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Microbial fuel cell as innovative approach for bio-electricity generation: A review

ABSTRACT

The current global scenario is marked by substantial energy demands coupled with limited resources, leading to a widespread energy crisis. Non-renewable energy sources are depleting rapidly, while renewable sources remain underutilized. There is an urgent need for alternative methods of energy generation. In recent times, considerable attention has been directed towards microbial fuel cells (MFCs) due to their favorable operating conditions and the availability of a variety of eco-friendly substrates as fuel. Through the active breakdown of substrates by microorganisms, bioelectricity is produced, offering a sustainable solution to the escalating energy challenges. Extensive research has yielded new insights into Microbial Fuel Cells (MFCs), revealing that a diverse range of carbon sources, including various types of waste, can be effectively utilized with a wide array of microbes. Consequently, the microbial conversion of waste through innovative bioremediation techniques like utilizing MFCs present a potentially attractive alternative to conventional treatment processes in wastewater treatment, facilitating the direct generation of electric energy. This not only aligns with prevailing technological trends but also contributes to cost reduction in the overall process. This article comprehensively examines various components of Microbial Fuel Cells (MFCs), including the anode, cathode, and membrane. To address practical challenges within this field, pragmatic solutions are proposed. The review critically assesses diverse categories of wastes suitable for Bioenergy generation, exploring the associated microorganisms, power output, key advantages, challenges, and limitations and advancements of MFC technology.

Keywords: *Fuel cell, bio-electricity, Microorganisms, wastewater*

1. INTRODUCTION

The global demand for energy continues to escalate, with projections indicating an increase from 565 quadrillion British Thermal Units (BTUs) in 2015 to an anticipated 724 quadrillion BTUs by 2030. Traditional fossil fuels have long been a major contributor to satisfying global energy demands, contributing substantially to the depletion of these resources and causing ecological imbalances (Fig 1). Furthermore, the burning of fossil fuels emits a significant volume of carbon dioxide, a major greenhouse gas associated with serious environmental repercussions [1].

Exploring energy production from renewable sources holds immense potential to address these challenges sustainably and reduce reliance on fossil fuels. Consequently, the quest for alternative, cost-effective, and eco-friendly sources of energy has become an imperative necessity (Fig 1).

Conversely, the depletion of water resources necessitates greater investments in water and wastewater treatment infrastructure. Harnessing energy from "negative value" waste streams can serve the dual purpose of fulfilling global energy demands, mitigating pollution, and cutting down costs related to water and wastewater treatment [2].

The technology of Microbial Fuel Cells (MFC), extracting energy from the metabolism of microorganisms in wastewater, presents an attractive avenue for energy generation [3]. Fuel cells operate through a combustion reaction, bypassing thermal processes to directly convert

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chemical energy into electrical energy. In particular, microbial fuel cells (MFCs) directly convert the chemical energy present in organic, bio-convertible substrates in wastewater into electrical energy. This conversion is facilitated by exo-electrogenic bacteria catalyzing the half-reaction of substrate oxidation [4].

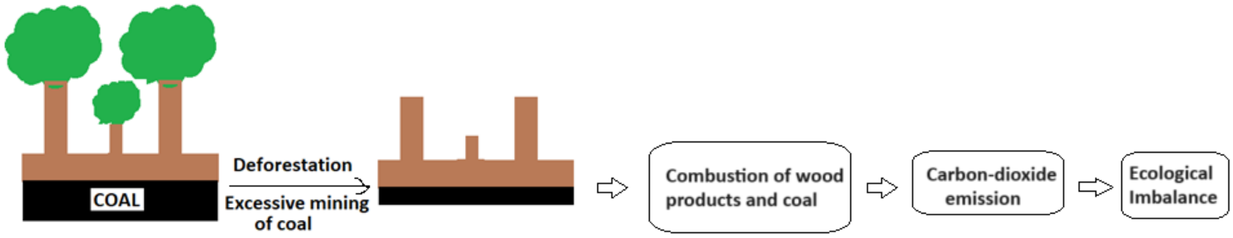

Figure 1. Schematic diagram showing the over-exploitation of natural resources leading to ecological imbalance

The concept of electric current generation by microorganisms has been envisioned for over a century, with MFC devices for electricity production intensively studied for about 50 years. The initial evidence of this phenomenon was uncovered in 1911 [5], but practical progressions were inadequate until the first patent for mediator-less MFCs in 1999 [6]. MFC technology has been utilized for wastewater treatment and as an energy source in various field applications, including environmental sensors and process biomonitoring [7,8].

The application of MFCs to municipal wastewater treatment holds potential as a striking alternative to traditional processes, including indirect energy recovery from wastes (e.g., anaerobic digestion with methane fermentation). These devices are suitable for operating with low-concentration substrates and temperatures below 20°C. The primary constraints for MFC application in natural-scale plants are the high initial capital costs, especially for electrode construction and membranes, and the restricted power density that can be achieved [9-11].

A microbial fuel cell (MFC) is a bio-electrochemical device employing bacteria to catalyze the conversion of organic matter into electricity. Bacteria, located at the anode, generate electrons and protons through substrate oxidation. Electrons traverse an external circuit, while protons diffuse through the solution to the cathode, where they, along with electrons, combine with oxygen to form water [2].

