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Sediment Microbial Fuel Cell as Sustainable Power Resource

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SEDIMENT MICROBIAL FUEL CELL AS SUSTAINABLE POWER RESOURCE

by

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ABSTRACT

SEDIMENT MICROBIAL FUEL CELL AS

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Under the Supervision of Professor Zhen He

This research demonstrates that Ceratophyllum demersum a root less non vascular aquatic plant has negatively affected the power generation from a Sediment Microbial Fuel cell (SMFC). In SMFC the reduced organic matter in the sediment in water produces electrons, which reduces oxygen. Whereas in Plant SMFC continuous supply of organic matter to the anode is done by rhizodeposition (root exudates). Six SMFCs were run for more than 3 months to see the effect of plants, pH and temperature on power generation. Out of six only two SMFC showed stable data. The maximum power density 18 ± 1mW/m^3 was generated from the control SMFC which is higher than Plant SMFC (9 ± 1mW/m^3). The Plant SMFC has less dissolved Oxygen 2 ± 1 mg/L than SMFC(5 ± 1 mg/L) as the large quantities of this plant grown as thick mat actually caused oxygen depletion at night. Since the experiments were conducted about few days for each SMFC there was not much significant data to explain the effect of pH and temperature on the power generation of this SMFCs.

Control SMFC has a stable pH value 8. However, Plant SMFC pH were fluctuating in the range of 7 and lower than control SMFC. The dissolved oxygen concentration for Control SMFC is 5 ± 1 mg/L which has higher power density than plant SMFC with Dissolved Oxygen (DO) 2 ± 1 mg/L.

TO

my parents, my husband

and

my lovely kids (Kartik & Vaidehi)

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1: Introduction

1.1 Microbial Fuel Cell

Renewable energy and sustainable water resources are essential for human life across the globe today. Microbial fuel cell (MFC) technology is significant as innovative form of renewable energy by producing electricity from what would otherwise be considered waste. It is considered as crucial developing technology for sustainable power production and waste treatment. MFCs convert biochemical energy of feedstock into electricity by using micro-organisms and act as biocatalysts. MFCs are still in their initial stages of development but with great potential to bring about innovation and become true alternatives to fossil fuel energy generation. A combination of both electricity production and wastewater treatment would reduce the cost of treating primary effluent storm water and wastewater. M. Potter, a botany professor at the University of Durham first got the idea of using Microbial fuel cells to produce electricity. He managed to produce current from E.coli bacteria but not received much attention in the scientific field. Later In 1931 a scientist named Barnet Cohen created a series of microbial fuel cells and achieved 2 milli amps of current. Using micro-organisms or enzymes for current generation includes range of substrates that can be oxidized or oxidants that can be reduced. So biological fuel cells can perform specific jobs, and/or have niche applications, in addition to electricity generation. Two main topics that are essential for a sustainable society are environmental protection and the generation of clean energy. MFCs are drawing worldwide attention, determined by the potential of clean and renewable energy from several wastes and waste waters. Currently, MFCs can only generate low power outputs (< 6 W m^{-2}; ≤ 500 Wm^{-2}) due to many features related to the anode, the

cathode, the chemical species present in the electrolyte, the ion–exchange or filtration membrane, the microbial species present and their metabolisms, fuel cell configuration, and operational parameters (Feng Zhao et al). Microbial fuel cell (MFC) technology has recently been of great interest as a prospective application for future sustainable energy production. With the increasing worldwide energy crunch, various renewable energy technologies have been continuously studied. Microbial fuel cells are one of the emerging technologies for renewable energy that decomposes organic matter to generate electricity using microorganisms. The sediment microbial fuel cell (SMFC) is more applicable due to it can supply electricity for the sensors without changing batteries. The purpose of this study is to establish a sediment microbial fuel cell in the laboratory and investigate the factors like dissolved oxygen, pH, temp and presence of plants affecting sediment microbial fuel cell performance.

Organic substances are converted into electricity through the action of bacteria as catalysts in MFCs (Chaudhuri 2003). A classic MFC system consists of two electrodes. 1. An anode for substrate oxidation and 2. A cathode for oxygen reduction, and they are usually separated by a proton conducting membrane. In anaerobic conditions electrons and protons are produced from organic substrates by bacteria attached to the anode. Afterwards the electrons and protons flow and diffuse through an external circuit and the membrane respectively, to the cathode where they react with oxygen to form water (Rabaey and Verstraete, 2005). Lot of previous studies have demonstrated that MFCs can be used to produce bio electricity from organic wastes such as wastewaters (Liu et al., 2004 and Min et al., 2005), sediments (Reimers et al., 2001 and Tender et al., 2002), and even rhizodeposits (De Schamphelaire et al., 2008). However, the MFC knowledge has been also used as sensors for the measurement of biochemical oxygen demand and the detection of

toxic compounds (e.g., heavy metals and anthropogenic chemicals) in both freshwaters and wastewaters (Chang et al., 2004 and Kim et al., 2007).

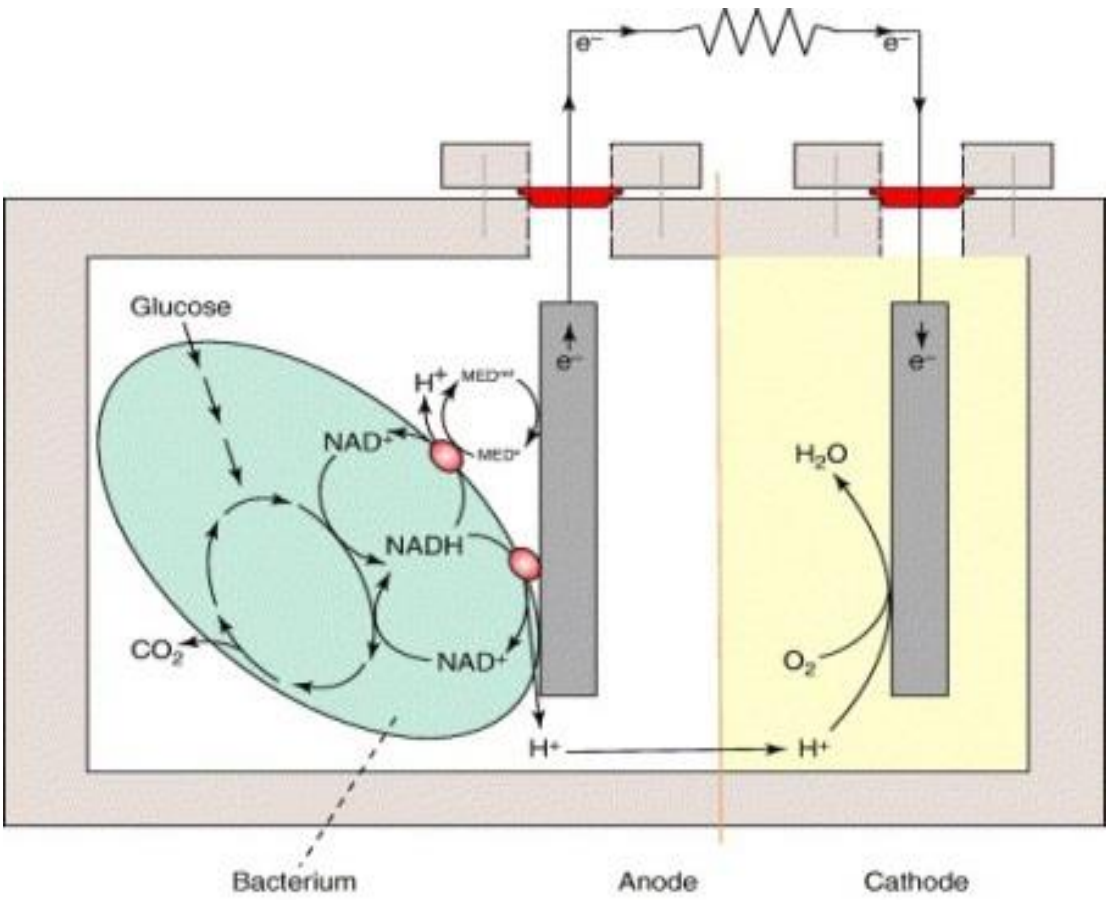

Figure 1: Schematic Diagram of MFC.

Image source: Trends in Biotechnology

1.2 Role of microorganisms in Microbial Fuel cell

Several microbes own the gift to transfer the electrons derived from the metabolism of organic matters to the anode. Marine sediment, soil, wastewater, fresh water sediment and activated sludge are all rich sources for these microorganisms (Niessen et al,). A number of latest publications conversed the screening and identification of microbes and the construction of a chromosome library for microorganisms that are able to generate electricity from degrading organic matters (Logan et all). The anodic electron transfer mechanism in MFC is a crucial topic in accepting the theory of how

MFCs work. As stated above, microorganisms transfer electrons to the electrode over an electron transport system that either consists of a series of components in the bacterial extracellular matrix or together with electron shuttles dissolved in the bulk solution. Geobacter is in dissimilatory metal reducing microorganisms, which yield biologically advantageous energy in the form of ATP during the dissimilatory reduction of metal oxides under anaerobic conditions in soils and sediments. The anodic reaction in mediator-less MFC constructed with metal reducing bacteria belonging primarily to the families of Shewanella, Rhodoferax, and Geobacter is alike to that in this procedure since the anode performances as the final electron acceptor similar to the solid mineral oxides.

