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Microbial Fuel Cell: An Emerging Technology for Wastewater Treatment and Energy Generation

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Abstract

Microbial fuel cells (MFCs) are enticing surprising attention due to their dual functions of energy generation and waste removal from wastewaters. Microbial fuel cells use microbial metabolism to convert biochemical metabolic energy into electrical current by using different substrates. Microbes are fed in the anode with the substrate (e.g., domestic, industrial, leachates, etc.) to enhance the performance of microbial fuel cells. It provides an opportunity for the feasible production of energy from bio-degradable organic matters while treating wastewater. In recent years, despite the extensive efforts to improve the efficiency of the cell, energy production is still low, especially in scaled-up systems. However, the construction cost of microbial fuel cells is relatively higher than fossil fuel prices, so it makes doubtful that power generation can ever be competitive with existent energy generation approaches but improvements in power densities, reductions in materials costs may make microbial fuel cells real-world for electricity generation. In-depth review of literature, the study summarizes the role of microorganisms and substrate in the anode chamber. It includes types, components, mechanism and operation of microbial fuel cells. This review highlights various parameters affecting microbial fuel cells, current challenges and applications in the production of electrical energy in a sustainable way.

Keywords: Biodegradable; Metabolic energy; Microbial fuel cell; Nutrient removal; Wastewater treatment

1 Introduction

The demand for renewable energy will possibly comprise a huge portion of global energy production and their usage in the future (1-2). Present prospects for global energy have been direct us to move towards non-renewable energy (3-4). Now a day; non-renewable resources of energy are exhausting at a much faster rate which suggests the development of different cost-effective renewable energy technologies. India has abundant sources of renewable energy, biomass (organic matters) is one of them (5). The total available volume for electricity generation in India was about 2670 GW till 2013 in which the contribution of renewable energy was 10.5%. Biomass contributes 12.83% of total renewable energy generation (6). Hence, a lot of biomass (substrate) is available, which has a high potential to generate energy with the help of microbial fuel cell (MFC). The MFC is one of the technologies with the potential for promoting self-sustainability and resource efficiency in the treatment of wastewater (7-12). MFC comprises anode and cathode compartment. The proton/cation/anion membrane or salt bridge divides the anodic and cathodic compartments. Anode creates biofilm at its surface which acts as a catalyzer to transform biochemical energy into electrons, while the oxygen acts as an electron acceptor to form water at the cathode (13-15). MFC has the capability to transform biochemical energy which is present in waste biological matter into electrical energy with bacterial catalysis (16-20). Currently, MFC is considered as a sustainable technology for the generation of energy (21-24). Material selection is important because it affects the efficiency of MFC in terms of microbial growth and efficiency of reactions involved. Finding the best suitable materials and architectures for maximizing the columbic efficiency and power generation is the main challenge for an MFC. Further challenges coming in the way are to reduce the cost and make architecture for MFC that are intrinsically scalable (25-28). This study highlights different factors affecting the performance of MFC, its benefits, limitations, and role of substrates and microorganisms.

2 Classification of microbial fuel cells (MFC)

The classification of MFC is essential because it states about the efficiency of MFC, i.e. coulombic efficiency, permanency, robustness, and power output. The design which produces high power and coulombic efficiency based on cost-effective materials are required for practical applications, which can be implemented on a large scale (25). There are a number of designs for the manufacturing of an MFC depending upon different chambers, type of operation, etc. Some principally include the following types of MFC.

2.1 Single chamber MFC

A modest and more competent MFC can be prepared by neglecting the cathode compartment and inserting the cathode electrode directly into the PEM (Proton exchange membrane). Single chamber MFC contains both the anode and the cathode in a single compartment. Single chamber microbial fuel cells (SCMFCs) are supposed to be superior for their simple design, flexibility, low internal resistance, and relatively low cost. There is no need for oxygen in air-cathode MFC because oxygen is directly transferred to the cathode. The cathode electrode is covered with the membrane in single chambered

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MFC (29-32). Cathode electrode kept open in the Air-cathode single chamber MFC as shown in fig. 1 (c).

