused acids would support mixotrophic algae growth.

4.2.2 MFC performance

Figure 4.3a depicts voltage v/s time for different MFC reactors. For the first 8 days, 10% RP-MFC performed better than 5% RP-MFC and CW-MFC. The voltage values were 188 mV, 150 mV and 132 mV for 10% RP-MFC, 5% RP-MFC, and CW-MFC respectively. After 200 h of operation, voltage profiles for all experimental setups were the same. The CW-MFC took the lead from 500th h and started to exhibit voltage higher than the RP MFCs. The voltage output of CW-MFC remained consistently higher, with a value of 350-425 mV. On the other hand, RP MFCs could reach a maximum of 340 mV.

The lower performance of RP blended MFCs can be attributed to several reasons. One of them can be increased porosity of blended claywares after rock phosphate dissolution. This is expected to enable oxygen diffusion in the anodic chamber and resulting in lowered potential differences across anode and cathode. The anodic pH varied from 5.5 to 6 for all MFCs. The degradation of LEA biomass liberates fatty acids, which can solubilize the RP.

The oscillations observed in the voltage v/s time curve are due to light and dark periods of algae growing in the cathodic chamber. The light period enables photosynthesis and oxygen liberation, which supports high voltage while the dark period involves oxygen consumption by algae, which lowers voltage output. In this study, DO levels varied from 3.5 mg/l in the dark period to 6 mg/l during the day period. The drop in DO level is accompanied by a drop in power output at night.

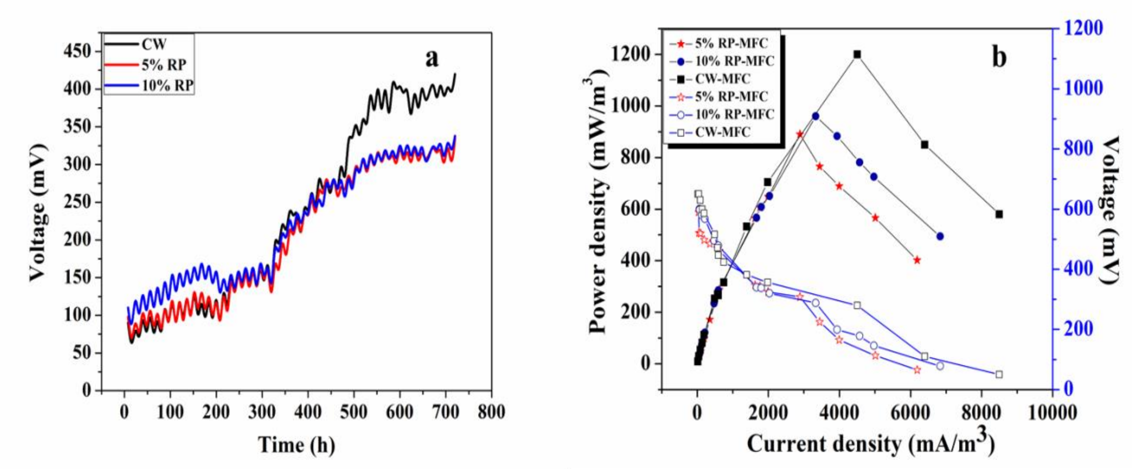

Figure 4.3: a) Profile of voltage with respect to time obtained for different MFC reactors. b) Polarization curve.

The temperature during the MFC operation varied from 28 to 39° C. Since; there were no drastic variations in temperature, the voltage values remained more or less stable. The power output from the CW-MFC, 10% RP-MFC, and 5% RP-MFC was 1200 ± 152 mW/m^3, 960 ± 120 mW/m^3, and 890 ± 95 mW/m^3, respectively (Figure 4.3 b). The previous study of small scale