1.3 Electron transfer mechanisms in the biofilm

Some microorganisms are electrochemically active, proficient of accepting electrons from an outside source or donating electrons to an external thing such as an electrode. These microorganisms are acknowledged as electro genic microorganisms. Not all microorganisms are electro genic, but non electro genic microorganisms can still be part of a synergistic electro genic biofilm group as they accomplish other jobs such as providing some organic nutrients to the electro genic microorganisms in the group. Microbial cells are usually non-conductive since their cell membranes typically contain non-conductive materials such as polysaccharides, lipids and peptidoglycans. Electron transfer between microorganisms and electrodes depends on two things, namely direct electron transfer (DET) and mediated electron transfer (MET). It should be noted that some electro genic microorganisms, such as some microorganisms in biofilm consortia in activated sludge, have yet to be characterized although such uncharacterized mixed-culture biofilms have been used widely. DET needs direct physical contact between the microbial cell membrane or a membrane organelle and

the anode electrode surface, without the requirement for any diffusional redox species.

1.4 Typical Design of microbial fuel cells and components

A typical MFC consists of an anodic chamber and a cathodic chamber separated by a Proton exchange membrane (PEM).

1.4.1 Two chamber Microbial Fuel cell

Two chambered MFCs are usually run in batch Mode frequently with a chemically defined medium such as glucose or acetate solution to generate energy. They are presently used simply in laboratories. A classic two chamber MFC has an anodic chamber and a cathodic chamber linked by a PEM, or occasionally a salt bridge, to permit protons to move across to the cathode while obstructive the diffusion of oxygen into the anode. The sections can take various useful shapes.

1.4.2 One chamber Microbial Fuel cell

Due to their intricate designs, two chamber MFCs are tough to scale-up even though they can be functioned also in batch or continuous mode. One chamber MFCs offer simpler designs and cost effective. They normally possess only an anodic chamber without the requisite of aeration in a cathodic chamber. Park and Zeikus designed a one chamber MFC comprising of an anode in a rectangular anode section linked with a porous air cathode that is open directly to the air. Protons are transported from the anode solution to the porous air cathode (Park and Zeikus). Liu and Logan designed an MFC containing of an anode positioned inside a plastic cylindrical chamber and a cathode located outside. The anode was made of carbon paper without wet proofing. The cathode was either a carbon electrode. The PEM association is done by

connecting the PEM directly onto a flexible carbon cloth electrode, or a separate rigid carbon paper without PEM (Cheng et al.). A tubular MFC s with an exterior cathode and an interior anode using graphite granules was constructed by Rabaey et al. In the nonexistence of a cathodic chamber, cathode solution is supplied to the cathode by soaking an electrolyte over the outer woven graphite mat to keep it from drying up.

1.4.3 Up flow style Microbial Fuel cell

Jang et al. constructed another style of an MFC operating in continuous flow mode. A Plexiglas cylinder was separated into two segments by glass wool and glass bead sheets. These two units helped as anodic and cathodic chambers correspondingly. The disk-shaped graphite felt anode and cathode were positioned at the end and the first of the reactor, correspondingly. There are no distinct anode solution and cathode solution. And the diffusion barricades concerning the anode and cathode offer a DO gradient for appropriate action of the Microbial Fuel cells.

1.4.4 Stacked microbial fuel cell

A stacked Microbial Fuel cell is constructed for the examination of operation of several MFCs connected in series and in parallel (Aelterman et al). Improved voltage or current output can be attained by connecting several MFCs in series or in parallel. No noticeable adverse effect on the maximum power output per MFC unit was observed. The MFC technology has to meet with the established methanogenic anaerobic digestion technology that has seen wide profitable claims (Holzman; Lusk) because they can utilize the same biomass in many cases for electricity generation. MFCs are proficient of transforming biomass at temperatures under 20 °C and with little substrate concentrations, both of which are difficult for methanogenic digesters (Pham et al). A key drawback of MFCs is their dependence on biofilms for electron transport, while anaerobic digesters such as up flow anaerobic sludge blanket reactors

remove this need by powerfully reusing the microbial consortium without cell immobilization (Pham et al). It is likely that the MFC technology will co-exist with the methanogenic anaerobic digestion technology in the future. To improve the power density output, new anodophilic microbes that vastly improve the electron transport rate from the biofilm covering an anode to the anode are much needed (Angenent et al). Lovley appealed that an MFC's electron flow could increase by four orders of magnitude if Geobacter transports electrons to the anode at the same rate as it does to its usual electron acceptor that is ferric iron (Holzman et al.). It is potential in the future that an enhanced microbial group can be found to operate an MFC without any mediators or biofilms while attaining greater mass transfer and electron transfer rates.

1.5 Prospective Applications for Microbial Fuel Cells

One of the best energetic fields of Microbial fuel cell research is the generation of electricity from wastewaters coupled with the oxidation of organic or inorganic compounds. Research studies are signifying that any compound decomposed by microorganisms can be transformed into current (Pant et al). The capacity of the Microbial fuel cell microbial communities to degrade an extensive range of environmental contaminants could be more important than production of power itself in certain circumstances, particularly whenever the MFC technology can be used for environmental protection. Among the microbial consortium Geobacter species have been known to be main in the anaerobic degradation of petroleum components and landfill leach ate pollutants in ground water. When an electrode is an electron acceptor in the soil is efficient, as the microorganisms responsible for degradation will form a biofilm with the trace elements at the graphite anode. After establishing of the electrode it will offer a continuous long term electron reservoir for the degradation of the toxic environmental contaminants. In this situation the electrons produced by the

microorganisms in the form of electricity is immaterial when compared to the improved conditions by bioremediation. Similar research studies have demonstrated that Microbial fuel cells may be prospective and able to eliminate fermentation inhibitors which formed during the process water after the pretreatment of cellulosic biomass .The elimination of the inhibitors helps in increased fermentation product yields while offering less amounts of energy. An uncommon application of MFC technology is to power implanted medical devices using glucose and oxygen from blood. This kind of implanted MFC may be helpful to generate power indefinitely and prevents the necessity for surgery to change batteries. Abiotic fuel cells built on noble metal catalysts and activated carbon has been proved to generate electricity from blood glucose. Fuel cells built on enzymatic catalysts have also been revealed to operate under physiological conditions but still demand much improvement to become sustainable. There is lot of Interest in using human white blood cells as a source of electrons for an anode (Calabrese Barton S et al). Research studies using white blood cells in phosphate-buffered saline solution with a ferric-cyanide cathode generated a low current in the range of 1-3 μAcm^{-2} but it may not be conclude if electron to the anode was done by a direct or indirect process. Microbial fuel cell power generation is still far lower than that desirable for practical power generation beyond powering small sensors, in spite of new improvements in reactor design. Complicated reactor designs may advance power output, but the cost could be excessive for real time applications. Even though improved biofilms have been obtained from activated sludge and other natural sources, a more innovation in biofilm performance is desired. Genetic modifications can better results with MFC performance.

1.6 Organic carbon removal by MFC

So far, several synthetic and real wastewater have been treated with Microbial fuel cells, like brewery wastewater, beer brewery wastewater, chocolate industry wastewater, domestic wastewater, food processing wastewater, meat processing wastewater, paper recycling wastewater, protein-rich wastewater, real urban wastewater, starch processing wastewater and swine wastewater (Pant et al). The organic carbon elimination from the anode of Microbial fuel cells is the first approach in organic matters removal in the anode is another. For instance, sulfide and ammonia oxidation have been effectively performed in the anode of MFCs (He et al., 2009b; Rabaey et al., 2006. Although microbial oxidation at the anode might be chiefly used for organic matters deletion, the innovation of bio cathode and associated reduction processes at the cathode offer a break to increase the application of MFCs in waste water treatment. In this perspective, several contaminants such as nitrate, nitrite, perchlorate, chlorinated compounds, copper, mercury and iron can be removed. (Clauwaert et al,)

One classic application is nitrogen species removal in MFCs. The first study of nitrate denitrification in MFC was proved by Clauwaert et al. (2007), where a complete denitrification at cathode without extra electron donor supply was effectively accomplished in a tubular reactor. At the same tim2, Lefebvre et al examined the same process in a dual chamber MFC. In order to more improve this application, Virdis et al established a new method which incorporates MFC with aerobic nitrification for concurrently carbon and nitrogen removal. In their loop configuration method, the effluent from the anode of a synthetic wastewater-powered MFC was nourished to an external aerobic nitrification vessel for oxidation of ammonium to nitrate. This nitrate-enriched stream was afterward nourished back to the MFC

cathode for denitrification. In addition to solve the problem that ammonia diffusion from anode to the cathode through CEM, Virdis et al combined the nitrification stage into the cathode chamber, where concurrent nitrification and denitrification (SND) were achieved. Other systems for the same purpose have been developed. A combined use of the membrane aerated biofilm and MFC processes were proposed. Xie et al developed an oxic/anoxic biocathode system for simultaneous carbon and nitrogen removal. A simultaneous nitrification and denitrification was also attained in a single-chamber MFC pre-enriched with a nitrifying biofilm.

1.7 Sediment Microbial Fuel Cell (SMFC)

While most of the microbial fuel cell (MFC) research has focused on the performance and characteristics of laboratory reactors, Sediment Microbial Fuel Cells (SMFCs), or those that rely on a potential gradient at a sediment water interface, have played an important role in the development of MFC technology. Whereas laboratory microbial fuel cells offer a distinctive chance to examine fundamental attributes of MFC performance and microbial physiology (e.g. ohmic resistance, current density, and mechanisms of electron transfer by laboratory cultivated microbes), Sediment MFCs offer a unique opportunity to examine how energy flows through microbial communities, the efficiency of collecting energy from natural systems, and the potential role that Sediment MFCs may play in power generation or bioremediation in the natural Environment. In Contrast to wastewater or other laboratory Microbial Fuel cells, there is no clear or repeatable procedure for inoculating remote Sediment MFCs; they are populated by the native microbial species occur in the natural environment. Even if laboratory microbial communities could be inoculated onto field deployed Sediment MFCs, it remains indistinct if they would remain a dominant member of the electrode microbial population, or if they would be question to

competition and predation along with native microbial community. In any of the above situations, microorganisms play two major responsibilities in the generation of electricity by Sediment MFCs. Sediment microbial fuel cells (SMFCs) can produce energy without managing in in the field. SMFC is one of the alternative renewable and sustainable power resources. Sediment microbial fuel cells (SMFCs) produce energy from the electro-potential difference between aerobic water and anaerobic sediments (T.K.Sajana et al).The concept of the sediment MFC is simply easy to be applied. Inserting an electrode as anode in the anaerobic sediment is the first step. It is the place where both organic substrates and bacteria for the current generation are present, then connecting it to an electrode which works as cathode in the overlying aerobic water. After the innovation of the sediment MFC, some improvements have been taken to enhance power levels, essentially from marine sediments, resulting in boosting the performance in terms of power output SMFCs are gaining lot of importance of the sustainable energy research as they help in treating of marine or freshwater sediments and generate electricity. The generation of energy in the form of readily available electrical power is the most important application of SMFCs.

