A review of a sustainable bio-electricity generation from microbes grown in waste water

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Abstract. The high growth of world population, increase global urbanization and rapid rise of industrialization have driven a drastic escalation in demands not only for food, and water but also energy. In addition to decreasing the natural oil reserve, excessive utilization of fossil fuel for the conversion into various forms of energy, including electrical power, also contributes to atmospheric pollution due to the release of gases from combustion which eventually will cause climate change. Consequently, recent years, great attention has been focused on energy production and generation from microalgae, because it is sustainable, environmentally friendly and economical. Microalgae fuel cell (MFC) is a device which utilizes microalgae capable of oxidizing organic matter by generating electron, obtaining energy for their own and providing electricity generation. Wastewater contains inorganic and organic nutrients which could be used as the source of substrate for microalgae to grow. A combination of MFC and wastewater would offer a great promising technology in the future for the simultaneous treatment of wastewater and electricity generation. This paper review the potentials of electrical energy generation with the application of MFC, the concept of MFC and the current development of MFC.

1. Introduction
One of the biggest challenges the world is facing in the 21st century deals with on how to fulfil the energy needs, in addition to food, for its inhabitants due to the increase of the population. At the present time, the world's population highly depends on its energy from fossil fuels, such as petroleum, coal and natural gas. It is undeniable that fossil fuels are the most efficient source of energy to power the world economy and activity. It should be noted, however, that the formation of these fossil fuels takes millions of years. In recent decades, these fossil fuel reserves have been exploited in enormous quantities to produce energy for electricity, transportation, and other activities such as heating. Martins et al. [1] conducted a statistical and mathematical analysis of the current trend on world fossil fuel consumption, and they predicted that by the year 2050, the world's petroleum reserves would remain only 14%. Therefore, it is estimated that in the next few decades, the oil will be scarcely available. This situation requires efforts to find other sustainable sources of energy for the future need of the world population [2].

Various renewable energy sources have been proposed to replace the current fossil fuels. The first generation of renewable bio-fuels was proposed to come from starch, sugar, animal fat and vegetable oil. In this first-generation, raw materials containing sugar or starch can be converted into alcohol, while
animal fats and vegetable oils can be converted into biodiesel. The second generation of renewable energy sources were proposed to use fibrous plants so that they can be fermented and convert it into alcohol. In Indonesia and several other ASEAN countries, they are very active in converting vegetable oil, such palm oil, into biodiesel [3], [4], meaning that it is still categorized as the first-generation fuel source. In the second generation, various efforts have been seen to convert fibre waste from palm oil into renewable fuels. However, it is now recognized that the development of the first and second-generation fuel sources creates various problems, such as competition with food sources, deforestation, water scarcity and land issues [5], [6]. The third generation of energy sources is a new term that describes the development of renewable fuels that come from algae in the form of biofuels and bioelectricity [7], [8]. So far, this generation of fuels is still in the research phase and does not yet exist on a commercial scale, but it is believed algae will be a future energy source to replace fossil fuels.

The energy in the form of electricity has become the most vital necessity for individuals in the world. In Indonesia, the demand for electricity continues to increase by 11 - 12% every year [9]. As a country with diverse geographic conditions and a dispersed population, Indonesia still faces challenges in fulfilling energy for all of its citizens. In 2016, there were still 7 million households or around 28 million Indonesians who did not have access to electricity. Inequality in access to electricity in Java and outside Java is relatively high, where the electrification ratio of Jakarta has reached almost 100%, while provinces outside Java, particularly eastern Indonesia, for example, East Nusa Tenggara and Papua, are still below 70%. This means that the energy supply in Indonesia is not evenly distributed. Therefore, a suitable technology to produce electricity in the remote islands of Indonesia utilizing the local potential must be sought and developed. In the long term, fuel cell technology will become a model for sustainable power generation that could be operated in remote areas of which currently are having lack of access to electricity. The present paper deals with the review of technological aspects of implementing Microbial Fuel Cell (MFC) for recovering energy in the form of electricity from wastewater by the aid of microbes.

