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A Review on Microbial Fuel Cell-Photobioreactor (MFC-PBR) Systems: Wastewater Treatment, Bioenergy Recovery, and CO_2 Sequestration

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ABSTRACT

A variety of technologies, including chemical, physical, and biological processes, have been employed for wastewater treatment. However, these conventional methods face several limitations: high energy consumption, excess sludge production, chemical dependency (as seen in coagulation and flocculation), membrane fouling, and inefficiency in harnessing the energy stored in wastewater. The drawbacks of these technologies not only raise operational costs but also exacerbate environmental concerns. Therefore, the need for more efficient and sustainable treatment methods is urgent. The Microbial Fuel Cell Photobioreactor (MFC-PBR) is an integrated system combining algae cultivation and microbial fuel cells for wastewater treatment. It generates algal biomass and produces energy by oxidizing organic substances in the anodic chamber. The CO_2 released is absorbed by microalgae, which converts it into biomass and oxygen for cathodic reduction. The success of this method depends on factors like reactor configuration, electrode material, membrane type, electrode surface area, and external resistance. However, MFC-PBR has a low energy output, necessitating optimization strategies to enhance feasibility for large-scale applications. This review highlights recent advances, challenges, and perspectives in improving energy recovery, wastewater treatment performance, CO_2 sequestration, and algal biomass production. This review also examines the opportunities and challenges in MFC-PBR development.

1. INTRODUCTION

Water demand has surged due to urbanization, population growth, and pollution [1]. In several developing nations, there is now an imbalance between the demand for freshwater and its available supply. Water scarcity significantly affects a population exceeding one billion people and poses a risk to the ecological balance of numerous global ecosystems [2]. The United Nations reports that approximately one-third of the global population lives in areas facing water scarcity, a number that could double by 2025. Safe and clean drinking water is a crucial necessity for human existence on Earth. Despite the abundance of water as a natural resource, nearly 97% of the Earth's water requires additional treatment before it can be safely consumed. Furthermore, out of the remaining 3% of freshwater, only 1% is readily accessible for practical use [3].

Traditional water treatment is essential for providing clean and safe water, but it has limitations. These limitations include high energy costs, such as in the aeration of activated sludge using air or oxygen. Membrane filtration requires energy to pump water through membranes, overcoming resistance and preventing clogging. Additionally, chemical usage in processes such as disinfection, flocculation, and coagulation increases operational costs. Furthermore, excess sludge generation in biological processes requires additional treatment. As global demand for clean water rises, so does the energy footprint of these operations, leading to increased greenhouse gas emissions and higher operational costs. MFC-PBR provides feasible solutions by combining energy recovery and wastewater treatment. Compared with conventional water treatment, MFC-PBR requires less external energy by utilizing generated bioelectricity, minimizes sludge formation through direct electron transfer by microbes, reduces membrane fouling as bioelectricity mitigates biofouling, and operates with fewer chemical inputs. This technology reduces the total energy required for water treatment sustainably by generating electricity or biogas while simultaneously treating wastewater.

2. MFCS WORKING PRINCIPLE

The chemical power stored in organic materials is converted into energy by electroactive microorganisms in microbial fuel cells, which is a form of bioelectrochemical field. Integrating microbial metabolic and electrochemical techniques and a variety of substrates enhances the performance of MFCs to instantly convert chemical power into energy [4]. MFCs can produce renewable energy, as well, as bioremediation of natural contaminants and toxins, which is one of MFCs' many advantages. In addition to being environmentally friendly, it is an inexhaustible source of energy, and the electrochemical parameters in MFC can be easily controlled and monitored [5]. Currently, MFC generation is the major subject of extensive research and development. The proper advancement in this technology results in an effective decomposition of hazardous contaminants and the production of clean energy [6]. The MFC includes two chambers separated by a proton exchange membrane (PEM). The anode chamber contains microorganisms as exoelectrogens, which operate as biocatalysts, and anolytes under anaerobic conditions, while the cathode chamber works as an electron accepter under aerobic conditions. Electrons are generated at the anode and transported to the cathode via an electricity connection. Water is formed when electrons react with protons and oxygen [7].