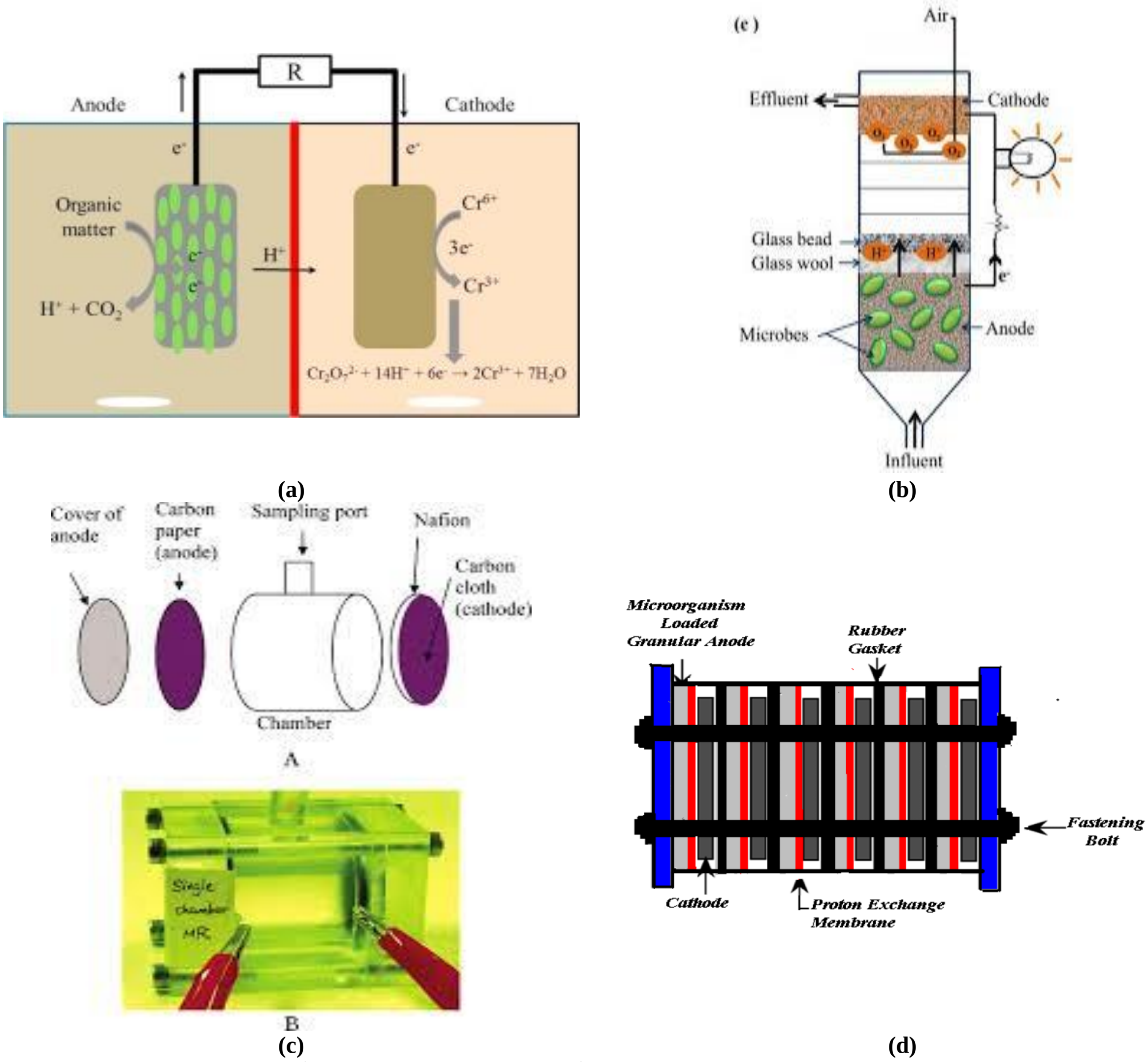

Figure 1: Schematic diagram of (a) Dual chamber MFC (b) Up-flow MFC (c) Single chambered Air-cathode MFC (d) Stacked MFC