2. Concept of microbial fuel cells technology
Microbial Fuel Cell (MFC) is an emerging technology consisting a device that utilizes microbes as a catalyst to oxidize organic and inorganic compounds, during this step oxidation and reduction happens, and generate an electric current. The distinctive feature of the MFC is that it consists of anode and cathode sections separated by a cation-specific membrane, as shown in Figure 1. The electrons generated by the microbe from the substrate will be transferred to the anode (negative terminal) and flow to the cathode (positive terminal). In the anode section, organic and inorganic compounds are oxidized by microorganisms, producing electrons and protons. Electrons are transferred to the cathode via an electrical circuit, and the protons are transferred to the cathode through the membrane. Electrons and protons are used at the cathode, combined with oxygen to form water to complete the reaction [10], [11].

MFC was first introduced in the early 20th century, using a mediator: a chemical that transfers electrons from microorganisms into the anode. In 1911, Michael C. Potter initiated the idea of using microorganisms to produce electricity. Potter produces electricity from Saccharomyces cerevisiae and E. coli. Francis Thomas Bacon developed fuel cells in 1932. In the early 1980s, Robin M. Allen and H. Peter Bennetto began to study how the working principle of microbial fuel cells. Then in 2006, Bruce E. Logan et al. published articles about materials, and methods used to construct MFCs, as well as techniques for analyzing the performance of MFC systems [12]. Commercial use of MFCs in wastewater treatment began in the 21st century [13].
2.1 Design of MFCs
Considering from the types of microorganisms utilized in the bio-electricity production process, microbial fuel cells can be categorized into several types as tabulated in Table 1. However, if considered from the design and configuration of the system arrangements, microbial fuel cells are categorized into single-chamber microbial fuel cells, double-chamber microbial fuel cells, and stacked microbial fuel cells.

Table 1. Types of microbial fuel cells.

| Type                    | Description                                                                                           | Reference |
|-------------------------|-------------------------------------------------------------------------------------------------------|-----------|
| Mediated                | Most microorganisms are not electrochemically active. Mediators that can facilitate electron transfer to the electrode include red neutral, methyl blue, humic acid, thionine, and methyl viologen. Electron transfer to electrodes is carried out using electrochemically active microorganisms, such as *Aeromonas hydrophila* and *Shewanella putrefaciens*. | [15]      |
| Mediator-free           | The principle of microbial electrolysis is to use the voltage from microorganisms to produce hydrogen or methane. Microbial electrolysis cell (MEC) is more focused on producing methane. | [16]      |
| Microbial electrolysis  | The most widely used wastewater treatment technology is sediment microbial fuel cells. Sediment fuel cells use plants, similar to wetland constructed. | [17]      |
| Sediment Microbial Fuel Cells | Utilize photosynthetic microorganisms as an anode. Electrons are formed due to photosynthesis at the anode. Commonly used microorganisms are *Chlorophyta* and *Candyanophyta*. | [18]      |

2.1.1 Single-chamber MFC (SCMFC). The SCMFC is the simplest and most economical design. SCMFC is composed of one space filled with porous cathodes, and separated by a membrane (proton exchange membrane/PEM) or gas diffusion layer as illustrated in Figure 2 [19], [20]. The transfer of
protons from anode to cathode occurs by diffusion of electrolytes. The percentage of oxygen diffusion in SCMFC is higher than that of DCMFC [21]. The disadvantage of SCMFC is that it is very easy to intervene, so it is necessary to add a buffer solution to control acidification [20].

![Figure 2](image1.png)

**Figure 2.** Design of single-chamber microbial fuel cell [19].

![Figure 3](image2.png)

**Figure 3.** Design of double-chamber microbial fuel cell (A) using PEM and (B) using salt bridge [19].

2.1.2 **Double-chamber MFC (DCMFC).** DCMFC is arranged for anode space, cathode, and proton exchange membrane, as shown in Figure 3 [12], [19], [22]. The use of membrane can limit the diffusion of oxygen from the cathode to the anode. Furthermore, the use of membrane can also improve MFC performance because it reduces MFC ohm resistance [21].

