An overview of recent advances in sediment microbial fuel cells for wastewater treatment and energy production

N Emalya¹, E Munawar², S Suhendrayatna², U Fathanah² and Y Yunardi²*  
¹Doctoral Program, School of Engineering, Universitas Syiah Kuala, Banda Aceh, Indonesia  
²Department of Chemical Engineering, Faculty of Engineering, Universitas Syiah Kuala, Banda Aceh, Indonesia  
*Email: yunardi@unsyiah.ac.id

Abstract. In developing countries, the presence of wastewater is undesirable due to a costly investment for the treatment unit and energy-intensive for the operation. The wastewater treatment units in developing countries usually are not appropriately operated due to lacking operational cost. Therefore, it is not surprising if wastewater has never been considered a potential resource, even though it is rich in organics and nutrient substances. Biological treatment enables the conversion of wastewater into valuable products and energy. Sediment microbial fuel cells (SMFCs) are emerging technologies envisaged as a feasible solution for simultaneous removal of carbonaceous compounds and generation of electricity. In SMFCs, power can be generated naturally by embedding an anode in the sediment and immersing the cathode in the water above the sediment. One of the most significant obstacles to upscaling and practical applications of the SMFCs appears to be the low-power output. The entire performance of an SMFC is determined by microorganisms, proper electrode materials, optimal SMFC designs, and process parameter optimization. This paper will discuss the recent progress of SMFC research related to its application in wastewater treatments and energy production. The advantages and obstacles of using SMFC in wastewater treatment are also presented.

1. Introduction

In developing and underdeveloped countries, wastewater treatment is still a significant challenge. It has been a common practice that most wastewater treatment units in such countries, including Indonesia, are usually not operated properly due to high operational costs and excessive energy use [1]. Often in many cases, the domestic wastewater, in particular, is directly discharged into water bodies without any prior treatment, resulting in a negative impact on human life and the surrounding environment [2, 3]. The wastewater contains significantly high organic and nutritional substances, as measured by biological oxygen demand (BOD), chemical oxygen demand (COD), nitrogen (N) and phosphate (P) [4, 5], which can become valuable resources. At the present time, the wastewater should be viewed as an asset, not as a waste. Through anaerobic processes, for example, organic compounds in the wastewater with the help of microorganisms can be converted into biogas which could be utilized as a renewable energy source [6-8]. The presence of organics and nutrient substances in the
wastewater provides a suitable environment for microalgae growth. Microalgae are promising feedstocks for the production of biofuels, including bioethanol [9, 10], biodiesel [11, 12], and bio-oil [13, 14]. In recent years, there has been a significant increase in research examining the possibility of treating wastewater and generating electricity [15-18]. A microbial fuel cell is a technological device that may produce electricity while also treating wastewater. Implementing this type of technology in the future not only solves the issue of wastewater in third world countries but also helps them to produce energy.

In addition to the issue of wastewater, developing and underdeveloped countries also challenge in energy supply. The rapid population and industrial development in these areas are not followed by energy growth, resulting in inequality [19]. Fossil fuels, including coal, oil, and natural gas, currently provide about 80% of the world's energy demand. These non-renewable fuels are created by the thousands-year-long breakdown of plants and other organisms. Exploitation and utilization of petroleum are currently carried out on a large scale to meet the need for various purposes, such as the production of electricity, transportation and even for the manufacture of plastics. It is not surprising if scientists predict minimal fossil fuel reserves remaining by 2050 [11, 13]. Besides being limited and non-renewable, continued use of fossil fuels can harm the environment and pollute the air. The combustion of fossil fuels will release carbon dioxide and other greenhouse gases, leading to climate change and global warming [13, 15, 16].

Scientists and governments worldwide are currently working and looking for solutions to minimize environmental damage, reduce greenhouse gas emissions, and prevent global warming. These efforts generally focus on replacing fossil fuels with renewable energy sources, such as biological sources or commonly referred to as bioenergy. The development of the first- and second-generation bioenergy faced competition in raw materials with food sources for humans and animals, water shortage, and restricted land. The third generation of bio-energy is made by using microalgae to produce biofuels and bio-electricity [13]. Regarding the latter, microbial fuel cells (MFCs) are one of the emerging technologies that utilize microorganisms to generate electricity by degrading organic substances in wastewater. Among the MFCs, the sediment microbial fuel cell (SMFC) is more practical because it can power sensors without the need for batteries.

