Preliminary investigation of constructed wetland incorporating microbial fuel cell: Batch and continuous flow trials

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Abstract

This study has served as more encouraging signs that constructed wetlands (CWs) can incorporate microbial fuel cells (MFCs) into their design to produce electrical energy while treating wastewater. Two 3.7 L CW-MFCs have been constructed to treat swine wastewater with one (System 1) operated in batch mode while the other (System 2) was operated in continuous, upward flow mode and incorporated air diffusion heads to aerate the cathode. System 1 removed, on average, 71.5 % of COD (with initial concentration of 3190-7080

mg/L) and produced a peak power density of 12.83 μW/m^2. The aeration of the cathode significantly enhanced the performance of the CW-MFC, with System 2 demonstrating an average of 76.5 % COD removal (average influent COD concentration of 1058.45±420.89mg/L) with a peak power density of 9.4 mW/m^2.

Keywords Microbial fuel cell, Constructed wetland, Energy, Electricity, Wastewater treatment

1 Introduction

Microbial fuel cell (MFC) is an emerging technology which is gaining significant attention among researchers worldwide because of its bioelectricity generation potential during wastewater treatment [1,2]. MFCs use bacteria as the catalysts to convert organic and inorganic matter (fuel) in wastewater directly into electricity. A typical MFC consists of an anodic chamber (anaerobic) and a cathodic chamber (aerobic) separated by a proton exchange membrane. The bacteria oxidize fuel in the anodic chamber and generate electrons and protons. Electrons are then passed to the cathodic chamber through an external circuit and electric current is generated. Development of membrane-less/mediator-less MFCs and air-cathode MFCs allows significant reduction in construction and operation costs [3,4]. Despite these significant developments, MFCs are still limited by low power densities, power stability and energy conversion efficiencies [5]. One of the first challenges to be addressed for widespread MFC implementation is a drastic improvement of wastewater treatment and

robust energy generation. To this end it is important to foster a collaborative approach between MFCs and existing wastewater facilities/technologies.

The expansion of the use of MFCs will not only be dependent on the optimisation of the performance of the microbes but the design and architecture of the MFC [6]. It is noted from the literature that some ingenious designs have been developed in recent years incorporating/embedding MFCs into other wastewater treatment processes. Strik *et al*., [7] designed a plant-MFC that incorporated reeds (*Glyceria maxima*) growing in the anode chamber. It was thought that the rhizodeposits of the reeds would provide fuel for the MFC and the naturally occurring microbes in the rhizosphere of the reeds would enhance MFC voltage production. The MFC achieved a maximum voltage of 253 mV and a maximum power output of 67 mW/m^2. This is an early example of plants being used to enhance MFC voltage production. Similarly, so called sediment microbial fuel cells (SMFCs) were developed under the principle of turning biomass (organic matter) into electrical energy. Rice plants have been tested [8,9] and the rice rhizosphere was investigated to explore the effect of root excreted oxygen on MFCs [10]. It has been found that the excreted oxygen from wetland plant roots could be used for the construction of highly efficient biocathodes, thus promoting MFCs. Venkata Mohan et al., [11] studied the feasibility of bioelectricity generation in a miniature floating macrophyte ecosystem (FME) through embedded sediment type fuel cells from treatment of domestic sewage and fermented distillery effluents. Through the three fuel cell assemblies, their results show that current generation of >211.14 mA/m^2 and COD removal of 86.7 % can be achieved although the fuel cell assemblies, particularly the position of the anode, influenced the power generation potential. More importantly, they claimed that designing a comprehensive system by integrating multiple technologies such as ecological treatment and fuel cells will make the whole process economic and eco-friendly [11]. Yadav *et al*., [12] investigated the first constructed wetland (CW)-MFC based on the rational that the

stratified redox conditions in CWs can serve as cathode and anode compartments for developing a unique CW-MFC. They achieved proof of this principal using synthetic dye wastewater, operated under batch conditions. Removal of 75 % of COD from the wastewater with 1500 mg/l initial concentration of dye was obtained and a maximum power output of 15.7 mW/m^2 was achieved [12].

CWs are recognised as a green technology and have been increasingly applied for various wastewater treatments worldwide. Recent developments of CW technology allows it to be able to treat high strength wastewater with robust organic and nutrients removal, with minimal construction and operating costs, by employing alum sludge as the main substrate and operating with a tidal flow strategy [13-16]. In order to function efficiently the anode compartment of a MFC must remain anaerobic while freely available oxygen at the cathode will combine with protons and electrons to complete the circuit. In a flooded wetland system anaerobic and aerobic conditions exist throughout the bed depth [12]. Near the surface aerobic conditions are likely to prevail; oxygen intrusion from the atmosphere in tandem with oxygen leakage from the rhizosphere of wetland plants should supply dissolved oxygen to sustain cathodic reactions, while increasing depth and water saturation will ensure anaerobic conditions in the wetland bed. The stratified redox conditions that exist may be exploited by incorporating an anode in the anaerobic section and a cathode in the aerobic section thereby creating an in-situ, non-destructive CW-MFC [12]. This forms the basis of the current study on integrating MFC and the novel alum sludge-based CW, which is trialled in batch and continuous mode for renewable power generation and advanced wastewater treatment.