2.1.3 **Stacked MFC.** Some MFCs arranged in series or parallel are known as stacked microbial fuels as illustrated in Figure 4. The performance of stacked microbial fuel is better than SCMFC and DCMFC [23]-[25]. The configuration of electrodes on stacked microbial fuel is divided into four types, (1) series electrodes in parallel flow, (2) parallel electrodes in parallel flow, (3) series electrodes in series flow, and (4) parallel electrodes in the series flow [22].

![Figure 4](image3.png)

**Figure 4.** Design of stacked MFC with (a) series and (b) parallel connection [25].
3. Electricity generation using MFCs technology

The performance of the MFC mainly relies on the selection of electrode material, as the bond of the microbes, transfer of electrons, and efficiency of the electrochemical substance depend on this material.

The metabolism of microorganisms at the anode in the form of electrons is transferred to the cathode. Mostly, electrons are transferred through proton exchange membranes (PEM) [26]. Table 2 presents some common electrodes used in MFCs. In aerobic conditions, the sugar consumed by microorganisms will produce carbon dioxide and water. Meanwhile, under anaerobic conditions, the products obtained include carbon dioxide, hydrogen ions, and electrons.

Table 2. Some common electrodes used in MFCs [27].

| Chamber | Electron donor/acceptor |
|---------|------------------------|
| Anode   | Acetate                |
|         | Glucose                |
|         | Butyrate               |
|         | Glycerol               |
|         | Malate                 |
|         | Citrate                |
|         | Sulphur                |
| Cathode | Bicarbonate            |
|         | Acetate                |
|         | Nitrate                |
|         | Nitrite                |
|         | Permanganate           |
|         | Manganese dioxide      |
|         | Iron                   |
|         | Copper (II)            |
|         | Potassium persulfate   |
|         | Ferricyanide           |

3.1 Factors affecting MFCs

Some important factors that need to be considered in MFCs, such as anode, cathode, membrane, substrate, pH, temperature, and light. The following subsections will explain these factors.

3.1.1 Anode. An anode is a significant component in MFC because it is very influential in the growth of microorganisms. Carbon is an electrode that is frequently used in MFC. Its form can be in the form of graphite, carbon nanotubes, plates, and rods [13]. Microalgae can be used as exoelectrogenic microorganisms, but the results do not always produce high power densities [28,29]. Algae degrade organic compounds in wastewater into electrons and protons. Algae actively produce electrons and protons in the light phase, because the photosynthesis process occurs in the presence of light and CO₂. While in the dark phase, algae will consume oxygen produced from the light phase. Eq. 1-4 illustrate the oxidation reactions that occur at the anode [30], depending on the substrate used.

Glukose: \[ \text{C}_6\text{H}_{12}\text{O}_6 + 12\text{H}_2\text{O} \rightarrow 6\text{HCO}_3^- + 30\text{H}^+ + 24\text{e}^- \quad E^0 = -0.429 \text{ V} \] (1)

Glycerol: \[ \text{C}_3\text{H}_6\text{O}_3 + 6\text{H}_2\text{O} \rightarrow 3\text{HCO}_3^- + 17\text{H}^+ + 14\text{e}^- \quad E^0 = -0.289 \text{ V} \] (2)

Malate: \[ \text{C}_4\text{H}_5\text{O}_4^- + 7\text{H}_2\text{O} \rightarrow 4\text{H}_2\text{CO}_3^+ + 11\text{H}^+ + 12\text{e}^- \quad E^0 = -0.289 \text{ V} \] (3)

Sulfur: \[ \text{HS}^- \rightarrow \text{S}^0 + \text{H}^+ + 2\text{e}^- \quad E^0 = -0.230 \text{ V vs. SHE} \] (4)

3.1.2 Cathode. The efficiency of the power plant at MFC is influenced by the oxygen reduction reaction that occurs at the cathode (Eq. 5-11) [30]. The efficiency of the electron flux at the cathode is directly
proportional to its oxygen concentration. One cathode material that is commonly used is platinum. Energy production by microalgae is tabulated in Table 3.