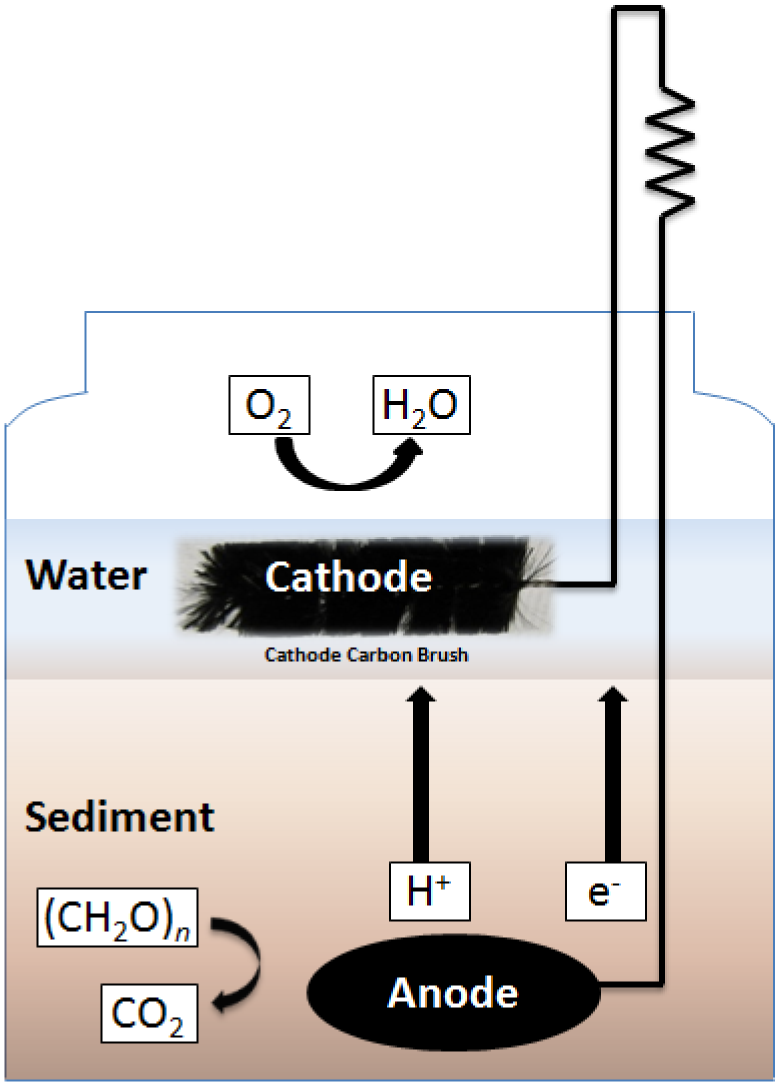

Figure 2: Schematic Diagram of Sediment MFC

Electricity Production in Sediment MFCs. Electrons are produced at the anode from the anaerobic degradation of substrates by bacteria in the sediment and transferred through an external circuit to the acceptors (e.g. oxygen) at the cathode, while a charge-balancing number of proton/ions are transferred between the anode and cathode.

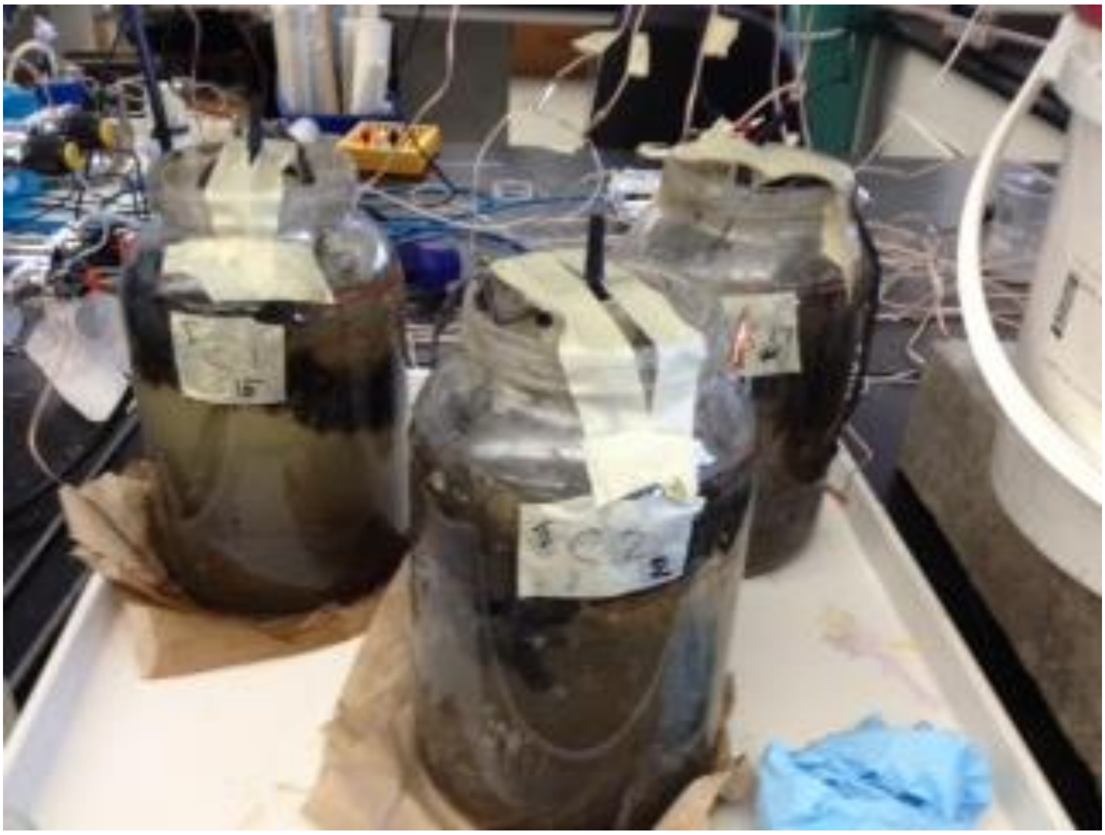

Figure 3: Photo Image of Control SMFC

1.8 Plant Sediment Microbial Fuel Cell (Plant SMFC)

Research on plant SMFCs is still in budding stage. Recent works explain that plant SMFCs with freshwater plants can generate a maximum power density ranging from several to dozens of mWm^2, whereas that with the seawater plant Spartina anglica can generate a maximum power density of 222 mWm^2 99 (M. Helder et al.). The implementation of Plant SMFC provides energy requirements in remote areas where power is not readily available. In addition to this helps in power scientific instruments for tracking and monitoring remote wild animals. Plant SMFCs works as biosensor for measuring contaminants in constructed wet lands.

The plant MFC involves in transforming solar radiation into green electricity in a clean and efficient manner by integrating the roots of a living plant in the anode

compartment of a microbial fuel cell. The living plant is photosynthesizing in its leaves whereby solar energy is used to fix carbon dioxide in the form of carbohydrates. It is sensible to understand that in addition to the bacteria in the anode section also the cathode section plays an essential part for higher power output from Plant MFC. The Plant MFC systems rely on two common principles, excretion of organic compounds by plant roots and current production by electrochemically active bacteria in a MFC. In the Plant MFC, the plant roots are integrated in the anode section of a MFC. Plant roots provide the electrochemically active bacteria with substrate through rhizodeposition. The electrochemically active bacteria, present in the anode section of the Plant MFC, convert the substrate into carbon dioxide, protons and donate the electrons to the anode (RUDD A Timmers et al).