2 Materials and methods

2.1 Materials

Two CW-MFCs were built using two identical PVC columns, 500mm in height and 145mm in internal diameter. Uncoated graphite plates of grade Y597 and dimensions of 95×95×10mm (Olmec Advanced Materials Ltd., UK) were used as both the anode and the cathode for the two CW-MFCs. The electrodes were connected via copper wires, which were sealed to the graphite plates using silver epoxy (Radionics Ltd., Ireland) for the purpose of a better electroconductivity. Here, it is worth noting that the silver epoxy may cause toxicity to microbe for biological activity in wastewater degradation and an alternative material should be considered in the future study. Glass wool was used to separate the anode and cathode sections of the CW-MFCs. Dewatered alum sludge (produced inevitably from drinking water treatment plants when aluminium sulphate is used as coagulant for raw water purification), previously used in a pilot scale CW system as the main substrate to develop an alum sludge-based CW [14], was collected and used as wetland medium for the anode chamber to enhance the removal of phosphates from the wastewater, while gravel (with average size of 25.5mm) was used in the cathode chamber as the wetland substrate. The common reed, *Phragmites australis*, sourced from the same pilot scale CW system [14], was planted in both CW-MFCs. Swine wastewater, collected from an animal farm at Newcastle, Co. Kildare, Ireland, was used as the influent source [14]. After collection, it was diluted with tap water to obtain the desired strength.

2.2 CW-MFCs configuration and setup

Configuration of the two CW-MFCs (System 1 and System 2) is schematically shown in Fig. 1. System 1 was setup by placing dewatered alum sludge at the base of the column to a height of 210 mm, with the anode embedded. A 15mm layer of glass wool, which acted as a

physical barrier, was then placed in the column (this layer was compressed to 10mm with the addition of further materials). The glass wool helped to establish a sharp aerobic/anaerobic interface between the cathode and anode compartments. A further 190mm of gravel (average size 25.5mm) was placed above the glass wool before the cathode was put in position. A final 90mm layer of gravel (with same size of 25.5mm), in which the reeds were planted, completed the CW-MFC. Anode and cathode were connected to an external resistance of 12,000 Ω (Fig. 1), which was selected from the normal MFC studies in the literature without specific purpose. An outlet pipe was connected at the base of the MFC to allow it to be drained and the column was wrapped in black plastic to prevent algae growth.

In System 2, the anode compartment (anaerobic section) followed the same arrangement and materials used as outlined in System 1. However, in the cathode compartment (aerobic section) 60mm of gravel were placed above the glass wool separator. At this point air diffusion heads were embedded in the cathode section above which an additional 130mm of gravel was added and the cathode placed on top. Again, a final 90mm layer of gravel, in which the reeds were planted, was placed to complete the CW-MFC. The electrodes were connected externally via an electrical resistor of 1,200 Ω. An inlet pipe, connected to a pump, was supplied at the base of the MFC and two further connection ports were added at the top of the column to allow the system to operate in continuous flow mode. The column was wrapped in black plastic to prevent algae growth.

[Fig. 1 here]

2.3 Operation and analysis

Each CW-MFC had a capacity of 3.7 L. System 1 was operated in batch mode while System 2 was operated under a continuous upward-flow basis. For System 1, the wastewater was added to the top of the column and allowed to trickle through the system. Five batches were added to the system with COD ranges between 3190-7360 mg/L. The first batch (Batch 0) was added for 11 days and served to allow bacterial adhesion to the electrodes and facilitate the growth of the reeds. No samples were taken in this batch. Batch 1 and Batch 2 were operated for 10 and 11 days, respectively. Batches 3 and 4 investigated the effects of diluting the wastewater (to 3190 mg/L and 3620 mg/L, respectively) and were run for 11 days. The wastewater was introduced in day 1 of each batch, rather than gradually throughout the 10-11 days period. At the end of the fourth batch the effects of aerating the cathode were investigated by temperately inserting an air diffusor in the cathode area and bubbling the cathode compartment to increase the DO content from 0.72 mg/L to 7.39 mg/L and measuring the change in voltage drop across the external resistor in a daily basis.

System 2 was operated under a continuous vertical upward flow with the influent controlled via a peristaltic pump (Fig. 1). The flow rate was varied between 2.9 and 4.1 L/d during the experiment, giving hydraulic retention times in the CW-MFC of between 1.25 and 0.9 days. The wastewater had variable COD concentrations of between 455-3220 mg/L with an average of 1058 ± 421 mg/L. Air diffusion heads embedded in the cathode section supplied air via an air pump (Fig. 1) at a rate of 128 mL/s.

The ability of the CW-MFCs to treat wastewater was examined in terms of its removal efficiencies of COD, suspended solids (SS), total nitrogen (TN), nitrite (NO_2-N), nitrate (NO_3-N), ammonium (NH_4-N), total phosphorous (TP) and phosphate (PO_4-P). Grab samples from influent (for System 2) and effluent (for Systems 1 and 2) were collected daily and analysed. COD, NH_4^+-N, NO_2^--N, NO_3^--N, PO_4^{3-}-P and SS were analyzed using a Hach DR/2400 spectrophotometer according to its standard operating procedures. TP and TN were

determined with ascorbic method and persulfate method, respectively [17]. pH was measured for batches 2, 3 and 4 with a pH meter (Orion 920 A+, Thermo). DO was monitored with a microprocessor oximeter (Oxi 325, WTW).