Sediment microbial fuel cells (SMFCs) are one of the technologies being developed to produce energy in the forms of bioelectricity and, at the same time, can reduce organic substances in wastewater. In SMFCs, power can be generated naturally by embedding an anode in the sediment and immersing the cathode in water above the sediment. The performance of SMFCs is determined by the microorganism, the appropriate type of electrode, the SMFC design, and the optimal process parameters. This paper discusses the latest advances in SMFC research related to its application in the wastewater treatment and energy production. It also presents the advantages and disadvantages of using SMFC in the wastewater treatment.

2. Sediment Microbial Fuel Cell (SMFCs)
A sediment microbial fuel cell (SMFC), one type of microbial fuel cells (MFCs), is a device that generates electricity from organic-rich sediments. Microbial fuel cells (MFCs) were first introduced in the early 20th century by Michael Cresse Potter [13]. Basically, SMFCs work in a similar way to MFCs in that microorganisms living in the sediment oxidize organic compounds and transmit the created electrons to the anode, where the pollutant removal or energy production process begins [19, 20]. However, in SMFCs, the organic-rich sediment acts as an anodic medium, while the oxygen-rich aqueous phase operates as a cathodic medium. Therefore, the anode is placed at a certain depth in the sediment, whereas the cathode is located above the sediment under aerobic conditions [21], as demonstrated in Figure 1. Naturally, the sediment is rich in nutrients from decaying plants and other settled organisms, which contains various microorganisms, including electrogenic bacteria. In the SMFCs system, aerobic microorganisms are also present in the sediment, acting as oxygen filters,
similar to the proton exchange membrane (PEM) in the MFCs system. As a result, the depth of the sediment also affects the redox potential.

Based on the sediment source, SMFCs are generally divided into two types: seawater and freshwater SMFCs. Using Pt wire electrodes, the electricity produced from the seawater SMFC at the early stage of this research subject was relatively very small, around 10 mW/m² [22]. Currently, seawater SMFCs have started to gain popularity from turning on remote sensors [23], operating remote sensors that require large amounts of power [24], to being a power source for seawater temperature and oxygen sensors [25]. In the meantime, freshwater SMFCs applications focus more on the removal and treatment of organic compounds from wastewater [26, 27]. Most freshwater SMFC developments are also coupled with a constructed wetland plant system, as reported by Zhu et al. [28]. The investigators described that the generated bioelectricity increased in the Plant-SMFC system, and the reduction of metal concentrations such as As, Zn and Cd were observed.

![Figure 1. A schematic diagram of the Sediment Microbial Fuel Cell process [22]](image)

Basically, the performance of sediment microbial fuel cells (SMFCs) is influenced by the growth of microorganisms in the anodic and cathodic regions. The growth of these microorganisms depends on the sediment source, temperature, pH, and organic compounds [22]. In addition, the reactor configuration, anode-cathode material and design, electrode surface area, the distance between electrodes, external resistance, presence of oxygen and effect of the light-dark cycle also affect the performance of the SMFCs [21, 22].

3. Application of SMFC for Wastewater Treatment and Energy Production

Since early 2000, researchers have had a growing interest in investigating the possible application of sediment microbial fuel cells (SMFCs) for wastewater treatment and electricity production. Numerous modifications have been carried out to maximize the removal of pollutants and optimize the generation of electricity. He et al [29], for example, employed a rotating cathode in the SMFC reactor in an effort to increase the dissolved oxygen in the wastewater. The installed anode and cathode were made of carbon cloth and reticulated vitreous carbon (RVC), respectively. The results showed that the performance of SMFC with rotating cathode increased by 69% compared to the one without rotating cathode, as indicated by the rise of power density from 29 mW/m² to 49 mW/m². In addition to modifying the electrodes, a study report on the bacterial community in the SMFC system was presented by Aswad et al. [30]. They described that proteobacteria were more dominant in the SMFC system. The effect of pre-treatment on SMFC performance was also investigated by Song and Jiang.
[27], demonstrating that the sediment power density heated at a temperature of 150°C for 180 minutes could generate energy up 54.5±26.2 mW/m².