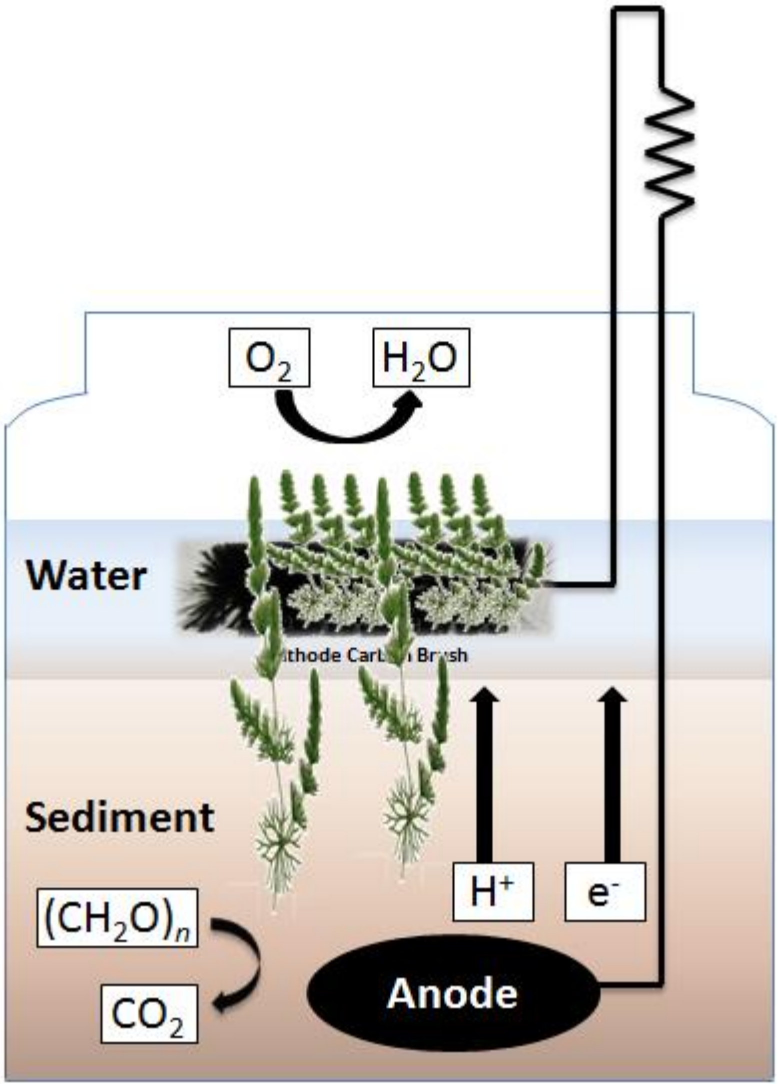

Figure 4: Schematic Diagram Plant SMFC

Electricity production in plant SMFC. The organic substrates are mostly from rhizoids, and electricity is generated by the anaerobic degradation of the rhizoids by bacteria.

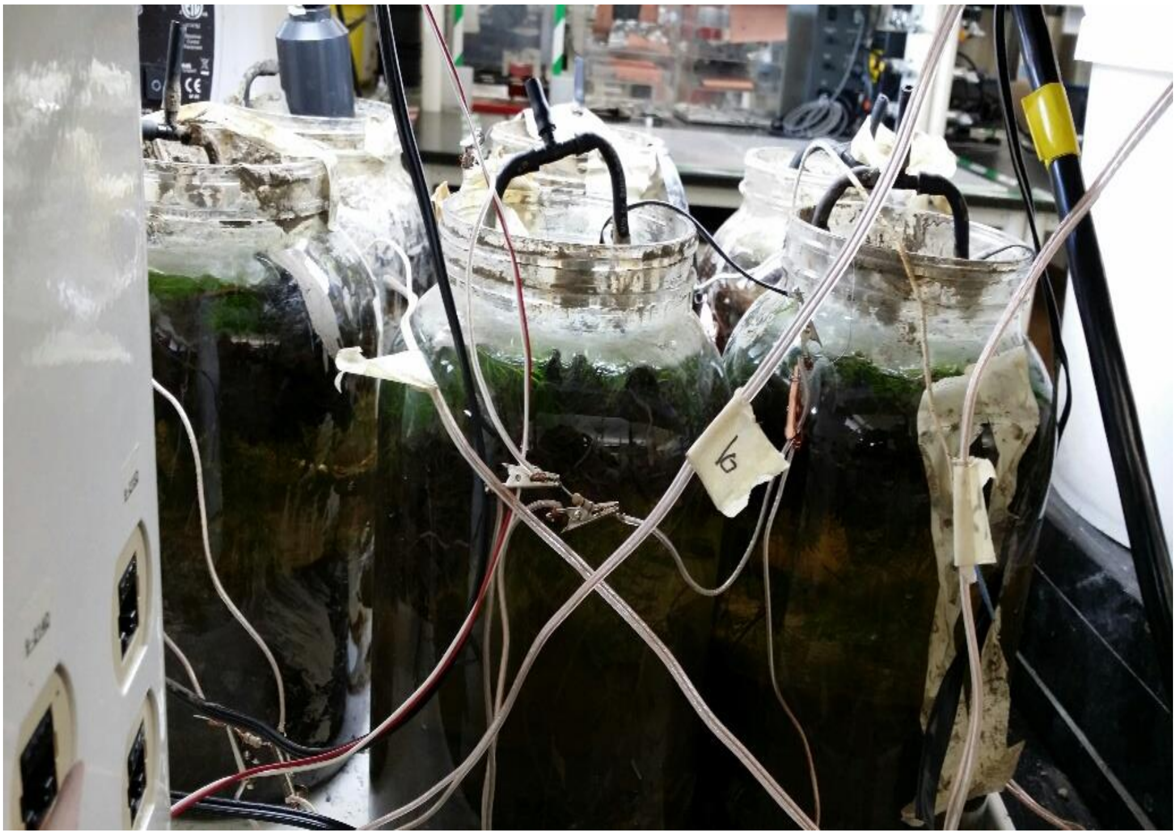

Figure 5: Photo Image of Plant SMFC

Photo Image of Plant Sediment Microbial Fuel Cells under illumination of full spectrum light bulbs.

Depending on plant species, age and environmental conditions up to 60% of the net fixed carbon can be transferred from its leaves to the roots. The plant root system produces and releases different types of organic compounds into the soil which include ***(a) Exudates*****:** sugars, organic acids etc.; **(*****b) Secretions:*** polymeric carbohydrates and enzymes; ***(c) Lysates:*** dead cell materials; **(*****d) Gases:*** ethylene and CO2.

1.9 Plant selection for SMFC

Aquatic plants are main choice for plant MFCs. Selecting appropriate plant is an optimistic approach for having high electricity production. To evade conflict with agricultural food production, aquatic species should be tested in the Plant SMFC.

Aquatic plants are very sensitive to solution conductivity, for example, rice growth is negatively affected at conductivities under 0.6 Sm^{-1} (L.H Zeng et al.). The conductivity of the electrolyte can be improved by an increase in salinity when using seawater in Plant MFCs. In addition, rice has to be harvested after four months; utilizing perennial aquatic plants in the system will decrease the installation costs for the electrodes and elongate power generation. Soil is a very good source of electron donors, if it is used as sediment. Inorganic compounds in soil can generate electrons by anaerobic respiration or through chemical processes. The processes that play important role in generating electric power include (a) the chemical oxidation of microbial produced reductants, such as humic acids, iron (b), and sulfur compounds, the microbial oxidation of sulfur to sulfate, (c) ammonia-oxidizing bacteria. Aquatic plants survive without oxygen by providing their root systems with oxygen from the atmosphere. The transportation of oxygen in the plant is facilitated by a tissue named aerenchyma (U. stottmeister et al).

Figure 6: Photo Image of Ceratophyllum demersum

Aquatic macrophyte helps in bio remediation of trace elements.

Image source: http://tolweb.org/Ceratophyllaceae/20667

Aquatic plants have been investigated for their capability to eliminate metals to decrease pollution, and as an indicator of and treatment for environmental pollution (Pip, 1990; Wells et al., 1980; Marmot & Oki, 1983). In wetland treatment structures, aquatic plants serve as one of the major tools of heavy-metal removal (Kadlec & Knight, 1996). Plants for these systems are often selected casually, although differences in performance between species can be proved (Jain et al., 1989).

Ceratophyllum demersum is commonly called as hornwort, rigid hornwort, coon tail, or coon's tail. It is a species of Ceratophyllum. In cold weather It is submerged and during summer time it is a free-floating aquatic plant. It grows in lakes, ponds, and quiet streams and prefers summer water temperatures of 15-30 °C. This plant has high capabilities to remove trace elements directly from the contaminated water and helps

in refining the wastewater. It is one of the important plants used in the phytoremediation of trace elements in natural and Constructed wetland.

The present study was conducted to evaluate the efficiency of sediment microbial fuel cells in electricity generation (in terms of current and power) in the presence of aquatic macrophyte Ceratophyllum demersum. To understand the effect of operational parameters on sediment microbial fuel cell performance, six sediment microbial fuel cells were established and investigated in the laboratory.

2: Materials and Methods

2.1 Sediment and Plant SMFC setup

Six Sediment MFCs were built in 4000ml glass jars. The Anode made of carbon cloth (surface area 9 $cm^{2,}$ PANEX 30-PW03, Zoltek, Corporation, St Louis, MO) was placed in the bottom. A 100 cm long carbon brush (Gordon Brush Mfg. Co., Inc., Commerce, CA) was used as the cathode electrode. Before use, the carbon brush electrode was pretreated by immersing in acetone overnight and heating at 450 °C for 30 min. Carbon brush was 7 cm above the anode and floating on surface of water. Sediment was collected from Lake Michigan near Milwaukee downtown. The jars were filled with sediment up to 4cm. Remaining space was filled with Deionized water. The anode and cathode electrodes were connected by copper wires to an external circuit across 68 ohms resistance. Plants were added to 3 SMFC jars and remaining 3 jars were Control SMFCs. Glucose feed (25 ml) was added to Anode surface area every 5 days. Deionized water was added to prevent evaporation losses. The six sediment MFCs were operated at batch mode throughout the experiment. Illumination was achieved by full spectrum light bulbs, which were controlled by a timer to adjust the light/dark period. All the experiments were carried out at room

temperature. In General to reduce inert resistance and oxygen diffusion two chamber plant MFC are preferred. But membrane is very expensive in this configuration (A. patra et al). When single chamber MFC is developed there is no need to use a membrane as the oxygen concentration gradually decreases in the bottom near sediment. To accomplish large scale application of these SMFCs capital costs should be decreased. Instead of using costly graphite conductive electrode materials like carbon cloth are very economical.

