Integrated Desalination and Wastewater Treatment Systems

Kokabian, B.; Blair, M.; Gude, V. G.

Water, energy and environment play a vital role in the sustainability of mankind. Environmental degradation associated with water and energy production/supply processes is the immediate concern faced by many parts of the world. Utilizing wastewater and produced waters as resources to provide for potable water and energy needs could serve as a sustainable alternative to mitigate environmental degradation. Towards this goal, microbial desalination cells allow for efficient wastewater treatment combined with electricity generation and desalination of saline waters. The premise for this research is based on the principles that the bio-electrochemical (BES) systems convert wastewaters into treated effluents while producing electricity and ionic species migration within the system facilitates desalination. A microbial desalination cell (MDC) can be constructed by including an additional saline water chamber in a microbial fuel cell using anode and cathode exchange membranes. Domestic wastewater can serve as a substrate provider while air cathodes can provide oxygen to accept electrons. A new concept to provide in-situ oxygen generation in the cathode section by algae to increase electron mobility (i.e. electric current) in microbial desalination cells is presented in this paper. Treated wastewater in the anode chamber will be allowed to pass through the cathode chamber to serve as CO2 and nutrient rich medium for algal biomass growth and in-situ oxygen generation. This process eliminates current issues encountered in microbial desalination cells such as salt accumulation in treated wastewater, pH drop and rise in anode and cathode chambers and provision of strong electron acceptors such as oxygen. This paper presents the results from experimental studies and energy analysis on the feasibility of algal microbial desalination cells.

INTRODUCTION

The conventional aerobic wastewater treatment processes such as activated sludge are both energy and cost intensive. An energy cost of 30 kWh per capita per year is needed for aeration of wastewater in aerobic treatment technologies (Aelterman et al., 2006). Considering, sludge disposal and treatment, the overall cost will be about $25 billion per year for all types of wastewater treatment in USA (Wei et al., 2003; Win, 2001). Microbial fuel cell technology can be an alternative to reduce the cost of treatment by recovering electrical energy from wastewater while at the same time treating wastewater. This process will reduce both the energy input and the excess sludge production (Rabaey and Verstraete, 2005) for wastewater treatment. In MFCs, microorganisms oxidize organics in the anode chamber and generate electrons which then flow through a resistor to the cathode chamber to reduce the electron acceptors (typically oxygen) (Logan et al., 2006; Lovley, 2008). However, besides organic removal, water desalination can be achieved by inserting an additional chamber consisting sea water between anode and cathode chambers in a microbial fuel cell. This new configuration is called Microbial Desalination Cell which was first introduced by Cao et al. (2009). A cation exchange membrane (CEM) is inserted next to the cathode chamber while an anion exchange membrane (AEM) is used next to the anode chamber. Due to the difference in anode and cathode potentials, anions move to the anode chamber while cations transfer to the cathode chamber and as a result water is desalinated. Desalination of seawater by reverse osmosis requires a considerable amount of energy (at least 3.7 kWh/m^3) (Mehanna et al., 2010a) while in MDCs water can be desalinated without the use of any external energy source. MDCs can serve as an efficient pretreatment step for RO systems in water and wastewater treatment plants to reduce the energy required in these systems. The researchers used sacrificing catholytes to provide electron acceptors which are not an environmental-friendly approach for long term sustainability of this system. A new concept of MDC is developed in this research which is based on in situ oxygen production by presence of algae in the cathode chamber called “algal biocathode”. The effect of algal biocathode on current/ voltage production, organic removal and desalination was examined.

