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Simulation of Hybrid Microbial Fuel Cell-Adsorption System Performance: Effect of Anode Size on Bio-Energy Generation and COD Consumption Rate

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ABSTRACT

Landfill leachate discharged into watercourse without proper treatment can pollute the water source due to its high chemical oxygen demand (COD). The high pollutant load in landfill leachate has become one of the potential substrates in bio-energy generation by using microbial fuel cell (MFC). MFC integrated with adsorption system has been introduced as an approach to overcome the limitation of stand-alone MFC, which is able to treat the landfill leachate more effectively while simultaneously generating bio-energy. Anode size has been reported to have a significant influence on the power generation of MFC via lab-scale experiments, however the simulation studies on MFC are still limited. This study aimed to develop a simulation model to predict the effect of graphite fiber brush anode size on the performance of a single chamber air-cathode hybrid MFC-Adsorption system, in terms of COD removal and bio-energy generation. The highest power density of 1.33 mW/m^2 was achieved with 20% anode brush removed. The highest current generation of 2.37 mA and voltage of 7.11 mV was obtained with the largest anode surface area of 0.1288 m^2 and resistance of 2.76 Ω. The highest COD consumption by electrogenic microorganisms was 4.96 x 10^{-9} Lmol/mg, and predicted to decrease with decreasing anode size. The efficiency of the simulation model could be further improved by incorporating parameters such as charge transfer kinetic at anode and cathode, adsorption effect by activated carbon as well as the substrate and microbial population behaviour. The simulation model developed was significant towards enhancing the bio-energy generation and reducing the cost of MFC for industrial application.

Keywords: Bio-energy; chemical oxygen demand; landfill leachate; microbial fuel cell; simulation model

INTRODUCTION

Landfill leachate consists of various components characterised as high chemical oxygen demand (COD), biochemical oxygen demand (BOD), BOD/COD ratio, suspended solids, pH, turbidity, ammonium-nitrogen (NH_3-N) and heavy metals. Energy production from landfill leachate has become a recent interest due to the potential of this highly polluting wastewater as the source of bio-electricity generation (Tan *et al*., 2023). MFC has demonstrated advantages as compared to other wastewater treatment processes as MFC can convert substrate energy to electricity directly, and operate at ambient or low temperatures, thus producing less amount of excessive sludge (Sorgato *et al*., 2023). The MFC design for practical application as it single chamber air-cathode is the most suitable produces higher power generation, low cost and simple design (Samudro *et al*., 2022; Li *et al*., 2023). In terms of voltage generation and treatment efficiency, hybrid system is generally more reliable and efficient than a stand-alone MFC (Tee *et al*., 2016). Yazdi *et al*. (2016) obtained a higher power density of 2400 mW/m^2 by using 2.5 cm^2 graphite fiber brush (GFB) as an anode electrode material. However, the optimization of bio-energy through the MFC design still needs to be further researched for industrial application. Numerical studies on MFC can be extensively used to offer deeper insights into MFC performance (Gadkari *et al*., 2019a).

The performance of MFC depends on the improvement through modifying system architecture, materials and better understanding of the solution chemistry (Liang *et al*., 2022). The metabolic pathway of the microorganism and the potential of anode are the key parameters for cell potential determination. The anode used in MFC should be able to reduce the internal resistance and increase power density when placed together with the cathode. According to Sakai *et al.* (2018), the surface area of anode has an important role in energy production. Rossi *et al*. (2019) reported an 18% reduction in the power density with a larger anode due to increasing in the internal resistance. A shorter anode-brush diameter was found to maintain a closer spacing of electrodes which reduced the internal resistance and improved MFC performance (Lanas *et al*., 2014). In a single chamber MFC, a carbon brush with 27 cm^2 produced 48 mW/m^3 whereas an anode with 9 cm^2 produced 41 mW/m^3 (Houghton *et al*., 2016). As the number of experimental studies on MFC has been increasing, it is not the same for mathematical modelling and simulation studies. Mathematical models are able to help in understanding the influence of different operational, design and biological parameters affecting the MFC performance, and to optimize the new reactor configurations as well as aiding in up-scaling the technology (Ortiz-Martínez *et al*., 2015). Improvement in simulation design is crucial as the innovation of MFC for industrial application is restricted by the electrode material cost, requirement of precious metal, low power density and low performance of the system. These issues can be overcome at the lab scale, however the vital part is the performance on a large scale particularly when managing wastewater that does not have steady conditions with time (Logan, 2010). A few mathematical models have been developed to study the influence of anode on MFC performance, such as the model on bioanode (Gadkari *et al*., 2019b) and two-dimensional model of air-cathode MFC with GFB as anode (Gadkari *et al*., 2019a). Gadkari *et al*. (2019a) used Nelder-Mead Simplex algorithm for prediction of power generation to estimate the parameters in the model, which reported little change in power density around 15% to 60% of brush removed in which the power density was reduced by 21%.

