Pol. J. Environ. Stud. Vol. 25, No. 2 (2016), 503-510
DOI: *10.15244/pjoes/61115*

Original Research

Performance of Single-Chamber Microbial Fuel Cells Using Different Carbohydrate-Rich Wastewaters and Different Inocula

Safwat Ahmed*, Ehab Rozaik, Hisham Abdel-Halim

Sanitary and Environmental Engineering Division, Public Works Department,
Faculty of Engineering, Cairo University, PO Box 12613, Giza, Egypt

Received: 4 November 2015
Accepted: 20 December 2015

Abstract

A microbial fuel cell (MFC) can use wastewater as a substrate; hence, it is essential to understand its performance when seeded with different inocula and during the treatment of carbohydrate-rich wastewaters to simultaneously optimize electricity production and wastewater treatment. This study investigates the performance of single-chamber membraneless MFCs used to treat three different carbohydrate-rich synthetic wastewaters (glucose, sucrose, and soluble starch) while seeding with two different inocula (a microbial solution containing different species of microorganisms, and anaerobic sludge). The results showed that the highest voltages, power densities, and COD removal efficiencies were obtained using microbial fuel cells fed with glucose-based synthetic wastewater, and were 351 mV, 218 mW/m^2, and 98.8%, respectively, for the microbial solution, and 508 mV, 456.8 mW/m^2, and 94.3%, respectively, for the anaerobic sludge. The lowest results of voltages, power densities, and COD removal efficiencies were obtained using microbial fuel cells fed with the soluble starch-based synthetic wastewater, and were 281 mV, 139.8 mW/m^2, and 86.4%, respectively, for the microbial solution, and 396 mV, 277.6 mW/m^2, and 79.4%, respectively, for the anaerobic sludge. In all experiments, the voltages and power densities obtained for the anaerobic sludge were higher than those obtained for the microbial solution, and the COD removal efficiencies obtained for the anaerobic sludge were less than those obtained for the microbial solution. This study determined that voltage generation, power densities, and COD removal efficiencies were inversely proportional to the complexity of the carbohydrate used in single-chamber microbial fuel cells.

Keywords: microbial fuel cell, anaerobic sludge, glucose, sucrose, soluble starch

Introduction

Non-renewable energy sources are becoming increasingly limited; therefore, the development of sustainable energy alternatives is necessary due to environmental pollution, energy depletion, and climate change [1, 2]. Because bacteria gain metabolic energy through transferring electrons from an electron donor (substrate) to an electron acceptor, many researchers believe that fuel cell systems could be an acceptable alternative to non-renewable energy. Microbial fuel cells (MFCs) can offer great economic and environmental benefits through the

*e-mail: safwat@eng.cu.edu.eg

simultaneous generation of electricity and treatment of waste; therefore, MFCs are a promising technology [3-5].

MFCs can have various configurations, including a single-chamber microbial fuel cell where electrons produced at the anode under anaerobic conditions can transfer through an external circuit from the anode to the cathode, producing current [6-10]. MFCs can utilize different substrates in the anodic chamber, ranging from simple organic molecules to complex wastes [11-16], and can be inoculated with monocultures of bacteria [17, 18] or with mixed inocula [19-23]. Mixed cultures are generally preferred for practical applications because they are more readily available in large quantities, more tolerant to environmental fluctuations, and more responsive to different substrates [24]. The efficiency of converting organic wastes into bioenergy depends on the chemical composition and concentrations of the components of the waste material [25-27]. Moreover, the substrate has a direct effect on the fingerprint of the bacterial community in the anodic biofilm [28]. The main advantage of MFCs over other energy recovery methods, such as anaerobic digesters, is the direct generation of electricity [29]. The performance of the MFC is influenced by several factors, including the rates of fuel oxidation and electron transfer to the electrode by microorganisms, types and concentrations of substrate, hydraulic retention time, and circuit resistance [30-32]. At low external resistance, more electrogenic microorganisms can transfer electrons to the anode and gain more energy; as a result, a more diverse and dense anode biofilm can be formed [33, 34].