2.2 Dual chamber MFC

Generally, batch mode study is conducted for dual chambered MFCs to generate electricity and waste reduction. It is most widely used in laboratory scale. A typical dual chamber MFC consists of an anodic compartment and a cathodic compartment connected with the help of membrane or salt bridge as shown in Fig. 1(a). In the anode chamber, microorganism decomposes organic matter and produces free electrons and hydrogen ions. Protons (H^+) are allowed by a membrane to move towards the cathode and at the same time electrons are transferred via external circuit (33-35). Free electrons and hydrogen ion form water in the presence of oxygen in the cathode chamber.

2.3 Up-flow MFC

The cylindrical MFC comprises of the anode in the bottom of the MFC and the cathode at the top separated by glass layers (separators) or glass wool as in Fig. 1(b). The substrate is fed from the bottom to the anode compartment that passes upside of the cathode and exits at the top. For proper operation of the MFCs, a gradient is provided by transmission barrier among the electrodes. There is no separate anolyte and catholyte provided (8).

2.4 Stacked MFC

An assembly of MFCs in series or parallel connection associated with each other is as shown in Fig. 1(d) (8). MFC can be stacked by attaining unlike configurations of both anode and cathode electrodes as well as organic flow. It can be classified in four categories i.e., Series electrodes in parallel organic flow mode, Series electrodes in series flow mode, Parallel electrodes in parallel flow mode and Parallel electrodes in series flow mode (36). The parallel connected stack MFC has higher electrochemical reaction rate than in series. So, parallel connection is preferred over a series to achieve maximum COD removal (48). Some researchers varied anode, cathode electrodes, catalyst and mediators with microbial fuel cells as shown in Table 1.

3 Electron transfer mechanisms

Two leading mechanisms are conveyed for the electron transfers from the biological matter to the anion electrode in the MFC i.e., direct electron transfer and mediated electron transfer. Bacteria are well-known medium to the electron transfer to anode surface through electron shuttling with self-generated mediators like *pycocyanin* formed by *Pseudomonas* *aerginosa* (25, 49). Some bacteria needs external mediators to generate electricity i.e. *Shewanella onedensis*, *Geothrix fermentans,* etc.

Table 1: Various types of implementation with microbial fuel cells

Type of MFC	Wastewater	Anode	Cathode	COD removal	Energy generation	References
MFC-AFMBR	Domestic	Graphite fiber brushes with a titanium wire core	Wet-proofed carbon cloth	92.5%	0.0197 kWh/m^3	37
MAC-MFC	Domestic	Graphite rods	Carbon cloth	80%	-	38
HUSB-CW-MFC	Domestic	Graphite rod wrapped with a stainless steel mesh marine grade	Graphite rod wrapped with a stainless steel mesh marine grade	61%	219 mA/m^2 39 mW/m^2	39
FME-MFCs	Domestic	Noncatalyzed graphite discs	Noncatalyzed graphite discs	>71%	80.08 mW/m^2	40
Catalyst- and mediator-less membrane microbial fuel cell	Dairy industry	Graphite plate	Graphite plate	90.46%	621.13 mW/m^2	41
Earthen pot MFC	Rice industry	Stainless steel	Graphite plate	96.5%	2.3 W/m^3	42
Alum sludge ebased CW-MFC	Swine industry	Granular graphite around 3 graphite rod	Granular graphite around 3 graphite rod	81%	0.268 W/m^3	43
Upflow microbial fuel cell	Sea	Activated carbon fiber felt	Activated carbon fiber felt	95%	105 mW/m^2	44
Stacked MFC	Swine wastewater	graphite felt	carbon fiber cloth containing MnO2 catalyst	83.8%	175W/m^2	45
Cross-linked MFC	Domestic	Carbon rod	Carbon rod	82%	337 W/m^3	46
ML-MFC	Domestic	Graphite rod	Graphite rod	88%	10.13mW/m^2	47