Table 1 shows the development of MFC numerical studies. Limited numerical studies have focused on air-cathode MFC. Additionally, optimisation using simulation on hybrid MFC-Adsorption system has not been reported up to date, and the study on the effect of anode size in hybrid MFC-Adsorption system has not been found. Simulation study is significant towards the development of MFC for industrial application as the system is currently in its infancy stage due to the challenges on reducing the high cost and improving the power generation. Anode generally should have the characteristics of larger surface area, best chemical and microbial stability, high electrical conductivity, biocompatibility and inexpensive in cost (Liang *et al*., 2022). The power output of the system is determined by the wellness of biofilm attached to the anodic surface area. Thus, the best method to enhance the performance of the MFC is by increasing the affinity of the biofilm through anode modification (Banerjee *et al*., 2022). Therefore, the main focus of the present study was to develop a simulation model using Microsoft Excel 365 Proplus by correlating the anode size of a single chamber hybrid MFC-Adsorption system with the bio-energy generation of the system and COD consumption rate, by using landfill leachate as the MFC substrate. In addition, the current and voltage generated in the hybrid MFC-Adsorption system with different anode size were predicted through simulation of the maximum power densities.

MATERIALS AND METHODS

Simulation Design

The simulation used in this work was adopted from Gadkari *et al*. (2019a) which was the two-dimensional simulation focusing on single chamber air-cathode MFC. Microsoft Excel 365 Professional Plus was used to develop the simulation in predicting the bio-energy generation and COD consumption rate. GFB anode was represented in the simulation and was connected using twisted titanium wire and placed at the central of the closely packed-bed of granular activated carbon (GAC). The air-cathode existed as activated carbon fiber felt (ACFF) and was connected to the circuit by a copper rod. The electrode was exposed to air on its outer surface while being in contact with the earthen pot and hydrogel was applied evenly between them, following the configuration of the hybrid MFC-Adsorption system of Tee *et al*.

Table 1. Development of MFC numerical studies

Mathematical and simulation study on MFC	Description	Range of study	Reference
1-Dimensional mathematical model	Developed model coupling biological, heat and mass transfer processes occurring in MFC. Numerical tools: Microsoft Excel and MATLAB.	1. Effect on cathode and anode overpotential as a function of current density. 2. Effect of substrate concentration on biofilm thickness. 3. Effect of temperature on MFC performance. 4. Effect on biomass and acetate concentration as a function of current density.	Oliveira *et al*. (2013)
Modelling based on Freter equations	Developed model simulation towards electrochemical performance in batch and continuous mode of MFC operation. Numerical tools: MATLAB.	Batch mode: 1. Effect of initial substrate on external voltage. 2. Effect of external resistor on overall energy efficiency. Continuous mode: 1. Effect on power generation as a function of influent substrate concentration and dilution rate. 2. External resistor effect on the overall energy efficiency.	Lin *et al*. (2018)
Dynamic model based on bioanode kinetic	Developed model based on batch operated single chamber MFC with biotic anode and an air-cathode.	1. Effect of initial substrate concentration on maximum voltage, CE and COD removal rate. 2. Effect of external resistance on MFC performance.	Gadkari *et al*. (2019a)
2-Dimensional model	Developed model with charge transfer kinetic coupled to the mass balance for both anode and cathode electrode.	1. Effect of anode size on power densities. 2. Effect of anode distance from cathode on power densities. 3. Effect of initial substrate concentration on power densities, CE and COD removal rate.	Gadkari *et al*. (2019b)

(2016). The reactor was assumed to be operating in fed-batch mode. Anode GFB is known with high porosity characteristics. Gadkari *et al*. (2019a) successfully simulated the anode GFB by using a mathematical model to optimize the GFB anode-based air-cathode MFC in a directed way, which helped in optimizing the performance relationship across the scale. Therefore, a simulation on GFB anode size of hybrid MFC-Adsorption system was performed in this study to evaluate its effect on bio-energy generation.

The simulation incorporated a few assumptions for the development and simplicity. The parameters such as pH and temperature were neglected, carbon dioxide (CO_2) released during substrate oxidation in the anode stayed dissolved in the bulk solution, leachate and CO_2 remained in the anode chamber and did not diffuse to cathode assembly, similar with the oxygen from air-cathode which did not diffuse in the anode chamber. The substrate used was landfill leachate which functioned as the only electron donor in the anolyte. The effective porosity of the brush anode was remained when the concentration of bacteria/substrate changed. The last assumption was the reverse reaction of substrate oxidation at anode and oxygen reduction at cathode were negligible. The parameters of landfill leachate were obtained from Shanmugham (2019) while power generation values were obtained from Tee *et al*. (2016). The MFC working volume was 5.65 L whereas the GFB anode was designed as 100 mm in diameter and 360 mm long. The anode was maintained at 4 cm from the cathode. Other parameters were estimated by using the best fit correlation equation obtained using the Microsoft Excel 365 Professional Plus.

Calculation of Anode Surface Area

The area of GFB anode was calculated using Equation 1 [Eq. (1)] to estimate the power generation. The anode size was reduced by removing the sections of the brush incrementally from the side farthest from the cathode (Gadkari *et al*., 2019a). The same was used in this simulation study by maintaining the distance between the anode and cathode at 4 cm. The area of anode after the removal was calculated using Equation 2 [Eq. (2)]

$$A = 2\pi rh + 2\pi r^2 \qquad \text{Eq.(1)}$$
$$A_i = A_0 + A_0(i\%) \qquad \text{Eq.(2)}$$

where A (m^2) indicated surface area while h (m) was length of brush and r (m) was radius of brush. A_i (m^2) was area of anode after removal, A_0 (m^2) was initial area of brush, i indicated percent of removal.