2.2 Importance of Electrodes in Microbial Fuel cells

Maintaining greater performing electrode materials can increase the performance of a Microbial Fuel cell as different anode materials result in different activation polarization losses. Platinum and Platinum black electrodes are greater to graphite, graphite felt and carbon-cloth electrodes for both anode and cathode constructions, but their prices are much greater. Schroder et al reported that a current of 2 to 4 mA could be attained with platinum Carbon cloth anode in a disturbed anaerobic medium of E. coli using a standard glucose medium while no microbial assisted current flow is observed with the unchanged carbon cloth with the same operating conditions. Platinum too has advanced Catalytic action with regard to oxygen than graphite materials. Microbial fuel cells with Platinum or Platinum coated cathodes produced greater power densities than those with graphite or graphite felt .Electrode alteration is vigorously examined by quite a few research Scientists to improve Microbial fuel cell performances. Park and Zeik observed an increase of 100-folds in electricity generation by using NR woven graphite and Mn (IV) graphite anode compared to the woven graphite anode alone. NR and Mn (IV) served as mediators in their MFC reactors. Doping ions such as Iron 3 or Mn (IV) in the cathode too catalyze the cathodic reactions causing in better electricity production. The source for their

catalytic activity is the same as that of electron shuttles. Four folds of greater current can be attained with the arrangement of Mn(IV)-graphite anode and Fe3+-graphite cathode Related to plain graphite electrodes (Park and Zeikus).One disadvantage of using Platinum electrodes is that their activities are decreased by the creation of a PtO layer at the electrode surface at positive potentials. Schroder et al studied the function of a polyaniline overlay on a Platinum black anode. Their current density increased from 0.84 with Platinum black anode to 1.45 mA−1 cm−2 with a polyaniline coated platinum black anode.

Seafloor MFCs also benefit from electrode modifications. Some people have a tendency to think that a big cathodic surface area would help electrode reactions on the cathode's surface. However, it was stated that different cathode surface areas had only a small effect on internal resistance and the power output.

2.3 Effect of operating conditions on MFC anode section

Concentration Of substrate and type, feed rate are essential features that influence the efficiency of a Microbial Fuel cell With a Given microorganism group. Power density Differs significantly by different Substrates.. Many systems have shown that electricity generation is dependent on substrate concentration both in batch and continuous-flow mode MFCs. Usually a higher fuel concentration yields a higher power output in a varied concentration range. Several studies stated that a greater electricity level was attained with lactate as substrate concentration bigger till it was in excess at 200 mM in a one chamber MFC inoculated with S. putrefaciens. Moon et al. studied the influence of substrate concentration on the performance of an MFC. Their study also showed t that the power density was improved with the increase in substrate Concentration Moon et al observed that the current improved when wastewater concentration was up to 50 mg/L in their MFC. In addition to that, the

electricity generation in an MFC frequently higher at a comparatively little level of feed rate before going down. This may be because a high feed rate facilitated the growth of fermentative bacteria quicker than those of the electrochemically active bacteria in a mixed culture However, if microorganisms are growing about the electrodes as biofilms, the higher feed rate is doubtful to influence the consortia. This may be that the increased feed rate causes another electron acceptors competing with the anode to decrease the output.

2.4 Effect of operating conditions on MFC cathode section

Oxygen is the mostly used as electron acceptor in MFCs for the cathodic reaction. Power output of a Microbial fuel cell powerfully determined by the concentration level of electron acceptors. A number of studies showed that Dissolved Oxygen was a most important limiting one when it stayed below the air-saturated level. Unexpectedly, a cathode solution with pure oxygen that gave 38 mg/L DO did not further increase the power output paralleled to that of the air-saturated water

Rate of oxygen diffusion toward the anode chamber goes up with the DO concentration. So part of the substrate is used up straight by the oxygen as a substitute of transferring the electrons though the electrode and the circuit pham et al. Power generation is plentiful when using ferricyanide as the electron acceptor in the cathode compartment. Till now, the research with very high power generations like 7200 mW/m2 was achieved using ferricyanide in the cathode compartment whereas lower than1000 mW/m2 was described in studies using Dissolved oxygen irrespective of the electrode material. The reason for this is due to the larger mass transfer rate and lesser activation energy for the cathodic reaction accessible by ferricyanide (oh et al) when hydrogen peroxide was used as the final electron acceptor in the cathode compartment power output and current density was higher. According to Tartokovsky et al. As a

result, aeration is not required for one chamber Microbial fuel cells. With a cathode that is openly out to air. Rhoades et al calculated the cathodic polarization curves for oxygen and manganese and observed that decreasing manganese oxides resulted in current density 2 folds more than that by decreasing oxygen However, modifying operating parameters will enhance the power production level of the Microbial fuel cells. Though, it is not an innovative technique to improve the MFCs from small energy source to an applicable power system at the very present. The problems are mainly due to the small rate of metabolism of the microorganisms in the MFCs. It is very difficult even with the Rapid growth rate microorganisms are pretty sluggish transformers. The conversion rate of organics to electrons has a stable limit which is naturally slow. Studies should be kept on how to break the natural metabolic drawback of the microorganisms for the Microbial fuel cell technology. A very High range temperature can increase almost all the mechanisms like chemical and biological reactions. When thermophilic microorganisms are inoculated it helps in enhancing the rates of electron generation. However, so far, no such research is described in the works. Thus this may be alternative possibility of enhancement for the MFC technology from the research laboratory to a large scale applicable power resource.

3: Measurement and Analysis:

3.1 Calculation of Microbial fuel cell efficiency:

COD removal from wastewater reveals the total energy collected from the organic matters. The COD removal efficiency ηCOD can be calculated from the following equation

$$\eta COD = (CODinf - CODeff) / CODinf \times 100\%$$

Where CODinf and CODeff are the influent and effluent COD (mg L−1), respectively. Not all the energy collected from bioconversion of an organic matter is converted to electricity. Some energy is consumed by the biofilm as conservation energy that is necessary for its existence and condition. Some energy is wasted due to over potentials, such as activation over potential, concentration (or mass transfer) over potential near an electrode, and ohmic loss due to internal resistance. The wasted energy is out as unrecoverable low grade heat. The real closed circuit potential output of an MFC is much lower than the theoretical open circuit potential. The real closed circuit potential is calculated from standard potentials as

$$output = Ecathode - Eanode - \eta j + I \,.\, Ri$$

Where $\sum \eta j$ is the sum of activation and concentration over potentials for the anode and cathode. Ri is the internal resistance and I is the current flow. The electrode potentials (E cathode and E anode) are calculated based on the Nernst equation, which depends on standard potentials and activities and partial pressures. several over potentials and the internal resistance all add to the Columbic efficiency loss.

The cell voltage was recorded every 1min by a digital Multimeter (2700, keithley Instruments, Inc., Cleveland, OH). The Current (I) was calculated from ohms law, where I = V/R. Power density (P) is calculated as $P = V^2/R\ A$ .Total coulombs generated in each batch were calculated by using $\int I\, dt$. The pH, temperature, and dissolved oxygen (DO) were measured using a 556 MPS hand-held multi parameter instrument (YSI Incorporated, Yellow Spring, OH).

4: Results and discussion

4.1 Polarization Curves and Fuel Cell behavior

The word polarization which is old fashioned and sometimes confusing is the change of electrode potential or Microbial fuel cell voltage from its equilibrium state due to a flow of current. (Feng Zhao et al) Polarization curves are plots of electrode potential or Microbial fuel cell voltage as a function of current or current density. Such plots contain a wealth of information and can easily be obtained with a suitable potentiostat, which measures power inputs. Power is provided to the instrument from the power source being studied or a variable external resistance load. To achieve highly reproducible, precise measurements it is needed that an electronic load with the proper current ranges is used. Power density of a Plant MFC is determined by various characteristics of the system like sun light, photosynthetic ability of the plant, organic matter transfer from plant to sediment etc.

In the initial days of experiment six SMFC of which three were planted with Ceratophyllum demersum were set up with lake sediment as support and were held in open circuit (no current was allowed) until a cell potential higher than 0.6 V was reached, indicating anaerobic conditions around the anode electrode. The six SMFC were run for more than 3 months. The open circuit voltage for some control SMFC and plant SMFCs were high in the range of 0.45 V to 0.8 V.

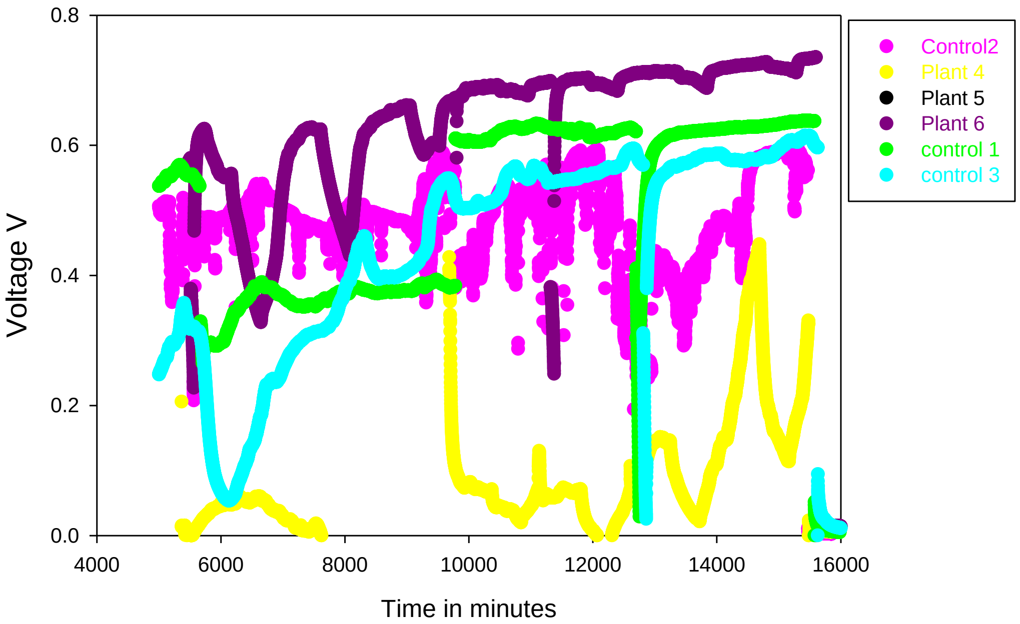

Figure 7: Open Circuit Voltages

Open circuit voltages for three control Sediment MFCs without plans and three plant sediment MFCs with Ceratophyllum demersum.