At the cathode, protons are simultaneously transported internally via the membrane to form water molecules. A potential difference between the anode and cathode arises due to the difference in solution concentrations. The electron moving through the external circuit generates electricity. The variety of protons and electrons produced in the anode chamber depends on the organic substances used by microorganisms, as explained by the following mechanisms:

If the substrate used is acetate the oxidation reaction:

$$CH_3COO^- + 2H_2O \xrightarrow{microbes} 2CO_2 + 7H^+ + 8e^- \quad (1)$$

Reduction reaction:

$$O_2 + 4e^- + 4H^+ \longrightarrow 2H_2O \quad (2)$$

When glucose is employed as the sole substrate for metabolism, the reaction of oxygenation occurs at the anode.

$$C_6H_{12}O_6 + 6H_2O \longrightarrow 6CO_2 + 24H^+ + 24e^- \quad (3)$$

The reduction reaction at the cathode is:

$$24H^+ + 24e^- + 6O_2 \longrightarrow 12H_2O \quad (4)$$

The overall reaction is [6]:

$$C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2 + 6\ H_2O + \text{electricity} + \text{biomass} \quad (5)$$

Electron transfer mechanisms can be broadly classified into two: direct electron transfer and indirect electron transfer [8]. Direct electron transfer (DET) mechanisms proposed that electrons can directly be transferred from the microbes to the electrode surface cytochrome (C-type) via the outer microbial membrane or by utilizing conductive nanowires as shown in Figure 1, proved in certain strains belonging to *Shewanella* and *Geobacter*. Indirect electron transfer occurs through outer or inner mediators. The process implies the macrocycles or molecules that assist in the transfer of the electrons of the microorganism to the anode. Either it can be created by the bacteria themselves (internally) or added externally (outside) to expedite electron transfer at the anode. Mediators, whether inside or outside, will be responsible for transporting the electron from the mass of bacteria toward the substrate of the anode. The mediated electron transfer shows more electron transfer compared with DET [9].

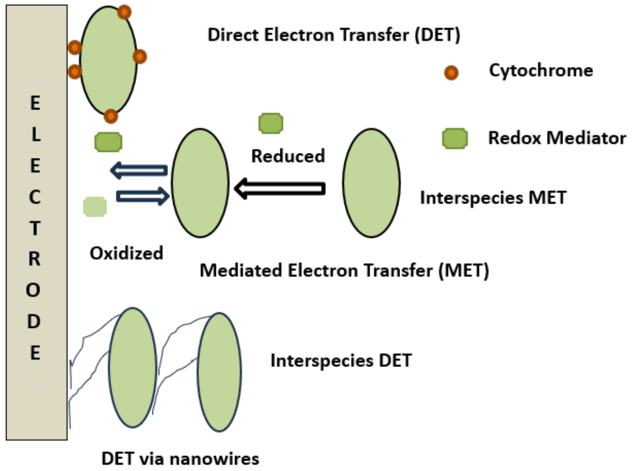


Figure 1. Different electron transfer mechanisms to the anode surface

3. MFC-PBR SYSTEM

The process by which photosynthesis occurs mimics the lagoon process, which is naturally a method of treatment. It involves a synergetic relationship between microorganisms and algae, where algae produce oxygen in the presence of light and nutrients generated by the decomposition of organic matter by microorganisms. This interrelationship enables the replacement of conventional aeration systems with sustainable photosynthetic ones. Electricity will be generated through cathodic algae support in MFC-PBR, with oxygen produced through photosynthesis. On the other hand, the system applies an algal biocathode that serves as both a biological electron acceptor and CO_2-to-biomass converter, as well as a substrate that is oxidized at the anode. Conventional MFCs involve electrons in separate reduction-oxidation reactions at the cathode and anode, where the chemical energy in organic matter converts to electrical power, basically through microbial-electro-chemical catalysis. One of the major drawbacks of MFCs, in comparison to the benefits, is the fact that carbon dioxide has evolved as one of the byproducts due to the oxidation of organic materials in an anodic chamber, which ultimately leads to more environmental issues. Hence, microbial carbon-capture cells, or MFC-PBR, also known as a light-driven microbe-based electrochemical system, have been considered a promising apparatus for carbon capture, storage, and utilization [10].