Simulation Study of Hybrid MFC-Adsorption System

The first simulation was performed by comparing the trend with Gadkari *et al*. (2019a). The power density was predicted against the brush removal by using the maximum power density from Tee *et al*. (2016) as the reference. The power was calculated using Equation 3 (Eq.(3)) whereas the current generated for each anode size was calculated using Equation 4 (Eq.(4)). The voltage generated was calculated using Equation 5 (Eq.(5)). The second simulation was performed on the current generation against time by referring to the data of Penteado *et al*. (2018) where the maximum current value was calculated from the first correlation developed on power density. This study focused on the ratio of anode surface area to the volume of anode compartment (ESAVR) towards the performance of current generated (Penteado *et al*., 2018). The predicted values were used to calculate the voltage generated against time by using Equation 5.

$$P = P_d A \qquad \text{Eq.(3)}$$

$$I = \sqrt{\left(\frac{P}{R}\right)} \qquad \text{Eq.(4)}$$

$$V = IR \qquad \text{Eq.(5)}$$

where P (W) was power, P_d (W/m^2) was power density, A (m^2) was area of anode and I (A) was current. For voltage (V) calculation, the constant resistance, R of 30 Ω was multiplied with the current.

Prediction of COD Consumption Rate

The COD consumed in relation to the anode size was predicted by referring to Penteado *et al*. (2018). The COD consumption rate was predicted to decrease by 1000 mg/Lday with decreasing anode size. With the prediction of COD consumed in the hybrid MFC-Adsorption system, the fraction of COD or COD consumption by electrogenic microorganism (Lmol/mg) was then calculated using Equation 6 (Eq. (6)) (Penteado *et al*., 2018). For the largest anode surface area, the COD of landfill leachate was 729 mg/L (Shanmugham, 2019) and the consumption rate was 6.12 L/h (Tee *et al*., 2016), thus the COD consumption rate was 107,075.52 mg/Lday.

$$ratioelectrogenic = \frac{\frac{jA}{4F}}{rCOD} \qquad \text{Eq.(6)}$$

where $rCOD$ (mg/Lday) indicated the rate of COD consumed in the anode chamber, F (96,485 As/mol) was Faraday's constant, j (A/m^2) was current density and A (m^2) was anode surface area.

Parameters of Simulation Study

The parameters shown in Table 2 were used to simulate the effect of anode size on the bio-energy generation and COD consumption rate of the hybrid MFC-Adsorption system.

Table 2. Parameters of simulation studies

Parameter	Value	Unit	Reference
GFB initial diameter	100	mm	Tee *et al.* (2016)
GFB initial length	360	mm	Tee *et al.* (2016)
Maximum power density	1.21	mW/m^2	Tee *et al.* (2016)
Maximum current	2.37	mA	Tee *et al.* (2016)
Maximum voltage	0.66	mV	Estimated
Resistance	30	Ω	Estimated
COD	729	mg/L	Shanmugham (2019)
Volume of anode compartment	5.65	L	Tee *et al.* (2016)

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RESULTS AND DISCUSSION

Effect of Anode Size on Bio-Energy Generation

In the first simulation, the bio-energy generation in terms of power, voltage and current in relation to the change of anode size was studied. The maximum power density (Figure 1(a)) showed insignificant change of about 1±0.3% to 40% of brush removed and predicted to show a greater decrease of 2% when compared to the results of Gadkari *et al*. (2019a) as shown in Figure 2. This was possibly due to the same type of anode used that had been heat-treated. The power density was the highest with 20% brush removed as the over-potential in the brush increased (Gadkari *et al*., 2019a). Additionally, the local current density and reaction rate was higher as the distance of brush end from cathode decreased. It could be observed in Figure 2 that the local current density and reaction rate in the brush anode decreased with decreasing anode size. The increase in 20% to 40% reduction of anode size indicated that the average local current density and reaction rate had reached its maximum capacity. The maximum average local current density and reaction rate showed a major drop in the case of 60% of brush removed, hence this caused the reduction in power density after a nearly constant power density was achieved between 20% to 40% of brush removed. Higher power density could be achieved by using a more conductive electrolyte as power density could be affected by the substrate concentration (Logan *et al*., 2015) which influenced the speed of bacteria in removing the oxygen and reducing oxygen mass transfer into the anode (Hays *et al*., 2011). Di Lorenzo *et al*. (2010) also suggested to include the mass transfer effect of a substrate in anode electrode for a better understanding of MFC behaviour.