MATERIALS AND METHODS

Microbial Consortium and Algae Preparation

Microbial consortium used in anode compartment was collected from the aerobic sludge of the wastewater treatment plant in Starkville, Mississippi. The sludge was allowed to acclimatize to anaerobic conditions in synthetic wastewater containing 300 mg/l of COD. The microbial consortium grown in air and algal cathode MFCs were further transferred into the air and algal MDCs. The synthetic wastewater used in anode chamber has the following composition: glucose 281.25mg/l, KH_2PO_4 (4.4 g/l), K_2HPO_4(3.4 g/l), NH_4Cl(1.5 g/l), $MgCl_2$ (0.1 g/l), $CaCl_2$ (0.1 g/l), KCl (0.1 g/l), $MnCl_2$4. H_2O(0.005 g/l), and $NaMo.O_4.2H_2O$(0.001 g/l) (Cao et al., 2009). The COD concentration used in MDC anode chamber was 500 mg/l. The microalgae *Chlorella Vulgaris* which was used in cathode compartment was grown in the following mineral solution: $CaCl_2$ (25 mg/l), NaCl (25 mg/l), $NaNO_3$ (250 mg/l), $MgSO_4$ (75 mg/l), KH_2PO_4 (105 mg/l), K_2HPO_4 (75 mg/l) , and 3 ml of trace metal solution with the following concentrations was added to the 1000 ml of the above solution: $FeCl_3$ (0.194 g/l), $MnCl_2$ (0.082 g/l), $CoCl_2$ (0.16 g/l), $Na_2Mo.O_4.2H_2O$ (0.008 g/l), and $ZnCl_2$ (0.005 g/l).

MFC-MDC Construction

The cylindrical-shaped MFC chambers were made of plexiglass with a diameter of 7.2 cm. The anode and cathode chambers were separated by an ion exchange membrane. Graphite papers were used as cathode and anode electrodes. The Volume of the anode and cathode chambers was 180 ml after inserting the electrodes. The MDC reactors were prepared by inserting a desalination chamber between anode and cathode chambers in MFC reactors. Cation exchange membrane (CEM, CMI 7000, Membranes international) separated the cathode and desalination part while an anion exchange membrane (AEM, AMI 7001, Membranes international) separated the anode and desalination chambers. The volume of desalination chamber was about 200 ml3 with a salt concentration of 10 g/l NaCl.

A 10 k ohm resistor was used in closed circuit tests. The voltage was recorded using digital multimeter (Fluke, 287/FVF). The current was calculated using the Ohm’s law, I = V/R. The Power density was calculated (using P = V.I) as per anode volume or cathode surface. COD tests were carried according to Standard methods (APHA, 1992). Electrical conductivity, TDS removal and salinity removal were tested by a conductivity meter (Extech EC400 ExStik Waterproof Conductivity, TDS, Salinity, and Temperature Meter).

RESULTS AND DISCUSSION

Current Production in Air and Algae MFCs and MDCs

Figure 1 presents the voltage profile for air cathode MFC and algal cathode MFC. The maximum open circuit voltage difference between the cathode and anode for air cathode MFC and algal cathode MFC were 0.425 V and 0.488 V, respectively. The maximum power density with algal cathode MFC was 4.06 mW/m^2, about 3 times greater than the air cathod MFC (1.33 mW/m^2). Figure 2 represents the voltage profile for air cathode MDC and algal cathode MDC. The voltage for the air cathode MDC increased slowly for the first 50 hours of operation which can be related to the lag phase for the growth of microbial consortium in anode and the formation of biofilm on the electrodes (Powell et al., 2009). This lag phase was shorter for the algal cathode showing the influence of in situ oxygen generation by algae in the cathode side which increase the electron mobility. The maximum produced voltage in the closed circuit for the algal cathode MDC (0.236 v) was also higher than the air cathode MDC (0.219 V). In another study, an aerobic consortium was used as a bacterial catalyst in the cathode part, which produced maximum voltage higher than that of an air cathode MDC operated under similar conditions (Wen et al., 2012).

Organic Removal Efficiencies

Table 1. shows the COD removal efficiencies of both MFCs and MDC with air and algal cathodes. This table shows that in both MFCs and MDCs, systems with algal biocathode remove higher quantities of organic carbon from synthetic wastewater. This also confirms the higher produced voltage in algal type MDC and MFC compared to the air cathode type. However based on the analysis of coulombic efficiencies, the energetic conversion efficiencies of COD to power are still below the maximum theoretical energetic conversion efficiency which is about 100% (Alterman et al., 2006).