The electrical performance of the Systems 1 and 2 was determined by daily measuring the voltage drop (V) across the external resistor using a digital handheld multimeter. Current (I = V/R) and power (P = VI) were determined through basic electrical calculations. The power density (mW/m^2) was then calculated by dividing the power with the surface area (m^2) of the anode. The coulombic efficiency (the fraction of electrons used for electricity generation versus the electrons in the starting organic matter) of System 2 was determined using the formula shown in Eq. (1), which was derived from Logan [18] for MFCs fuelled by complex wastewaters at a continuous rate.

$$CE = \frac{MI}{FqbΔCOD} \qquad (1)$$

Where, *CE* is coulombic efficiency (%), *M* is molecular mass of O_2 (g O_2/molO_2), which is 32. *I* is current (A) and *F* is Faraday's constant (C/mol), which is 94,685. *q* is flow rate (L/s) while *b* is number of electrons donated per mole O_2 (mol e-/mol O_2), which is 4. Finally, ΔCOD represents the change in COD between influent and effluent (g O_2/L)

3 Results and discussion

3.1 System 1 (batch tests)

Each batch was treated by the CW-MFC in a similar fashion. Initially a sharp decline in COD was observed over the first 2 or 3 days before a more steady decrease and finally arriving at a constant value with fluctuations of 50 mg/L (Fig. 2). Final COD removal efficiencies for batches 1 to 4 ranged from 65.8% to 75.1% (Table 1). Turbidity readings were taken at the

beginning and end of batches 2, 3 and 4 as a further illustration of the system's ability to treat wastewater (Table 1). For the four batches the system had an average COD removal efficiency of 71.5%. In all four batches the COD values had become steady for at least 3 days immediately prior to a fresh batch being added, suggesting that the maximum COD removal had been reached. The congruency of results in relation to the final COD removal efficiency between all 4 batches together with the agreement of final effluent COD values between Batches 1 & 2 and Batches 3 & 4 suggests that the system is capable of handling real, complex wastewaters in a predictable fashion. The pH of the wastewater was determined during batches 2, 3 and 4 in both the anode and cathode compartments (Table 1). The pH in the anode was between 0.90 and 0.98 lower than in the cathode in all three cases with the hypothesising that this is a result of the formation of fatty acids during the degradation of organic matter by anaerobic bacteria in the anode compartment. It has to be pointed out that the batch trial was more likely the feasibility study. It was mainly focusing on the COD reduction and electricity generation to reflect the rationale of the infant CW-MFC. Therefore, nitrogen and phosphorus were not monitored in this stage.

The CW-MFC produced electricity consistently during the experiment. Upon the addition of Batch 1 the voltage dropped over the first day before climbing to its peak voltage of 58 mV on day 5 and falling rapidly on day 6 followed by a steadier decline over the remaining days before the addition of Batch 2. Batches 2, 3 and 4 performed similarly. Again there was a drop in voltage recorded during the first day in all three cases after which the voltage began to rise. Although Batch 1 recorded the highest maximum voltage, higher averages were recorded by Batches 2, 3 and 4 and there was much less fluctuation in the amount of electricity produced by the system (Fig. 2). The electricity generation in Batches 3 and 4 was more efficient than that in Batches 1 and 2. This may be attributed to the growth of the reeds as the experiment proceeded. The role of wetland plants for the enhancement of electricity

production has been highlighted by Strik *et al*., [7], claiming that plant rhizodeposits can be utilized as substrates by the bacteria to generate electricity in the MFC.

[Fig. 2 here]

[Table 1 here]

Power densities (normalized to anode surface area) peaked during Batch 1 at 12.8 $\mu W/m^2$ with the highest average power density produced by Batch 4 (4.4 $\mu W/m^2$) despite the wastewater in Batch 4 having been diluted to slightly less than half the strength of Batch 1. Encouragingly, it is noted that the system was performing more predictably during the final three batches with an increase in average power densities at lower standard deviations. Given that the initial COD loading for Batch 2 was more than double the loading for Batches 3 and 4 the congruency of results between these batches is promising, suggesting that the system is becoming mature and is capable of dealing with variable loads. Power outputs remained consistent even after the COD had reached its minimum value, suggesting that there was either a delay in the delivery of electrons to the anode, or only a small percentage of bacteria were contributing to power production as a result of the system's architecture or a lack of electrogenic bacteria. It is likely that the small ratio between the electrode surface area and the anodic compartment volume limited the amount of electrons being accepted by the anode. Although no imaging was undertaken, it is likely that the gravel and alum sludge contained a plethora of anaerobically respiring bacteria that were oxidising the organics in the wastewater and releasing electrons that were used in processes other than electricity generation. Obviously, further study is desirable to explore this.

During the operation of Batch 4 DO concentrations were determined for both the anodic and cathodic compartments as 0.54 mg/L and 0.72 mg/L, respectively. At the end of Batch 4 the cathode was aerated for 30 minutes increasing the DO concentration to 7.39 mg/L. This was met with a significant increase in voltage from 31 mV to 333 mV, indicating that the system was greatly restricted by the limited availability of DO. This is the reason to set up the ensuing continuous flow trial of CW-MFC with aeration in cathode chamber.

3.2 System 2 (continuous flow trial)

3.2.1 Wastewater treatment efficiency

The system was fed with swine wastewater on a continuous flow basis at a rate of between 2.85 and 4.06 L/day and treated 224.8 L of wastewater over 62 days. The performance of the system is summarised in Table 2 while the COD variation over the course of the experiment is illustrated in Fig. 3. The loading was highly variable with COD concentrations fluctuating between 455 - 3220 mg/L and an average COD concentration of 1058 ± 421 mg/L. However, the variation in the quality of effluent was much lower (Fig. 3), demonstrating the system's ability to handle real, complex, variable wastewater. An average COD removal efficiency of 76.5% was recorded during the system's operation.