MFC-PBR integrates algal cultivation systems with MFCs for wastewater treatment, producing energy alongside the treatment process, similar to the MFC principle. When the organic substances in the anodic chamber oxidize, CO_2 is released. This gas is subsequently absorbed by the microalgae, which convert it into biomass through the photosynthesis process, producing O_2 and used as a biofuel. In the MFC-PBR system, Algae are used to supply oxygen at the cathodic reduction.

Furthermore, the performance of MFC-PBR is influenced by several factors. Among them are reactor configuration, electrode material, membrane type, electrode surface area, and external resistance. Additionally, it has been proven that electrode properties affecting electricity generation, and subsequently pollutant degradation, such as promoting bacterial adhesion, substrate oxidation, and electron transfer from bacteria to the electrode surface, play a significant role

[11]. Hence, the review highlights recent advances, challenges, and perspectives for improving energy recovery, wastewater treatment performance, CO_2 sequestration, and algal biomass production of the MFC-PBR system. A schematic diagram of the MFC-PBR is shown in Figure 2.

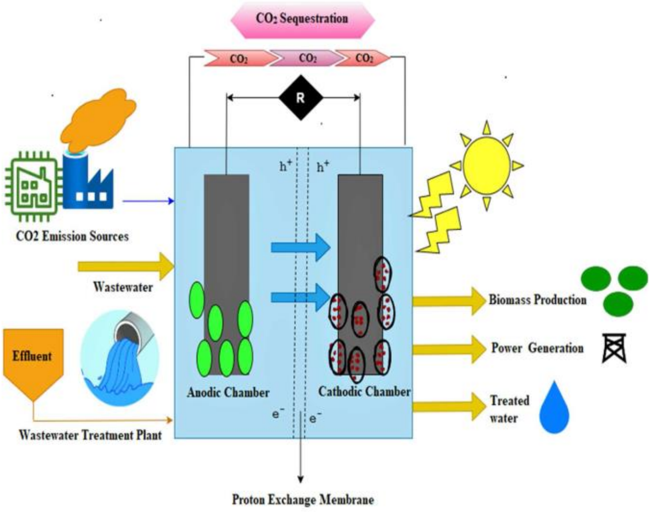


Figure 2. Diagram scheme of the MFC-PBR [12]

4. CONFIGURATION OF THE MFC-PBR

MFC-PBR integrates microbial fuel cell principles with carbon capture to generate electricity while treating wastewater and sequestering CO_2. There are two main configuration types.

4.1 Single chamber of MFC-PBR

In a single-chamber MFC-PBR, both microbes and algae are cultivated within one (membrane-free) chamber, where small algae create a biofilm on the anode's surface, while the cathode is generally an air cathode [12]. Microalgae utilize carbon dioxide produced by both autotrophic and heterotrophic organisms during photosynthesis. This system encourages the synergistic development of co-cultures of microbes and tiny algae [13]. The single-chamber MFC-PBR offers several benefits, including reduced internal resistance, improved proton transfer, lower costs, enhanced oxygen reduction rates at the cathode, user-friendliness, and effective aeration, making it suitable for varying conditions. However, the scale-up of this technique faces several issues, such as vaporization and rapid oxygen dispersion [14]. The suggested design shows better microalgae adhesion on the electrode surface, compared with, conventional MFC, which might serve as a photosynthetic biocatalyst for energy production, as shown in Figure 3(a).