\[
\begin{align*}
O_2 + 4H^+ + 4e^- & \rightarrow 2H_2O & E^* = + 1.230 \text{ V vs SHE} \\
O_2 + 2H^+ + 2e^- & \rightarrow H_2O & E^* = + 0.269 \text{ V vs SHE} \\
NO_3^- +2e^- + 2H^+ & \rightarrow NO_2^- + H_2O & E^* = + 0.433 \text{ vs SHE} \\
NO_2^- + e^- + 2H^+ & \rightarrow NO_2^- + H_2O & E^* = +0.350 \text{ V vs. SHE} \\
NO + e^- + H^+ & \rightarrow 1/2N_2O + H_2O & E^* = +1.175 \text{ V vs. SHE} \\
Fe^{3+} + e^- + H^+ & \rightarrow Fe^{2+} + 1/2 H_2O & E^* = +0.773 \text{ V vs. SHE} \\
MnO_2 + 4H^+ + 3e^- & \rightarrow Mn^{2+} + 2H_2O & E^* = +0.602 \text{ V vs SHE}
\end{align*}
\]

Table 3. Energy production by microalgae strains [26].

| Microalga  | MFC type | Anode        | Cathode                  | Max. power density (mW. m\(^2\)) |
|------------|----------|--------------|--------------------------|----------------------------------|
| *Scenedesmus obliquus* | Double chamber | Toray carbon paper | Toray carbon paper | 102                              |
| *Chlorella pyrenoidosa* | Double chamber | Graphite rod   | Graphite rod             | 20.15                            |
| *Spirulina platensis* | Double chamber | Platinum       | Platinum                 | 6.5                              |
| *Arthrospira axima* (Spirulina maxima) | Double chamber | Graphite       | Graphite                 | 20.5                             |
| *Chlorella vulgaris* | Single chamber | Graphite fiber brush | Carbon cloth-coated Pt | 980                              |
| *Dunaliella tertiolecta* | Double chamber | Graphite plate electrodes | Graphite plate electrodes | 5.3                              |
| *Chlorella vulgaris* | Double chamber | Carbon felt | Carbon fiber cloth | 8.79                             |
| *Scenedesmus obliquus* | Double chamber | Toray carbon cloth | Toray carbon cloth | 13.5                             |
| *Desmodesmus sp. A8* | Double chamber | Plain carbon paper | Carbon paper-coated Pt | 154                              |
| *Desmodesmus sp. A8* | Double chamber | Plain graphite felt | Plain graphite felt | 99.09                            |

3.1.3 **Membrane materials.** In dual-chamber microbial fuel cells, membranes are usually used to separate the anode and cathode chamber. Utilization of membranes facilitates the transfer of electrons from the anode to the cathode, as well as prevents oxygen and substrate crossovers [21]. Commonly membranes used in MFCs include proton exchange membranes, ceramic membranes, salt bridges, and others [22],[31]-[33].

In MFCs, aside from the types used, membrane materials are also an important consideration, because it will affect the rate of electron transfer. The ability of the membrane to separate the pH of the substrate necessary to consider when selecting membrane material [34]. The performance of MFCs using various membranes shown in Table 4.

3.1.4 **Substrate.** Synthetic wastewaters usually used are glucose, sucrose, acetate, and xylose. The simplest and most widely used synthetic wastewater in MFC is acetate. The acetate substrate power density is higher compared to glucose substrate and domestic wastewater. Nowadays, the focus of the study has shifted to the use of actual wastewater as a source of the substrate, because the composition is
very different. Studies on energy recovery from various wastewater substrates in MFC have been conducted by researchers, as shown in Table 5.