[Fig. 3 here]

After the first 10 days of operation the CW-MFC was producing effluent streams which varied from 142 - 267 mg/L despite the influent fluctuating from a minimum of 594 mg/L to a maximum of 3220 mg/L. The predictability of the system under such variable loading

conditions holds great promise. Similarly, the concentration of SS in the influent varied dramatically over the course of the 62 days. The maximum (1344 mg/L) and minimum (123 mg/L) influent concentrations differed by an order of magnitude whereas the corresponding effluent values were 24 and 23 mg/L, respectively. TN was removed with an average efficiency of 49.7%, while NH_4-N was removed with an average efficiency of 77.4%. The average concentrations of nitrate and nitrite were two orders of magnitude larger in the effluent than in the influent, suggesting that nitrification was the primary source of NH_4-N removal, while the net decrease of TN may suggest that denitrification was also taking place. TP was reduced, on average, by 65.9%, while PO_4-P removal was at an efficiency of 46.2%. The removal of P was not as good as expected due, most likely, to the fact that the alum sludge had been used in a pilot scale CW system for 2 years before being seeded into the current CW-MFC system and the P adsorption capacity had been starting to decreased [13,14]. It is worth noting that this study is the preliminary investigation of CW-MFC, focusing mainly on exploring the wastewater treatment (mainly indicated by COD reduction) and power generation (voltage measurement). Nutrient removal or enhanced nutrient removal should be further studied after the basic configuration of the CW-MFC is established. The pH of both the influent and the effluent varied for the duration of the testing period. However, with the variation within the range of 7.06 and 8.03 for the influent and 6.52 and 7.98 for the effluent and pH averages for the influent and effluent of 7.76 ± 0.23 and 7.29 ± 0.42, respectively, the pH can be considered as circumneutral during the testing period.

[Table 2 here]

3.2.2 Electricity production

While operating under continuous flow the system constantly produced electricity, generating 642.8 J of energy over the course of 62 days. Fig. 4 illustrates the power density and the COD

net removal (Influent – effluent). It seems that there is no discernible link between the COD reduction and the power density. Microbial activity, the wetland plants, HRT and the configuration and materials of the system will all affect the production of power within the CW-MFC. These factors would need to be controlled before the effects of organic loading could be established. Nevertheless, despite fluctuating loads, the average voltage was 371.14 ± 78.97 mV, peaking at 495 mV. Normalized to the anode surface area, the CW-MFC produced an average power density of 5.49 ± 2.17 mW/m^2 and a maximum of 9.35 mW/m^2. Current production was greatly affected by the coulombic efficiency (CE) of, on average, just 0.1%. In complex wastewaters the plethora of microorganisms may reduce the CE of the system. Methanogenesis and aerobic respiration are typical examples of electrons being "wasted" and the reason why CEs in wastewater MFCs are typically in the range 0.7 - 8.1% [19]. Although lower values of CEs are often reported [20,21], Ahn and Logan [22] achieved a CE of 40% while treating domestic wastewater. Nevertheless, the current system was able to continuously produce electrical power despite a fluctuating COD load of between 455 - 3220 mg/L.

[Fig. 4 here]

Although there was no discernible link between the organic loading and the power density, the CE seems affected by the influent COD. Increases in COD were met with decreases in CE (Fig. 5), suggesting that the system would be more efficient under lower organic loading. However, at COD concentration as low as 533 mg/L the CE, although 6 times higher than the average across the 62 days, was still only 0.6 %, indicating that the CE was affected by more than the organic loading. Similarly to System 1, it is likely that the low ratio of electrode area to reactor volume in combination with the alternative surfaces for bacterial attachment and growth, provided by the gravel and alum sludge, have contributed greatly to the low CE.

[Fig. 5 here]

3.3 Outlook

The experiments have demonstrated that both System 1 and 2 effectively treated the high strength swine wastewater, delivering effluents with small standard deviation in the COD removal efficiencies despite varying loads. The average COD removal efficiencies of 71.5% (System 1) and 76.5% (System 2) were comparable to similar CW trials reported in previous studies [13,15]. In a laboratory scale CW developed by Hu *et al.*,[15] for high rate nitrogen removal, an average of 74% of COD was removed. Similarly, Zhao *et al.*,[13] developed a laboratory scale alum sludge-based CW in a pyrex column with the same internal diameter as Systems 1 and 2 and removed 82.9 ± 12.3% of COD in this tidal flow CW operated over 2 years. When the system was scaled up (4 hydraulically linked 1100L plastic bins) between 36% and 84% COD removal efficiencies were achieved. In comparison with other litre-scale MFCs, treating real wastewaters, the COD removal efficiencies achieved here are similar (Table 3). The treatment performance of the CW-MFC developed by Yadav *et al*., [12] is mirrored in this study with COD removal efficiencies of 74.9% and 76.5%, respectively. The congruency of results between this study and similar alum sludge based CWs, and other MFCs, indicates that the incorporation of MFC technology has no adverse effects on the ability of the CW to fulfil its primary objective of wastewater treatment. This can also been evidenced by the bacteria images (Fig. 6) captured in System 2 of the CW-MFC towards the end of the testing period. Flocs of bacteria were abundant in the sample (Fig. 6A), which are indicators of good treatment having occurred. Although a confocal microscope was used to capture the images of the micro fauna and the confocal microscope observation is a qualitative description of the micro fauna, by comparing the captured images with the

standard image of the micro fauna [23], a number of different kinds of micro fauna could be identified in the CW-MFC system. Protozoa of the family *Clitiates* were found. *Clitiates Epistylis* sp. can be seen in Fig. 6B and *Clitiates Paramecium* sp. in Fig. 6C. These types of protozoa are useful indicators as they feed on bacteria and algae and are present in wastewater when most of the organic material has been removed [23].