LEA-fed MFC (100 ml) exhibited 2.7 W/m^3 of power density, as described in chapter 3. The scale-up is associated with a decrease in power output. Also, the previous system involved different materials such as Nafion membrane as separator and MFCs were kept in regulated/controlled conditions. However, the substrates, inoculum, and other culture conditions were the same. In addition, several studies report separators with efficiency closer or even better than the nafion membrane [Neethu et al., 2018; Yousefi et al., 2020]. The power output obtained in this study compares better than what is reported in the literature with similar systems. In a recent study, algae-assisted MFC (100 ml) gave a power density of 34.2 mW/m^2 [Commault et al., 2017]. In another study, a bubbling-type photosynthetic MFC reactor achieved a power density of 1.1 W/m^3 [Li et al., 2019]. The use of bubble column reactor or aerated systems can significantly enhance both power output and algae growth enabling higher gains. Similarly, an algal biofilm MFC gave a power density of 62.93 mW/m^2 [Yang et al., 2018]. These studies were carried out in controlled conditions. However, the present study discusses an outdoor operation where no external efforts were made to control temperature and other environmental conditions.

4.2.3 Algal growth

Algal growth in the cathode chamber significantly impacts the performance of MFC, as it provides oxygen for oxygen reduction rate (ORR). Therefore, higher growth rates and productivities are desirable for both high power/biomass output. Figure 4.4 shows the algae growth rate in the experimental MFCs. The algae biomass obtained at the end of the operation were 4.6 ± 0.164 g/l, 4.1 ± 0.155 g/l, and 3.92 ± 0.144 g/l in 5% RP-MFC, 10% RP-MFC & CW-MFC respectively. The initial concentration of algae was 0.005 g/l. Algae showed rapid growth during the first 8 days, and the rate dropped after the 8th day. This could be due to the shading effect. The overall specific algae growth rate observed during the exponential growth phase in 5% RP-MFC, 10% RP-MFC & CW-MFC was 0.63 ± 0.056, 0.59 ± 0.049 and 0.54 ± 0.035 d^{-1}, respectively (Table 4.2). The porous nature of clayware enables gas exchange required for algal growth. In addition, the dissolution of rock phosphate happens at acidic pH, and the blends were expected to provide a slow and steady source of phosphates for algae growth. This is the reason why the algae growth rate was higher in the blended CW. The difference between 5% and 10% RP-MFCs may be due to the N/P ratio, with 5% contributing a more optimal ratio for algae growth. Similar results were reported earlier in algae growing in wastewater rich in phosphate (1460 mg/l) but low in nitrogen content. *C. vulgaris* reached a biomass density of 4.7 g/l, and it was limited by the nitrogen concentration in the system [Huang et al., 2017].

The algal productivity and biomass concentration realized in this study fares well when compared with other outdoor algae cultivation systems. A 50 L vertical tubular type photobioreactor operated outdoor with *C. vulgaris* achieved algae productivity of 0.26 g/l/d [Chen et al.,, 2016]. In another study, *Chlorella sp. FC2* grown in outdoor bubble column photobioreactor achieved a remarkable 0.8 g/l/d of algal productivity. A novel CO_2 feeding strategy was used in this study to enhance algal biomass production [Naira et al., 2019]. Similarly, *Chlorella ellipsoidea* productivity, when cultivated in a bubble column photobioreactor under natural sunlight was 0.031 g/l/d [Wang et al., 2014]. The difference in algal productivity is likely due to variable environmental conditions where these studies were conducted.

Several factors affect the algal growth in a MFC, and this includes the rate of CO_2 transportation from anode to cathode chamber, temperature fluctuations, shading effects, and ORR. The control of these factors will enhance algae productivity, albeit at an increased cost. Furthermore, the long term operation of algae assisted MFCs can lead to biofouling of cathode, which may decrease the MFC performance due to reduced ORR. However, periodically renewing the biocathodes or addition of antifouling agents can reduce biofouling and impart longevity to the operation [Noori et al., 2019]. In addition to this, the outdoor algae cultivation is prone to contamination. Therefore, the samples were taken from cathodic chamber on regular intervals and analysed. The microscopic investigation did not reveal the presence of any other algal species.