Carbohydrates are among the major components of organic matter found in domestic wastewater [35, 36]. The simplest form of carbohydrates are monosaccharides with three to seven carbon atoms [35]. They react with each other to form disaccharides and polysaccharide, which are polymers of monosaccharides [35]. Glucose, a monosaccharide, is the most important simple carbohydrate in human metabolism. Sucrose, a disaccharide, is the most highly purified organic chemical used in the world. Starch, a polysaccharide, is a polymer of glucose [35]. It is difficult from previous studies to compare MFC performances due to several reasons, including differences in operating conditions, surface area, electrode type, and inocula used. To our knowledge, there is no single study showing the performance of certain single-chamber microbial fuel cells under different types of carbohydrates and inocula. Since MFC can use domestic wastewater as a substrate, it is essential to understand the performance of MFC during the treatment of carbohydrate-rich wastewaters to simultaneously optimize electricity production and wastewater treatment. The overall objective of this study was to investigate the treatment of three different carbohydrate-rich synthetic wastewaters using single-chamber microbial fuel cells seeded with two different types of inocula. The three carbohydrate-rich synthetic wastewaters were glucose-based, sucrose-based, and soluble starch-based, and the two different inocula were a microbial solution containing different species of microorganisms and an anaerobic sludge.

Materials and Methods

MFC Setup and Operating Procedures

We used a single-chamber membraneless MFC (Fig. 1). The effective volume of the circular chamber was 0.5 l. The electrodes were graphite fiber felt (MudWatt, USA), and the vertical distance between them was 4 cm. The total surface area of each electrode was 113 cm^2. MFCs inoculated with mixed cultures can generate greater power densities than those inoculated with pure cultures [37, 38]; consequently, two different inocula were used. One was a microbial solution

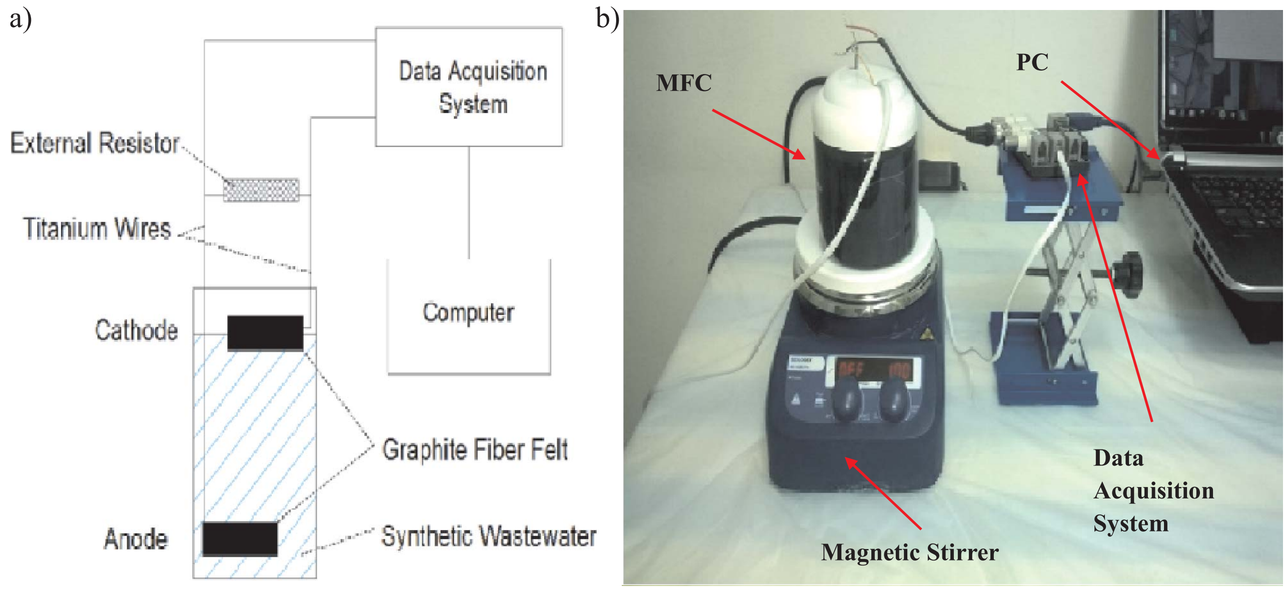

Fig. 1. Single-chamber microbial fuel cell: a) schematic diagram, b) photo.