[Fig. 6 here]

However, it is noted that the ability to produce electrical power was restricted and improvements are required for further study. The power density of 9.4 mW/m^2 is similar to that achieved by the CW-MFC developed by Yadav *et al.*,[12] which used a synthetic wastewater in batch mode but some way short of other, more traditional MFC designs using real wastewater. This study aims to incorporate MFCs into an existing, traditional form of wastewater treatment, similarly, Zhang *et al.*,[14] have developed an MFC to be incorporated into an anaerobic digestion chamber and produced power densities a factor of 30 higher than reported in this study. The low ratio of electrode area to reactor volume may result in comparatively low power densities. The gravel and alum sludge provided an alternative surface to the electrodes for bacterial attachment and growth. This in conjunction with the small electrode surface area meant that the majority of COD was utilised by bacteria not contributing to electricity generation. The 390 mm spacing between the electrodes undoubtedly contributed massively to the internal resistance particularly in System 1 which was operated in batch mode and so was limited in its ability to transfer products and reactants. Power was further limited by the lack of oxygen supply at the cathode illustrated by the 10 fold increase in voltage when oxygen was injected into the cathode compartment. In theory, oxygen injection/bubbling will benefit the reaction in cathode [24]. This came at an

energy cost associated with the air diffusion heads, however, and so alternative methods to optimise the reduction reactions at the cathode should be explored. Both systems were designed using basic materials (uncoated graphite plates) and architecture (upflow configuration with cathode above the anode), which leaves ample room for the improvement of power density. Increasing the specific surface area of the electrodes by impregnating the surfaces with multiwalled carbon nanotubes, nanopowder [25] or graphene [26] results in higher power production as the increased available surface area for bacterial growth increases the number of direct electron transfer centres. Scaled-up MFCs should have relatively small liquid volumes when compared with their high electrode specific surface areas, while the electrode spacing should be brought to a minimum. Reaction kinetics is slower at the cathode, and so the surface area of the cathode should be increased relative to that of the anode. Doubling the size of the cathode may increase the power produced from domestic wastewater by 62% while doubling the anode shows only a 12% improvement: the specific surface area of the cathode is the critical parameter in MFC scale-up [27].

[Table 3 here]

4 Conclusions

This study explores the potential to integrate MFC technology into CWs to concomitantly achieve dual goals of power generation and advanced wastewater treatment with minimal construction and operating costs. Two model laboratory-scale CW-MFCs were built and tested in batch and continuous flow mode, respectively. The results demonstrated that MFC technology has no adverse effects on the ability of the CW to fulfil its primary objective of efficient wastewater treatment. The continuous flow CW-MFC with cathode aeration is worth

further investigation regarding high power generation. Although the current study is the preliminary investigation of the CW-MFC configuration and operation, the attempt may attract more research interest towards further exploration of this topic.

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Table 1 Performance of System 1 (batch operated) CW-MFC.

	COD (mg/L)			Turbidity (NTU)		pH		Power ($\mu W/m^2$)	
Batch	Initial	Final	Removal Eff. (%)	Initial	Final	Cathode	Anode	Max.	Mean
1	7080	1760	75.14	-	-	-	-	12.83	2.39 ± 3.58
2	7360	1940	73.64	325	87	8.38	7.48	5.08	3.81 ± 1.08
3	3190	1090	65.83	352	52.6	8.30	7.32	4.86	3.69 ± 0.73
4	3620	1030	71.55	321	25.6	7.86	6.96	5.59	4.39 ± 0.77

Table 2 Wastewater treatment performance of System 2 (continuous flow) CW-MFC.

	Mean Concentration (mg/L)		
	Influent	Effluent	Removal Efficiency (%)
COD	1058.45 ± 420.89	227.80 ± 73.31	76.48 ± 9.97
Soluble COD	515.75 ± 200.01	184.13 ± 31.63	60.16 ± 14.08
SS	422.95 ± 252.26	25.80 ± 25.73	92.92 ± 7.91
TN	146.73 ± 49.23	68.99 ± 11.33	49.73 ± 13.18
NH4-N	89.91 ± 15.93	19.75 ± 11.50	77.37 ± 11.50
NO_3-N	0.28 ± 0.35	40.5 ± 13.01	-
NO_2-N	0.08 ± 0.11	4.12 ± 1.81	-
TP	11.34 ± 6.00	3.47 ± 1.11	65.89 ± 14.18
PO_4-P	6.18 ± 3.34	2.90 ± 0.99	46.18 ± 22.99
pH	7.76 ± 0.23	7.29 ± 0.42	-

Table 3 Comparative performance of selected litre scale MFCs treating real wastewaters.

Type of MFC	Reactor volume (L)	Wastewater	COD (mg/L)	COD removal (%)	Max. power (mW/m^2)	Reference
Submersible	1.0	Anaerobic Digester Sludge	17000	71.9	290.0	[21]
Single Chamber	1.5	Fermented human faeces	880	71.0	240.0	[28]
Single Chamber	0.5	Canteen	1740	64.8	108.0	[29]
Multi-Anode Cathode	20.0	Domestic	100-500	80.0	380.0	[30]
Multi-walled carbon nanotubes	0.5	Distillery	82200	49.32	245.4	[25]
CW-MFC	5.4	Synthetic	1500	74.9	15.7	[12]
CW-MFC	3.7	Swine	1058	76.5	9.4	This study

Figure captions:

Fig. 1. Schematic description of the CW-MFCs configuration and setup: (A) system 1 and (B) system 2

Fig. 2. COD and voltage fluctuations with time. Dash line indicates addition of fresh batch.

Fig. 3. Influent COD, effluent COD and removal efficiency with time.

Fig. 4. Amount of COD removed and power density produced with time.

Fig. 5. Coulombic Efficiency versus Influent COD.

Fig. 6. Microscope image of the bacteria in System 2 of the CW-MFC.