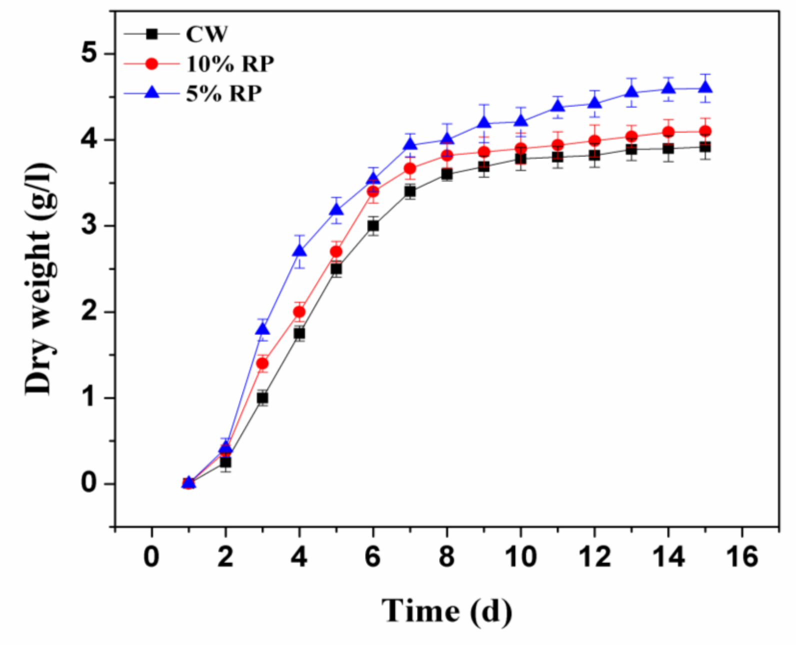

Figure 4.4: Algal growth curve obtained for different MFC reactors.

Table 4.2: Table showing MFCs performance operated with different separators.

Parameters	**5% RP-MFC**	**10% RP-MFC**	**CW-MFC**
Voltage across 1000 ohm (mV)	335 ±14.5	340 ± 37.5	425 ± 29.5
Power Density (mW/m^3)	890 ± 95	960 ± 120	1200 ± 152
Current Density (mA/m^3)	6186 ± 130	6833 ± 170	8500 ± 200
COD Removal (%)	72 ± 2	68 ± 3.5	74.4 ± 4
Algal biomass (g/l)	4.6 ± 0.164	4.1 ± 0.155	3.92 ± 0.144
Specific Algal growth rate (d^{-1})	0.63 ± 0.056	0.59 ± 0.049	0.54 ± 0.035

4.2.4 Microbial community analysis

LEA biomass is a complex substrate composed primarily of carbohydrates and proteins. Algal cell walls are composed of complex carbohydrates, and utilization of these requires an acclimatized microbial consortia. The inoculum for this study was obtained from pre-existing MFCs degrading LEA. Anodic biofilm was analyzed through the 16s rRNA sequencing. The major Phyla observed were Proteobacteria (45.14 %), Bacteroidetes (34.94 %), Firmicutes (8.6 %) and Synergistetes (3.1 %), followed by Verrucomicrobia (2.78 %), Deferribacteres (1.19 %),Spirochaetes (1.17 %), Actinobacteria (0.66 %), Chloroflexi (0.26 %), Acidobacteria (0.22 %) and Others (0.5 %) (Figure 4.5a). Similar observations were made in the literature on algae biomass hydrolysate [Zhao et al., 2018]. The class-level analysis revealed that Bacteroides (33.17 %) belonging to phylum Bacteroidetes were dominant (Figure 4.5b). The other abundant classes include Betaproteobacteria (17.46 %), Alphaproteobacteria (15.71 %), Clostridia (7.72%), Gammaproteobacteria (7 %), Deltaproteobacteria (4.41 %) and Synergistia (3.1 %). At family level, the distribution was Marinilabiaceae (15.3 %), Porphyromonadaceae (9.47 %), Comamonadaceae (8.91 %), Rhodocyclaceae (7.46 %), Rhodospirillaceae (5.88 %) and Xanthomonadaceae (4.8 %) (Figure 4.5c). Besides these, Rhodobacteraceae (3.57 %), Ruminococcaceae (2.96 %), Rikenellaceae (2.62 %), Geobacteraceae (2.52 %), Synergistaceae (2.16 %), Phyllobacteriaceae (2.06 %), Pseudomonadaceae (1.76 %), Sphingomonadaceae (1.71 %), Desulfovibrionaceae (1.24 %), Deferribacteraceae (1.19 %), Brucellaceae (1.13 %) and Alcaligenaceae (1 %) were also predicted. Marinilabiaceae are chemo-organoheterotrophs capable of growing on complex substrates. The genera from this family have been reported in marine mud containing decaying algae [Ludwig et al., 2015]. The prominent genera of Porphyromonadaceae and Comamonadaceae have been reported in MFC previously [Sotres et al., 2016]. Comamonadaceae preferably metabolize organic acids, including amino acids [Willems et al., 1991]. Rhodocyclaceae have genera with the ability to break down a wide range of carbon sources, including many aromatic compounds. This family also includes sulfur-oxidizing chemoautotrophs, methylotrophs, and anaerobes that perform propionic acid fermentation. Major genera of this family are anaerobic and mostly occur in soil, sewage treatment plant, and polluted pond [Rosenberg et al., 2014]. Earlier studies have also confirmed the presence of the family Rhodocyclaceae in anodic biofilm of MFC [Zhao et al., 2018].