Table 1. Characteristics of different inocula used in the study.

Type of Inocula	Microbial Solution	Anaerobic Sludge
pH	7.1	7.1
Total Suspended Solids (TSS)	3,532 mg/l	17,552 mg/l
Volatile Suspended Solids (VSS)	2,817 mg/l	13,458 mg/l

prepared with different species, including: *Anaerobacter polyendosporus, Bacillus amyloliquefaciens, Bacillus licheniformis, Bacillus subtilis, Clostridium butyricum, Desulfovibrio aminophilus, Desulfovibrio vulgaris, Pleomorphomonas oryzae, Pseudomonas citronellolis, Methanomethylovorans hollandica, Rhodopseudomonas faecalis,* and *Wolinella succinogenes* [19]. The second inoculum was an anaerobic sludge obtained from the Al-Fayoum wastewater treatment plant in Egypt. Table 1 shows the characteristics of the two inocula.

The synthetic wastewater consisted of the following (per liter of distilled water): NH_4Cl, 0.2 g; $CaCl_2{\cdot}2H_2O$, 0.15 g; KCl, 0.33 g; NaCl, 0.30 g; $MgCl_2$, 3.15 g; K_2HPO_4, 1.26 g; KH_2PO_4, 0.42 g; and trace metals (1 mL) [39]. Individually, glucose, sucrose, and soluble starch were used as the carbon sources in the experiments. The chemical oxygen demand (COD) of the synthetic wastewater used in the experiments was adjusted to approximately 1,000 mg/l, and the pH value at the beginning of each experiment was 6.6 0.2. The MFC was examined by fed batch mode. Each experiment lasted for six days (144 hours). In order to remove any air inside the compartment, nitrogen sparging was performed before starting the experimental works. During experiments, mixing of wastewater was maintained at a rate of 100 rpm [19].

Analysis

A sterile syringe was used to collect samples for further analyses. Every 24 h, the concentration of chemical oxygen demand was determined using HACH COD vials and DR 220 spectroscopy (HACH, USA). Titanium wires were used to allow the passage of electrons from anodes to cathodes. The external resistance was adjusted to be 50 Ω, and the voltage across this resistance was measured every 1 h using a data acquisition system (USB DrDAQ Data Logger, Pico Tech., UK) connected to a computer [37].

Power generation and coulombic efficiency are considered the main parameters used to evaluate the performance of MFCs [19]. Power generation can be evaluated by determining power density, which is the ratio of the power generated to the surface area of the anode. In order to determine coulombic efficiency, this equation can be used:

$$CE = \frac{8\int_0^t I dt}{FV\Delta COD}$$

...where $\int_0^t I dt$ is the actual coulombs generated over the time period (t), F is the Faraday constant (96,500 C/mol electrons), V is the active volume of the compartment, and is the reduction in the chemical oxygen demand over time period (t) [17]. During the operation of MFCs, temperature was maintained at 23ºC±0.5. All data measured were reported as the average of three replicate experiments, and the means of different groups were compared using the analysis of variance. Statistical significance was considered for p value less than 0.05.