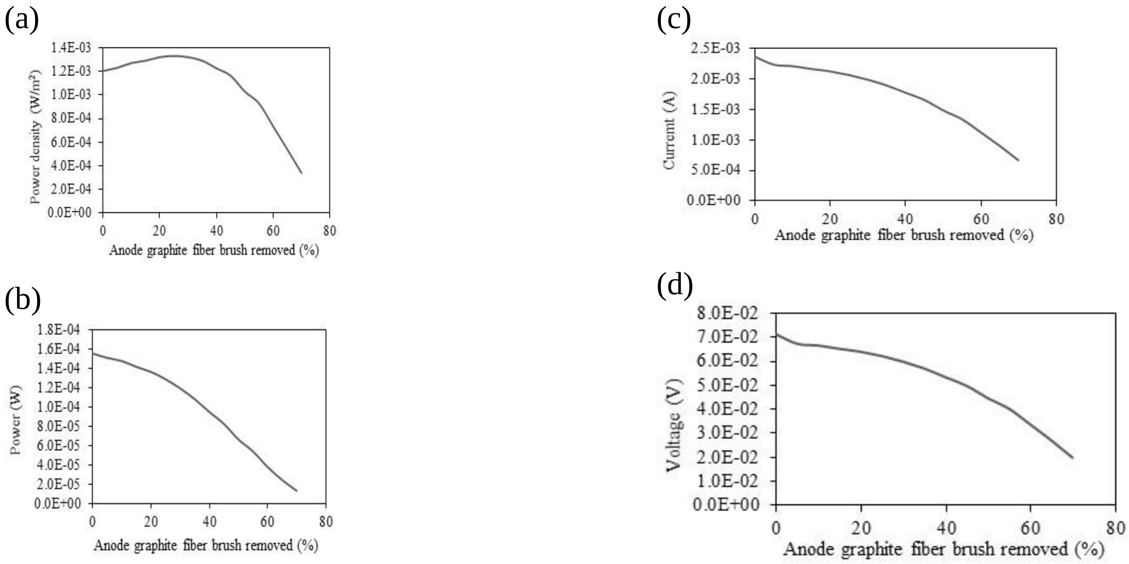

Figure 1. Simulation of (a) power density, (b) power, (c) current and (d) voltage generation in hybrid microbial fuel cell-Adsorption system against percentage of anode graphite fiber brush removed

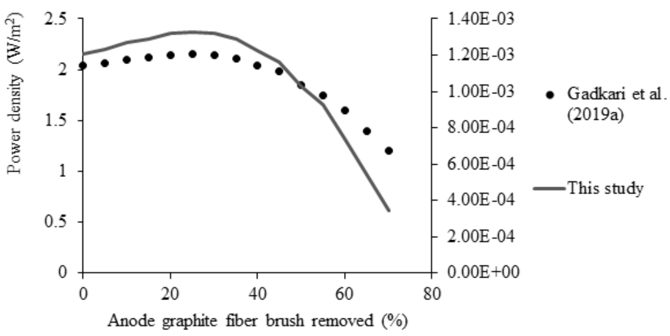

Figure 2. Predicted value of power density obtained from correlation to the corresponding value adopted from Gadkari *et al*. (2019a)

Power Generation in Hybrid MFC-Adsorption System

The power generated was found to decrease with decreasing anode size (Figure 1(b)). By comparing the gradient of the graph, an assumption could be drawn where huge changes in power generation occurred with 20% and 60% of brush removed. According to Rossi *et al*. (2019), lower power output was obtained with smaller anode primarily due to the decrease in cathode potential. The cathode performance could decrease because of cathode fouling (Yang *et al*., 2017). This was supported by Houghton *et al*. (2016) where increasing anode area did not improve the system performance since cathode had been the limiting factor for the power production. Houghton *et al*. (2016) also reported that anode electrode contributed to lower ohmic losses as compared to cathode electrode.

Current Generation in Hybrid MFC-Adsorption System

Figure 1(c) shows that the current generation decreased with the decreasing anode size with a fluctuation between no brush removal and 5% of brush removed. This simulation used 30 Ω resistance, which was different from the resistance value (27.6 Ω) used by Tee *et al*. (2016), which affected the current generation. Gadkari *et al*. (2019b) proved that the increase in the applied external resistance caused a decrease in the current density, coulombic efficiency and COD removal rate of the MFC. Kumar *et al.* (2018) explained that sufficient electrode spacing and surface of anode were obligated for bacterial growth as well as for electron transformation from anode to cathode. Lower current and power density were obtained with higher total internal impedance where diffusion resistance had been the contributor (Lanas *et al*., 2014). Wider spacing between the cathode and edge of anode brush also caused an increase in the total internal impedance (Cheng *et al*., 2006). In this simulation study, the electrode spacing could be reduced to less than 4 cm to generate a higher current. Close electrode spacing in the hybrid MFC-Adsorption system was significant due to the lower conductivity of substrate which resulted in higher ohmic losses. The anode acts as a surface for bacteria to associate to generate electron and proton during respiration (Kumar *et al*., 2018). Additionally, the current generation was highly dependent on the concentration of bacteria attached onto the surface of anode. This suggested that lower surface area for bacterial attachment would reduce the anoxic condition for the exoelectrogenic activity (Penteado *et al*., 2018). Less bacteria attached would reduce the electron transfer to the anode surface. The reduction of anode size caused a reduction of the surface area of brush anode from 0.1288 cm^2 to 0.1224 cm^2, thus resulted in the descending current generated. Generally, specific current generation also depended on current density that was dependent on the over-potential which was a function of electrode potential, electrolyte potential and equilibrium potential of the charge transfer reaction at the particular electrode (Gadkari *et al*., 2019a).

