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A Review on Microbial fuel Cells Employing Wastewaters as Substrates for Sustainable Energy Recovery and Wastewater Treatment

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Abstract: *Renewable and green energy resources are paramount to environmental sustainability. The need for alternative energy sources to fulfill the environmental friendliness goals in energy production and substitute the depleting fossil fuel. Microbial fuel cells (MFCs) are amongst the potential alternative solutions to the energy dilemma. The advantages of Microbial fuel cell (MFC) include degradation of pollutants in the wastewater and electricity production. In the present research article the usage of different wastewaters as substrates in MFC has been discussed also this research review on several types of wastewaters with performance of different MFC designs, operational conditions, wastewater treatment parameters such as chemical oxygen demand (COD) removal rate and power density. Also, various applications of MFC such as wastewater treatment, generation of bioelectricity, secondary fuel production and biosensors has discussed.*
Keywords: *Microbial fuel cell, substrates, wastewater treatment and energy conservation.*

I. Introduction

The rising concern over protection of environment and depleting energy resources has made it inevitable to taken over the waste management system from merely treating the waste to new horizon of recovery of energy from waste [1, 2]. Microbial fuel cell (MFC) is a promising technology which produces electricity and simultaneously removes the pollutants from the wastewater. The MFC is a bio-electrochemical system exploiting bacterial oxidation of biodegradable organic matter, to generate electricity [3-5]. The microorganisms generally present in anode chamber of fuel cell act as biocatalyst and generate electrons (e^-) and protons (H^+) by way of anaerobic respiration of organic substrate. The electron transfer through the anode integrated with an external circuit to cathode and protons diffuse through the proton exchange membrane (which separates cathode and anode chamber) into the cathode chamber where they combine with help of mediator. The potential between the respiratory system and electron acceptor generates the current and voltage needed to make electricity [6]. The potential advantages of Microbial fuel cells (MFCs) compared to traditional technologies such as activated sludge are reduced operational costs, due to passive oxygen diffusion to the cathode (no wastewater aeration), reduced sludge production, and electricity production. Tremendous advances have been made in recent years in increasing power densities by improving reactor configurations and developing new electrode materials. The use of inexpensive materials, such as activated carbon cathodes and graphite fiber brush anodes, has substantially decreased the cost of MFC electrodes which could enable cost effective systems at larger scales [7].

II. Microbial Fuel Cell

MFCs employ microbes to generate electricity from biochemical energy produced during metabolism of organic substrates and simultaneously treating wastewater. MFC consists of anode and cathode connected by an external circuit and separated by proton exchange membrane (PEM). In anode chamber decomposition of organic substrate by microbes generates electrons (e^-) and protons (H^+) that are transferred to cathode through circuit and membrane, respectively. Organic substrates are utilized by microbes as their energy sources. In anaerobic condition certain bacteria can transfer electrons to anode. The electrons then move across a conductor at a specific resistance to the cathode, where they combine with protons and oxygen to form water. Further, these electrons flow from anode to the cathode, which includes current and voltage to produce electricity. Bacteria are being used in MFC to generate electricity while accomplishing biodegradation of organic matters present in the wastewaters. Fig 1 shows a schematic diagram of a typical MFC. It consists of anodic and cathodic chambers partitioned by a PEM [8].