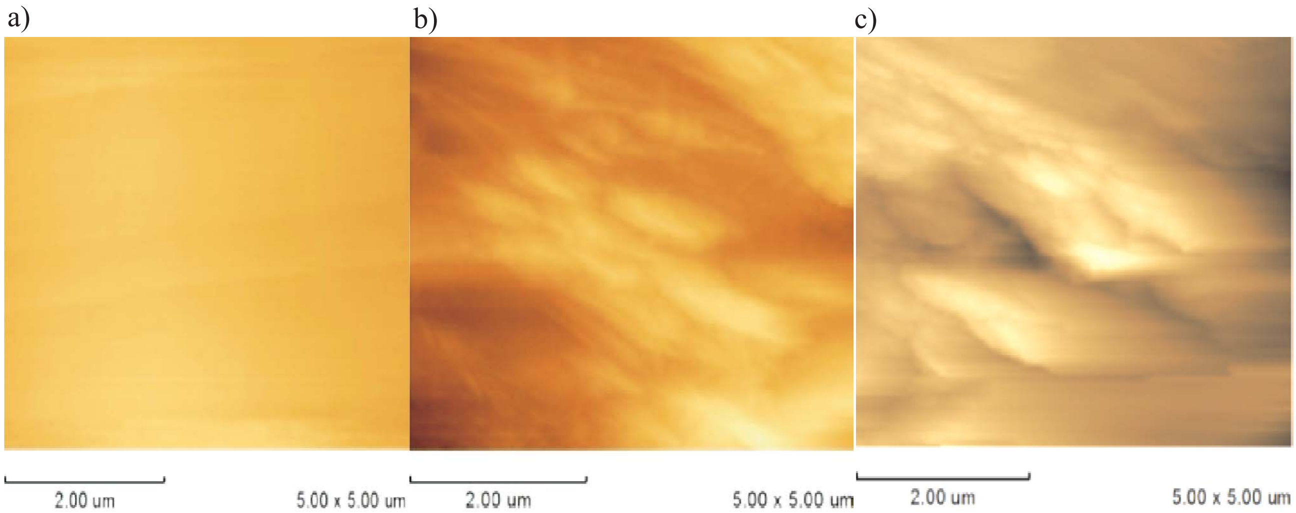

Fig. 2. a) Anode under AFM before immersion process, b) Anode under AFM after immersion in microbial solution, c) Anode under AFM after immersion in anaerobic sludge.

Results and Discussion

Morphology of the Electrodes

To enrich the anodes with microorganisms, the anodes were immersed in either a microbial solution or an anaerobic sludge for one week [19]. The morphology of the electrodes before and after the immersion process are shown in Fig. 2. The figure shows changes in morphologies, which indicate the formation of layers of microorganisms on the surface of the anodes. It is clear that these layers of microorganisms on the electrodes immersed in the anaerobic sludge were thicker than the electrodes immersed in the microbial solution. This is because the anaerobic sludge had more suspended solids than the microbial solution, and this led to the attachment of these solids to the surface of the electrodes.

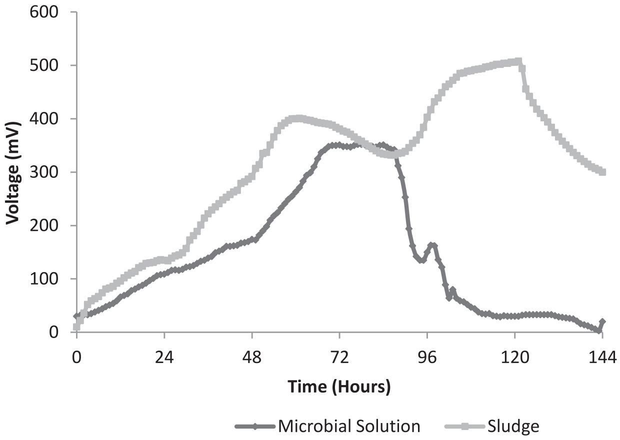

Fig. 3. Voltage over time with the microbial solution and anaerobic sludge for glucose-based wastewater.