Some chemical mediators were added to MFCs to transfer electrons by micro-organisms like yeast, glucose, acetate, etc. The direct electron transfer mechanism: It indicates direct transfer of electrons in between microbes and cathode electrode in the MFC. In this biofilm is created at the surface of anode electrodes through which electron transfer takes place and it generates additional energy in the process (50). An electrochemical reaction occurs at the anode when electrons reach to electrode surface which liberates electrons into anode. Direct electron transfer process takes place in the presence of outer membrane. *Shewanella putrefaciens, Geobacter sulferreducens, Rhodoferax ferrireducens* etc. are examples of direct electron transfer mechanism. Indirect electron transfer mechanism: In this type of mechanism, an external mediator is required to transfer the electrons to the cathode which may be generated by microbes or externally added.

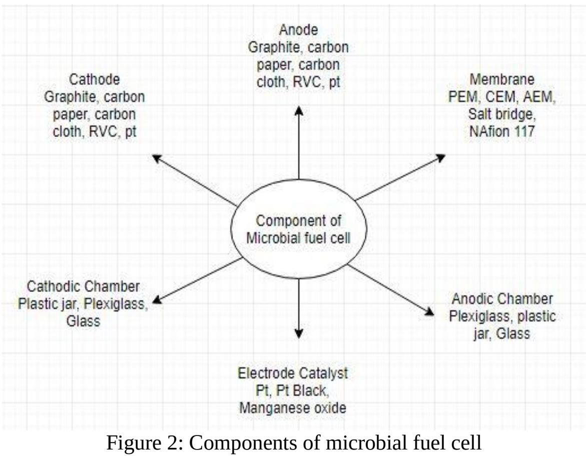

Figure 2: Components of microbial fuel cell

It takes place in the presence of soluble shuttles. Electron shuttles act as electron carrier which transfers electrons from microbes to the surface of electrode. The essential and optional components of MFC shown in Fig. 2. In the anode compartment, the anaerobic reactions occur which results in conversion of biological matter into electrons (e^-) and hydrogen ions (H^+). Electrons (e-) are transferred to the cathode via an external circuit and hydrogen ions (H+) are passed to the cathode compartment through a membrane. In cathode compartment hydrogen ions (H^+) and electrons (e^-) combine with oxygen which acts as an electron acceptor to form water. For specimen, if glucose ($C_6H_{12}O_6$) is used as anolyte in anode and oxygen (O_2) as an electron acceptor, Eqs. 1 and 2 reactions occur in MFC.

At Anode: $$C_6H_{12}O_6 + H_2O \rightarrow 6CO_2 + 24e^- + 24H^+ \quad (1)$$

At Cathode: $$O_2 + 4e^- + 4H^+ \rightarrow 2H_2O \quad (2)$$

4 Role of microorganisms in MFC

A vast variety of the bacteria are available, having the capability of oxidizing the organic compounds and transferring the electrons towards anode. For the decomposition of the organic matter from the electrode potential, Microbial Fuel Cell (MFC) makes use of both types of bacterial cultures i.e., pure culture and mix culture. The benefit of mixed cultures over the pure bacterial culture is its high substrate consumption, great resistance against process disturbance and consists of higher power based output (51). Many such types of microorganisms have been found and reported which are self-mediated i.e., which by themselves transfer the electrons across the membrane from anode to cathode. These microorganisms comprise of high columbic efficiency and are stable in nature. These microorganisms form a thin film on the surface of the anode and directly transfers electrons across the membrane to the electrode. The names of some such effective microorganisms are Actinobacillus succinogenes (52), Aeromonas hydrophila (53), Clostridium butyricum (54), Escherichia coli (55), Shewanella *putrefaciens* (56), *Geobacteraceae sulferreducens* (57), *Geobacter metallireducens* (58) and *Rhodoferax ferrireducens* (50) etc. Being self-mediated, these bacteria have reduced the use of mediators, has played a major role in bringing the revolution in the study. The cathode enhances the generation of the electricity and acts as the cell electron donor. In the cell, mediators play a major role to behave as a shuttle between electron carriers and anode. Some of the commonly known mediators are neutral red, humic acid, methylene blue, $Mn4^{+}$ and Fe (III)-EDTA (52, 55, 59). Because of having a larger variety of substrates, mixed cultures is preferred most of the time for the treatment of wastewater and electricity generation. An array of substrates used in the blend of andophiles and electrophiles is proposed to be used to generate electricity from wastewater. Microbes enhance the reaction rate in the anode. It also increases the performance of MFC. It acts as a catalyst in the anode compartment with substrate and anolyte. Some of the microbes are tabulated in Table 2.