Microorganisms can transfer electrons to the anode electrode in three distinct ways: through exogenous mediators (external to the cell) such as Thionine or Neutral red; utilizing mediators produced by the bacteria; or via the direct transfer of electrons from respiratory enzymes (e.g., Cytochromes) to the electrode [12]. These mediators capture electrons from the respiratory chain, becoming reduced to facilitate electron transfer to the electrode via the outer cell membrane [13].

In mediated MFCs, Clostridium butyricum, Saccharomyces cerevisiae, and Proteus vulgaris are known to transfer electrons, while Shewanela putrefaciens, Geobacter sulfurreducens, Geobacter metallireducens, and Rhodoferax ferrireducens have demonstrated electricity generation in mediator-less MFCs. Bacteria in mediator-less MFCs possess electrochemically active redox enzymes on their outer membranes, facilitating the transfer of electrons to external materials without the need for exogenous chemicals to accomplish electron transfer to the electrode [14].

MFCs offer functional as well operational benefits over existing organic matter energy generation technologies. They directly convert substrate energy to electrical energy which allows high conversion efficiency. They operate efficiently at ambient temperature. MFC does not require gas treatment because the off-gases of MFCs are enriched in carbon dioxide and normally have no useful energy content. MFCs do not need energy input for aeration; provided the cathode is passively aerated. They can run on a variety of fuels (substrates) to meet our energy needs and have the potential to be widely used in areas without electricity infrastructure.

Recent advancements enable high conversion rates and efficiencies in the transformation of simple carbohydrates such as glucose, as well as complex carbohydrates like starch and cellulose [15-17]. While microbial fuel cells (MFCs) produce a lower amount of energy compared to hydrogen fuel cells, integrating both electricity production and wastewater treatment could potentially reduce the overall cost of treating primary effluent wastewater.

The operational principle of MFCs relies on the separation of the half reactions involved in oxidation and reduction, constituting a typical redox reaction, allowing them to take place in distinct compartments (Fig 2). In the anodic compartment, exo-electrogenic bacteria catalyze substrate oxidation, releasing electrons from the cellular respiratory chain to a metal electrode (anode). These electrons traverse an external electric circuit towards the cathodic compartment, where they reduce the terminal electron acceptor (TEA), typically oxygen [12]. To maintain electric neutrality, for every electron released at the anode, an H^+ ion must traverse the electrolytic solution saturating the cell to reach the cathode and internally close the circuit. Consequently, electrons and protons react with oxygen at the cathode, resulting in the generation of water vapor. When utilizing a complex wastewater as fuel, a biofilm forms on the anode, along with microbial clumps loosely associated with the electrode. These microbial clumps are thought to ferment the complex fuel into simple fermentation products, subsequently oxidized by electrochemically active microorganisms within the biofilm [18].