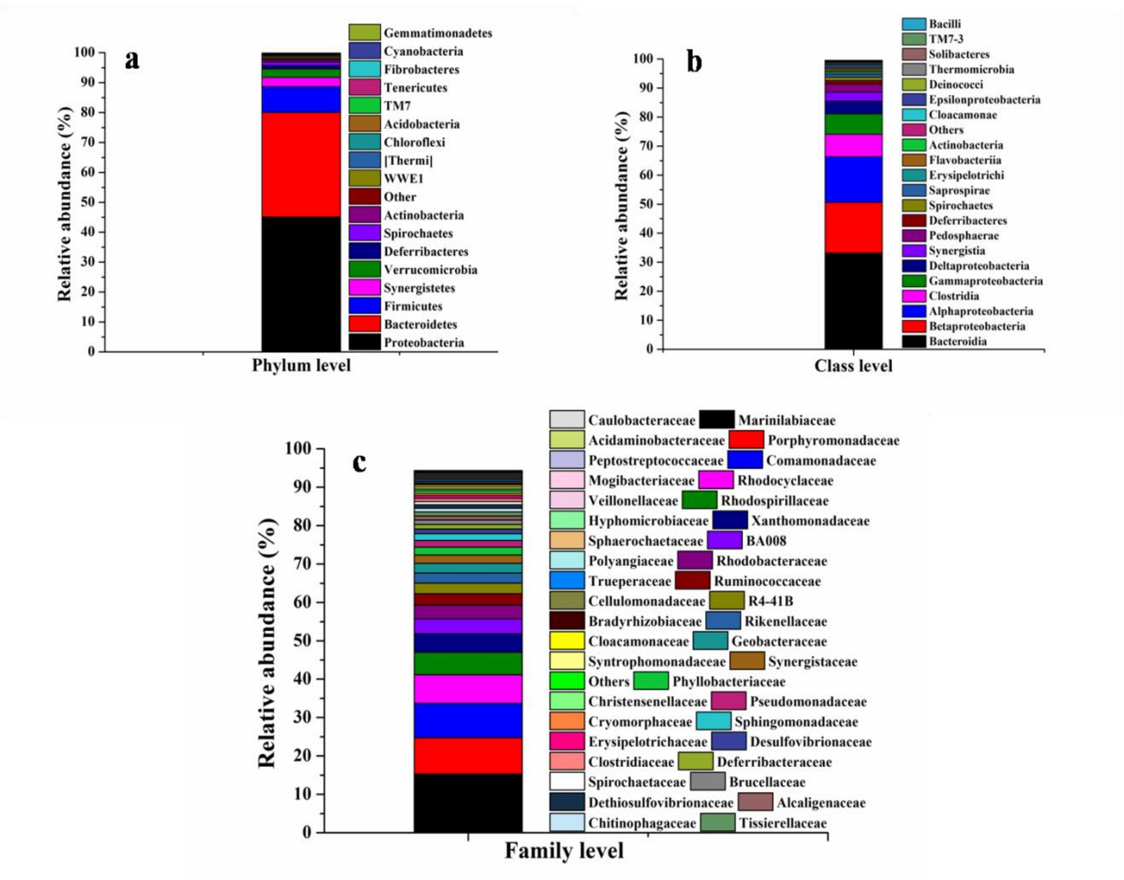

Figure 4.5: Graph showing the relative abundance at a) Phylum level, b) class level, and c) family level.

Figure 4.6 is a heatmap which displays raw OTU counts per sample. Intense colour (Red) represents OTU having relatively higher abundance whereas light color (yellow) represents OTUs having relatively lower abundance. OTUs are clusters of sequences that represent some degree of taxonomic relatedness with each cluster typically representing a genus. The most abundant genera predicted in the system are shown in figure 4.6 and include *Alicycliphilus* (5.74%), *Dechloromonas* (4.04%), *Azospirillum* (3.5%), *Paracoccus* (3.39%), *Geobacter* (2.52%), *Thermomonas* (2.03%), and *Azoarcus* (1.79%). *Alicycliphilus* is Known to degrade cyclohexanol and other aromatic & alicyclic compounds [Ye et al., 2019]. *Dechloromonas* and *Geobacter* have been identified as alkyl benzene sulfonate degraders in an anaerobic reactor treating wastewater and also discovered in MFC anodes [Carosia et al., 2014]. *Geobacter* is a known electrogen and reported in many MFC studies.