5 Parameters measuring the performance of MFCs

While talking about the performance of MFC, the two facets it covers are; its efficiency/capability of producing the power and second, the efficiency with which a given feedstock can be treated. Measuring the power of MFC is easy and straightforward, but a presentation of its data report to the research community is typical, creating confusion to the readers. Considering the different operating conditions in which the researchers operate and different compartment materials available, some of the standards are required to be universally accepted. For instance, the power density to opt as standard output for measuring the power of MFC widely. However, many other factors like size of cathode and anode or membrane are responsible for normalizing it (60). The power density can also be expressed in the terms of cathodic, anodic or liquid volumes (61). However, according to many researchers, some standard is required, to be universally accepted in this context. The reason behind this is that due to the lagging of such parameter, the reporting output is available in various formats. Due to numerous parameters involvement, there may be over or underestimation of the information. Hence, because of non-standardization, the component dimensions and reactor information is not fully stimulated. Performance depends upon two important aspects, one is how much it produces voltages and other is the efficiency of treatment of the substrate. The efficiency of MFC depends on several factors like biological, chemical and physical parameters. Here some key parameters in Table 3 that describe the performance of MFC.

Table 2: Different researchers used microbes and synthetic substrate in MFC

Micro-organisms	Synthetic substrate	References
Clostridium butyricum	Glucose, lactose	54
Aeromonas hydrophila	Acetate	53
Actinobacillus succinogenes	Glucose	52
Desulfovibrio desulfuricans	Sucrose	59
Escherichia coli	Glucose, Sucrose	55, 59
Geobacter metallireducens, Geobacter sulfurreducens, Rhodoferax ferrireducens	Glucose, Acetate	50, 58
Erwinia dissolven, Lactobacillus plantarum, Streptococcus lactis	Glucose	62
Pseudomonas aeruginosa	Glucose	49
Shewanella putrefaciens	Glucose, Lactate	56
Shewanella oneidensis	Lactate	63

6 Factors affecting MFC

To improve the efficiency and lowering overall design cost of MFC, several factors need to be highlighted.

6.1 Anode and cathode materials

The efficiency of MFC may be improved in terms of power output, operation, and durability of the electrode.

Table 3: Key parameters for MFC performance (25)

Parameters	Unit	Formula
Electrode Potential	Volts	$E_{cell}= E°- \frac{RT}{nF} In(\Pi)$ $\Pi= (Product)^{p}/(reactant)^{r}$
Open circuit voltage	Volts	OCV (open circuit voltage), Voltage obtained with indefinite resistance
Current	Ampere	$I=V/R_{ex}$
Power	Watt	P=I.V
Current density	A/m^2	j= I/A, A= Electrode surface area (m^2)
Power density	W/m^2	$P_D=P/A$ A= Electrode surface area (m^2)
Internal Resistance	Ω	Using Polarization curve, $P_{max} =V_{ocv}^2R_{ex}/ (R_{in} + R_{ex})^2$ $R_i= (OCV/I_L)- R_e$
Organic loading rate	$Kg/m^3/day$	$OLR= COD.\ V_{reactor}/V_{anodic}$
Hydraulic retention time	Hour	HRT= Discharge per hour in reactor/ Volume in the anode
COD removal efficiency	%	$COD\ efficiency\ (\%) = \frac{\text{Initial COD} - \text{final COD}}{\text{Initial COD}}\ X\ 100$
Coulombic efficiency	%	$C_E = (M_S\int_0^{tb} I\ dt)/ (F.\ V_{an}.\ \Delta C)$
Energy efficiency	%	$E_E= V_{measured}/E_{emf}$