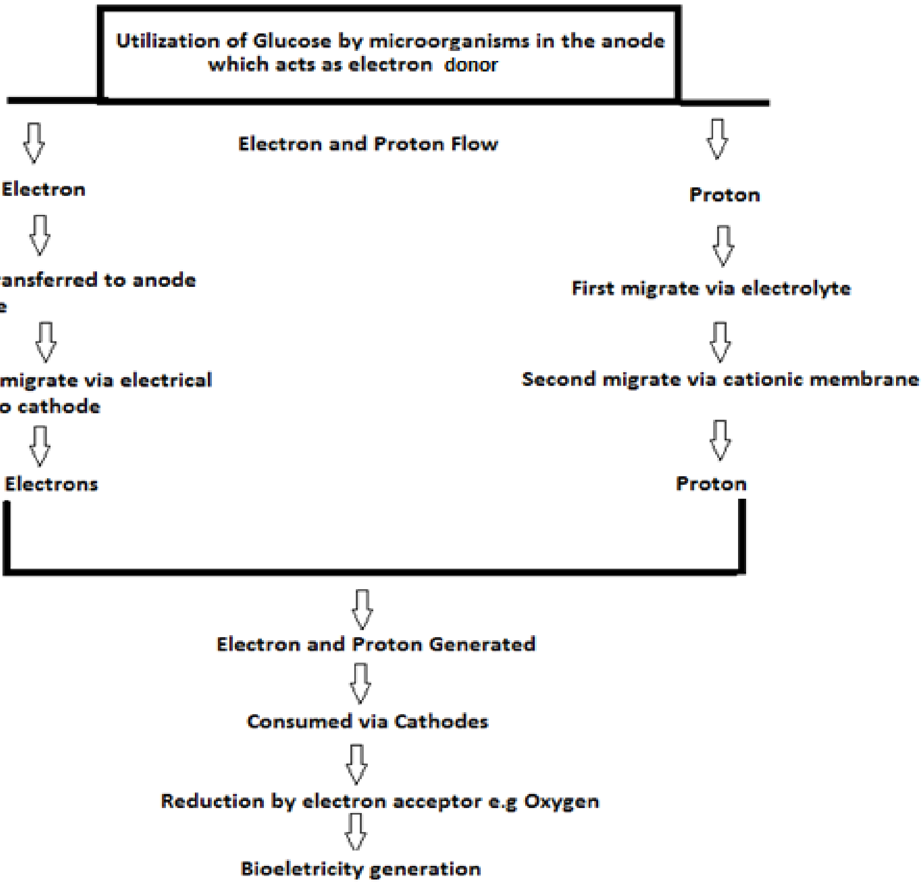

Figure 2. Working Principle of Microbial fuel Cell

The MFC's maximum current output is contingent upon the rate of substrate biodegradation, while the maximum theoretical cell voltage, also known as electromotive force (emf), is determined by the Gibbs free energy of the overall reaction. This voltage can be calculated as the disparity between the standard reduction potentials of the cathodic oxidant (typically oxygen) and the selected anodic substrate. It's essential to note that the cell's emf is a thermodynamic value that doesn't consider internal losses [19]. In practical terms, measured experimental values consistently fall significantly below their theoretical counterparts.

A protonic or cationic exchange membrane (PEM or CEM) divides the anodic and cathodic chambers of a dual-chamber cell, which is the standard design for an MFC. This membrane permits internal ionic fluxes but hinders the mixing of the anodic reducing solution and cathodic oxidant. Despite its functionality, the membrane stands out as a significant cost factor in MFC plants and contributes to increased internal resistance of the cell, representing the sum of all internal voltage losses occurring during current flow in the system [20].

To address this challenge, current research on MFCs is trending towards the adoption of single-chamber, membrane-less microbial fuel cells (SC-ML-MFCs). In these setups, the cathode is directly exposed to the atmosphere, commonly referred to as air-cathode. While dual-chamber MFCs persist in investigations, particularly when the specific objective is to leverage the cathodic reduction half-reaction for nutrient removal from wastewater [21,22].

In the context of SC-MFCs, the cathode emerges as a pivotal element in the overall process. Specifically, the cathode must serve as the interface among three distinct phases: the oxidant gas (atmospheric oxygen), the liquid electrolyte (containing mobile H^+ ions), and the solid conductor (external circuit) facilitating the flow of electrons. Consequently, the cathode is likely to be the limiting electrode for power generation. Numerous studies have explored methods to enhance its electrical performance, while simultaneously avoiding the use of expensive chemical catalysts and/or ionic exchange membranes/resins. The determination of the optimal material for electrode construction and the definition of the most suitable dimensional ratios between electrode surfaces and cell volume remain active areas of investigation [1].

2. MFC DESIGN AND OPERATION

There are fundamental parts of MFCs which are critical in developments. Electrodes, wirings, and salt bridge all have a critical part. Salt bridge is supplanted with Proton exchange membrane in PEM power device [13]. Aside from that MFC can be designed by many ways, but major designs fall under three categories [23-25].

1. Single chambered MFC
2. Double chambered MFC
3. Stacked MFC

Single Chambered MFC

There are many designs of single chambered MFC available and can be made in different ways. Standard Single chambered MFC is shown in the Figure 2. In this design, anode and cathode are not placed in different compartment. They have simple anode compartment where there is no definitive cathode compartment and may not contain proton exchange membranes as shown in Figure 3. Porous cathodes form one side of the wall of the cathode chamber utilizing oxygen from atmosphere and letting protons diffuse through them. They are straightforward anode compartment where there is no complete cathode compartment and may not contain PEM as appeared in Figure 3 [26]. Permeable cathodes structure one side wall of the cathode chamber using oxygen from air and letting protons diffuse through them. They are very easy to build up than the two MFC and in this manner have discovered broad use and research interests recently. The anodes are ordinary carbon terminals yet the cathodes are either permeable carbon cathodes or PEM reinforced with adaptable carbon fabric cathodes [27]. Cathodes are frequently secured with graphite in which electrolytes are poured in unfaltering style which carries on as catholytes and keep the layer and cathode from drying. In this manner water administration or better liquid administration is a critical issue in such single chambered energy components [10].