Voltage Generation in Hybrid MFC-Adsorption System

Figure 1(d) shows that the voltage generation demonstrated similar trend as the current generation, which decreased with the decreasing anode size. The simulation results showed that the highest anode area of 0.1288 m^2 produced the highest voltage of 0.71 mV. Wang *et al.* (2013) reported 97.9 mV was generated with higher anode graphite plate size of 81.1 cm^2 while smaller anode with 74.5 cm^2 surface area generated 71.5 mV. The higher voltage also indicated the higher amount of the attached biomass (Lin *et al*., 2018). The low voltage generation could be mainly due to the mediator-less MFC system which had caused most microorganism species to be inactive in transferring electron to the anode (Tee *et al*., 2016). The ease of electron transfer process in the bio-electrochemical system enhanced the voltage production. Mediator would act as the electron shuttler which enhanced the electron efficiency. However, a few studies have reported the unnecessary use of mediator which made the mediator-less MFC to be more commercially feasible since the electron generated was transferred to the anode surface by a few mechanisms such as through conductive appendages, direct contact, provided chemical mediators or self-produce mediators (Das & Mangwani, 2010; Kumar *et al*., 2016). Modification of anode was found to be able to increase the biofilm attached on its surface area to produce higher power output (Santoro *et al*., 2013). The comparison of the performance of the hybrid MFC-Adsorption system developed in this study with other MFC systems are summarized in Table 3. The power density obtained was lower than previous studies due to smaller size of anode was used. Higher power density of hybrid MFC-Adsorption system with anode area of 0.1030 m^2 could be achieved by using a more conductive electrolyte as the substrate considering the low microbial kinetic of the landfill leachate.

Table 3. Comparison of performance of various microbial fuel cell (MFC) systems

Type of MFC	Anode type	Anode size	Findings		Reference
			Current	Power density	
Dual chamber	Graphite plate	74.5 cm^2	186.2 µA	NA	Wang *et al.* (2013)
		81.1 cm^2	271.3 µA		
Single chamber	Graphite pellets	12.5 cm^2	0.03 mA	0.01 W/m^3	Di Lorenzo *et al.* (2010)
		90 cm^2	0.067 mA	0.043 W/m^3	
		499 cm^2	0.0171 mA	0.247 W/m^3	
		1247 cm^2	0.47 mA	8.1 W/m^3	
Single chamber	Carbon brush	9 cm^2	NA	48 ± 1.3 W/m^3	Houghton *et al.* (2016)
		18 cm^2		44.5 ± 0.88 W/m^3	
		27 cm^2		48 ± 1.3 W/m^3	
Single chamber air-cathode	Carbon fiber brush	2.5 cm in diameter	0.32 mA/cm^2	1270 mW/m^2	Lanas *et al.* (2014)
		1.2 cm in diameter	0.29 mA/cm^2	910 mW/m^2	
		0.8 cm in diameter	0.23 mA/cm^2	600 mW/m^2	
Single chamber air-cathode	GFB	0.1288 m^2	2.37 mA	1.2 mW/m^2	This study
		0.1030 m^2	2.13 mA	1.32 mW/m^2	
		0.0772 m^2	1.78 mA	1.23 mW/m^2	
		0.0515 m^2	1.12 mA	0.736 mW/m^2	

*NA-not applicable

Optimisation of Bio-Energy Generation

The optimised current generation took shorter time to increase and achieved a stable state with higher ESAVR (Figure 3). The rapid increasing state indicated the start-up with prediction of a day extended to the function of decreasing ESAVR. The largest anode size was estimated to have ten days of start-up. The study simulated in terms of best fit graph on the first current generation against time which was for the largest surface area of anode by referring to Tee *et al.* (2016). The next current generation was estimated by taking the difference of the maximum current generation between the anode size. This resulted in the continuous plot of current generation against time. The low initial concentration of bacteria attached on the anode surface justified that more time was needed for the system to generate electricity (Wang *et al*., 2015). According to Angelaalincy *et al.* (2018), large surface area and robust structure played an important role for supporting the biofilm in MFC. Moreover, the presence of active electron transferring live organism at the outer layer of the biofilm caused high current generation (Sun *et al*., 2016). It was speculated that bacteria existed under more anoxic conditions with larger anode brush size. Therefore, more exoelectrogenic consortia developed on the anode brush in order to generate current. As the mass of biofilm increased over time, more brush could achieve sufficient anoxic condition and improved the current generation. Start-up for the removed brush was delayed until sufficient biofilm could consume oxygen in order for exoelectrogenic to grow (Penteado *et al*., 2018). However, high diffusion resistance was found in the electrochemical system as time elapsed due to the dead cell accumulated in the inner layer of the biofilm. This explained the lower current generation at lower surface area of anode. The presence of activated carbon in the anode compartment helped to shorten the start-up time due to the rough surface which offered high surface area for bacteria to grow and form a mature bio-membrane (Tee *et al*., 2016). Tee *et al*. (2016) took 10 days for start-up with 5.65 L working volume. Another study on hybrid MFC-Adsorption system by Selvanathan (2018) used palm oil mill effluent as the substrate reported three days for start-up with 655 mL of working volume and 300 µM methylene blue as the mediator. The start-up time was shorter due to the mediated transfer of electrons from microorganism to anode. Penteado *et al*. (2018) explained that lower volume of anode chamber promoted the competition of microorganism towards substrate. The shorter time obtained in this simulation study was due to a more stable power over time could be achieved using GFB as the anode (Ahn & Logan, 2013).