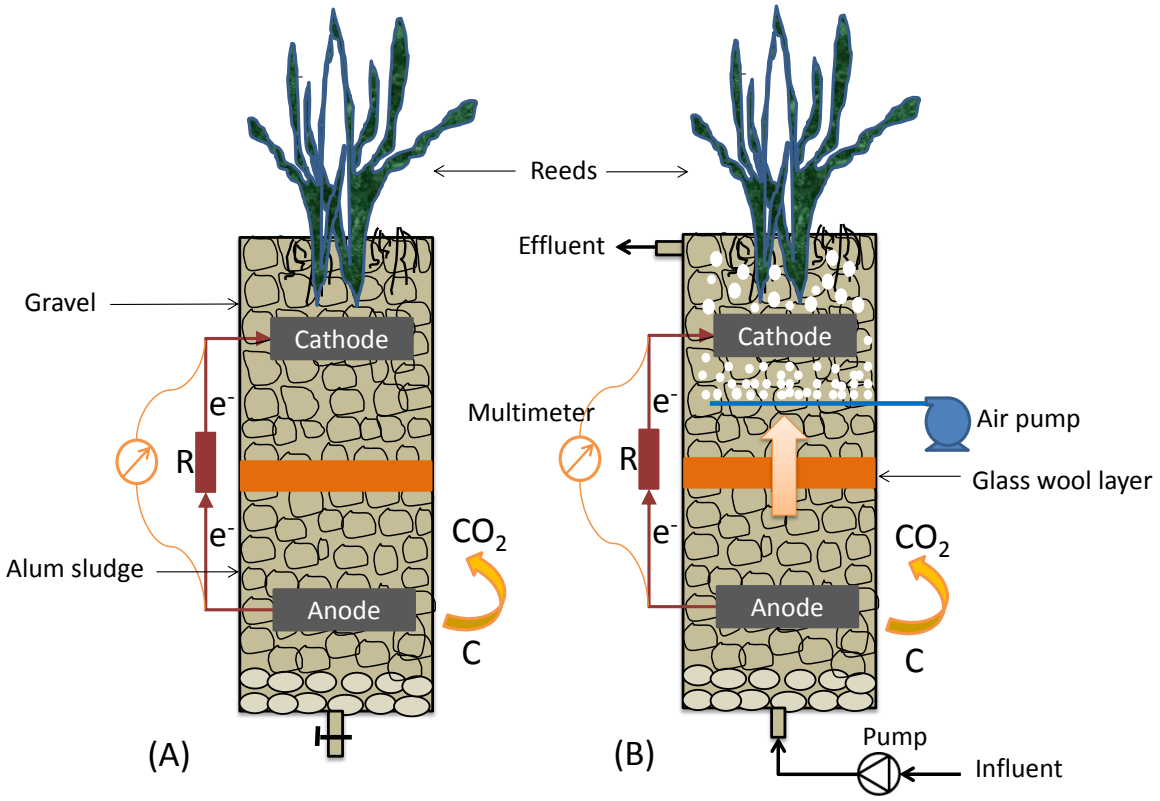

Fig. 1

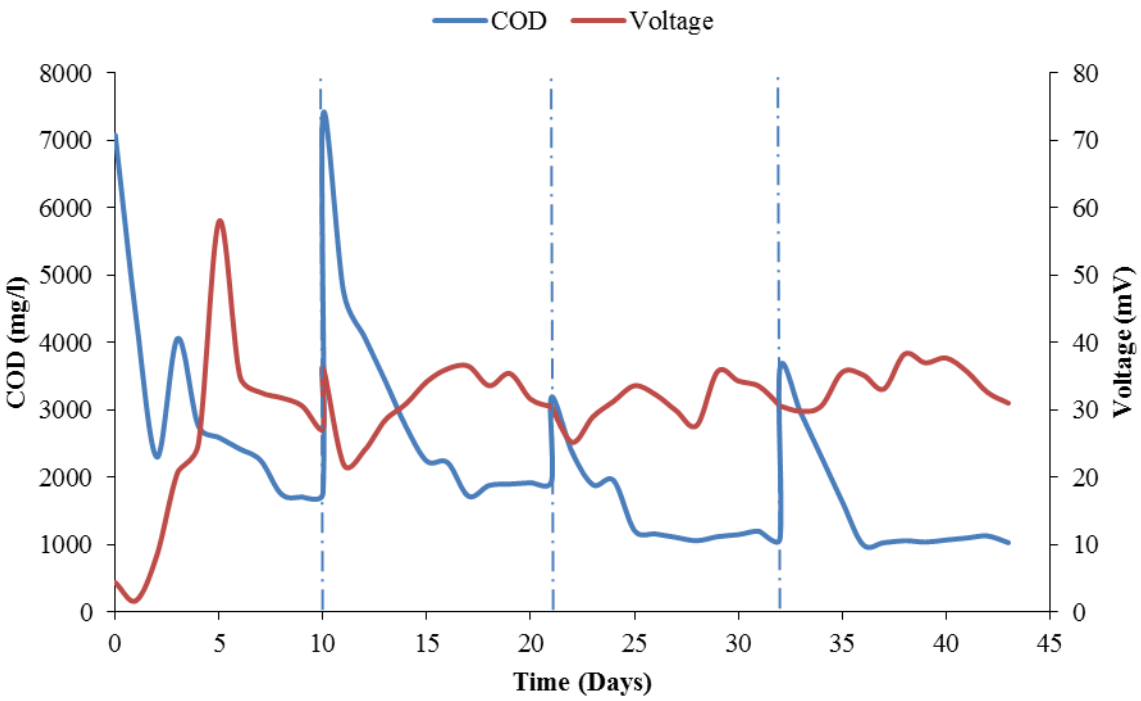
COD
Voltage
8000
7000
6000
5000
4000
3000
2000
1000
0
COD (mg/l)
80
70
60
50
40
30
20
10
0
Voltage (mV)
0
5
10
15
20
25
30
35
40
45
Time (Days)