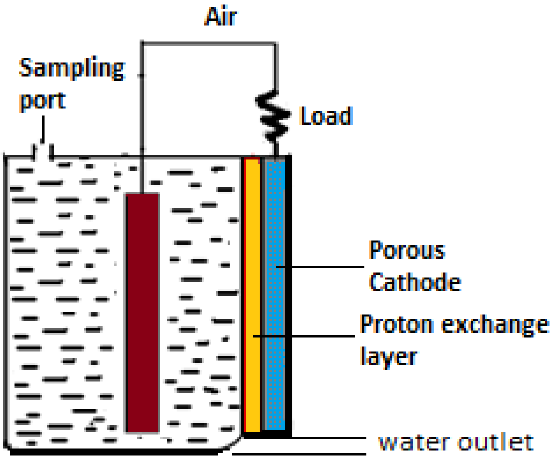

Figure 3. Single chambered MFC

Double Chambered MFC

To design and construct two chambered MFC various types of material can be used like plastic and stainless steel with coating. These two compartments are either separated by proton exchange membrane or salt bridge [28]. H-type of MFC is very commonly used design. The two chambers are called as anode chamber and cathode chamber (Figure 4). Then the electrode can be fixed into each chamber. Material of the electrode can be of carbon or graphite. Carbon brush or carbon clothes can be used as an electrode. Anode and cathode electrode are connected by external wires to complete the electrical circuit [29]. H-shape frameworks are well-intentioned for essential parameter examination, for example, looking at power creation utilizing new materials, or sorts of microbial groups that emerge amid the debasement of particular mixes, however they normally deliver low power densities. The measure of power that is created in these frameworks is influenced by the surface range of the cathode with respect to that of the anode and the surface of the membrane [30]. The power density P delivered by these frameworks is normally inhibited by high interior resistance and cathode-based losses. It is important to examine the differential power produced by these frameworks assuming that the anodes, cathodes, and membrane have equal dimensions. Using ferricyanide as the electron acceptor in cathode chamber, there is substantial increase in the power density of MFC. The primary cause of the increased power densities when using ferricyanide was the higher cathode potentials (500 ± 12 mV) for the ferricyanide MFCs as compared to the air–cathode MFCs (233 ± 5 mV) [31].

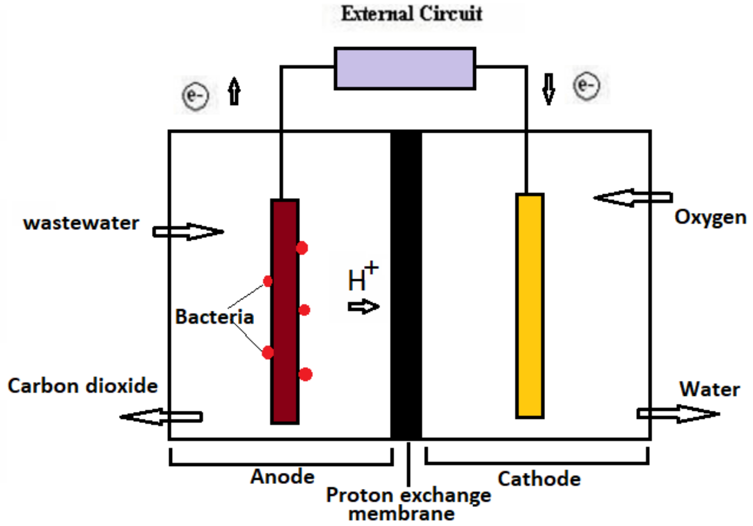

Figure 4. Double chambered MFC

Stacked MFC

These are additional kind of development in which power devices are stacked to form battery of fuel cell. This sort of development doesn't impact every cell's individual coulombic proficiency however in together it expands the yield of by and large battery to be similar to ordinary force sources as appeared in figure 5. These can be either stacked in series or stacked in parallel. Both connections provide power efficiently and can be utilized as a power source for a variety of practical applications [25].

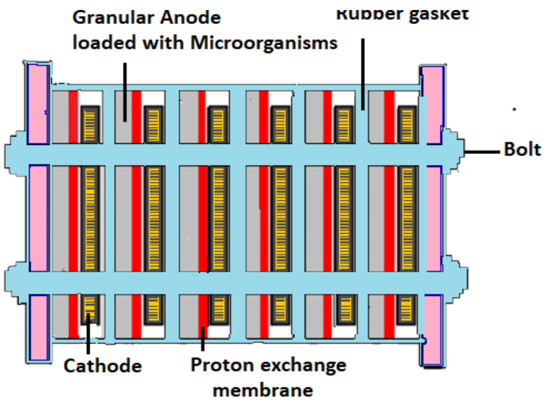

Figure 5: Stacked MFC

3. MFC REACTOR PARAMETERS

In order to compare the bio-electrochemical performances of different MFCs reactor configurations and electrodes, a series of parameters and experimental methods have been proposed. First of all, the mean power (and current) produced by the cell must be normalized by a relevant geometric characteristic of the reactor that could be one of the electrodes' surface area or the volume of anodic chamber (when dealing with SC-MFCs). In this study we have chosen to express current density with respect to cathode surface (the limiting electrode in our process) and power density with respect to the total reactor volume [32].

The polarization curve is also one of the important parameters to analyze the behaviour of a MFC. A MFC polarization curve yields the overall fuel cell performance under specific operating conditions. It shows the dependence of cell's voltage on the electrical current flowing in the circuit and allows to estimate the values of electrode overpotentials and the internal resistance of the cell. It represents the overall measurement of cell's internal voltage losses. From the polarization curve the power curve can be calculated and it describes the power output of the cell as a function of the current. Generally, it has a parabolic shape with a single point of maximum (called Maximum Power Point or MPP), and occurs when the external resistance of the circuit equals internal resistance of the cell [33].

For using MFC's in the wastewater treatment, the substrate conversion rate of a MFC is evaluated in terms of chemical oxygen demand (COD), through the determination of the COD removal efficiency or, better, of its removal rate (thus taking into account the retention time of the substrate in the cell).

