Performance Analysis and Mathematical Modeling of MFCs: A Study on Lapindo Mud and Fishery Waste Treatment

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ABSTRACT

The application of MFCs for electricity generation requires a microbial culture source. Lapindo mud, with a total carbon content of 54.75–55.47% and electrigenic bacteria, serves as a viable option. Previous studies indicate that Microbial Fuel Cell systems can also degrade waste, including fishery waste. This study aims to develop a mathematical model of MFC performance, focusing on electricity generation and fishery waste degradation, and to compare the model results with experimental data. Simulations were conducted using MATLAB and the ODE 45 method. The model results closely align with experimental findings. For greater accuracy, integration with a hydrodynamics module using computational fluid dynamics (CFD) is recommended.

***Keywords**: MFCs, Lapindo mud, mathematical modeling, MATLAB*

INTRODUCTION

This research uses a Single Chamber Microbial Fuel Cell (SCMFC), where both anode and cathode are placed in a tubular PET chamber (triangle code 1) with an 8 cm diameter and 15 cm height (Triyadi and Ramadhoni, 2018; Hermawan and Hidayat, 2018). The substrate is liquid waste from the catfish soaking and washing processes at PT Dimas Rezia Perwira, a fish freezing facility in Surabaya (Rivaldo and Silma, 2020). Laboratory analysis shows the waste has a chemical oxygen demand (COD) of 602.30 mg/L and a five-day biochemical oxygen demand (BOD5) of 281.36 mg/L (Rivaldo and Silma, 2020). Government regulations set COD and BOD5 limits for fishery liquid waste from freezing activities at 200 mg/L and 100 mg/L, respectively (Ministry of Environment Regulation No. 5 of 2014).

The stages of the *single chamber microbial fuel cell mechanism in this experimental study are as follows* (Picoreneau et al., 2008).

Electricity-producing (electrogenic) bacteria in Lapindo mud metabolize the fishery liquid waste substrate, causing the degradation of organic compounds in the anode compartment. This metabolism occurs anaerobically, producing electrons (e-) and protons (H+) through the following reaction:

$$C_6H_{12}O_6 + 6H_2O \rightarrow 6CO_2 + 24H^+ + 24^{e-} \qquad E^0 = 0{,}01\ V \qquad (1)$$

The produced electrons (e-) and protons (H+) are transferred to the cathode compartment according to the principle of a voltaic cell. The electrons generated from this reaction accumulate on the electrode (carbon cloth) in the anode compartment. The potential difference between the anode and cathode chambers causes the flow of electrons, which can generate power density. The electron flow moves through the electrode circuit and Ti-wire, while protons (H+) pass through the substrate from the anode to the cathode compartment.

The electrons (e-) and protons (H+) react with oxygen (O2) to form water through the following reaction:

$$O_2 + 4H^+ + 4^{e-} \rightarrow 2H_2O \qquad E^0 = 1{,}29\ V \qquad (2)$$

METHOD

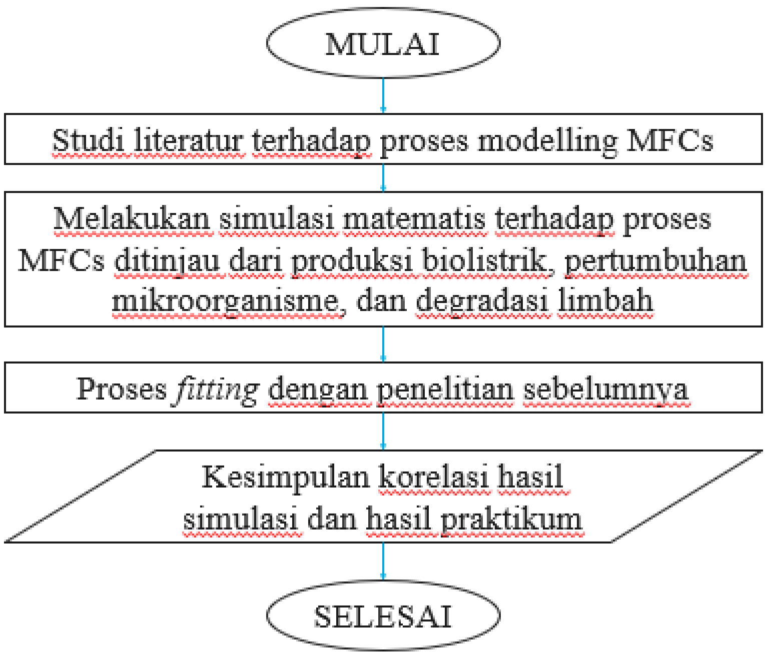
Materials

The culture source (microbial source) used is anaerobic bacteria from Lapindo mud, collected from below the mud surface in September 2019. The mud sample was taken near the center of the Lapindo mud eruption in Sidoarjo, at coordinates 7°31'45.6"S and 112°42'43.6"E, specifically in Renokenongo Village, Porong District, Sidoarjo Regency, East Java (Rivaldo and Silma, 2020).

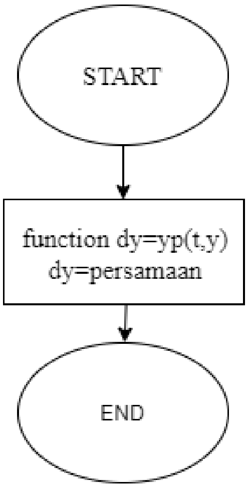
Instrumentation

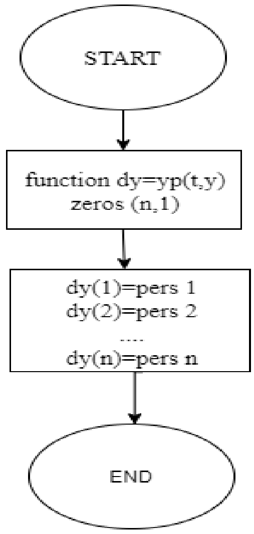
The basis for the experimental research used is 1 (one) kg in each chamber, consisting of 16 (sixteen) chambers with variations in substrates as a carbon source and Lapindo mud as a bacterial source. Variations between Lapindo mud and substrate made include: 100% Lapindo mud (w/w), Lapindo mud:substrate 3:1 (w/w), 1:1 (w/w), and 1:3 (w/w). The electrodes used are modified carbon cloth electrodes measuring 2 cm x 5 cm with thicknesses of 3 mm (3F) and 5 mm (5F) (Rivaldo and Silma, 2020).

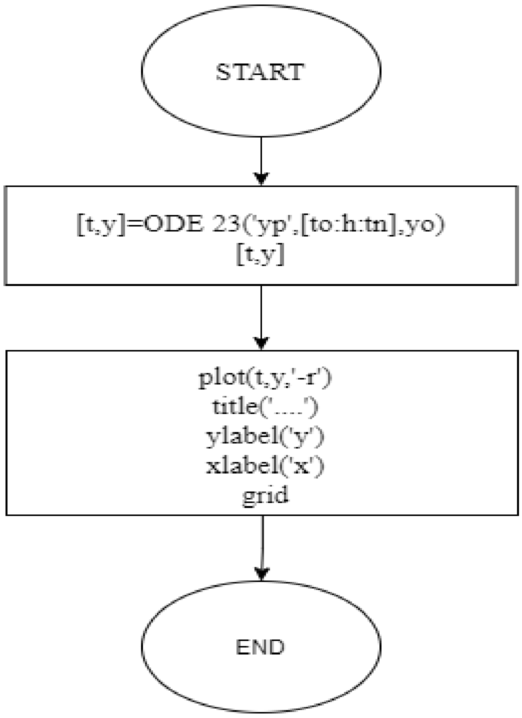
Procedure



Flow chart for ODE45 Using *Matlab* R2016a


START
function dy=yp(t,y)
dy=persamaan
END


START
function dy=yp(t,y)
zeros (n,1)
dy(1)=pers 1
dy(2)=pers 2
....
dy(n)=pers n
END


START
[t,y]=ODE 23('yp',[to:h:tn],yo)
[t,y]
plot(t,y,'-r')
title('....')
ylabel('y')
xlabel('x')
grid
END