Open and closed systems influenced the performance of the SMFCs, as demonstrated by Abbas et al. [31]. They claimed that the SMFCs open system provides better performance than the closed one, with the resulting voltage of 300.5 mV, 1.5 times larger than that of the closed SMFCs. The metal removal efficiency of Hg, Zn and Ag were 6.2%, 6.09% and 10.43%, respectively, in the exposed SMFC system. Alipanahi and Rahimnejad [32] investigated the influence of sediment collection sites on the performance of the SMFC system. Sediment samples were taken from Babolsar River, Mazandaran Province, Iran, at 200, 300 and 400 from the sea. The study results demonstrated that a maximum power density of 80 mW/cm² was obtained from the SMFC furnished with the sediment of 400 m from the sea. Tran et al. [33] conducted an experiment to improve the SMFC performance using sediment samples collected from a semi-enclosed bay in Busan, South Korea. The results reported that the electric current generated ranged from 40-45 mA.m² with a maximum power density of 23.43 mW/m² on a carbon cloth electrode heated at 500°C. The performance of the SMFCs for wastewater treatment coupled with plants has been observed Aswad et al [30]. They utilized five types of plants, including Juncus, Schoenoplectus triqueter, Phragmites australis, Typha latifolia and Cyperus alternifolius, to treat Al-Rustumiya raw domestic wastewater. The maximum voltage generated of 43±4 mV was obtained on the third day of observation when the SMFC coupled with Cyperus alternifolius plant. The maximum removal percentages of COD, TSS, PO₄, and NO₃ were 91.4%, 86%, 70.8% and 81.4%, respectively.

| Table 1. The present advantages and disadvantages of SMFC [22-24, 34, 35] |
|---------------------------------------------------------------|
| **Advantages**                                               | **Disadvantages**                          |
| 1. SMFC can produce electricity and at the same time reduces pollutants in wastewater | 1. The power generated from SMFC is small |
| 2. SMFC is more economical because it does not require a proton exchange membrane (PEM or CEM) | 2. Internal resistance of SMFC is high |
| 3. SMFC can be combined with a constructed wetland system to give better oxidation of organic compounds | 3. If the concentration of organic compounds in the sediment is small, mass transfer at the anode will be hampered |
| 4. SMFC can be used as a power source to turn on the sensor in the remote area | 4. Issues of scaling up and generating higher electric energy |

4. Future Development of SMFC: Challenges and Opportunity

Although sediment microbial fuel cells (SMFCs) have been extensively studied to extract energy from natural sediment, research of its use in wastewater treatment has only recently begun. The potential for the SMFC system to be used is enormous, but various aspects and hurdles must be solved, particularly in scale-up, to make it a reality. Up to now, most studies on SMFCs have primarily reported on their power density, with very few addressing the energy data that could be generated. Furthermore, the link between organic compound degradation and the process of generating power has not yet yielded optimal outcomes. According to Xu et al. [36], the average coulombic efficiency (CE) of SMFCs for wastewater treatment is relatively low; hence the power generation process has little impact on pollution removal. Even though many studies related to application of various electrode materials have been carried out, slight improvement has been achieved in electricity generation and pollutant removal. There is still a lot of room for research in this area. Table 1 summarizes the current advantages and disadvantages of SMFC for wastewater treatment as well as power generation.

4
SMFC's future uses include not only the degradation of contaminants in wastewater but also the bioremediation of sediments and the deployment of sensors in remote regions [24, 37]. SMFC can be used for the bioremediation of organic chemicals, cellulose waste, and petroleum hydrocarbons in sediments at the same time [34]. Since the current power generated by the SMFC system is still meagre, the SMFC is an excellent choice for powering low-power wireless equipment like oceanographic sensors and monitoring instruments. However, challenges of future application of SMFC must also be addressed. The SMFC system requires storage, called a power management system, because it cannot generate electricity continuously. The power management system consists of a capacitor, a voltage divider and a DC-DC converter, allowing the electricity generated to be constantly used to operate the remote sensor [34].

5. Conclusions

Sediment Microbial Fuel Cells (SMFCs) are one type of microbial fuel cells (MFCs) that provides the future potential to solve environmental problems and energy shortages. The performance of sediment microbial fuel cells (SMFCs) is influenced by several factors: the growth of microorganisms, temperature, pH, organic compounds, reactor configuration, anode-cathode material and design, electrode surface area, and distance between electrodes, external resistance, presence of oxygen, and the effect of the light-dark cycle. The potential for the SMFC system to be used is enormous, but various aspects and hurdles must be solved. The most likely applications of SMFC include pollutant degradation in wastewater, sediment bioremediation and wireless sensors in remote areas.

Acknowledgement

The authors would like to express their gratitude to Syiah Kuala University for the financial support for this research under Syiah Kuala University Excellence Research Program for Doctoral Acceleration (PRUU) contract No: 364/UN11.2.1/PT.01.03/PNBP/2021.