Fig. 2

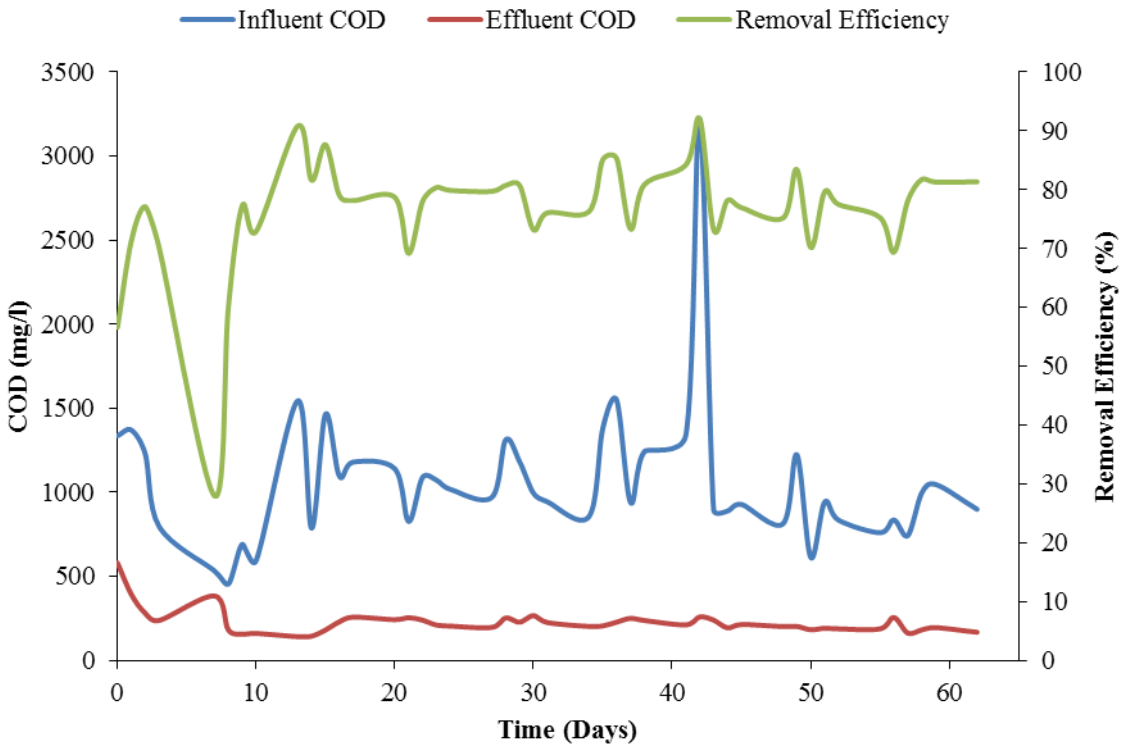
Influent COD
Effluent COD
Removal Efficiency
3500
3000
2500
2000
1500
1000
500
0
COD (mg/l)
100
90
80
70
60
50
40
30
20
10
0
Removal Efficiency (%)
0
10
20
30
40
50
60
Time (Days)

Fig. 3

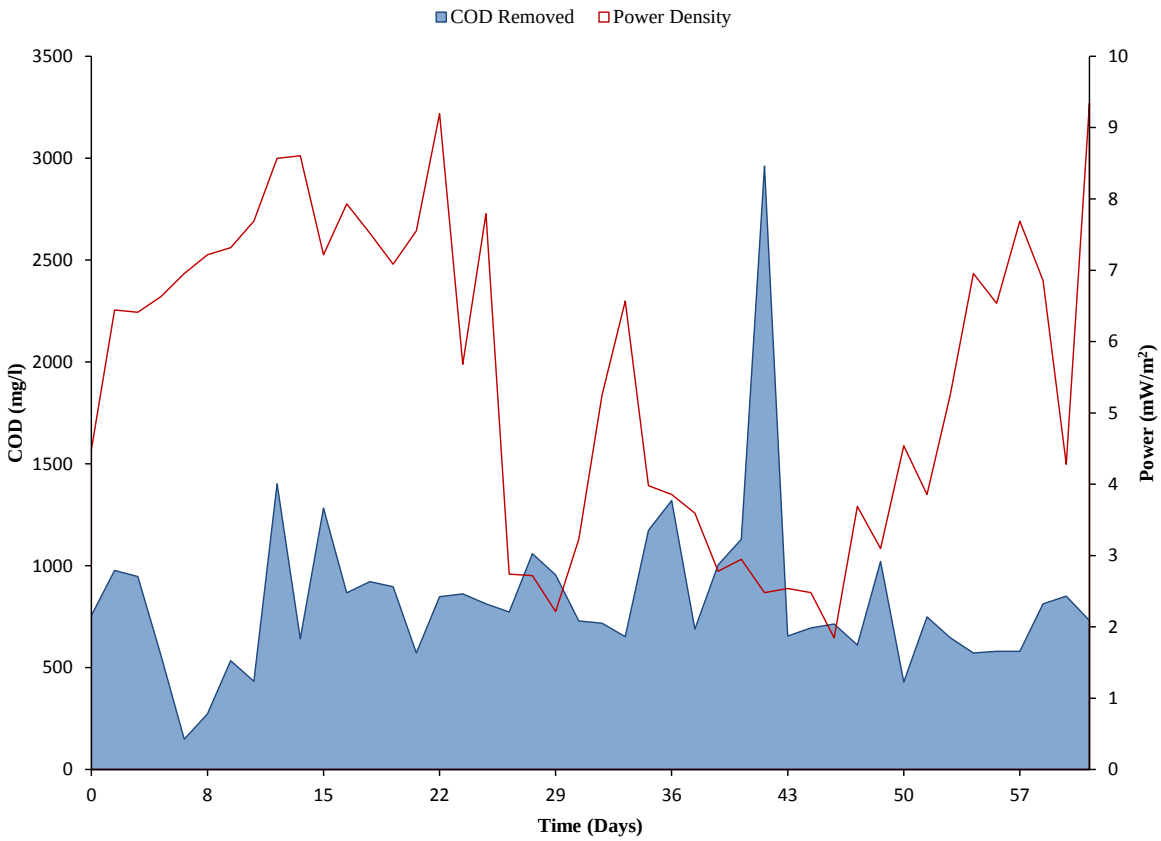
COD Removed
Power Density
COD (mg/l)
Power (mW/m²)
Time (Days)
0
500
1000
1500
2000
2500
3000
3500
0
1
2
3
4
5
6
7
8
9
10
0
8
15
22
29
36
43
50
57