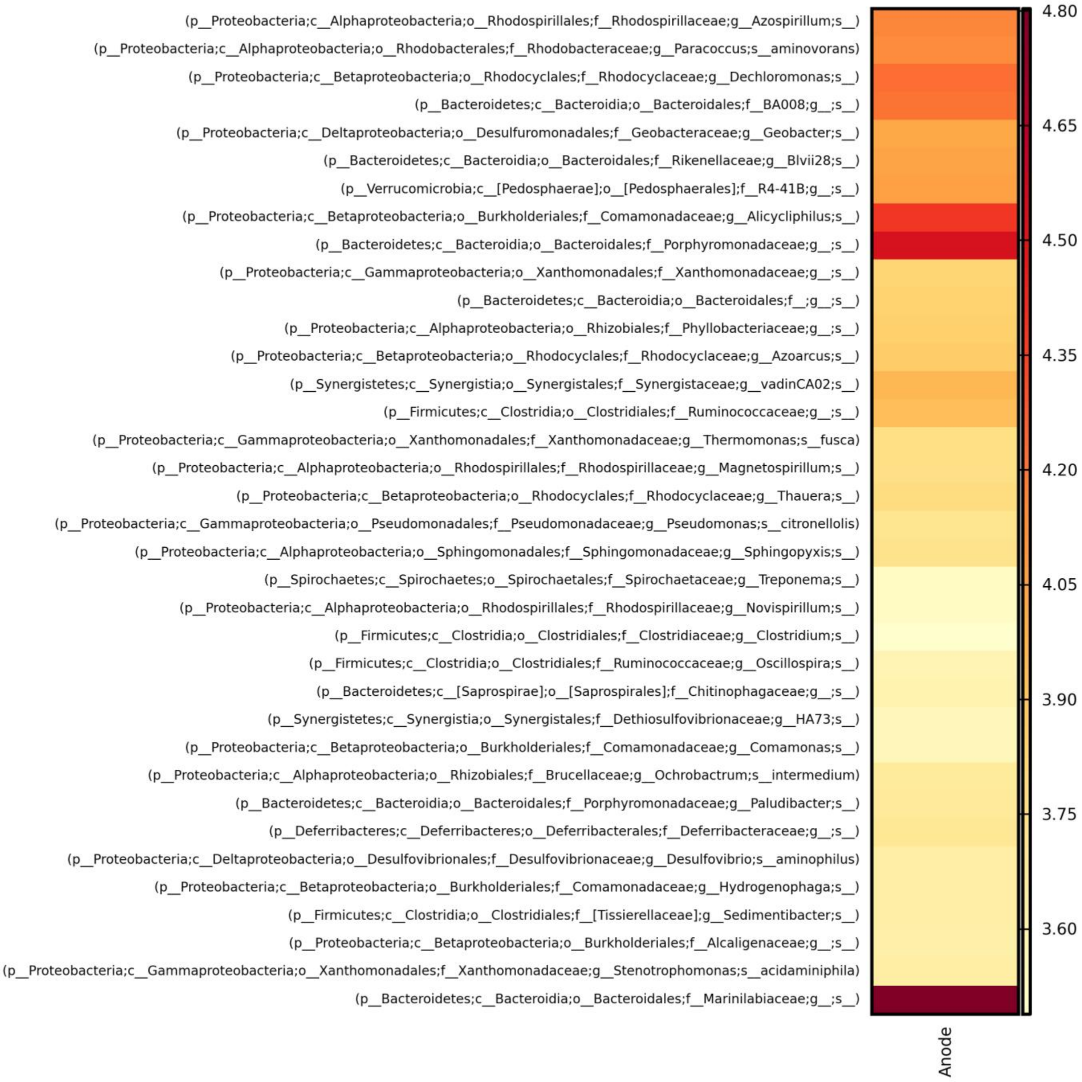

Figure 4.6: A heat map showing the taxonomy assignment for each OTU. [Intense colour (Red) represents OTU having relatively higher abundance whereas light color (yellow) represents OTUs having relatively lower abundance.

4.2.5 Energy analysis

The biomass of different *Chlorella* strains contains energy value in the range of 3.5-4 kWh/kg [Ghayal and Pandya, 2013]. Also, a net 7.82 kWh (after subtracting the energy needed for lipid extraction) of energy can be obtained from 1 kg of algal lipids [Chisti, 2008 ; Ou et al., 2013]. The normalized energy recovery (NER) is referred to as the energy value normalized with either volume or COD of waste treated. Net energy production (NEP) is calculated by subtracting process energy consumption from NER. Energy consuming components include pumps (both feeding and recirculation), external aeration, or power supply [Zou and He, 2018]. The system used in the study did not use any of them, rendering NER equal to NEP. The electric energy output obtained in this study was 0.016 kWh/kg COD, 0.017 kWh/kg COD, and 0.026 kWh/kg COD for 5% RP-MFC, 10% RP-MFC and CW-MFC respectively (Figure 4.7). The lipids were extracted from algal biomass, and their yields were 1.472 kg/m^3, 1.312 kg/m^3, and 1.25 kg/m^3 for 5% RP-MFC, 10% RP-MFC and CW-MFC, respectively. The energy recovery from algal lipids was 11.51 kWh/m^3, 10.25 kWh/m^3, and 9.8 kWh/m^3 for 5% RP-MFC, 10% RP-MFC and CW-MFC, respectively (Table 4.3).