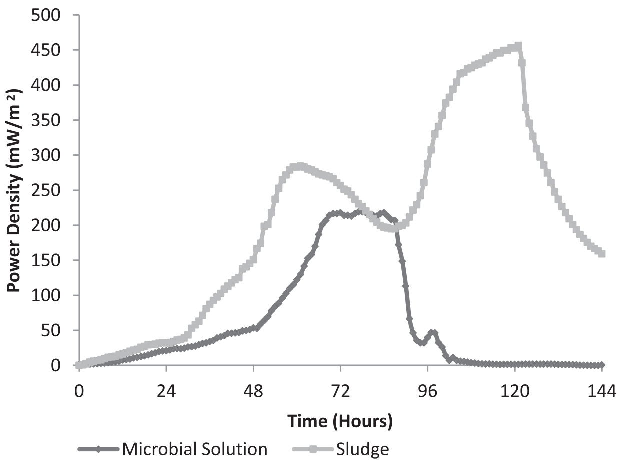

Fig. 4. Power density over time with the microbial solution and anaerobic sludge for glucose-based wastewater.

Performance of Single Chamber MFC Used to Treat Glucose-Based Synthetic Wastewater

Synthetic wastewater containing glucose as a carbon source was used in two different systems of MFCs: one containing an anode pre-immersed in a microbial solution, and one pre-immersed in an anaerobic sludge. The maximum voltages and power densities were 351 mV and 218 mW/m^2, respectively, for the microbial solution, and 508 mV and 456.8 mW/m^2, respectively, for the anaerobic sludge (Figs 3 and 4). Fig. 3 shows the occurrence of two peaks (after 61 and 121 hours) for the anaerobic sludge, and only one peak after 79 hours for the microbial solution, due to the differences in their characteristics.

For the anaerobic sludge, the voltage generation began to decrease after 61 hours because the rate of electron transfer to the anode decreased. This may be due to the increase in thickness of layers of microorganisms on the surface of the electrode, which prevented the inner layer of microorganisms (directly attached to the surface of the electrode) from reaching the substrate (glucose). Due to the shear forces generated by the continuous mixing of the contents, the accumulation of layers did not last for a long time; therefore, the rate of electron transfer began to increase again. The decrease in the rate of voltage generation at the end of experiments may be due to the increase in the growth rate of microorganisms that are unable to transfer electrons to the anode (these microorganisms became dominant). These microorganisms competed with the electrogenic bacteria for the carbon source (glucose), so voltage generation decreased while COD removal increased (Fig. 5).

For the microbial solution, no thick layers of microorganisms were formed. Thus, one peak only was formed when the microorganisms that cannot transfer electrons became dominant. Fig. 5 shows the COD removal efficiencies over time for the microbial solution and anaerobic sludge. The overall efficiency of COD removal was 98.8% for the microbial solution and 94.3% for

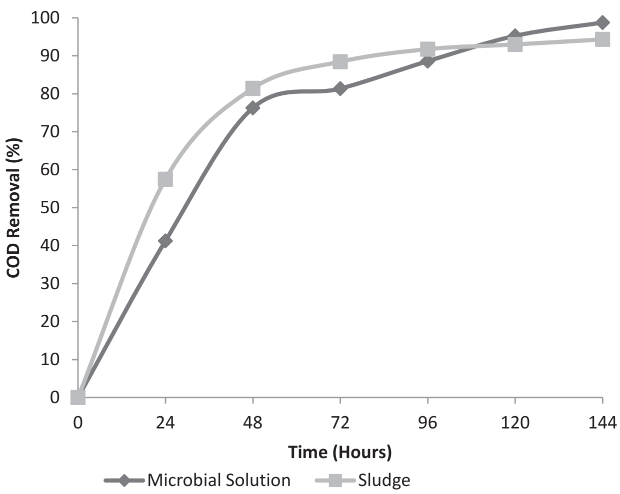

Fig. 5. COD removal efficiency over time with the microbial solution and anaerobic sludge for glucose-based wastewater.