**Table 4. Performance of MFC using various membrane materials [34].**

| Type of membrane | Materials | Max. power density (mW/m²) |
|------------------|-----------|---------------------------|
| Cation Exchange Membrane | Sulfonated poly-ether ether ketone (SPEEEK) | 77.3 |
| Exchange | Sulfonated polystyrene-ethylene-butylenepolystyrene (SPSEBS) | 80 |
| | Cation exchange membrane (CMI)-7000 | 480 |
| | Hyflon Ion | - |
| Anion Exchange Membrane | Anion (AMI)-7001 | 610 |
| Porous materials | Salt bridges | 40 |
| | J-Cloth | 46 |
| | Glass fiber filters and nylon | 48 |
| | Non-woven paper fabric filter | 69 |
| | Earthenware pot | 24.32 |
| | Ceramic and terracotta | 40 |
| | Starch-based compostable bags | 25 |
| | Latex glove | 0.06 |
| Nafion 117 | | 514 |

**Table 5. Energy recovery from various wastewater substrates in MFCs [30].**

| Wastewater source | MFC type | Power density |
|-------------------|----------|---------------|
| Acetate | Dual | 0.08 (mA/cm²) |
| Glucose | Dual | 283 (mW/m²) |
| Alcohol distillery | Dual | 1000 (mA/m²) |
| Agriculture wastewater | Single | 13 (mA/m²) |
| Bad wine wastewater | Dual | 3.8 (W/m³) |
| Brewery and bakery | Single | 10 (mA/m²) |
| Cheese whey | Dual | 42 (mA/m²) |
| Chocolate industry wastewater | Dual | 0.302 (mA/m²) |
| Dairy wastewater | Single | 25 (mA/m²) |
| Distillery wastewater | Single | 245.3 (mA/m²) |
| Farm manure | Single | 0.004 (mA/m²) |
| Food processing wastewater | Dual | 0.05 (mA/cm²) |
| Food waste | Single | 207 (W/m³) |
| Food waste-compost leachate | Dual | 209 (mA/m³) |
| Hospital wastewater | Dual | 14 ± 1 (W/m³) |
| Human feces wastewater | Dual | 70.8 (W/m³) |
| Landfill leachate | Single | 344 (mW/m³) |
| Pre-digested landfill leachate | Single | 114 (mA/m²) |
| Liquid waste from solid waste | Dual | 418-548 (mA/m²) |
| Meat processing wastewater | Dual | 152-218 (mA/m²) |
| Paper recycling wastewater | Dual | 622 (mW/m²) |
| Paper wastewater | Single | 125 (mA/m³) |
| Pharmaceutical | Single | 8 (mA/m³) |
| Protein-rich wastewater | Single | 177.36 (W/m³) |
| Real urban wastewater | Dual | 0.008 (mA/cm³) |
| Wastewater source                      | MFC type  | Power density |
|----------------------------------------|-----------|---------------|
| Sewage sludge                          | Single    | 105 (mA/m²)  |
| Starch processing wastewater           | Tubular   | 73 (mA/m²)   |

3.1.5 pH. The optimal metabolic activity of microorganisms requires pH that is near neutral and low ion concentration. The system's pH can be disrupted if the transfer of electrons, protons, and oxygen is unstable. The reduction of oxygen in the cathode chamber will cause the pH to become alkaline. Basic pH will inhibit the activity of microorganisms, so it needs to be an added buffer solution to neutralize.

3.1.6 Temperature. Operating temperatures affect electricity generation. The value of reaction kinetics, mass transfer, coulombic efficiency and power density are directly proportional to the operating temperature. The optimal temperature studied has ranged from 19°C to 35°C [34, 35].

3.1.7 Light. Light affects the growth of microalgae and the amount of oxygen released through photosynthesis. So, it takes the intensity of the light and light-dark cycle to optimize the growth of microalgae.

4. Conclusions
Microbial Fuel Cell technology requires microbes to convert chemical energy into electricity and is currently under development. Since microbial growth requires substrates and nutrients such as organic substances, nitrogen and phosphorus, the substrate for these microbes can utilize wastewater containing such substances. Therefore, in addition to generating electricity, this MFC technology also eliminates the level of pollution caused by wastewater. In short, the application of fuel cell technology provides multiple benefits, as a power generator and as well as the wastewater treatment plant. More importantly, the overall process is more environmentally friendly, economically feasible and sustainable. However, challenges on the efficiency of electricity produced, electrode development, biomass utilization, oxygen recovery and scale-up require further research.

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