Desalination Profiles

Desalination profile for both air cathode MDC and algal cathode MDC are represented in figure 3. The percentage salinity removal in air cathode and algal cathode MDCs were 24.2 and 40.1 % respectively. The total desalination rate (TDR) of algal MDC was 0.161 $g.L^{-1}.day^{-1}$, about 2 times greater than air cathode MDC with TDR equals to 0.076 $g.L^{-1}.day^{-1}$. The higher salinity removal rate for algal MDC is due to its higher potential difference between anode and cathode which stimulates the transfer of ions in the middle chamber to the anode and cathode chamber. A review of papers of microbial desalination cells showed high removal efficiency of salt was achieved in the cells with high ratio of wastewater volume to sea water (Kim & Logan, 2013). Mehanna (2010b) showed that 43–67% desalination of water is possible using equal volumes of anode solution and salt water. Our result also shows that algal cathode MDC can be used to substantially reduce salt concentrations prior to reverse osmosis and as a result the required energy for RO will also decrease. On the other hand, the RO systems can benefit from power generation of MDC which substantially decrease its energy usage.

Feasibility of Large Scale Application

Economic evaluation of bioelectrical systems for electricity production as well as wastewater treatment has been published recently (Pant et al. 2011). Powell and Hill (2009) studied the economic feasibility of novel CO_2 photosynthetic microalgae MFC that can generate power and oils for biodiesel. The economics of our system can be evaluated by assuming that in a 100,000 population with wastewater generation of 16 billion liters containing 300 mg/l COD has the potential for production of 2.3 MW of electricity annually (Logan, 2005). Based on the wastewater volume, produced power was about 64 mW/m3 in our algal cathode MFC. Considering the amount of wastewater generated, the overall power production will be about 1.024 MW which means about half of the energy in wastewater has been recovered as electricity. Assuming a typical consumption of 1.5 kW electricity per house, 1.024 MW of power can meet energy demand for 682 houses. Based on assumed cost of electricity of $0.07/kWh, this power would be worth$627916.8 which shows the economic potential of this type of MFC.

CONCLUSION

This study has demonstrated that algal MFCs and MDCs can improve electricity production by in situ-oxygen generation. Use of algae in the cathode part of MDC can decrease capital costs for chemicals and aeration while at the same time maintaining the sustainability feature. The salinity removal rate for algal MDC was much better than the air cathode MDC. MFC and MDC Systems can remove organic pollutants from wastewater. Alternatively, MDCs can be used as a pretreatment for downstream RO systems. In conclusion, application of algal biocathode MDCs as a sustainable method for water desalination and wastewater treatment has been proved in this study.