RESULT

In the power density measurement study, a comparison chart was obtained between experimental data and modeling data as shown below:

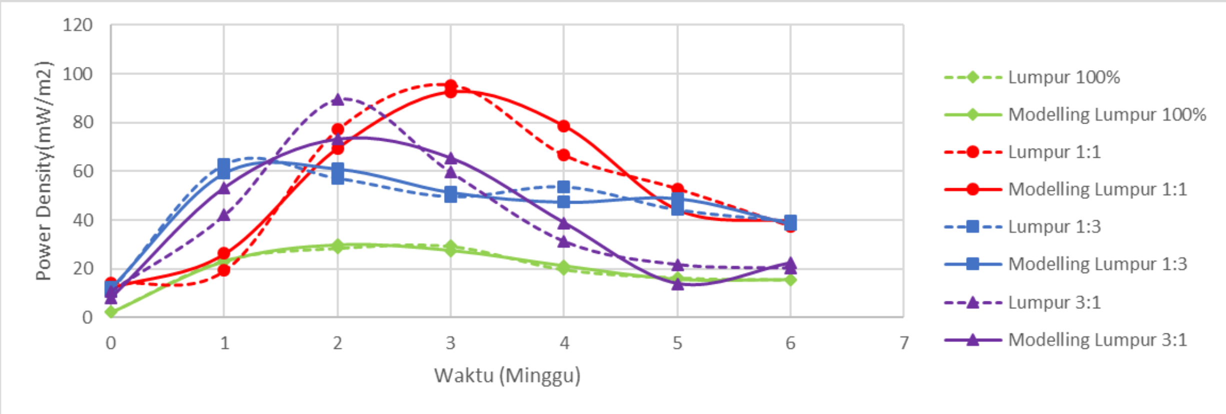


Figure IV.1 Fitting results of experimental data with modeling for *power density* vs. time

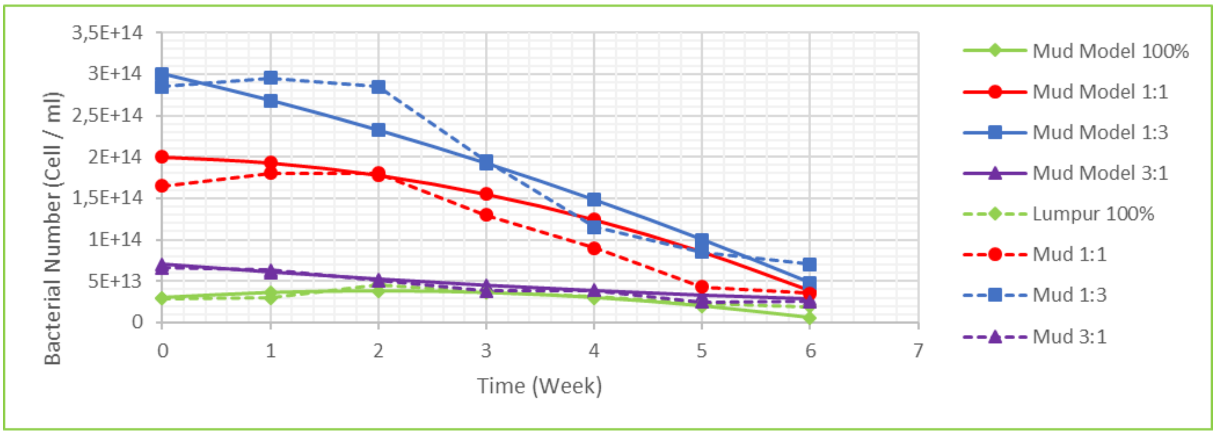


Figure IV.2 Fitting results of experimental data with modeling for number of bacteria vs. time