References

[1] Emalya N, Munawar E, Rinaldi W and Yunardi Y 2020 ICChEAS 2019 (Banda Aceh, Indonesia) Vol. 845 (IOP Conf. Series: Materials Science and Engineering)
[2] Vaccari M, Tudor T and Vinti G 2019 Waste Manag. 95 416-31
[3] Nastro R A, Falucci G, Minutillo M and Jannelli E 2017 159-71
[4] Yuan X, Kumar A, Sahu A K and Ergas S J 2011 Bioresour Technol. 102 3234-9
[5] Munawar E, Emalya N, Hayati A P, Yunardi Y and Hakim L 2019 RSCE 2018 (Manila, Philippine). (MATEC Web of Conferences)
[6] Baicha Z, Salar-García M J, Ortiz-Martínez V M, Hernández-Fernández F J, de los Ríos A P, Labjar N, Lotfi E and Elmahi M 2016 Fuel Process Technol. 154 104-16
[7] Wang P, Peng H, Adhikari S, Higgins B, Roy P, Dai W and Shi X 2020 Bioresour Technol. 309 123368
[8] Puyol D, Batstone D J, Hulsen T, Astals S, Peces M and Kromer J O 2016 Front Microbiol. 7 2106
[9] Soares R B, Martins M F and Goncalves R F 2019 J Environ Manage. 252 109639
[10] Alam F, Date A, Rasjidin R, Mobin S, Moria H and Baqui A 2012 Proc Eng. 49 221-27
[11] Sivasankar V, Mysamy P and Omine K 2018 Microbial Fuel Cell Technology for Bioelectricity. (Switzerland: Springer International Publishing AG).
[12] Chisti Y 2007 Biotechnol Adv. 25 294-306
[13] Emalya N, Malahayati N, Munawar E, Rinaldi W and Yunardi Y 2021 IOP Conf Series: Earth and Environ Sci. 667 012087
[14] Pragya N, Pandey K K and Sahoo P K 2013 Renew and Sustain Energy Rev. 24 159-71
[15] Coady D, Parry I, Sears L and Shang B 2017 *World Develop.* 91 11-27
[16] Abdallah M, Feroz S, Alani S, Sayed E T and Shanableh A 2019 *Rev Environ Sci and Biotechnology.* 18 543-78
[17] Logan B E and Regan J M 2006 *Trends Microbiol.* 14 512-8
[18] Liu H, Ramnarayanan R and Logan B E 2004 *Environ Sci Technol.* 38 2281-85
[19] Zabihallahpoor A, Rahimnejad M and Talebnia F 2015 *RSC Adv.* 5 94171-83
[20] Abbas S Z, Rafatullah M, Ismail N and Syakir M I 2017 *Int J Energy Research.* 41 1242-64
[21] Hong S W, Chang I S, Choi Y S and Chung T H 2009 *Bioresour Technol.* 100 3029-35
[22] Sajana T K, Ghangrekar M M and Mitra A 2017 *J Hazard, Toxic, and Radioac Waste.* 21 04016022
[23] Donovan C, Dewan A, Heo D and Beyenal H 2008 *Environ Sci Technol.* 42 8591-96
[24] Donovan C, Dewan A, Peng H, Heo D and Beyenal H 2011 *J Power Sources.* 196 1171-77
[25] Gong Y, Radachowsky S E, Wolf M, Nielsen M E, Girguis P R and Reimers C E 2011 *Environ Sci Technol.* 45 5047-53
[26] Wu M S, Xu X, Zhaoa Q and Wanga Z Y 2017 *RSC Adv.* 7 53433-38
[27] Song T-S, Yan Z-S, Zhao Z-W and Jiang H-L 2010 *J Chem Technol & Biotechnol* n/a-n/a
[28] Zhu S, Qin L, Feng P, Shang C, Wang Z and Yuan Z 2019 *Bioresour Technol.* 274 313-20
[29] He Z, Shao H and Angenent L T 2007 *Biosens Bioelectron.* 22 3252-5
[30] Aswad Z S, Ali A H and Al-Mhana N M 2020 *Des and Water Treat.* 205 153-60
[31] Abbas S Z, Rafatullah M, Khan M A and Siddiqui M R 2018 *Front Microbiol.* 9 3348
[32] Alipanahi R and Rahimnejad M 2018 *Int J Energy Research.* 42 4891-97
[33] Tran T V, Lee I C and Kim K 2019 *Int J of Hydro Energy.* 44 32192-200
[34] Sajana T K, Pandit S, Jadhav D A, Abdullah-Al-Mamun M and Fosso-Kankeu E 2019 *Nano and Bio-Based Technologies for Wastewater Treatment* (Beverly: Scrivener Publishing)
[35] Wang C-T, Lee Y-C, Ou Y-T, Yang Y-C, Chong W-T, Sangeetha T and Yan W-M 2017 *Appl Energy.* 204 620-25
[36] Xu B, Ge Z and He Z 2015 *Environ Sci: Water Research & Technol.* 1 279-84
[37] Algar C K, Howard A, Ward C and Wanger G 2020 *Sci Rep.* 10 13087