A number of anode electrode materials have been examined in recent years. Anode materials with having a large surface area and high electrical conductivity have a great ability for microbial attachment and higher current throng ability. Since anodes turn into biotic, it should be inactive to biochemical reactions as well as anoxic to micro-organisms. Carbon-based materials like carbon cloth, carbon fibre veil, graphite felt and graphite granules (64-68) are the most commonly used materials in MFCs due to their biochemical dullness, biological fouling resistance, high electrical conductivity, large surface area and moderately low cost (69-71). In past years, MFC research primarily was dedicated to the anode materials, due to its unique features which makes MFCs unalike from other traditional fuel cells. Several methodologies to the MFC cathodes are required to be compared with various fuel cell types, i.e. MFCs running at thermophilic conditions, pH variation and comparatively quick reaction rates. Platinum (Pt) is the most generally used catalytic agent for oxygen-reduction rate (ORR) in the cathode due to its pleasing catalytic capability (72).

6.2 External resistance

According to Jacobi's law (25), when internal resistance is equal to an external resistance, the maximum power transfer can be obtained. So selecting external resistance is important because it can affect columbic efficiency, the structure of the anodic film, current production, maximum bacterial growth, morphology and length of maturation (73-74).

6.3 Internal resistance

There is a direct linear relationship between voltage induced and current density due to the polarization curve, which can be expressed as Eq. 3.

$$E_{emf}= V_{oc}-I.R_{int}, \qquad (3)$$

where $I.R_{int}$ is algebraic sum of all internal resistance losses in the MFC and V_{oc} is open circuit voltage. Produced emf is directly proportional to internal resistance and current developed in the cell. No current will be developed in the circuit if high internal resistance is there, so it is assumed to be an essential factor and it will affect the efficiency of the MFC (66, 74).

6.4 Effect of Biofilm in MFC

Rate of the generation of current can never be greater than the rate of bacterial oxidization of a substrate and electrons transfer. So current density is proportionate to the density of bacteria near the surface. When the bacteria cover the anode surface, it forms an anodic biofilm. Theoretically, the biofilm grows infinitely but practically due to slough off of dead bacteria at the solid surface, its thickness reaches to a few millimeters. The thickness of electrogenic biofilm, a distance of microbes from surface and electron acceptor that uses it, is still unknown. If the thickness becomes thicker, the mass transfer rate would be limited. Extreme rate of mass transfer to a biofilm (J_b) is considered as Eq. 4.

$$J_b= k_w(c-c_{b0}), \qquad (4)$$

where c is bulk substrate concentration near the anode, J_b is rate of mass transfer and c_{b0}= concentration of substrate at the biofilm surface (75-76).

6.5 Operating temperature

In the laboratory, the temperature can be controlled but in practice or in the field the ambient temperature would be different, so the temperature is considered an important factor in MFC. Majority of research concluded that lower range of temperature reduces the performance of MFC (30, 75, 77), While upper ranges of temperature have higher output values (78-79).