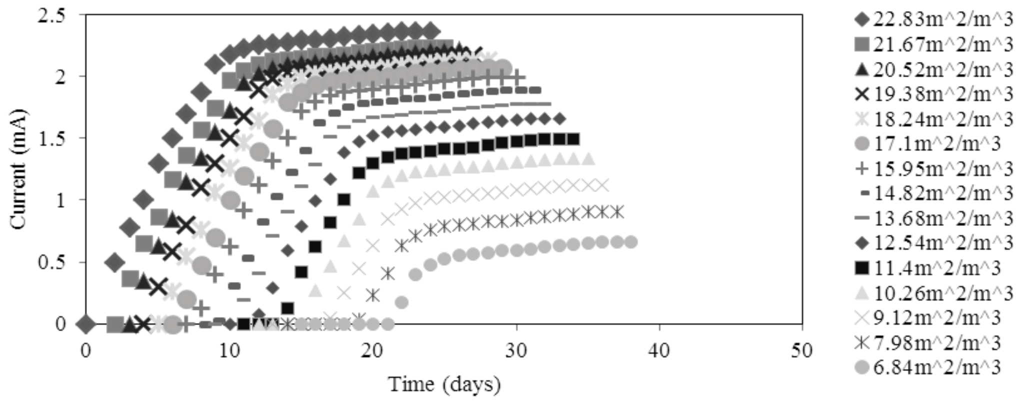

Figure 3. Optimized current generation of hybrid microbial fuel cell (MFC)-Adsorption system against time

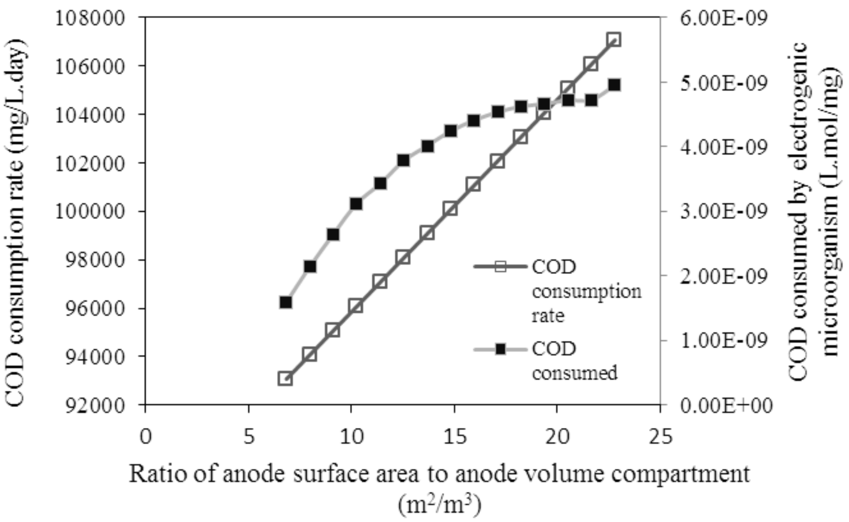

Figure 4. Chemical oxygen demand (COD) consumption rate and Chemical oxygen demand COD consumed by electrogenic microorganism in hybrid microbial fuel cell (MFC)-Adsorption system against ESAVR

Effect of Anode Size on COD Consumption Rate

The COD consumption rate was simulated by referring to Penteado *et al*. (2018) which focused on the effect of ESAVR. However, this study used different conditions by varying the anode surface area and assuming a constant anode volume whereas Penteado *et al*. (2018) varied the anode volume and assumed a constant anode electrode. The simulated COD consumption rate (Figure 4) showed a similar trend with Penteado *et al*. (2018). Fluctuation might occur depending on the load of a substrate which corresponds to the bacteria present in the load (Selvanathan, 2018). The COD consumption rate was also affected by the ESAVR where a higher ESAVR would increase the COD consumption rate. Several studies reported that higher COD removal was obtained when higher anode size was used. Wang *et al*. (2013) showed 14.86% and 6.87% of COD removal using 81.1 cm^2 and 74.5 cm^2 of anode graphite plate, respectively. Di Lorenzo *et al*. (2010) showed 70% of COD removal using 1247 cm^2 of graphite pellets as compared to the smaller anode size. The treatment efficiency depended on the total population of microorganism (Wang *et al*., 2015). Higher anode surface area led to higher nutrient consumption which indicated a positive effect on the degradation of the waste and promotion in the biomass formation. The COD consumption rate also depended on the anode volume where a lower anode compartment resulted in a higher COD consumption rate due to more competition among microorganisms for food (Penteado *et al*., 2018). Larger anode surface area enhanced the power generation of the hybrid MFC-Adsorption system which suggested that the role of microorganism was fixed in anodic biofilm. Penteado *et al*. (2018) stated the significance of fraction of COD consumption by electrogenic microorganism which was related to the MFC performance. In this study, the highest COD consumed by electrogenic microorganism was 4.96 x 10^{-9} Lmol/mg, which was obtained with the largest anode surface area of 0.1288 m^2. The COD consumed by electrogenic microorganism decreased with decreasing ESAVR. This could be explained in terms of higher ohmic losses due to the microbial community selection in lower shear force which was affected by a smaller anode size (Penteado *et al*., 2018).