Finally, the coulombic efficiency is also an important parameter for the evaluation of MFCs performance and is defined as the ratio of actual transferred electric charge and its maximum value obtainable, if all of the substrate's removal were to produce a current [34]. Substrates play a significant role in the working of MFC as they are source of nourishment and energy to microbes. They are therefore vital to the growth of biofilms. MFCs can use substrates from a variety of wastewater sources, including industrial, pharmaceutical, agricultural, and animal sources in addition to domestic wastewater [8,17,25,35-49]. Detail of substrates used for the generation of electricity described in Table 1. Higher substrate concentrations typically lead to increased availability of electron donors for microbial metabolism. This can result in higher rates of microbial activity and electron transfer within the MFC, potentially leading to higher power outputs. However, there is a limit to how much substrate can be utilized by the microorganisms in the MFC. Beyond a certain concentration, substrate availability may no longer be the limiting factor for power production. Other factors such as mass transfer limitations, pH changes, substrate inhibition, or microbial community dynamics may start to influence the current density.

Table 1. Various substrates and microbes used in MFC

Substrate	Concentration	Microbes	Current density (mA/m^2)
Cellulose [17]	5g/l	Parabacteroides, Proteiniphilum, Catonella and Clostridium	331
1,2-Dichloroethane [35]	99 mg/L	Microbial consortia from acetate enriched MFC	80
Lactose [36]	18mM	Geobacter *sp.,* Anaeromusa *sp.* *and* Pseudomonas *sp.*	50
Landfill leachate [37]	5000 mg/L	Leachate and sludge	151
Sucrose [38]	2674 mg/L	Sucrose waste water	19
Brewery Wastewater [8]	900 mg/L	Anaerobic mixed consortia	10.89
Domestic wastewater [39-40]	400 mg/L	Anaerobic sludge	6
Protein-rich wastewater [41]	1450mg/l	Mesophilic anaerobic sludge	80
Potato Pulp wastewater [42]	10 g/ L	Bacteroidetes*,* Proteobacteria *and* Firmicutes	9
Synthetic sugar industry [43]	20 g COD/day	B. cereus	185
Synthetic waste water [44]	2743 mg/l and 2560 mg/l COD	Anaerobic sludge as a source of microorganisms	61.718
Food-industry wastes [45]	8169 COD mg/ L	Aerobic sludge	25
Composite Vegetable based waste [46]	0.98 kg COD/m3-day	Anaerobic acidogenic mixed consortia	329
Swine wastewater [25]	8320±190 mg/L of soluble chemical oxygen demand (SCOD)	paddy field soil	261
Slaughter house wastewater [47]	900 COD mg/L	Granular anaerobic sludge inoculums	318
Food waste [48]	15 g/L	Anaerobic culture	5.6
Rice straw hydrolysate [49]	0.5–1 g/L	mixed culture of cellulose-degrading bacteria (CDB)	490

4. MICROBES IN FUEL CELL

As the biocatalyst of MFCs, microbes (mostly electroactive bacteria) are indispensable. Up to now, hundreds of microbes have been isolated and used in MFCs. Most of these electroactive bacteria belong to Proteobacteria and Firmicutes. Recent studies showed that the microbes in MFCs had a diverse tendency. Microorganisms that have the characteristics to generate electricity are still waiting to be discovered. In order to further understand the diversity and similarity of microbes, it is necessary to systematically summarize the existing electricity-producing microorganisms. (Table 2)

Table 2. Electricity Producing Microbes

Name of Microbes	Characteristics	Species	Power density
Archaebacteria [50]	survive in extreme environments such as high temperature and salinity which exert tremendous stress to the microorganisms. They have the potential to serve as electricigens in MFCs under special conditions	*Haloferax volcanii and Natrialba magadii,*	the maximum power density and current density reached 11.87/4.57 μW/cm^2 and 49.67/22.03 μA/cm^2 for *H. volcanii* and *N. magadii*, respectively
Acidobacteria [51]	physiologically diverse acidophilic bacteria. They can be found in a variety of environments and are able to utilize a wide range of substrates. Several members of this phylum showed electrochemical activity.	The iron-reducing bacteria *Geothrix fermentans* , *genus Arcobacter*	0.6 mA and the electron recovery was 97%, *Arcobacter*, belonging to acidobacteria, were isolated from an acetate-fed MFC. They accounted for about 90% of the population in the MFC which produced a maximum power density of 296 mW/L
Cyanobacteria [52]	The bioelectrochemical systems based on cyanobacteria are called photosynthetic MFCs (PMFCs), which work with light as the power source and generate electricity through the light-driven oxidation of water.	*Synechocystis PCC-6803, Spirulina platensis,* *Nostoc sp. ATCC 27893,* *Synechococcus elongatus*	72.3 mW/m^2 , 6.5 mW/m^2 , 250 mA/m^2 and 35 mW/m^2
Firmicutes [53]	Firmicutes have thick cell walls and are tolerant to harsh conditions. However, electrons need to pass through the cell wall to the anode and thus firmicutes show relatively lower electrochemical activity	*C. beijerinckii ,* *Thermincola sp. strain JR,* *Methylomusa anaerophila*	79.2 mW/m^2 , 0.42 mA
α-Proteobacteria [54]	phototrophic bacteria, good biocatalysts	*Rhodospirillum rubrum ,* *R. sphaeroides* *Rhodopseudomonas*	790 mW/m^2 2720 mW/m^2
β-proteobacteria [55]	facultative anaerobe that can transfer electron to Fe^{3+}	*Rhodoferax ferrireducens*	31 mA/m^2 ,efficiency reached 81%
γ-Proteobacteria [56]	a well-characterized model microorganism and has many advantages e.g., clear genetic background, convenience to be genetically modified and rapid growth property with low nutrients requirements	*E. coli*	1304 mW/m^2
δ-Proteobacteria [57]	ability to reduce Fe^{3+} using a variety of organic compounds as electron donors	*Geobacter metallireducens and Geobacter sulfurreducens*	1143 mA/m^2
Yeast [58]	Excellent electrochemical activity was constructed by displaying glucose oxidase on its cell surface	*S. cerevisiae*	300 mA/cm^2 and 70 mW/cm^2
Eukaryotic algae [59]	used as both electron donors in the anode and acceptors in the cathode	*Chlamydomonas reinhardtii and Chlorella sp.*	12.95 mW/m^{2,} 300 mA/cm^2