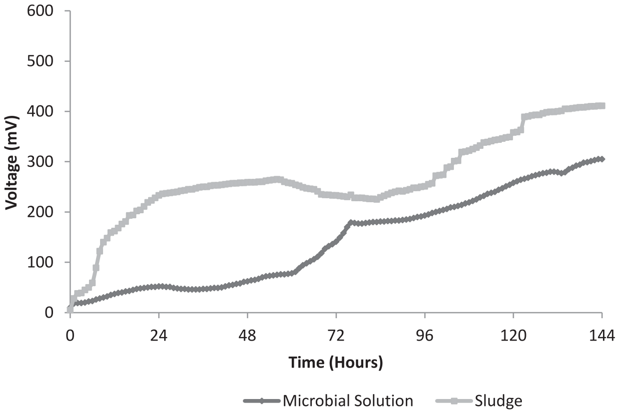

Fig. 6. Voltage over time with the microbial solution and anaerobic sludge for sucrose-based wastewater.

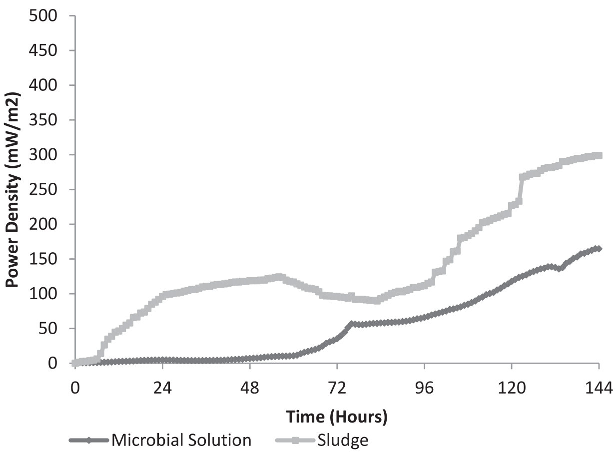

Fig. 7. Power density over time with the microbial solution and anaerobic sludge for sucrose-based wastewater.

the anaerobic sludge. The removal efficiency of COD was higher in the microbial solution than that for the anaerobic sludge due to the different species in each solution. Previous results indicated that, for power generation, the MFC using glucose operated more efficiently with anaerobic sludge than with the microbial solution.

Performance of Single Chamber MFC Used to Treat Sucrose-Based Synthetic Wastewater

Synthetic wastewater containing sucrose as a carbon source was used in two different systems of MFCs: one containing an anode pre-immersed in a microbial solution, and one pre-immersed in an anaerobic sludge. The maximum voltages and power densities were 305 mV and 164.6 mW/m^2, respectively, for the microbial solution, and 411 mV and 298.9 mW/m^2, respectively, for the anaerobic sludge (Figs 6 and 7). Fig. 6 shows that the initial rate of voltage generation for the anaerobic sludge was higher than for the microbial solution; however, this rate decreased with time for the anaerobic sludge. This is

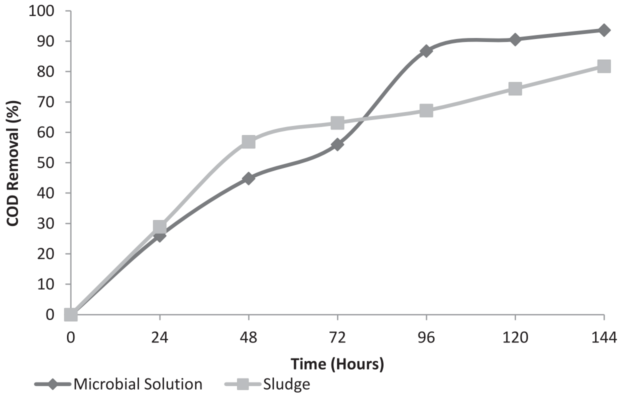

Fig. 8. COD removal efficiency over time with the microbial solution and anaerobic sludge for sucrose-based wastewater.

because the anaerobic sludge did not require a long period of adaptation to the synthetic wastewater because it was obtained from a wastewater treatment plant. In contrast, cultures in the microbial solution required more time for adaptation. Fig. 8 shows the COD removal efficiencies over time for the microbial solution and anaerobic sludge.

The efficiency of COD removal was 93.7 % for the microbial solution and 81.8 % for the anaerobic sludge. The removal efficiency of COD was higher in microbial solution than that for the anaerobic sludge because the species in the two treatments differed. Previous results indicated that, for power generation, the MFC using sucrose operated more efficiently with anaerobic sludge than with the microbial solution.