7 Substrates used in MFCs

The biological parameter which majorly affects electricity production is a substrate. Substrates are available in a broad range to be used in MFC for electricity production (Pant et al., 2010). The population of bacteria, anode biofilm, and the combination of MFC with coulumbic efficiency and power density all are affected by the presence of substrate (80). Because of the inertness of acetate, it is taken as the main source of carbon for various microbial conversions (methanogenesis and fermentations) to occur at room temperature. Also, acetate is the end product of humongous activity. Another substrate commercially used in MFCs is glucose. Acetate comes with better energy conversion efficiency as compared to glucose (81). All monosaccharides that can be produced directly from lignocellulosic biomass hydrolysis are proven to be the excellent energy production resources in MFCs. While the exoelectrogenic and cellulolytic activities in a microbial community are required for the generation of electricity from cellulose. MFCs also utilize definite composition of chemical or synthetic wastewater. Because of its low strength, breweries wastewater is preferably used as an MFC substrate. An MFC with starch processing wastewater is developed (77). This MFC has COD of 4900 mg/L above four of the cycles. In the third cycle, the highest voltage output is observed at 490.8 mV and a power density of 239.4 mW/m^2. Acetate and cellulose are the commercially available and inexpensive known substrates for the generation of electricity and are opted as major organic matter constituent in municipal wastewater and industrial wastewaters (82-83). Substrate mainly involves synthetic, domestic, urinal and industrial (distillery, wine industry, swine, slaughterhouses, paper mills, etc.). Some of the substrates with their output are shown in Table 4.

8 Implications for water-energy-food nexus

8.1 Electricity generation and wastewater treatment

Electricity is required in commercial wastewater treatment, which consumes the power in terms of electrical energy based sludge activation aeration (84). The effective utilization of MFC could be made by controlling and monitoring of the biological waste treatment. Strength of organic matter in wastewater in correlation with columbic yield of MFC acts as biosensor, which makes the effective utilization of MFC possible (85). The role of such integral wastewater treatment plants is the recovering of energy as well as reduction of excess sludge production without disturbing much the organic matter mineralization and the remaining process. Though, it is necessary to reduce the cost of the process for its economic viability. This can be achieved by either using a cheaper cationic membrane or do away with its need, eliminating the cost of its maintenance. Besides, MFC can be run in the plants established for the treatment of wastewater to reduce cost, and the expensive catalysts of the cathode can be avoided in the case when aerobic biomass occurs.

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Table 4: Various reactor with different anode, cathode and membrane materials

Reactor	Anode	Cathode	Membrane	Voltage V (max.)	COD Removal	References
Dual-chamber	Titanium wire	Carbon cloth	CEM, CMI-7000	890mV	85-90%	86
Dual-chamber	Graphite fiber brushes with titanium wire	Graphite fiber brushes with titanium wire	PEM, Nafion-117	567mV	-	87
Dual-chamber	Uncoated graphite sheets	Uncoated graphite sheets	Salt bridge of agar with KCl (Potassium chloride)	603mV	83%	88
Up-flow MFC	Activated carbon fibre felt	Activated carbon fibre felt	PEM, Nafion 117	590mV	78.8%	89
Dual-chamber	Carbon paper	Carbon cloth	PEM	900mV	-	90
Air-cathode MFC	Graphite fibre brushes wound by titanium wire	Activated carbon and carbon black with PVDF (poly vinylidenefluoride) binder ($40cm^2$)	Textile separator	750mV	59%	31
Single MFC, H-cell MFC	Carbon fiber cloth	Carbon fiber cloth	Nano filtration, PEM	756mV	94%	91
Osmotic-MFC	Two Carbon brushes	Carbon cloth with platinum coating (.3mg Pt/cm^2)	TFC FO membrane	780mV	81.1%	92
Dual-chamber	Bare graphite rods	Bare graphite rods	PEM	857mV	68.3%	93
Cassette-electrode MFC	Graphite felt	Graphite felt	PEM	303mV	81.3%	94
Single chamber	Sponge-like a cluster of stainless steel wire	Carbon cloth with $0.35mg/m^2$ Pt catalyst	-	235.11mV	40-55%	95
ML-MFC	Granular graphite	Granular graphite	Membrane less (ML)	190mV	42%	96
Bio-Trickling Filter MFC	Graphite rod	Carbon cloth	Polyvinyl alcohol-membrane electrode assembly (PVA-MEA)	658mV	79.8%	97

8.2 Nutrient removal

For the removal of organic matters, microbial oxidation is mainly used at the anode. MFC is now considered to be expanded in the treatment of wastewater due to bio-cathode discovery and relative reducing phenomenon occurring at the cathode Hence, numerous of the pollutants like perchlorate, nitrate, chlorinated compounds, copper, nitrate, iron, and mercury could be removed (98-99). The first study of nitrate denitrification in MFC was confirmed in 2007, where complete denitrification at the cathode was successfully performed in a tubular reactor, without extra donor supply (100). A novel procedure integrates MFC with aerobic nitrification for concurrent removal of carbon and nitrogen (101).