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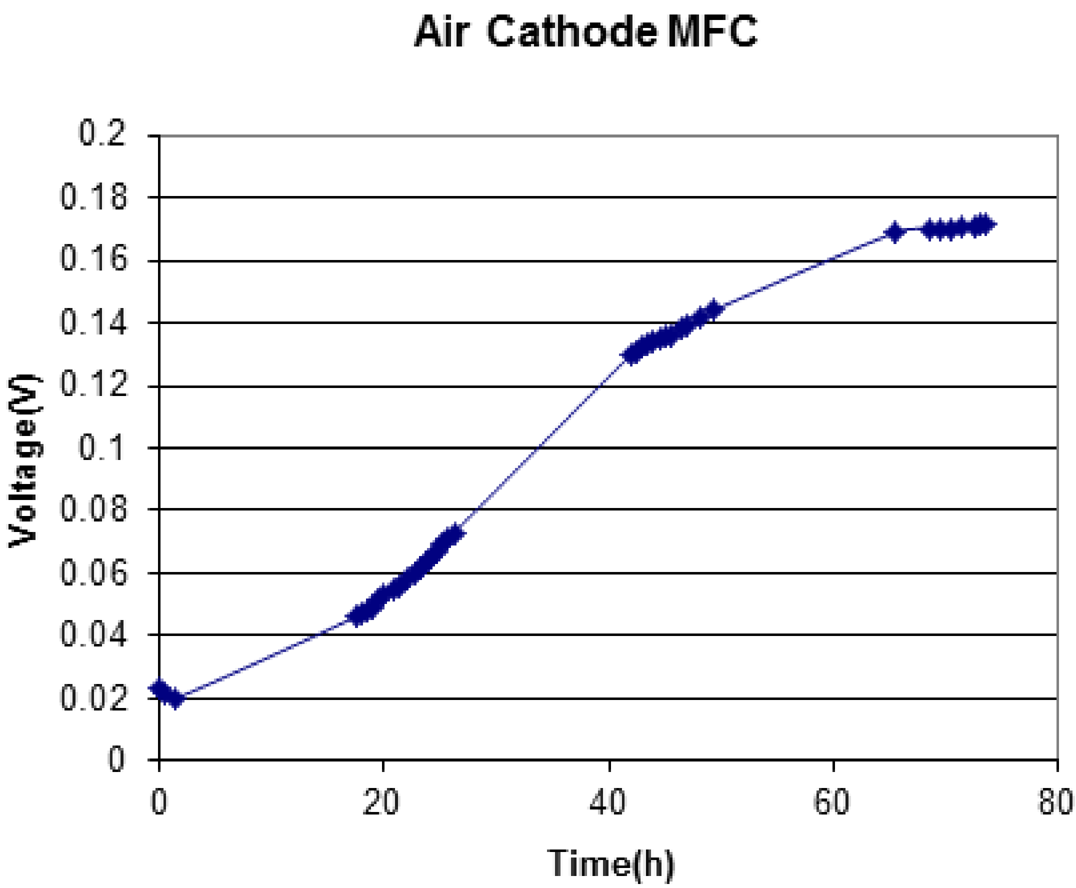
Table1. COD removal efficiencies of MFCs and MDCs

Type of BES	COD Removal %
MFC with air cathode	38.1%
MFC with algal cathode	59.2%
MDC with air cathode	56.65%
MDC with algal cathode	65.62%

Figure 1 Voltage profile for A) Air cathode MFC B) Algal Cathode MFC.