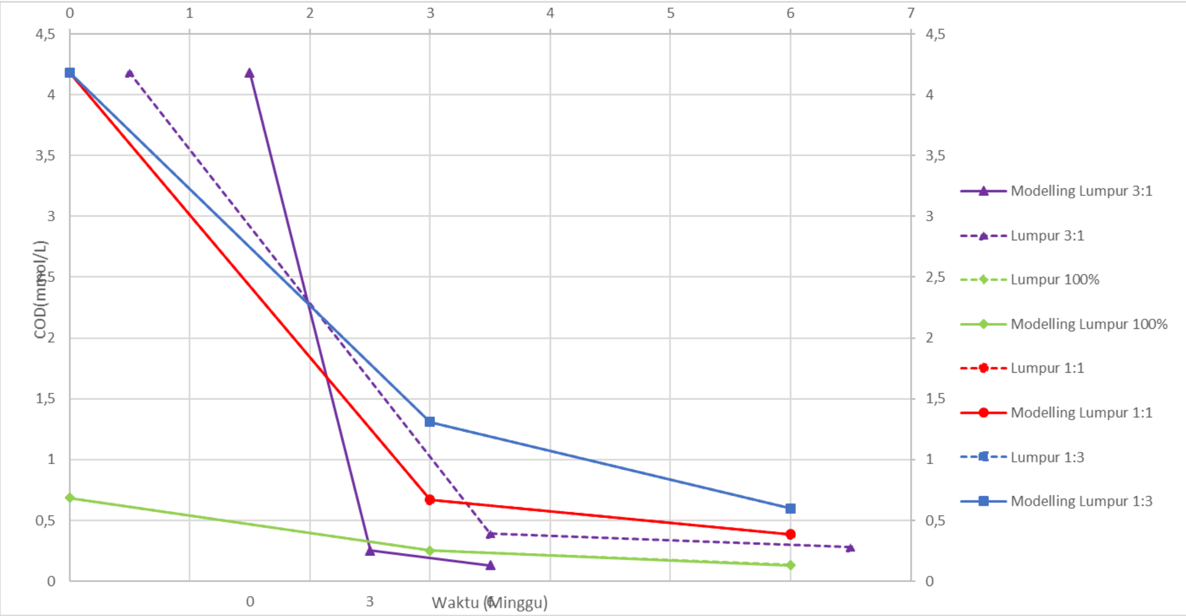


Figure IV.3 Fitting results of experimental data with modeling for organic component (COD) degradation vs. time

From the mathematical modeling of SCMFC, the following equation model for power density was obtained:

$y = 1{,}3838x^4 - 16{,}595x^3 + 54{,}794x^2 - 25{,}71 + 12{,}428,$
Lapindo mud and fishery wastewater with a ratio of 1:1

$y = -0{,}0081x^4 + 0{,}9124x^3 - 9{,}7617x^2 - 29{,}71 + 2{,}2429$
100% Lapindo mud

$y = -0{,}7159x^4 - 9{,}9881x^3 + 47{,}683x^2 - 85{,}518x + 12{,}265,$
Lapindo mud and fishery wastewater with a ratio of 1:3

$y = 0{,}4736x^4 - 3{,}2327 - 6{,}3037x^2 - 54{,}291x + 8{,}1345,$
Lapindo mud and fishery wastewater with a ratio of 3:1

Equation model for bacterial growth:
$y = 4 \times 10^{12}x^2 - 3 \times 10^{12}x + 2 \times 10^{14}$, for 1: 1
$y = -2 \times 10^{12}x^2 + 8 \times 10^{12}x + 3 \times 10^{13}$; 100% mud
$y = -2 \times 10^{12}x^2 - 3 \times 10^{13}x + 3 \times 10^{14}$, for 1: 3
$y = 5 \times 10^{11}x^2 - 1 \times 10^{13}x + 7 \times 10^{13}$, fo r 3: 1

Equation model for COD consumption:
$y = 0{,}2118x^2 - 1{,}9459x + 4{,}1826$, for 3: 1
$y = 0{,}1794x^2 - 1{,}7096x + 4{,}1826$, for 1: 3
$y = 0{,}12x^2 - 1{,}3174x + 4{,}1826$, for 1: 1
$y = 0{,}0175x^2 - 0{,}1974x + 0{,}6856$, for 100% mud.