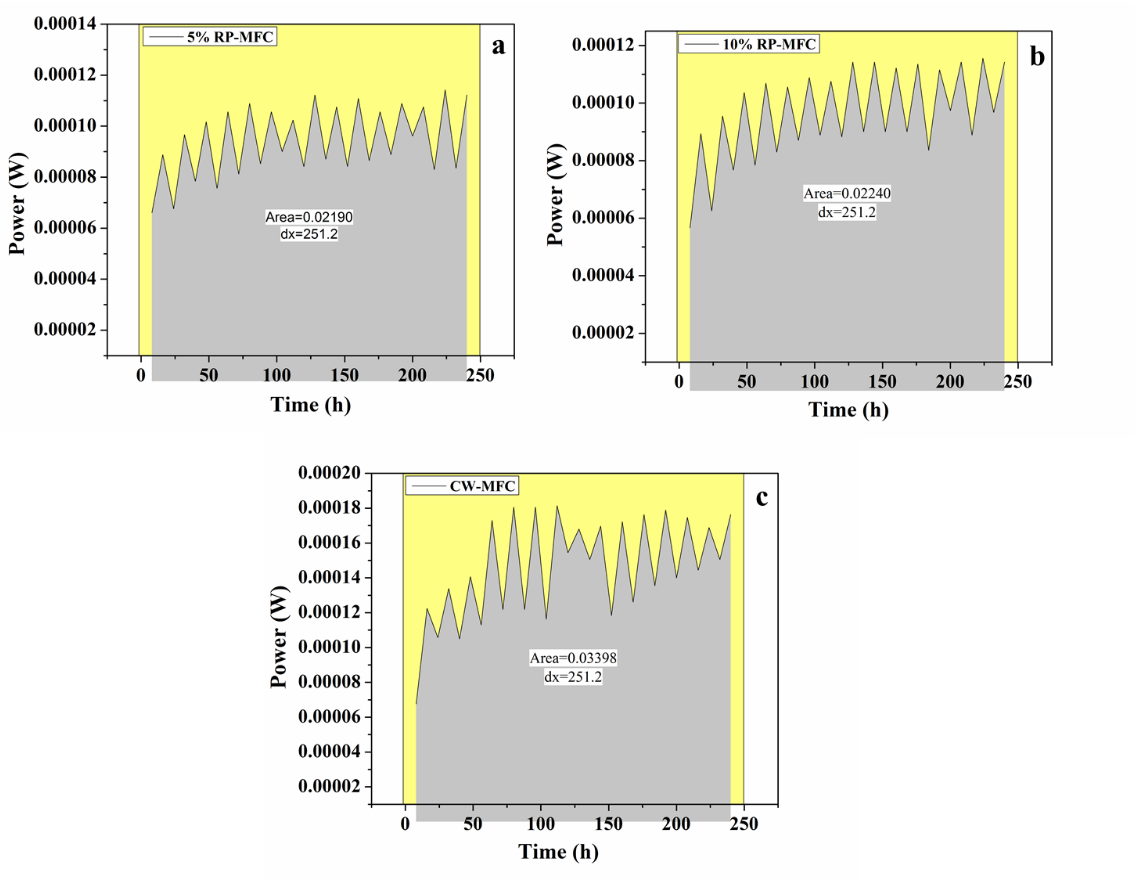

Figure 4.7: Energy curves obtained for different MFC reactors.

The specific energy productivity from algal lipids for 5% RP-MFC was obtained as 0.767 kWh/m^3/d, which is 9.8 times higher than that of formerly studied LEA-fed MFC at the lab scale in chapter 3. The increased energy productivity from algal lipids was due to the high production of algal biomass in this outdoor MFC reactor. The enhanced algae biomass showed the potentiality of RP both as a low-cost separator and algal growth promoter. Besides, this process demonstrates a low-cost photosynthetic MFC, which is a net energy positive system and can perform well in harsh environmental conditions, thus eliminating the requirement of any sophisticated lab conditions. The total energy produced is a sum of net energy obtained from algal lipids and electrical energy. This was 12.29 % and 17.44% higher in 5% RP-MFC than that of 10% RP-MFC and CW-MFC, respectively. The electrical energy contributes little to the total energy output, and this warrants coupling MFC technology with other processes as it has several indirect advantages.

Similar results were reported in the literature. The energy output of MFC in one of the studies was found to be 24.72 kWh/m^3, (a sum of electrical energy and energy from biogas). It was concluded that MFC contributed little to total energy production [Ge et al., 2013]. However, the use of bubble column reactor or aerated systems can enhance both power output and algae growth enabling higher gains. Nevertheless, the power produced from MFC can be utilized to power sensors or other low-power devices.

Table 4.3: Energy analysis of outdoor MFC reactors.