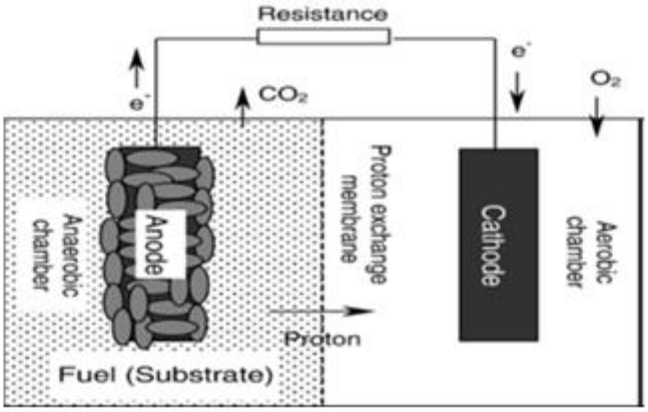

Fig-1: Schematic diagram of a typical dual compartment microbial fuel cell

Typical electrode reactions are shown below using acetate as an example substrate.
Anodic reaction:
$CH_3COO^- + 2H_2O \longrightarrow 2CO_2 + 7H^+ + 8e^-$ (1)
Cathodic reaction:
$O_2 + 4e^- + 4H^+ \rightarrow 2H_2O$ (2)
The overall reaction is the breakdown of the substrate to carbon dioxide and water with a concomitant production of electricity as a by-product. Based on the electrode reaction pair above, the MFC bioreactor can generate electricity from the electron flow from the anode to cathode in the external circuit [9].

III. Applications

MFCs are potential candidates for electricity generation with concomitant treatment of wastewater [10]. The operational and technological improvements as well as cost effectiveness and performance efficiency required to scale up and use MFC as a renewable energy resource. Also MFCs are known to generate less excess sludge as compared to the aerobic treatment process. The main applications of MFCs developed in recent decades are classified in the following forms:

3.1 Wastewater Treatment

MFC can perform dual duty of degrading organic pollutants with the help of microorganisms as well as generation of electricity. In recent advances researchers have investigated the use of wastewaters as substrates such as dairy wastewater, cheese whey, refinery and distillery wastewater, food processing, domestic and sewage wastewater etc., which has potential to recover energy resources by degrading organic matters with the help of microorganisms. MFC substrates have huge content of growth promotes that can enhance the growth of bio-electrochemically active microbes during wastewater treatment [11]. MFC may provide a new method offset operating costs of wastewater treatment plants, making advanced wastewater treatment more affordable in both developing and industrialized nation. In addition MFCs are also known to generate less excess sludge as compared to the aerobic treatment process [12].

3.2 Generation of Bioelectricity

MFC is a promising technology that can use different substrates with microbes to achieve energy recovery in terms of electricity despite the fact that power generation is relatively low. The main objective of MFCs is to achieve a suitable current and power for the application in small electrical devices [13].

3.3 Secondary Fuel Production

MFCs can be employed to produce secondary fuels like hydrogen (H_2) as an alternative source for the production of electricity with minor modification. Under standard experimental conditions, proton and electron produced in anaerobic camber get transferred to cathode, which combines with oxygen to form water [11]. Hydrogen production by modified MFCs operating on organic waste may be an interesting alternative. In such devices, anaerobic conditions are maintained in the cathode chamber and additional voltage 0.23V or more is applied to the cathode [14]. Under such conditions protons are reduced to hydrogen on the cathode. Such modified MFCs are termed as Bio-Electrochemically Assisted Microbial Reactor (BEAMR).

3.4 Biosensors

MFC technology can also be used as biosensor for online monitoring and pollutant analysis. MFCs are suitable for powering electrochemical sensors and are small telemetry systems to transmit obtained signals to remote receivers. To design this type of system, having appropriate cathodic and anodic reactions is the first step [15]. The conventional treatment methods are being used to determine the organic matters in terms of Biological oxygen demand (BOD) and Chemical oxygen demand (COD) in wastewater, most of them are unsuitable for online monitoring [11]. It is possible to use MFCs as BOD sensor [8], and it is exhibited that this type of BOD sensor has excellent operational sustainability.

IV. Use Of Wastewaters As Substrates In Microbial Fuel Cells

The researchers have investigated several types of wastewaters with different MFC designs and operational conditions and reported on various parameters such as COD removal rate and other treatment parameters, maximum voltage output and power density.

2.1 Cheese Wastewater

Patrick and Zhen [16] reviewed on treatment of cheese wastewater in which four identical MFCs to treat different stages of a cheese wastewater treatment process. Treatment performance and energy balance were examined. The two MFCs treating liquid wastes achieved more than 80% removal of total chemical oxygen demand (TCOD), while the other two MFCs fed with sludge or cheese whey removed about 60% of TCOD. The highest coulombic efficiency is 27.2 % and power density is 3.2 W/m^3.