Fig. 4

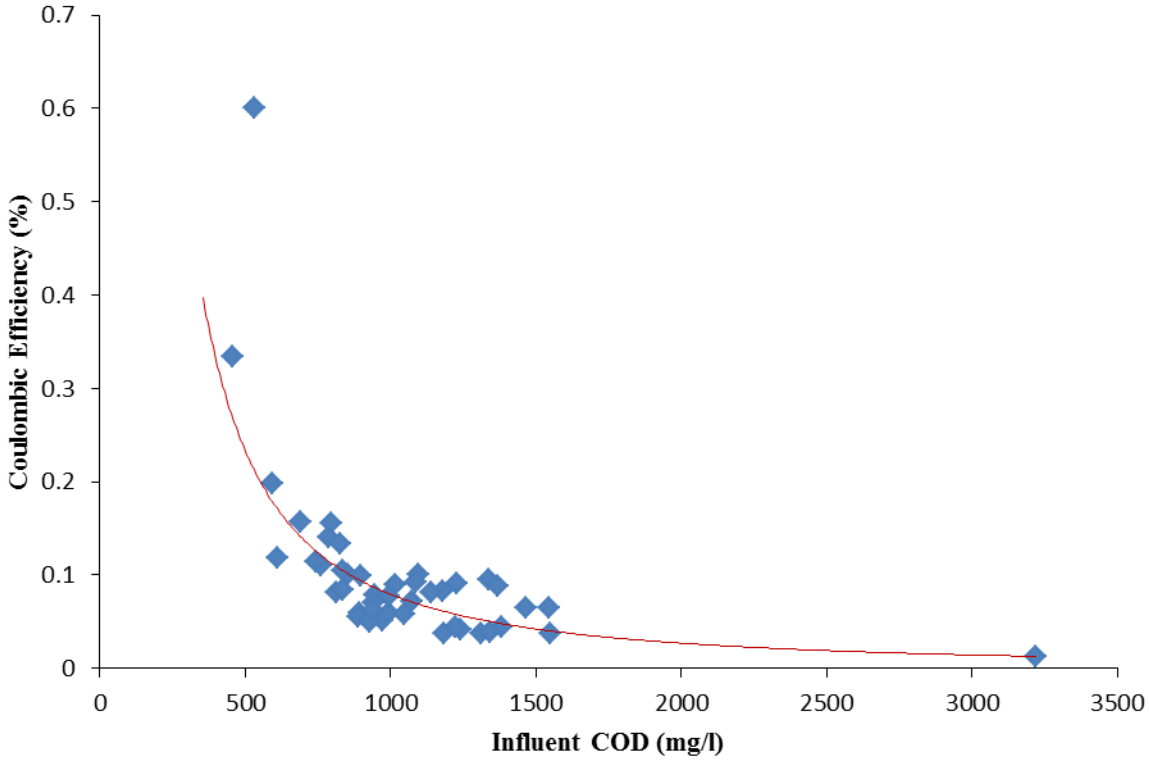
Coulombic Efficiency (%)
Influent COD (mg/l)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0
500
1000
1500
2000
2500
3000
3500

Fig. 5

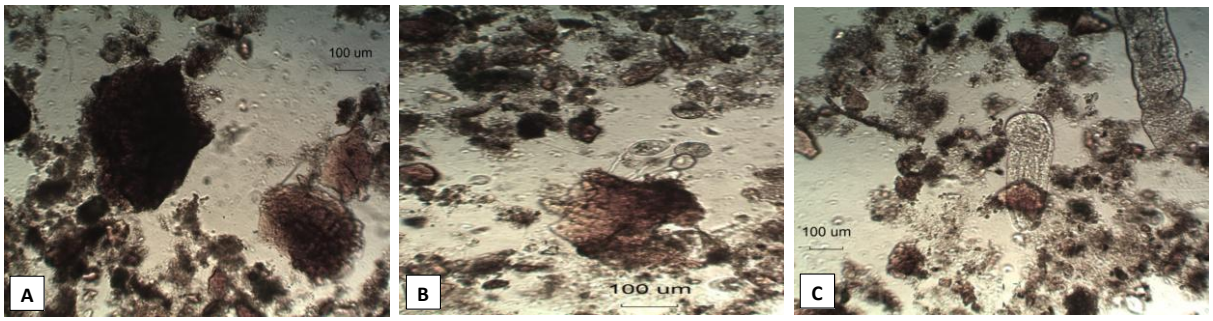

Fig. 6