5. IMPACT OF ANODE MATERIALS IN MFCS

Anode materials must be corrosion-resistant, have a high specific surface area and electrical conductivity, and have a low electrical resistance and a low cost. The anode must also be made of a chemically stable material that can operate in an environment where highly diverse organic and inorganic constituents are present, which can react with some anode materials and reduce MFCs performance [60,61]. Carbon-based electrodes, metal electrodes made up of silver, SS, aluminum, nickel, molybdenum, titanium, gold, and copper have high porosity, electrical conductivity, and a specific surface area [62-66]. For increasing the performance of MFCs, the modification of anode electrode could be useful. Several researchers have started to modify anode using different nanoengineering techniques that are able to make the electron transfer easier [67-70]. Moreover, the heterogeneous fabrication methods and modification manners involving nanomaterials have been tried for enhancing the power density and enlarging the capability of electron accepting. Carbon microfiber (CMF) paper and carbon nanofiber (CNF) mats have been tested as anode materials in MFC. The use of thinner carbon materials for CNF electrodes resulted in a larger specific surface area and a better morphology of the electrode surface, which promoted adhesion of bacteria and formation of a dense and stable biofilm, increasing energy production. Sanchez et al [71] illustrated that compared to CMF, CNF showed a 10-fold increase in current.

6. IMPACT OF CATHODES IN MFCS

Cathodes are crucial for assessing microbial fuel cell (MFC) performance, particularly with regard to power density and cost. For MFCs, a range of cathode types-including air-cathode, aqueous-cathode, and bio-cathode are employed, both with and without catalysts. Because cathode material has a greater oxidation reduction reaction (ORR), it greatly enhances both the power density and electrochemical performance [72].

The air-cathode is directly exposed to air, allowing abundant oxygen availability. It also contains a layer of catalyst and supporting materials. This type of cathode does not require any aeration and can achieve higher power density [73]. On the other hand, aqueous air-cathodes are submerged in the electrolyte containing dissolved oxygen, which acts as the electron acceptor. The performance of this type of cathode is limited by the solubility of oxygen in the electrolyte [74]. For air-cathodes and aqueous air-cathodes, many materials have been used to achieve more efficient performance, including graphite and activated carbon. Biocathodes utilize aerobic bacteria, which can biochemically catalyze ORR improving MFC performance. Biocathodes have the potential to outperform abiotic cathode catalysts in terms of performance. Because of its cheaper cost, longer lifespan, and resistance against catalyst poisoning, the biocathode is a better option than traditional catalysts [75,76]. In order for the bacteria to develop a biofilm and construct a biocathode, support is necessary. Stainless steel is frequently used in the production of biocathodes. For the creation of biocathodes, carbon-based materials are also employed, such as graphite felt, activated carbon, granular graphite, etc. By increasing the surface area available for biofilm production, biocathodes can function more efficiently [72].

7. IMPACT OF MEMBRANES IN MFCS

The materials that physically separate the anodic and cathodic chambers are called membranes. Membranes aid in chemical and ionic conjugation, permit proton transfer, and halt oxygen diffusion. A membrane contributes to the long-term efficiency of MFCs as they inhibit diffusion of oxygen and substrate and increases coulombic efficiency. An MFC membrane should have characteristics including internal resistance, selectivity, mechanical and chemical stability, and fouling resistance in addition to being less expensive [77]. A variety of membrane types are employed, including cation exchange membranes (CEMs), anion exchange membranes (AEMs), bipolar membranes and porous membranes. CEMs offers high proton conductivity and low internal resistance. However, biofouling results in reduction in ionic conductivity. AEMs produce a larger current than that of CEMs in MFCs. The hydroxyl ion absorbs the protons produced. This keeps the anode chamber's atmosphere from becoming acidic. Consequently, there is an increase in ion transport at the anode and a decrease in resistance at the cathode. They also undergo biofouling. A bipolar membrane containing both an AEM and CEM offers effective transport of both H^+ and OH^- ion over the membranes' water-splitting interface. But the main problem with using these membranes is that they are highly polarized, which increases internal resistance [78,79]].

Porous membranes are the membranes where separation occurs on the basis of pore size. Glass wools, microfiltration membranes, and ultrafiltration membranes are a few typical examples. The sole benefit of a porous membrane is that it has less internal resistance, but it fades out quickly because of biofouling [80].