CONCLUSION

The performance of a hybrid MFC-Adsorption system in terms of bio-energy generation and COD consumption rate has been simulated using different GFB anode size. The highest power density of 1.33 mW/m^2 was obtained with 20% of anode brush removed. The power density obtained was lower than previous studies due to the smaller size of anode used. Higher power density with an anode area of 0.1030 m^2 could be achieved by using a more conductive electrolyte as the substrate considering the low microbial kinetic of the landfill leachate. The current and voltage generation demonstrated a decreasing trend with the reduction in anode size. Besides, the start-up time was shorter when a larger anode surface area was applied. The COD consumption rate and COD consumed by electrogenic microorganisms decreased with increasing ESAVR. The simulation model developed in this study could be further improved for better performance of the hybrid MFC-Adsorption system by considering other parameters such as the reaction rate in anode brush, charge transfer kinetics, substrate and microbial population behaviour as well as the mass transfer of air diffused in both anode and cathode electrodes. A more precise simulation and numerical study on the hybrid MFC-Adsorption system would offer deeper insights into the mechanism of the system operation and potentially help in optimising the system performance. Overall, the simulation model developed was significant towards enhancing the bio-energy generation and reducing the cost of MFC for industrial application.

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REFERENCES

Ahn, Y. & Logan, B.E. (2013). Domestic wastewater treatment using multi-electrode continuous flow MFCs with a separator electrode assembly design. *Applied Microbiology and Biotechnology*, 97: 409-416.

Angelaalincy, M.J., Krishnaraj, R.N., Shakambari, G., Ashokkumar, B., Kathiresan, S. & Varalakshmi, P. (2018). Biofilm engineering approaches for improving the performance of microbial fuel cells and bioelectrochemical systems. *Frontiers in Energy Research*, 6: 63.

Banerjee, A., Calay, R.K. & Mustafa, M. (2022). Review on material and design of anode for microbial fuel cell. *Energies*, 15: 2283.

Cheng, S., Liu, H. & Logan, B.E. (2006). Increased power generation in a continuous flow MFC with advective flow through the porous anode and reduced electrode spacing. *Environmental Science & Technology*, 40: 2426-2432.

Das, S. & Mangwani, N. (2010). Recent developments in microbial fuel cell: A review. *Journal of Scientific & Industrial Research*, 69: 727-731.

Di Lorenzo, M., Scott, K., Curtis, T.P. & Head, I.M. (2010). Effect of increasing anode surface area on the performance of a single chamber microbial fuel cell. *Chemical Engineering Journal*, 156: 40-48.

Gadkari, S., Gu, S. & Sadhukhan, J. (2019a). Two-dimensional mathematical model of an air cathode microbial fuel cell with graphite fiber brush anode. *Journal of Power Sources*, 441: 227145.

Gadkari, S., Shemfe, M. & Sadhukhan, J. (2019b). Microbial fuel cells: A fast converging dynamic model for assessing system performance based on bioanode kinetics. *International Journal of Hydrogen Energy*, 44: 15377-15386.

Hays, S., Zhang, F. & Logan, B.E. (2011). Performance of two different types of anodes in membrane electrode assembly microbial fuel cell for power generation from domestic wastewater. *Journal of Power Sources*, 196: 8293-8300.

Houghton, J., Santoro, C., Soavi, F., Serov, A., Ieropoulos, I., Arbizzani, C. & Atanassov, P. (2016). Supercapacitive microbial fuel cell: Characterization and analysis for improved charge storage/delivery performance. *Bioresource Technology*, 218: 552-560.

Kumar, R., Singh, L. & Zularisam, A.W. (2016). Exoelectrogens: Recent advances in molecular drivers involved in extracellular electron transfer and strategies used to improve it for microbial fuel cell applications. *Renewable and Sustainable Energy Reviews*, 56: 1322-1336.

Kumar, R., Singh, L., Zularisam, A.W. & Hai, F.I. (2018). Microbial fuel cell is emerging as a versatile technology: A review on its possible applications, challenges and strategies to improve the performances. *International Journal of Energy Research*, 42: 369-394.

Lanas, V., Ahn, Y. & Logan, B.E. (2014). Effects of carbon brush anode size and loading on microbial fuel cell performance in batch and continuous mode. *Journal of Power Sources*, 247: 228-234.

Li, J., Lin, S., Zhang, Y., Wang, T., Luo, H. & Liu, G. (2023). Nitrogen removal with the physiological stratification of cathodic biofilm in air-cathode single-chamber microbial fuel cell under different external resistances. *Chemical Engineering Science*, 275: 118746.