MFC reactor	Parameters	Algal biomass	Algal lipid	Energy from algal lipid	Electrical energy recovery	Total
5% RP-MFC	Net yield	4.6 kg/m^3	1.472 kg/m^3	11.51 kWh/m^3	0.02189 kWh/m^3 **Or** 0.016 kWh/kg COD	**11.5318 kWh/m^3**
	Net productivity	0.307 kg/m^3/d	0.09 kg/m^3/d	0.767 kWh/m^3/d	0.002 kWh/m^3/d **Or** 0.002 kWh/kg COD/d	**0.769 kWh/m^3/d**
10% RP-MFC	Net yield	4.1 kg/m^3	1.312 kg/m^3	10.25 kWh/m^3	0.0223 kWh/m^3 **Or** 0.017 kWh/kg COD	**10.2723 kWh/m^3**
	Net productivity	0.274 kg/m^3/d	0.087 kg/m^3/d	0.689 kWh/m^3/d	0.002 kWh/m^3/d **Or** 0.002 kWh/kg COD/d	**0.691 kWh/m^3/d**
CW-MFC	Net yield	3.9 kg/m^3	1.25 kg/m^3	9.80 kWh/m^3	0.0339 kWh/m^3 **Or** 0.026 kWh/kg COD	**9.8339 kWh/m^3**
	Net productivity	0.26 kg/m^3/d	0.083 kg/m^3/d	0.65 kWh/m^3/d	0.003 kWh/m^3/d **Or** 0.003 kWh/kg COD/d	**0.653 kWh/m^3/d**

4.2.6 Cost assessment of single MFC assembly

The process cost was calculated according to the current Indian market, including tax rates, shipping, and labor charges. The MFC components with high capital costs include a membrane (e.g., Nafion- 117) and platinum-coated electrodes [Zhuang et al., 2012]. The price of a nafion 117 membrane varies from \$1500/m^2 to \$3000/m^2. Similarly, the Pt costs around \$140/g [Zhuang et al., 2012]. The high costs make them unusable in scaled-up systems. The present study used low-cost materials, and the estimated cost of a 5% RP blended clayware was \$0.725/piece. This was significantly less when compared to MFCs based on Nafion and plexiglass reactors. The use of polyethylene bags is widespread when it comes to extensive scale cultivation of algae. Table 4.4 shows the component-wise price distribution and the quantity used for constructing a single MFC reactor. Similar cost assessments have been done in literature [Zhuang et al., 2012] [Stoll et al., 2016]. MFC used in this study is several times cheaper than what was reported by these studies. The cost analysis indicated that the system could be further scaled up and researched to enhance its efficiency.

Table 4.4: Cost assessment and analysis for a MFC employed in the study.

S. No.	MFC components	Material used	Price as per the Indian market (USD)	Quantity used	Cost (USD)/ MFC reactor	Manufacturer
1.	Anode chamber	Clayware	\$0.72/piece (1L)	1	\$0.72	Local market
2.	Cathode chamber	Polythene bag	\$1.8/piece	1	\$1.8	Unique plastic industries
3.	Cation exchange membrane	Rock Phosphate	\$94.08/Metric Ton	10% RP-125g 5% RP- 62.5g	\$0.012 (10% RP) \$0.005 (5% RP)	Jhamarkotra Mines, Udaipur (Rajasthan)
4.	Electrode	Graphite felt	\$129.6/m^2	Anode-121cm^2	\$1.56	Nickunj Eximp Entp P Ltd
				Cathode-540 cm^2	\$7	
5.	Current collector	Cu wire	\$8.64/Kg	8.3 g each in anode & cathode	\$0.143	Local market
6.	Total	**CW-MFC -\$11.22, 10% RP-MFC – \$11.23, 5% RP-MFC - \$11.225**				

4.3 CONCLUSION

A 10-L scale algae assisted MFC was successfully operated outdoor. The 5% RP-MFC supported highest algal productivity at 0.307 kg/m^3/d. The system generated a net 11.53 kWh/m^3 energy at the cost of \$11.225 only. The energy and cost analysis indicated that the system has the potential of a sustainable process and can be further scaled up. Further studies are needed to enhance power output using modified electrodes, effective separators, aerated systems to support high algae growth rates, continuous operation, and harvesting of electrical energy for sensing and automated operations.

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