DISCUSSION

Developing an integrated descriptive model for MFCs, grounded in a comprehensive understanding of the process and enabling mathematical reproducibility, is essential for advancing MFC technology and supporting its industrialization, as observedDeveloping an integrated descriptive model for MFCs, based on a thorough understanding of the process and mathematical reproducibility, is essential for advancing MFC technology and supporting industrial applications (Capodaglio et al., 2017). The current model includes several assumptions and approximations and is likely limited to simulating double-component microbidomes and single-component synthetic substrates of the cell.

The ability of the MFC to generate electricity depends on the electrochemical reactions that occur between low-potential organic substrates and high-potential final electron acceptors, namely oxygen. These electrochemical reactions are highly dependent on bacterial activity, which in turn is affected by bacterial concentration, pH of the anode compartment, substrate, biofilm formation, temperature, and electrode modification. Heterotrophic microbes can degrade complex compounds and provide easily biodegradable molecules to electroactive bacteria for electricity generation. However, the presence of methanogenic bacteria can result in side reaction products (such as methane) and reduce the coulombic and energy efficiency of MFCs (Capodaglio et al., 2015).

Figure IV.1 shows that electricity generation is initially low, indicating that catalytic bacteria are adapting to the new environment and substrate (Logan, 2008). Power density increases until the second and third weeks, then decreases and fluctuates. In later weeks, reduced organic content or bacterial death leads to a continuous decline in power density. Logan (2006) also notes that in batch systems, electricity production decreases as organic substrates are depleted.

MFC electricity generation depends on electrochemical reactions between low-potential organic substrates and high-potential electron acceptors, such as oxygen. These reactions rely on bacterial activity, which is influenced by bacterial concentration, anode pH, substrate, biofilm formation, temperature, and electrode modifications. Biofilm formation affects electricity production, as much of the initial metabolic energy is used to form biofilm. Cells on the electrode surface grow, reproduce, and produce Extracellular Polymeric Substance (EPS) to form biofilm (Purwono, 2015). Bacteria within the biofilm may die due to limited substrate penetration. When the electrode is fully covered by biofilm, electron transfer is restricted, reducing current and *power density* (Kim et al., 2003).

In previous MFC research, bacteria counted using the chamber technique could not be distinguished as electrogenic or non-electrogenic, since the anode compartment contained a mixture from Lapindo mud and fishery liquid waste. This differs from systems using a specific electrogenic bacteria during the log phase. Puspitasari and Fartati (2019) found that higher concentrations of Shewanella oneidensis MR-1 increased electricity production, with 10^11 cells/ml yielding higher output than 10^9 cells/ml. Figure IV.2 shows bacterial numbers increased until the second week, then decreased, while power density remained stable. It is suspected that bacteria from fishery liquid waste died due to anaerobic conditions. Generally, higher proportions of fishery liquid waste resulted in higher bacterial concentrations, indicating more bacteria in the waste than in Lapindo mud (Rivaldo, Silma 2020).

With only Lapindo mud remaining, Figure IV.3 shows that mathematical modeling closely matches experimental data. The COD decomposition graph decreases, indicating that bacteria are metabolizing the organic content of the fishery liquid waste. As microorganisms adapt to break down complex substrates, power density fluctuates. Over time, as organic nutrients are depleted and bacterial numbers increase, the food-to-microorganism ratio becomes unbalanced, leading to bacterial death and decreased power density, which correlates with COD reduction (Ibrahim, 2014).

The resulting model tends to closely approximate the model closely approximates the experimental results, as shown in Figures IV.1, IV.2, and IV.3, with only minor differences. Some phenomena in the model can only be empirically controlled with external stimuli (Capodaglio et al., 2015). The model can be improved with algorithms that account for intervention effects. Currently, it assumes perfectly mixed cell behavior and simplifies complex substrates to glucose. The microbial community is also complex, with some microorganisms, such as methanogenic bacteria, inhibiting the process by diverting degradation toward methane formation. This can interfere with the MFC process, which aims to oxidize simple compounds into carbon dioxide and water vapor (Capodaglio et al., 2015). To better simulate cell performance, the model should integrate a hydrodynamic module, which can be achieved using computational fluid dynamics (CFD) (Zhao L, et al., 2016).