Performance of Single Chamber MFC Used to Treat Soluble Starch-Based Synthetic Wastewater

Synthetic wastewater containing soluble starch as a carbon source was used in two different systems of MFCs: one containing an anode pre-immersed in a microbial solution, and one pre-immersed in an anaerobic sludge. The maximum voltages and power densities were 281 mV and 139.8 mW/m^2, respectively, for the microbial

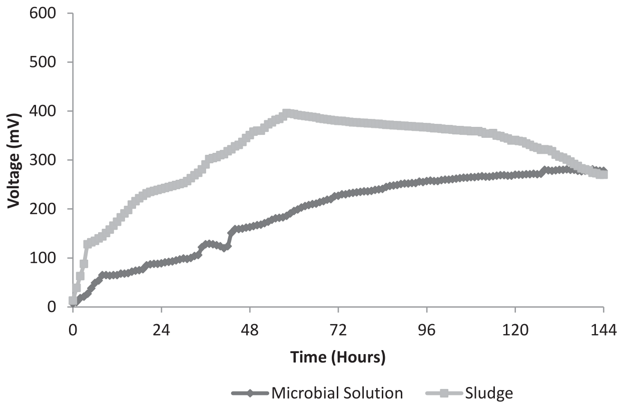

Fig. 9. Voltage over time with the microbial solution and anaerobic sludge for soluble starch-based wastewater.

solution, and 396 mV and 277.6 mW/m^2, respectively, for the anaerobic sludge (Figs 9 and 10). Fig. 9 shows that the voltage generation increased with time for the microbial solution and the rate of voltage generation increased to a peak value after 58 hours, then began to decrease over time for the anaerobic sludge. This change in the rate of voltage generation for the anaerobic sludge may be due to the increased growth rate of microorganisms that are not able to transfer electrons to the anode. These microorganisms compete with the electrogenic bacteria for the carbon source (soluble starch); therefore, voltage generation decreased while COD removal increased (Fig. 11). Fig. 11 shows the COD removal efficiencies over time for the microbial solution and anaerobic sludge. The efficiency of COD removal was 86.4% for the microbial solution and 79.4% for the anaerobic sludge. The removal efficiency of COD was higher for the microbial solution than that for the anaerobic sludge due to different species of microorganisms used. Previous results indicated that, for power generation, the MFC using soluble starch operated more efficiently with anaerobic sludge than with the microbial solution.

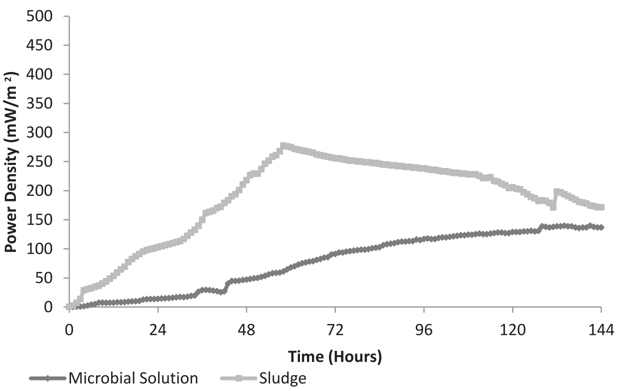

Fig. 10. Power density over time with the microbial solution and anaerobic sludge for soluble starch-based wastewater.

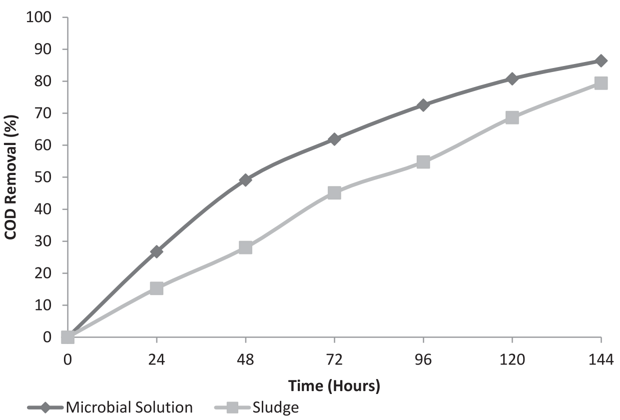

Fig. 11. COD removal efficiency over time with the microbial solution and anaerobic sludge for soluble starch-based wastewater.