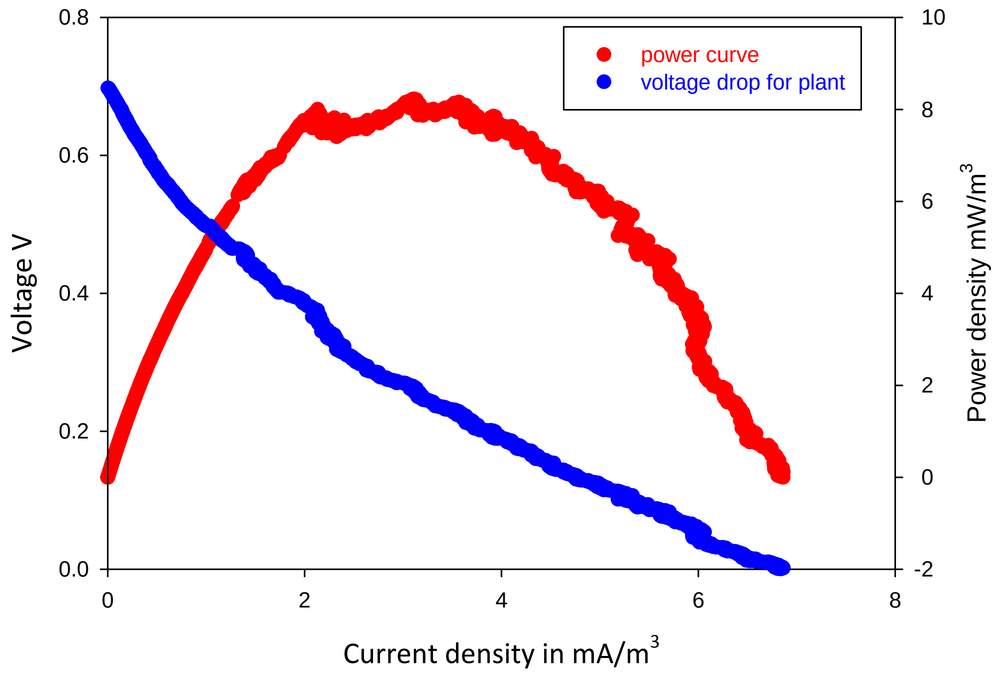

Figure 8: Polarization Curves for Plant SMFC

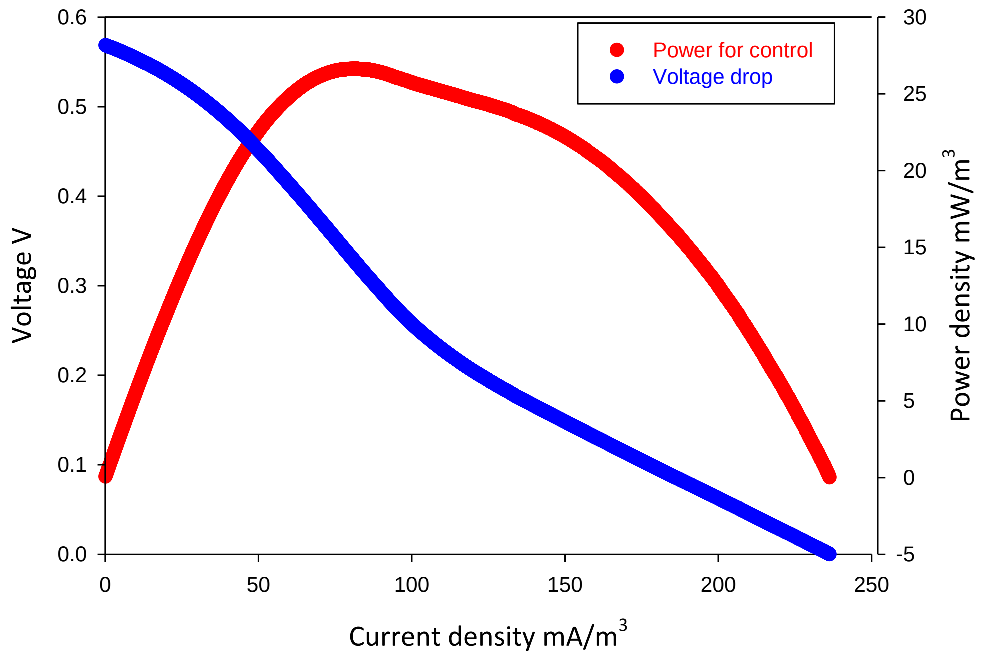

Figure 9: Polarization Curves for Control SMFC

The performance of plant SMFC was depicted and compared with the control Sediment MFC in terms of power density curves and polarization curves. It can be seen from FIG 1 and 2 that planting Ceratophyllum demersum in sediment MFC decreased the efficiency of electricity generation. The open circuit voltages of plant SMFC and Control Sediment MFC were 0.58V and 0.7V respectively, and the maximum power density of control sediment MFC was 25mW/m^3, which is much higher than Plant SMFC (8 mW/m). Only two out of Six SMFCs performed continuously throughout the experiment. Timmers et al. found that the Plant MFC has a high internal resistance, which limits the power density. In order to increase the power density, internal resistance should be reduced. Internal Resistance in Plant MFC Is 2487 ohms which is higher when compared with sediment MFC which has 826 ohms. It is generally known that maximum power output occurs when the internal resistance is equal to the external resistance. One of the factors effecting internal

resistance is the average distance between anode and cathode. When electrons are generated in the anode section, average transport distance for a proton to travel from anode through the membrane to the cathode is relatively long. A long distance from anode to cathode leads to transport losses in the anode (Strik et al,). Research by Timmers et al has shown that internal resistance of the Plant MFC, especially transport resistance, is an important limiting factor in the power output of the system.

SMFC	TOTAL COULOMBS PER BATCH
CONTROL 1	193
CONTROL 2	62
CONTROL 3	211
PLANT 1	13
PLANT 2	113
PLANT 3	99

Table 1: Total coulombs generated in a batch

4.2 Effect of illumination on the performance of plant SMFC

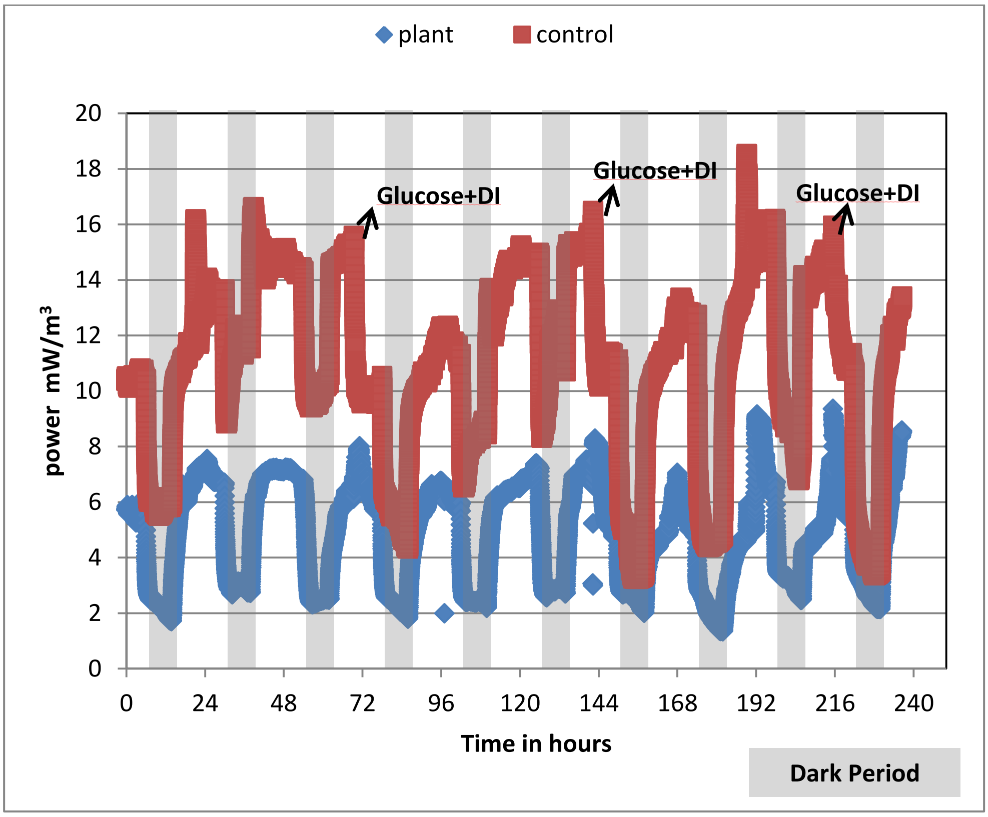

Figure 10: Effect of illumination

Effect of illumination on the performance of plant SMFC and control SMFC. Depicted in the chart is 8 hours of dark period and the remaining 16 hours in a day in a light period for electricity generation.

The effect of illumination on the SMFC performance was investigated. With 16/8 h light and dark period, power generation increased when the light was on and decreased in the dark. Total coulombs generated in batch was stable for both Plant(70) and control SMFC (160) over a period of time for 2 SMFC 's. However the maximum stable power density of 18 ± 1 mW/m^3 in control and 9 ± 1 in the case of plant SMFC were always observed at the end of light period. This result is different than similar plant MFC research papers where always sediment MFC has less power output than plant MFCS. In general the plant MFCs have more oxygen accumulation from plant photosynthesis during light period. Ceratophyllum demersum prefers low

light intensities and more shade. This could be one of the reasons for less power generation from plant SMFC.