However, one of the main obstacles for bacteria to deliver electrons exogenously to the anode is that most microorganism cell membranes and walls contain non-conductive materials, such as lipids or peptidoglycan (Lovley, 2006; Wen et al., 2011). Several studies have reported that the presence of the surfactant Tween 80 causes changes in cell membrane structure to form transmembrane channels, affecting the cell membrane by reducing resistance, increasing permeability and substrate degradation, and accelerating substance transport (Van Hamme et al., 2006; Singh et al., 2007).

CONCLUSIONS

The modeling results closely match the experimental data, as shown in the previous chapter's graphs. Minor differences arise because the model assumes thoroughly mixed cells and simplifies complex substrates into simpler forms, such as acetic acid or glucose. Internal cell hydrodynamics, including short circuits and dead microbe volume, also affect the results.

AUTHOR CONTRIBUTIONS

All authors contributed to conducted research and study and have approved the final version of the manuscript.

CONFLICT OF INTEREST

The authors declare no conflict of interest

REFERENCES

Agung, F. (2013). *Ekstraksi silika dari abu sekam padi dengan pelarut KOH.* Konversi, 2(1), 1–8.

Ahmad, H., Kamarudin, S. K., Hasran, U. A., & Daud, W. R. W. (2010). Overview of hybrid membranes for direct-methanol fuel–cell applications.

Ali. (2006). Prosedur penggunaan Matlab. Jakarta: Rineka Cipta.

Arisandi, P. (2006). *Menebar bencana lumpur di Kali Porong. Ecological Observation and Wetlands Conservation.*

Aulia, & Gusti. (2016). Pengaruh optical density b*akteri Bacillus subtilis terhadap*
Efisiensi listrik microbial fuel cells. Department of Chemical Engineering, University of Surabaya.

Allen, R. M., & Bennetto, H. P. (1993). Microbial fuel cells: Electricity production from carbohydrates. Journal of Applied Biochemistry and Biotechnology, 39, 27–40.

Cae, K.-J., Choi, M.-J., Lee, J.-W., Kim, K.-Y., & Kim, I. S. (2009). *Effect of different substrates on the performance, bacterial diversity, and bacterial viability in microbial fuel cells.* Gwangju Institute of Science and Technology; Elsevier.

Chandrasekhar, K., & Venkata Mohan, S. (2014). Bio-electrohydrolysis as a pretreatment strategy to catabolize complex food waste in closed circuitry. *39*(22), 11411–11422.

Cholid. (2007). Pengolahan limbah industri pengolahan ikan dengan teknologi g*abungan*. Balai Besar Teknologi Pencemaran Industri.

Chou, D. K., Krishnamurthy, R., Randolph, T. W., Carpenter, J. F., & Manning, M. C. (2005). Effects of Tween 20® and Tween 80® on the stability of Albutropin during agitation. Journal of Pharmaceutical Sciences, 94, 1368–1381.

David. (2014). Study pendahuluan pemanfaatan whey tahu sebagai substrat dan efek luas permukaan elektroda terhadap s*istem MFCs*. Journal Sains dan Matematika.

Dena, Y., & Rebaay, H. (2018). Effect of vitamin and cells construction on activity of microbial fuel c*ell.* Journal of Genetic Engineering and Biotechnology.

Ekowati. (2013). Fungsi MFC bagi COD maupun BOD. Jurnal, 2.

Hassett, J., & Gu, T. (2012). Microbial fuel cells in power generation and extended applications. Advances in Biochemical Engineering/Biotechnology, 128, 165–197.

Goff, H., 1997. Colloidal aspects of ice cream—A review. International Dairy Journal
7, 363-373.

Hoogers, G. 2002. *Fuel Cell Technology Handbook*.

Ibrahim B, Salamah E, Alwinsyah R. 2014. Pembangkit biolistrik dari limbah cair industri perikanan menggunakan microbial fuel cell dengan jumlah elektroda yang berbeda. Jurnal Dinamika Maritim. 4 (1): 1-9.

IbrahimB,Erungan.2009. *Nilai parameter kinetika proses denitrifikasi limbah cair industri perikanan pada rasio COD/TKN yang berbeda*. Jurnal Pengolahan Hasil Perikanan Indonesia (12:2); 154-166.