8. COMMERCIALIZATION OF MFC

Commercialization of any technology decides success and execution of technology when it is marketed in massive amounts and utilized by a large number of people. Since MFC involves electricity production by employing waste materials, its commercialization on large scale will offer numerous advantages described in Fig 6.

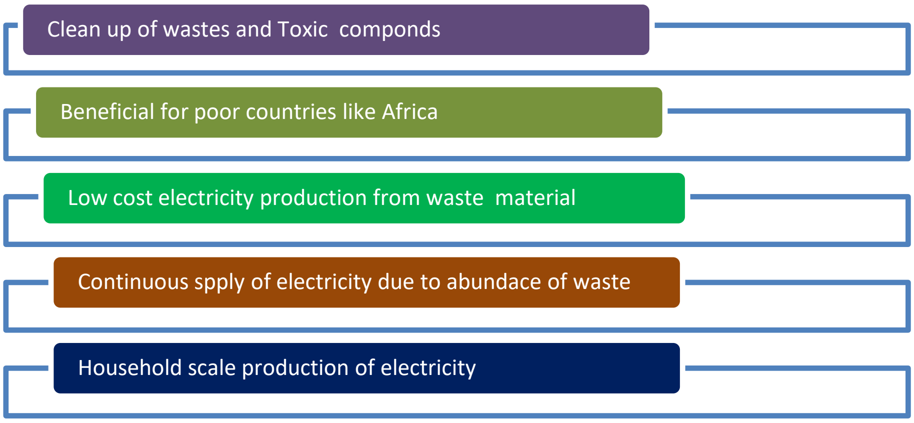

Figure 6. Advantages of MFC

The productivity of MFC depends upon a following parameters which play an important role in its performance [2] as mentioned in Fig. 7.

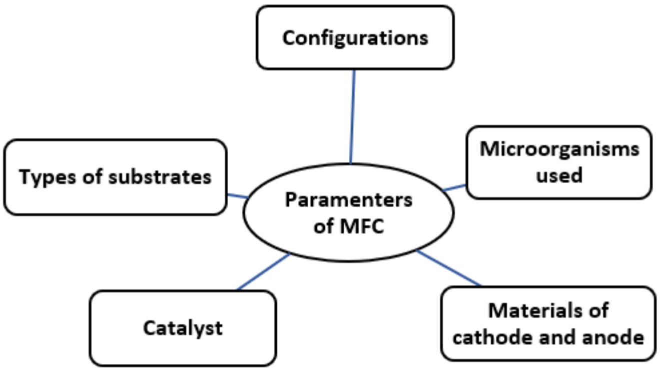

Figure 7. Parameters of MFC

There are numerous reports about MFC scaling up accessible. The results of these investigations have demonstrated that a significant barrier to the commercialization of MFCs is the decreased power output that results from scaling up. These investigations have demonstrated that the distance between the electrodes is the factor influencing power output in MFC when scaling up. The distance between electrodes is not raised to the same extent during scaling up because doing so will make the MFC bulkier. This is the reason why power output is decreased. The membranes used in MFC are usually costly. Another important factor is the substrate; in laboratory conditions, when MFC operating on pure substrates the power output is very high, however, MFCs operating on waste materials have significantly lower power outputs. This is because microbes are not able to break down waste materials as effectively as pure substrates. The price of electrodes is another barrier to its scaling up. It needs to be fairly low. But in actuality, the electrodes are highly expensive because they are not manufactured industrially and because the substance used to make them is expensive. These are the main things preventing this technology from becoming commercially viable [81].

9. MAJOR CHALLENGES

MFC is a technology that may effectively produce electricity from various organic substrates. However, there are certain disadvantages that have prevented it from becoming more useful for real-world applications. Low power density is the main disadvantage of MFC technology, but it may be overcome in two ways: either isolate strong microorganisms capable of effectively transferring electrons to anode, or create modified strains using genetic engineering that exhibit higher electron transfer rates. Numerous research have proven that bacterial consortiums with increased electron transfer rates to the anode surpass pure cultures. It has been demonstrated that a wide variety of bacterial strains can generate mediators that effectively transfer electrons to the anode. The performance of MFC technology can potentially be improved by finding novel mediators. The small surface area of the electrodes on which microorganisms cling is an additional drawback of MFC. Comprehensive study has been done to find strategies that improve MFC reactor performance, leading to the development of more effective laboratory-scale MFC designs. Among these technologies is the application of air cathodes, stacked reactors and cloth electrode assemblies [25,29,82]. Amongst them, employing air cathodes is particularly successful since it facilitates the effective utilization of airborne oxygen and eliminates the need for chemical catalysts like ferricyanide, which need to be replenished, or aerate water. Air cathodes have been made more efficient for use in MFCs, and several reactor designs have been used to assess how shape and location affect MFC performance [10, 69]. These efforts have resulted in highly efficient small-volume laboratory MFCs (~20 ml in anode volume) that produced electrical outputs of over 1000 Wm^3.