4.3 Effect of Dissolved oxygen on plant and control SMFC

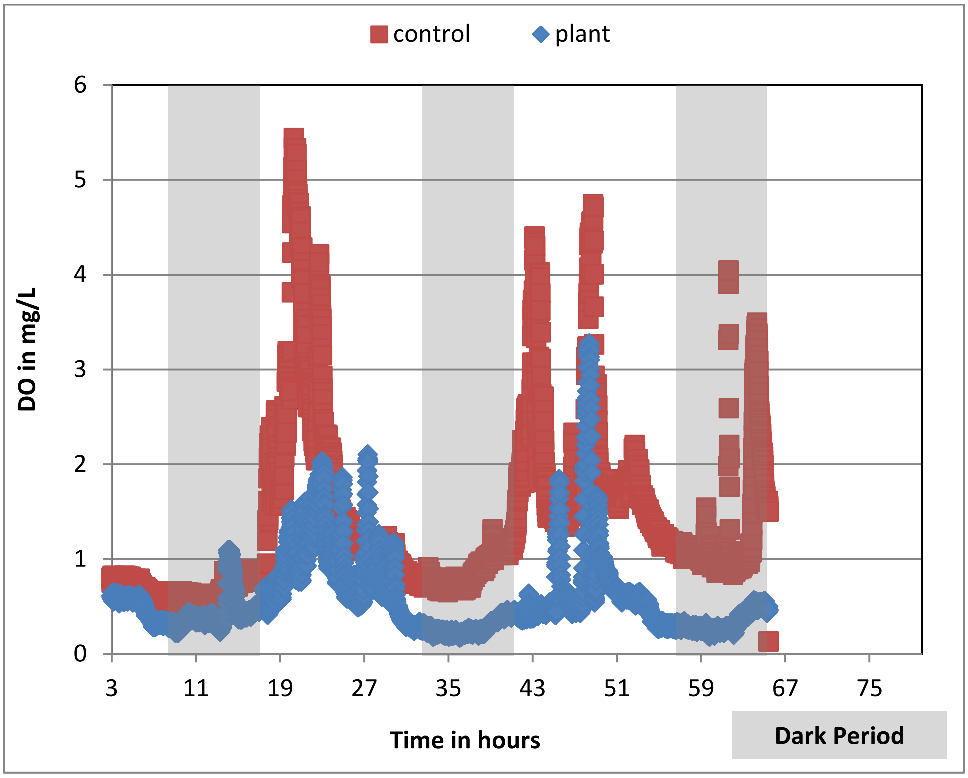

Figure 11: Effect of illumination on DO

Dissolved Oxygen (DO) concentration for plant and control SMFC during dark and light period for 70 hours of time.

It is generally known that the power density of a MFC depends on the photosynthetic oxygen production (Li Xiao, et al). The Dissolved oxygen has effect on power production. The DO for the plant SMFC is lesser than control SMFC which is different than other similar studies where plant MFC has more dissolved oxygen than control MFCs. The Plant SMFC has maximum DO of 2 ± 1 mg/L whereas the control SMFC has 5 ± 1 mg/L.

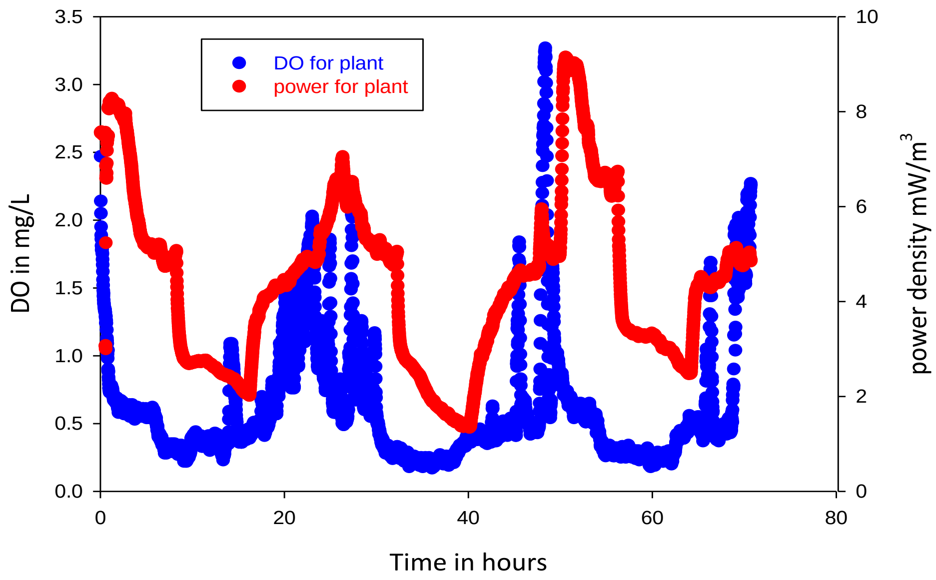

Figure 12: Effect of DO for Plant SMFC

Effect of Dissolved Oxygen (DO) on electricity generation for plant SMFC.

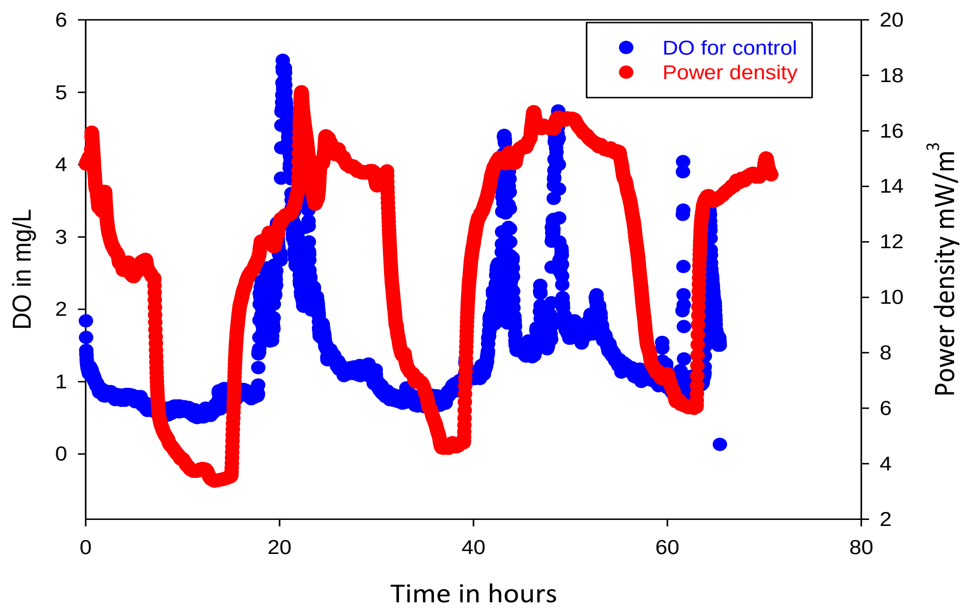

Figure 13: Effect of DO for Control SMFC

Effect of Dissolved Oxygen (DO) on electricity generation for control SMFC.

This plant has positive effect on the dissolved oxygen in a pond. It can actually add elemental oxygen to the water; however when large quantities of this plant grow as thick mat actually causes oxygen depletion at night. In this SMFC these plants growth

is very high which ultimately reduced the DO levels, because of either night-time oxygen use by plants or the decay process that consumed oxygen (some plants died initially when project was started).

4.4 Effect of pH on plant and control SMFC

Zhen He et al found that the air-cathode MFC can with stand an electrolyte pH as high as 10 when pH is between 8 and 10. The reduction of oxygen at cathode and bacterial oxidation at anode are effected by pH. Recent research (Sleutels, Helder, Strik) on Plant MFC showed that and pH conditions can affect the performance of the Plant MFC system. The research of T.K. SAJANA revealed that the Sediment MFC efficiency is affected with feed pH and the spacing between electrodes. Sediment MFC with feed pH of 6.5 gave Maximum COD removal and high feed pH of 8.5 helped total nitrogen removal. Operating Sediment MFCs with increased distance between electrodes was witnessed to give greater COD removal rate and reduced distance between the electrodes gave greater power density. In all the circumstances tested different distance between the electrode(100 and 50 cm) and feed pH (6.5 and 8.5), acceptable COD and TN removal efficiencies recommend that Sediment MFC can be used successfully for aquaculture water remediation. This will significantly decrease the operating price of aquaculture and lead to a substantial saving in the pumping cost of water.

The pH data is not enough to explain the power generation from these SMFCs as it requires some more time. The pH of Plant SMFC is lower than Control SMFC pH value. When measured continuously for 3 days in both SMFC the control SMFC has a stable pH of 8 and Plant SMFC has fluctuating values in the range of 7.