8.3 Biosensor

The biosensors, in which the electrodes make the bacteria immobile and the membrane prevents them to enter into the other chamber can be created. The potential difference between the electrodes measures any toxic component diffusion through the membrane across the sensor. The various applications where biosensors could be helpful include indications of toxins in the rivers, to carry out research where sites are found to be polluted, or for the measurement and indication of pollution and illegal dumping identification. For these applications, biosensors are implemented at the wastewater treatment plants entrance. Recently, the detection and quantification of the cocaine metabolite benzoylecgonine in human urine was exhibited using microbial fuel cells as biosensors (102).

9 Conclusion

MFC technologies can play an important role in conversion from fossil fuel-based technologies to renewable energy sources. The output achieved with MFC technologies can be enriched by a various ways i.e., alternative electrode materials selection, enhancement in the cathode, minimizing spacing of electrodes, substrate selection, Architectural design of MFC setup, the addition of nutrient media and introducing the magnetic field to MFC. Research into this area is noticeably progressing but there is still a deficiency in order for MFC technologies to be consistently adapted into large scale. MFCs have different applications like wastewater treatment, development of biosensor, power production, bi-hydrogen production, etc. MFC is capable to produce electricity from a variety of waste and biomass, so in future power production from bacteria can become the main source of bioenergy. However the construction cost of MFC is relatively higher than fossil fuel prices, so it makes doubtful that whether the production of power would ever be in competition with the currently trending energy producing techniques but improvements in power densities, reductions in materials costs may lead to MFCs, a practical approach for the production of electricity. The efficiency of MFCs can be enhanced by the suitable design which lowers internal resistance, using nano-particles by which the mechanism of transfer of electron is increased, using the microorganisms which are genetically engineered, adding the controlled or pretreated inoculum, lowering the MFC start-up time. In order to achieve efficient wastewater treatment, fuel cells are supposed to operate at the mesophilic temperatures.

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Abbreviations

A	Electrode surface area
C	Bulk Substrate Concentration Near Anode
$C_6H_{12}O_6$	Glucose
c_{bo}	Concentration of substrate at the biofilm surface
C_E	Coulombic efficiency
CEM	Cation exchange membrane
CO_2	Carbon dioxide
COD	Chemical oxygen demand
E	Electrode potential
e^-	Free Electrons
EDTA	Ethylene diamine tetra acetic acid
E_E	Energy efficiency
F	Faraday constant
Fe	Iron
GW	Gigawatt
H^+	Hydrogen ions
H_2O	Water
HRT	Hydraulic retention time
I	Current
J	Current density
J_b	Rate of mass transfer
MFC	Microbial fuel cell
ML-MFC	Membrane less microbial fuel cell
Mn	Manganese
mV	Millivolt
mW/m^2	Milli-watt per meter square
N	Number of electrons
O_2	Oxygen
OCV	Open circuit voltage
OLR	Organic loading rate
P	Power
P_D	Power density
PEM	Proton exchange membrane
Pt	Platinum
PVA-MEA	Polyvinyl alcohol-membrane electrode assembly
PVDF	Poly-vinylidene fluoride
R	Resistance
R	Gas constant
T	Temperature
V	Voltage

Ethical issue

Authors are aware of, and comply with, best practice in publication ethics specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests and compliance with policies on research ethics. Authors adhere to publication requirements that submitted work is original and has not been published elsewhere in any language.

Competing interests

The authors declare that there is no conflict of interest that would prejudice the impartiality of this scientific work.

Authors' contribution

All authors of this study have a complete contribution for data collection, data analyses and manuscript writing.

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