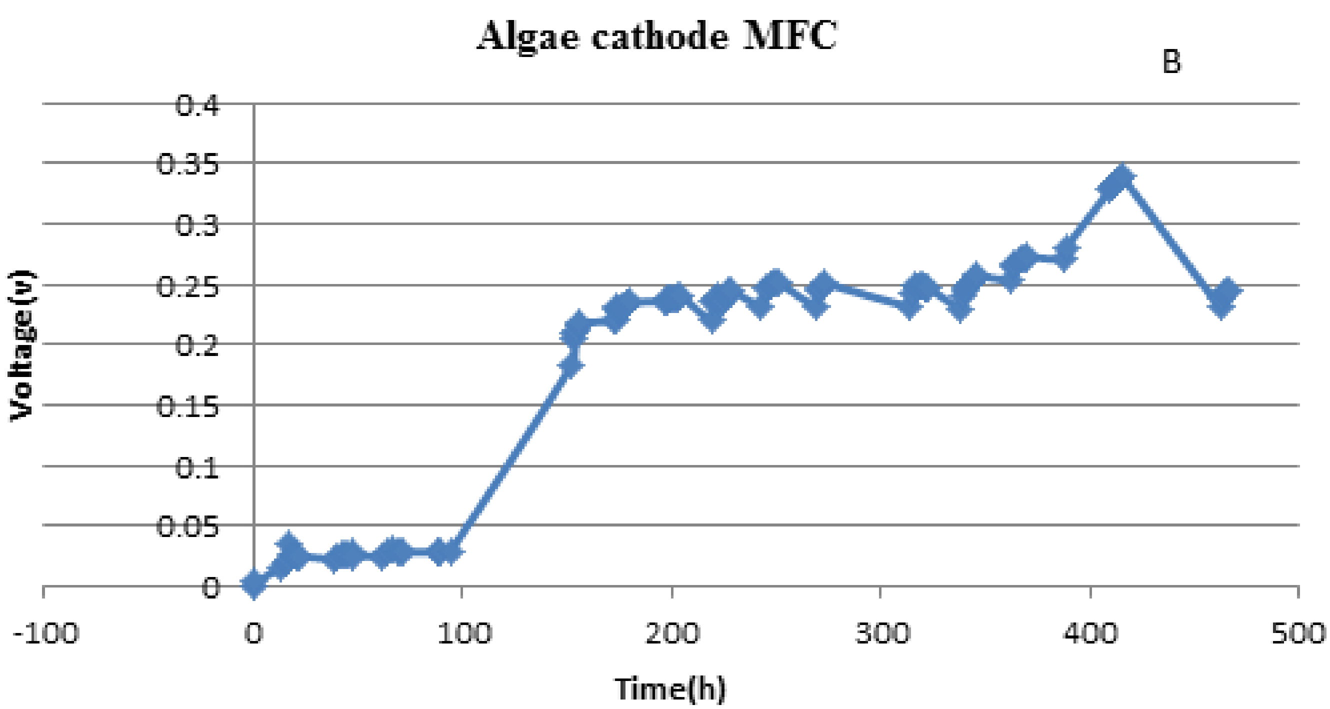


Figure 2 Voltage profile for air cathode MDC and Algal cathode MDC

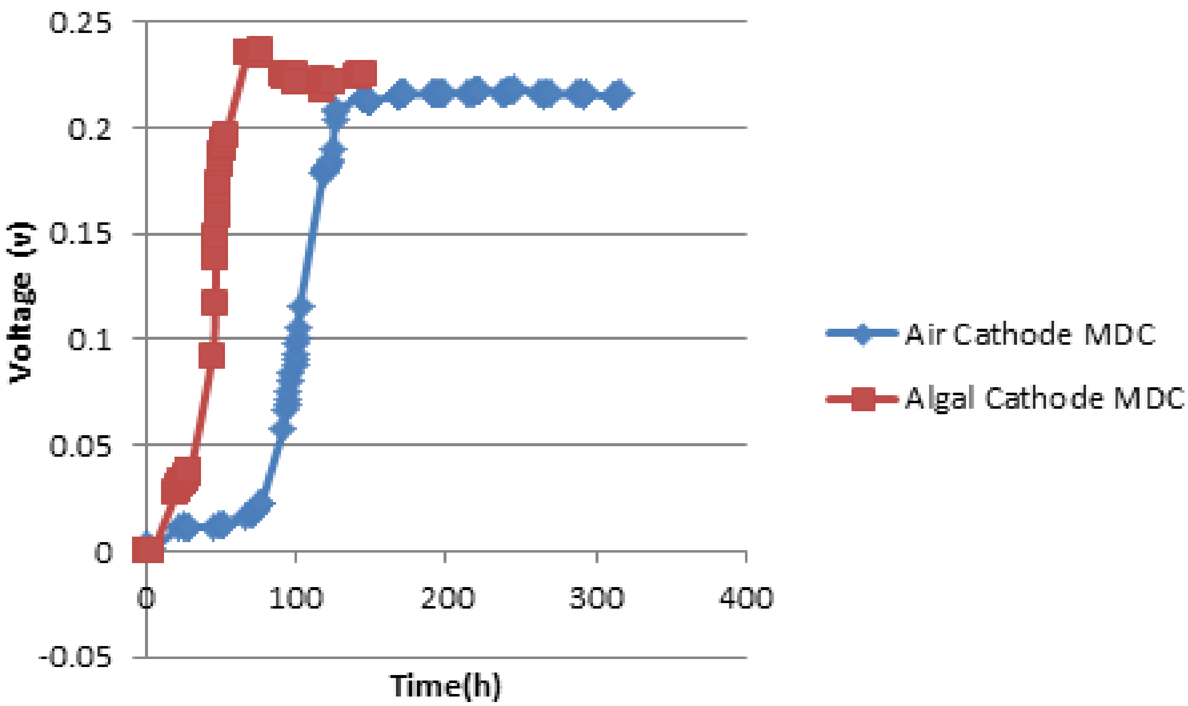


Figure 3 Desalination profile for air cathode and algal cathode MDC