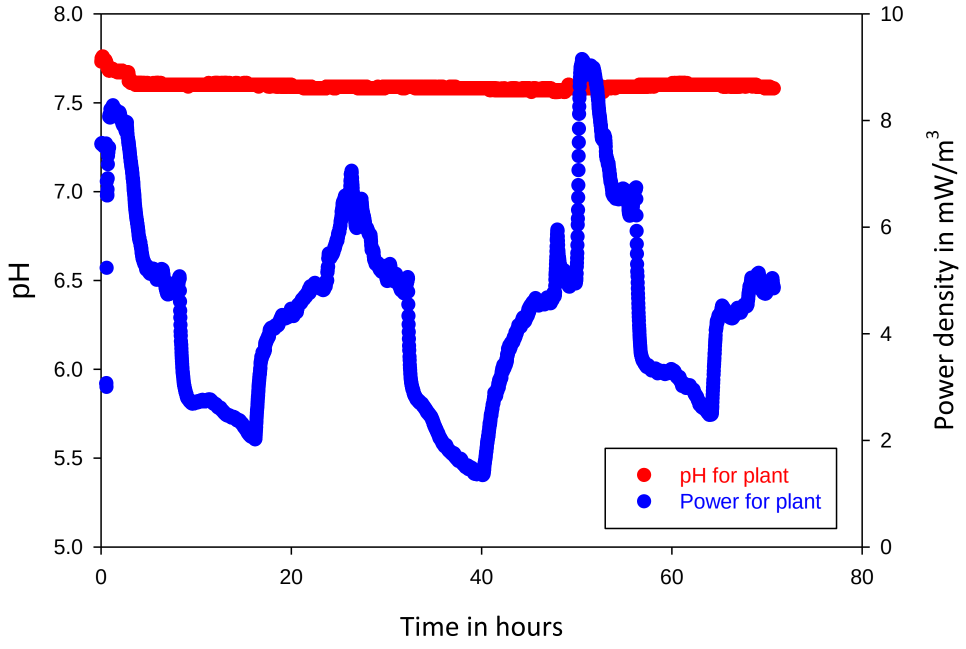

Figure14: Effect of pH for Plant SMFC

Effect of pH on electricity generation for plant SMFC

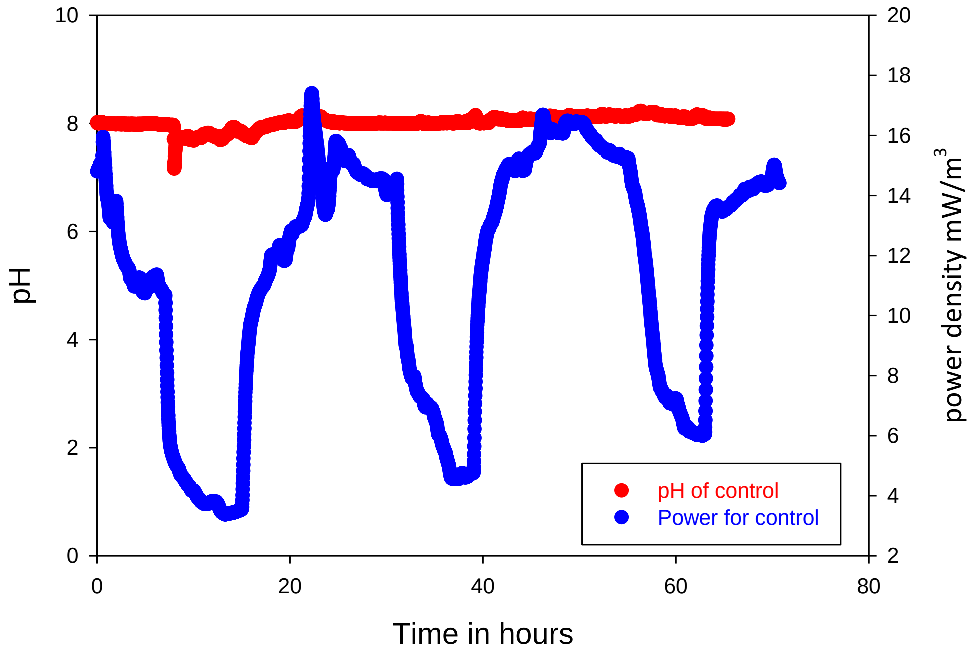

Figure 15: Effect of pH for Control SMFC

Effect of pH on electricity generation for control SMFC

4.5 Effect of temperature on plant and control SMFC

In plants the discharge of rhizodeposits and oxygen is determined by sunlight, (S. Soda et al) temperature, (T. Ando et al.) and growth stage. Changes in these factors may lead to a fluctuation of current and voltage in Plant MFCs. Kaku et al. found that electricity generation was sunlight dependent and artificially shading plants in the daytime inhibited electricity generation because of the reduction in photosynthesis and root exudates. Liu et al. (2005) proved that power output from single chamber MFCs was decreased by less than 10% when the temperature reduced from 32 to 20 °C. Hence It was a guess that the activity of bacteria associated with electricity might not be considerably affected by temperature within the mesophilic range. Previous research explains that current production from sediment MFCs would be significant over a continued period, specifically where the sediment temperature was nearly 20 °C. Since the experiments conducted in the presence of full spectrum light bulbs and for very limited time it will be hard to explain the temperature data effect on power generation.

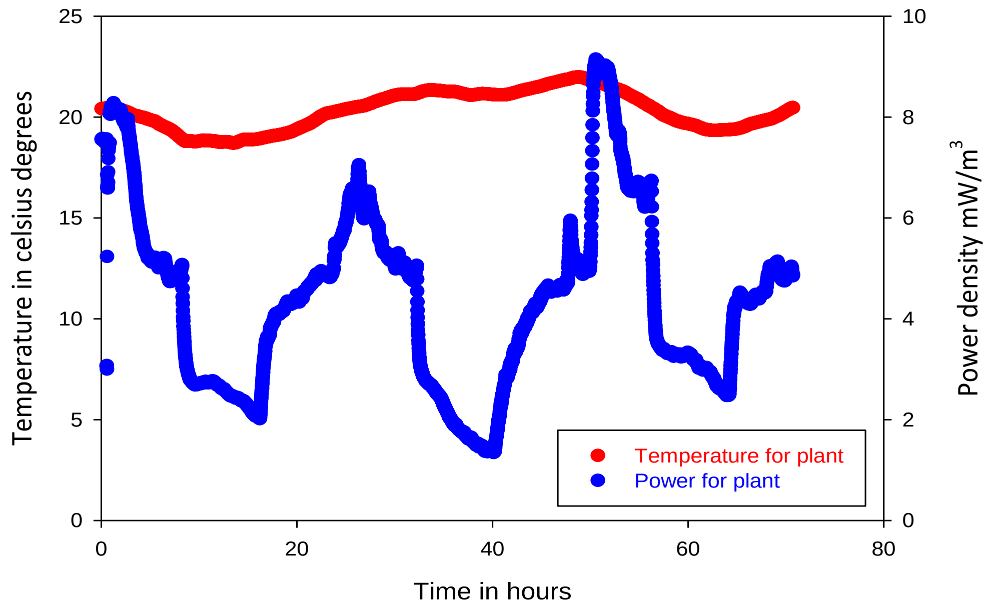

Figure 16: Effect of temperature for Plant SMFC

Effect of temperature on electricity generation for plant SMFC

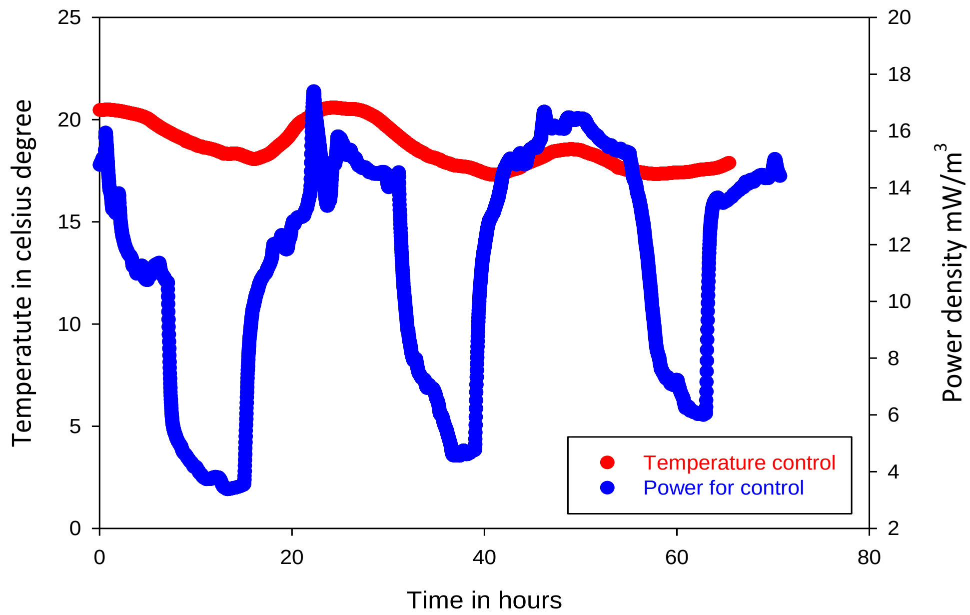

Figure 17: Effect of temperature for Control SMFC

Effect of temperature on electricity generation for control SMFC

5: Conclusion

In this study there is a clear relation between Dissolved oxygen and power generation. The SMFC with Ceratophyllum planted has decreased the efficiency of power generation. The over growth of the plant caused depletion of oxygen during night time. A mass balance Among COD, nitrogen and phosphorus should be established for elucidating the removal Mechanisms. The relation between COD and current generation was described as Michaelis–Menten like by De Schamphelaire et al In Plant Sediment microbial fuel cell.

Ceratophyllum demersum lacks proper root system but branches are sometimes modified as "rhizoids" giving the plants a rooted appearance. In a Plant MFC, roots exude organics which are oxidized by microbes, sending electrons to the anode. These electrons reach the cathode and oxygen gets reduced at cathode. This could be one of the possible reasons for this plant to have negative effect on power generation from SMFC. These plants cannot tolerate high light intensities and prefers shade. In this research we maintained 16h/8h of light and dark periods with Full spectrum light bulbs. In addition to this Dissolved oxygen concentration is less in Plant SMFC (because of excessive growth of plant) than control SMFC. Since time is a constraint, pH and Temperature effects on these SMFCs will be difficult to explain with the current data as the experiments need to be repeated.

The plant Sediment MFC can provide different benefits in terms of electrical power generation, relations in microbial processes but the practical and essentially, the cost-effective applicability needs to be further confirmed in terms of electrode usage and configuration (Jan B.A Arends et al). To date, the power generated by Plant SMFC is not reasonable. However, Plant SMFC represents a new technology that helps to

decrease the Global warming by reducing methane gas emissions. This is one of the main importance's of this technology and may be an important application in future.

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