2.2 Chocolate Industry Wastewater

Sunil A. Patil et al. [17] reviewed on feasibility of using chocolate industry wastewater as a substrate for electricity generation using activated sludge as a source of microorganisms was evaluated in two-chambered microbial fuel cell. The maximum current generated was 1.5 W/m^2 and significant reduction in COD, BOD, total solids and total dissolved solids of wastewater by 75%, 65%, 68%, 50%, respectively, indicated effective wastewater treatment in batch experiments.

2.3 Coal Wastewater

The coal and coal products represent one of the most abundant fossil energy resources in the world and are used as a source of energy in gasification processes. Ho Il Park and Chenjie Wu [18] reported on treatment of wastewater from a coal tar refinery and electricity production using a mediator-less, membrane-less MFC. 88% of COD, 57% of sulfate, and 41% of sulfur were removed. The highest voltage output and power density of the MFC were 543 mV and 4.5 mW/m^2, respectively.

2.4 Dairy Wastewater

Dairy wastewater consists of carbohydrates, proteins and fats, making it complex in nature. Dairy wastewater was investigated using dual compartment MFC resulted in higher power density, 192 mW/m^2 and COD removal, 91% [2]. Venkata Mohan et al. [19] reviewed on treatment of real field dairy wastewater in association with power generation documented higher organic degradation COD 95.49%, protein 78.07%, carbohydrates 91.98% and turbidity 99.02%. The maximum volumetric power production was 1.10 W/m^3, 308 mV and 1.78 mA at 4.44kgCOD/m^3. In a study by Ana Faria et al. [20] obtained maximum power density of 92.2 mW/m^2 and removal efficiency of COD 63% respectively. Mansoorian et al. [21] reviewed on treatment of dairy wastewater using catalyst-less and mediator-less membrane microbial fuel cell (CAML-MMFC) and observed maximum current intensity and power density production were achieved at 3.74 mA and 621.13 mW/m^2. The maximum removal efficiency for COD, BOD_5, phosphorus in suspended solids, total suspended solids (TSS) and was achieved at 90.46%, 81.72%, 72.45% and 70.17% respectively.

2.5 Distillery Wastewater

Distillery spent wash is generated during alcohol production and one of the recalcitrant wastes having extremely high COD, BOD, Suspended Solids, inorganic solids, color and low in pH. Distillery spent wash was examined in dual compartment microbial Fuel Cell (DC-MFC) and rotating biological contactor (RBC). MFC obtained average power density of 18.35 mW/m^2 and removal effiency in terms of COD 64%. The effluent further treated in RBC and obtained 84% COD removal [22]. In the study by Vanita R. Nimje et al. [23] a single chamber microbial fuel cell was operated with distillery spent wash. MFC yielded the maximum power density 29mW/m^2 and the COD removal efficiency was 81%. Mohan Krishna et al. [24] examined distillery wastewater in single chamber MFC obtained 48.47 mW/m^2 power density and 72.84% COD removal efficiency.

2.6 Domestic Wastewater

Jiang Hai-ming et al. [25] reviewed on treatability of domestic wastewater with simultaneous electricity generation. The up flow Membrane less microbial fuel cell (ML-MFC) produces a maximum power density of 481 mW/m^3 and COD removal efficiency 77.9%. Hong Liu et al. [26] evaluated domestic wastewater in single chamber MFC and resulted in 26 mW/m^2 power density and 80% COD removal.

2.7 Refinery Wastewater

The Wastewater generated from Petroleum Refinery contains many chemicals, such as benzene, volatile phenol, sulfides, ammonia, suspended solids, cyanides, nitrogen compounds and heavy metals. Xuan Guo [27] reviewed on the electricity generation performance, treatment efficiency and degradation mechanism of petroleum pollutants over MFCs using petroleum refinery wastewater. MFC showed the highest power density 330.4 mW/cm^3, COD removal 64% and oil removal 84%. Fang Zhang et al. [7] examined refinery wastewater in dual compartment MFC resulted in higher power density, 280 mW/m^2 and COD removal, 84%.