Ibrahim B, Suptijah P, Adjani ZN. (2017*). Kinerja Microbial Fuel Cell Penghasil Biolistrik Dengan Perbedaan Jenis Elektroda Pada Limbah Cair Industri Perikanan*. Jurnal Pengolahan Hasil Perikanan Indonesia. 20(2): 296-304.

Ibrahim B, Trilaksani W, Apriyani D. 2013. *Potensi Biolistrik Dari Limbah Cair Industri Perikanan Dengan Microbial Fuel Cell Satu Bejana*. Jurnal Dinamika Maritim. 3(2): 45-55.

Ibrahim B. 2005. *Kaji Ulang Sistem Pengolahan Limbah Cair Industri Hasil Perikanan Secara Biologis Dengan Lumpur Aktif*. Buletin Teknologi Hasil Perikanan. 8(1): 31-41

Idham F, Halimi S, dan Latifah S. 2009. *Alternatif Baru Sumber Pembangkit Listrik dengan*

Menggunakan Sedimen Laut Tropika Melalui Teknologi Microbial Fuel Cell. Bogor : Teknologi Hasil Perairan Institut Pertanian Bogor.

Jenicek. 2015. *High Performance Activated Carbon/Carbon Cloth Cathodes For Microbial Fuel Cells*. Biological and Ecological Engineering. Corvallis.97331 USA.

Juniawan, A., Rumhayati, B. dan Ismuyanto, B., 2013. *Karakteristik Lumpur Lapindo Dan Fluktuasi Logam Berat Pb Dan Cu Pada Sungai Porong Dan Aloo*. *Sains dan Terapan Kimia,* 7(1), pp. 50-59

Kim, B.H, Chang, I.S, Gil, G.C, Park, H.S, Kim, H.J., 2003. Novel BOD sensor using a mediatorless microbial fuel cell. *Biotechnol. Lett.* 25 , pp. 541–545.

Lai, Janice. 1999. *Automated Cell Counting and Characterization. Stanford, CA : Department* of Mechanical Engineering, Stanford University.

Li, Zhongjian, Xingwang Zhang dan Lecheng Lei., 2008. Electricity Production During The Treatment of Real Electriplating Containing Cr6+ Using Microbial Fuel Cell. *Process Biochemistry* , 43, pp. 1352 – 1358.

Liu. H. 2008. Microbial Fuel Cells: Novel Anaerobic Biotechnology for Energy Generation From Wastewater. Anaerobic Biotechnology for Bioenergy Production : Principle and Appllication S.K. Khanal lowa, Blackwell Publshing: 221-243

Logan E. Bruce, Bert Hamelers, Rene R, Uwe S, Jurg K, Stefano F, Peter A, Willy V dan K. Rabaey., 2006. *Microbial Fuel Cells : Methodology And Technology.* 40 (17), pp. 14000-14006

Lovley, D. R., 2006. *Bug juice: harvesting electricity with microorganisms*. [Erratum to document cited in CA145:079425]. *Nat. Rev. Microbiol.*, *4*, 797.

Novitasari, Deni., 2011. *Opimalisasi Kinerja Microbial Fuel Cell (MFC) untuk Produksi Energi Listrik Menggunakan Bakteri Lactobacillus bulgaricus*. Skripsi. Departemen Teknik Kimia FT Universitas Indonesia

Park, D., dan Zeikus, J., 2002. Impact of electrode composition on electricity generation in a single-compartment fuel cell using Shewanella putrefaciens. *Applied Microbiology and Biotechnology*, *59*(1), pp. 58–61.

Peraturan Pemerintah Lingkungan Hidup No 5 tahun 2014. *Tentang Baku Mutu Kegiatan Pengolahan Ikan*

Priambodo G. 2011. Technical and social impacts of wastewater from fish processing industry in kota muncar of indonesia. JATES 1(1): 1-17.

Reddy, L. V., Pradeep Kumar, S., dan Wee, Y.-J., 2010. *Microbial Fuel Cells (Mfcs) -A Novel Source Of Energy For New Millennium. Current Research, Technology And Education Topics In Applied Microbiology And Microbial Biotechnology*, pp. 956–964.