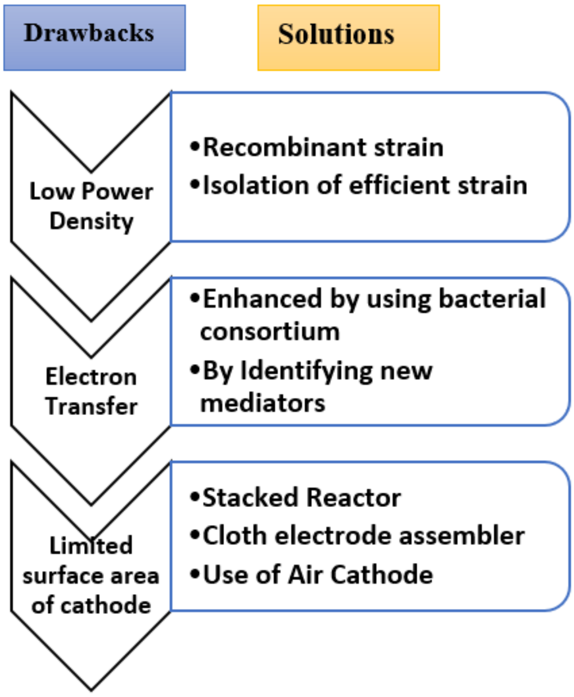

Figure 8. Drawbacks and solutions to improve efficiency of MFC

Building large-scale MFCs with consistent performance and high power production is still a problem for MFC researchers [83]. The large-scale uses of MFCs and their overall performance enhancement will aid in the treatment of wastewater, which is a substantial resource (Fig.8).

10. FUTURE PROSPECTS

The integration of MFC with additional processes is necessary to make this technology economically viable. First off, MFC can be applied to the treatment of wastewater. Utilizing MFC in wastewater treatment could be a promising substitute to lower the expense associated with present systems. The electricity needed by the wastewater treatment bioreactors would be decreased by the power produced by MFCs. Secondly, MFC can be used to produce valuable products (hydrogen, methane, ethanol, organic acids). Thirdly, MFC-based biosensors are suitable for real-time monitoring of environmental parameters. And lastly, bioremediation is the most promising application of MFCs. MFCs have been proposed for the clean-up of various types of contamination, ranging from aromatic and other organic compounds to heavy metals. However, there is not yet any useful utilization of MFCs because of the restrictions of their energy yields [81].

11. CONCLUSIONS

MFC is an innovative as well as productive technology for harnessing power from degradation of waste by microorganisms. This process has been used to effectively produce bio-electricity from a variety of industrial and domestic wastes, including those from agro-wastes, breweries, paper mills, dairy, sugar processing, and distilleries.

In this study, we have investigated to manage significant toxic substances from Industries, like lignin, agro-wastes, phenols, melanoidin and sewage for electricity generation. Some of them are harmful to the environment and cause damage to life because of decrease in dissolved oxygen. Moreover, it has altered the waste into harmless or less harmful metabolites, which demonstrates its significance in remediation of harmful materials and manageable energy creation. In order to simplify and develop large-scale MFC systems that are both cost-effective and increase electricity production, a deeper focus on the understanding of MFC technology's constituent parts, microbial processes, factors of limitation, and construction designs is imperative.

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IZVOD

MIKROBNA GORIVNA ĆELIJA KAO INOVATIVNI PRISTUP ZA PROIZVODNJU BIO-ELEKTRIČNE ENERGIJE: PREGLED

Trenutni globalni scenario je obeležen značajnim energetskim potrebama u kombinaciji sa ograničenim resursima, što dovodi do široko rasprostranjene energetske krize. Neobnovljivi izvori energije se brzo iscrpljuju, dok obnovljivi izvori ostaju nedovoljno iskorišćeni. Postoji hitna potreba za alternativnim metodama proizvodnje energije. U poslednje vreme, značajna pažnja je usmerena na mikrobne gorivne ćelije (MFC) zbog njihovih povoljnih uslova rada i dostupnosti raznih ekološki prihvatljivih supstrata kao goriva. Kroz aktivno razlaganje supstrata od strane mikroorganizama, proizvodi se bioelektrična energija, nudeći održivo rešenje za rastuće energetske izazove. Opsežna istraživanja su dovela do novih uvida u mikrobne gorivne ćelije (MFC), otkrivajući da se širok spektar izvora ugljenika, uključujući različite vrste otpada, može efikasno iskoristiti sa širokim spektrom mikroba. Shodno tome, mikrobna konverzija otpada kroz inovativne tehnike bioremedijacije kao što je korišćenje MFC-a predstavlja potencijalno atraktivnu alternativu konvencionalnim procesima tretmana u tretmanu otpadnih voda, olakšavajući direktnu proizvodnju električne energije. Ovo ne samo da je u skladu sa preovlađujućim tehnološkim trendovima, već takođe doprinosi smanjenju troškova u celokupnom procesu. Ovaj članak sveobuhvatno ispituje različite komponente mikrobnih gorivih ćelija (MFC), uključujući anodu, katodu i membranu. Za rešavanje praktičnih izazova u ovoj oblasti predlažu se pragmatična rešenja. Pregled kritički procenjuje različite kategorije otpada pogodnog za proizvodnju bioenergije, istražujući povezane mikroorganizme, izlaznu snagu, ključne prednosti, izazove i ograničenja i napredak tehnologije MFC.

Ključne reči: *Goriva ćelija, bioelektrična energija, mikroorganizmi, otpadne vode*

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