2.8 Sewage Wastewater

M. M. Ghangrekar and V. B. Shinde [28] reviewed that performance of mediator-less and membrane-less microbial fuel cell (ML-MFC) was evaluated for treatment of synthetic and actual sewage and electricity harvesting. Maximum COD removal efficiency of 91.4% and 82.7% was achieved while treating synthetic wastewater and actual sewage, respectively. Maximum current of 0.33mA and 0.17mA was produced during synthetic and actual sewage treatment, respectively. Maximum power density of 6.73mW/m^2 and maximum current density of 70.74mA/m^2 was obtained in this membrane-less MFC with successful organic matter removal from wastewater.

2.9 Slaughter House Wastewater

Animal wastewater is often particularly high in organic content and also contains high levels of nitrogen containing components like proteins and cellulose [29]. Slaughter house wastewaters from livestock related industry may also include lipids besides carbohydrates, organic acids and protein. The concentration of brewer wastewater vary, it is typically in the range of 3000-5000 mg/L COD which is ten times more concentrated than domestic wastewater [30]. Katuri K. P. et al. [31] evaluated in the dual compartment MFC and yielded the maximum power density 578mW/m^2 and COD removal efficiency 93%.

The comprehensive table for various substrates has been providing comparative information on various aspects such as electrodes employed in anode and cathode chamber, COD removal efficiency and power density (P_d) of MFC performance are presented in Table 1.

Table-1: The performance of MFC using wastewaters as substrate.

Sl. No.	Wastewater	Type of MFC	Anode	Cathode	Inoculum	COD Rem %	Power Density (P_d)	Ref.
1	Cheese wastewater	Two chamber	Carbon brushes	Carbon cloth	Digested sludge	80	3.2 W/m^2	[16]
2	Chocolate industry	Two chamber	Graphite rods	Graphite rods	Activated sludge	75	1.5 W/m^2	[17]
3	Coal tar wastewater	Single chamber	Graphite felt	Graphite felt	Activated sludge	88	4.5 mW/m^2	[18]
4	Dairy industrial wastewater	Single chamber	Plain graphite plate	Plain graphite plate	Anaerobic mixed consortia	95.49	1.1 W/m^3	[19]
		Dual compartment	Carbon Toray TP-090 sheet	Carbon Toray TP-090 sheet	Municipal wastewater	63	92.2 mW/m^2	[20]
		Two chamber	Graphite plate	Graphite plate	Activated sludge	90.46	621.13 mW/m^2	[21]
5	Distillery wastewater	Dual compartment	Graphite rod	Graphite rod	Domestic sewage	64	18.35 mW/m^2	[22]
		Single chamber	Carbon cloth	Carbon cloth	Cow dung and distillery spent wash	81	29 mW/m^2	[23]
6	Domestic wastewater	Upflow membrane - less MFC	Carbon fiber brush	Carbon fiber brush	Activated sludge and effluent of primary clarifier	77.9	481 mW/m^2	[25]
		Single chamber	Graphite rod	Graphite rod	Geobacter Metallireducem	80	26 mW/m^2	[26]
7	Refinery wastewater	Single chamber	Graphite fiber brush	Carbon cloth	Domestic wastewater	84	280 mW/m^2	[7]
		Dual compartment GC-packing type	Carbon rod	Graphite flake	Activated sludge	64	330.4 mW/cm^3	[27]
8	Sewage wastewater	Membrane less MFC	Graphite rod	Graphite rod	Anaerobic sludge	91.4	6.73 mW/m^2	[28]
9	Slaughter house wastewater	Dual chambered	Carbon cloth	Platinized titanium mesh	Anaerobic mixed sludge	93	578 mW/m^2	[31]

V. Conclusion

Increased human activities and consumption of natural energy resource have led to decline fossil fuels. Moreover, using of fossil fuels may cause environmental pollution. MFC is a technology for the treatment of wastewater and significant energy recovery. Recent advances have investigated the use of different sources of substrates in terms of wastewaters which has a great potential over degrading organics and efficient bioelectricity production. This review summarizes the various wastewaters as substrates that have been used in MFCs for wastewater treatment along with power generation. It is expected for the operational and technological improvements as well as cost effectiveness and performance efficiency required to scale up and to use MFC as a renewable energy resource and effluent treatment. Also necessary to research further for the development of MFC at large scales.

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