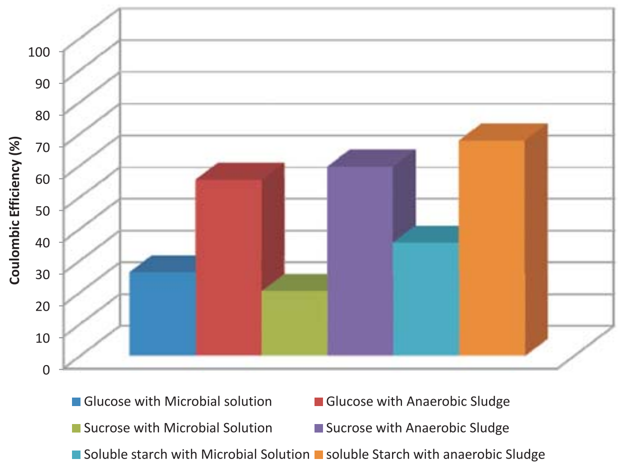

Fig. 12. Coulombic efficiencies of single-chamber MFC when fed with different substrates and seeded with different inocula.

Coulombic Efficiencies Obtained from the Experiments

To relate the power generation to COD removal, the coulombic efficiencies (CE) were calculated as shown in Fig. 12. For glucose-based wastewater, CE was found to be 26.2% for the microbial solution and to be 55.4% for the anaerobic sludge. For sucrose-based wastewater, CE was found to be 20.3% for the microbial solution and 59.5% for the anaerobic sludge. For soluble starch-based wastewater, CE was found to be 35.5% for the microbial solution and 67.7% for the anaerobic sludge. These results indicated that the performance of system when seeded with anaerobic sludge is better than that when seeded with microbial solution containing certain species. It is clear that the coulombic efficiency increased when increasing the complexity of wastewater, because some species can use the product formed by other species during the biodegradation process of complex wastewater.

Conclusion

This study evaluated the performance of single-chamber membraneless microbial fuel cells used to treat three different carbohydrate-rich synthetic wastewaters in order to better understand the mechanism of power generation and biodegradation of different substrates. The treatments were three synthetic wastewaters (containing glucose, sucrose, and soluble starch) and two different inocula (a microbial solution containing different species of microorganisms and an anaerobic sludge). Results showed that the highest voltages, power densities, and COD removal efficiencies were obtained using microbial fuel cells fed with the glucose-based synthetic wastewater, and the lowest values were in microbial fuel cells fed with soluble starch-based synthetic wastewater. The voltages and power densities obtained for the anaerobic sludge were higher than those obtained for the microbial solution; however, the COD removal efficiencies obtained for the anaerobic sludge were less than those obtained for the microbial solution. These values indicate that the best removal efficiencies can be obtained when using a microbial solution that contains specific species and that the highest voltages and power densities can be obtained when using an anaerobic sludge that contains a large number of microbial species. It is clear that in both cases, the voltage generation, power densities, and COD removal efficiencies were inversely proportional to the complexity of the substrate used in the microbial fuel cells. Based on coulombic efficiencies, the performance of MFC increased with the increasing complexity of substrate. These results indicate that single chamber membraneless MFCs are a promising technology in electricity generation and biodegradation of complex carbohydrates.

Acknowledgments

The authors wish to thank Dr. Maha Elshafai and the specialists at the Housing and Building National Research Center for help with the analyses, and the specialists at Micro Analytical Center, Cairo University, for assistance with the microbiological analyses. The authors kindly thank Taylor & Francis Editing Services for the English revision of this manuscript. The authors also would like to thank the reviewers for their valuable comments to improve the manuscript.

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