Liang, H., Han, J., Yang, X., Qiao, Z. & Yin, T. (2022). Performance improvement of microbial fuel cells through assembling anodes modified with nanoscale materials. *Nanomaterials and Nanotechnology*, 12: 1-14.

Lin, H., Wu, S. & Zhu, J. (2018). Modeling power generation and energy efficiencies in air-cathode microbial fuel cells based on Freter equations. *Applied Science*, 8: 1983.

Logan, B.E. (2010). Scaling up microbial fuel cells and other bio-electrochemical systems. *Applied Microbiology and Biotechnology*, 85: 1665-1671.

Logan, B.E., Wallack, M.J., Kim, K.Y., He, W., Feng, Y. & Saikaly, P.E. (2015). Assessment of microbial fuel cell configurations and power density. *Environmental Science & Technology Letters*, 2: 206-214.

Oliveira, V.B., Simões, M., Melo, L.F. & Pinto, A.M.F.R. (2013). A 1D mathematical model for a microbial fuel cell. *Energy*, 61: 463-471.

Ortiz-Martínez, V.M., Salar-García, M.J., de los Ríos, A.P., Hernández-Fernández, F.J., Egea, J.A. & Lozano, L.J. (2015). Developments in microbial fuel cell modeling. *Chemical Engineering Journal*, 271: 50-60.

Penteado, E.D., Fernandez-Marchante, C.M., Zaiat, M., Gonzalez, E.R. & Rodrigo, M.A. (2018). Optimization of the performance of a microbial fuel cell using the ratio electrode-surface area / anode-compartment volume. *Brazilian Journal of Chemical Engineering*, 35: 141-146.

Rossi, R., Evans, P.J. & Logan, B.E. (2019). Impact of flow recirculation and anode dimensions on performance of a large-scale microbial fuel cell. *Journal of Power Sources*, 412: 294-300.

Sakai, K., Iwamura, S., Sumida, R., Ogino, I. & Mukai, S.R. (2018). Carbon paper with a high surface area prepared from carbon nanofibers obtained through the liquid pulse injection technique. *ACS Omega*, 3: 691-697.

Samudro, G., Imai, T. & Reungsang, A. (2022). Determination of optimum retention time in an air-cathode single-chamber microbial fuel cell batch-mode reactor by comparing different substrate types and concentrations. *Process Safety and Environmental Protection*, 162: 694-705.

Santoro, C., Ieropoulos, I., Greenman, J., Cristiani, P., Vadas, T., Mackay, A. & Li, B. (2013). Power generation and contaminant removal in single chamber microbial fuel cells (SCMFCs) treating human urine. *International Journal of Hydrogen Energy*, 38: 11543-11551.

Selvanathan, J.R. (2018). *Palm oil mill effluent treatment and bioenergy generation using hybrid microbial fuel cell-adsorption system.* (Thesis), Universiti Malaysia Sarawak, Malaysia.

Shanmugham, B. (2019). *Hybrid microbial fuel cell adsorption system with mediator for landfill leachate treatment and bioenergy generation.* (Thesis), Universiti Malaysia Sarawak, Malaysia.

Sorgato, A.C., Jeremias, T.C., Lobo, F.L. & Lapolli, F.R. (2023). Microbial fuel cell: Interplay of energy production, wastewater treatment, toxicity assessment with hydraulic retention time. *Environmental Research*, 231: 116159.

Sun, D., Chen, J., Huang, H., Liu, W., Ye, Y. & Cheng, S. (2016). The effect of biofilm thickness on electrochemical activity of *Geobacter sulfurreducens*. *International Journal of Hydrogen Energy*, 41: 16253-16258.

Tan, W., Yang, Z., Feng, Q., Su, H., Xu, L. & Liu, C. (2023). Effect of $NiCo_2O_4$ and Ni-P modified anodes on the treatment of aging landfill leachate by microbial fuel cells. *Journal of Power Sources*, 577: 233233.

Tee, P.-F., Abdullah, M.O., Tan, I.A.W., Mohamed Amin, M.A., Nolasco-Hipolito, C. & Bujang, K. (2016). Performance evaluation of a hybrid system for efficient palm oil mill effluent treatment via an air-cathode, tubular upflow microbial fuel cell coupled with a granular activated carbon adsorption. *Bioresource Technology*, 216: 478-485.

Wang, J., Zheng, Y., Jia, H. & Zhang, H. (2013). In situ investigation of processing property in combination with integration of microbial fuel cell and tubular membrane bioreactor. *Bioresource Technology*, 149: 163-168.

Wang, Y.L., Deen, M.J., Marsal, L.F., Hoff, A., Aguilar, Z.P. & Lin, Z.H. (2015). Solid-state electronics and photonics in biology and medicine 2. *ECS Transaction*, 69: 51-55.

Yang, W., Rossi, R., Tian, Y., Kim, K.-Y. & Logan, B.E. (2017). Mitigating external and internal cathode fouling using polymer bonded separator in microbial fuel cell. *Bioresource Technology*, 249: 1080-1084.

Yazdi, A.A., D'Angelo, L., Omer, N., Windiasti, G., Lu, X. & Xu, J. (2016). Carbon nanotube modification of microbial fuel cell electrodes. *Biosensors and Bioelectronic*, 85: 536-552.