4.2 Double chamber of MFC-PBR

It works as a "proton exchange membrane" between the two compartments as shown in Figure 3(b). MFC with anaerobic biofilms located at the anode compartment could result in electricity while phototrophic biofilm located at the cathodic end produced oxygen due to the oxidoreduction reaction with green algae biomass production [15]. Dual-chamber systems are better than single chambers because the cathode can be easily optimized by changing the pH, flow rate, and addition of pure oxygen, and electron mediators into the cathode for better MFC-PBR performance [16]. The comparison between single and double chambers is illustrated in Table 1.

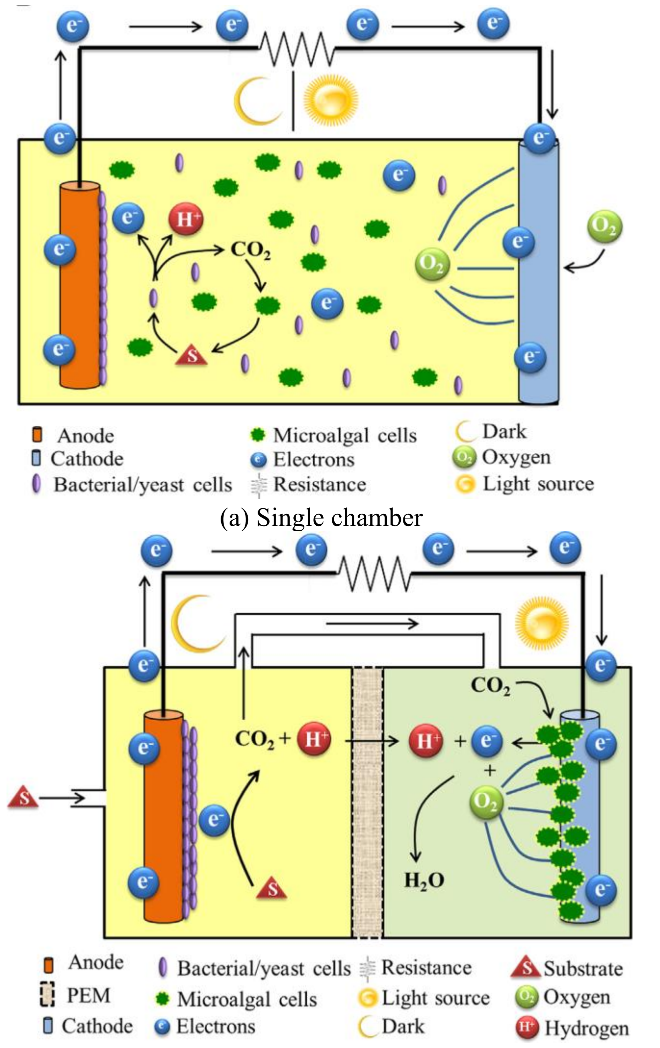


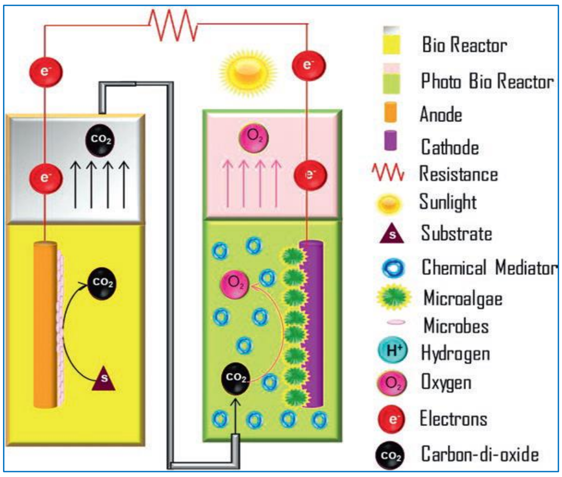
Figure 3. Single and double chambers MFC-PBR [14]

Table 1. Advantages and disadvantages of the two systems of single and double chambers MFC-PBR

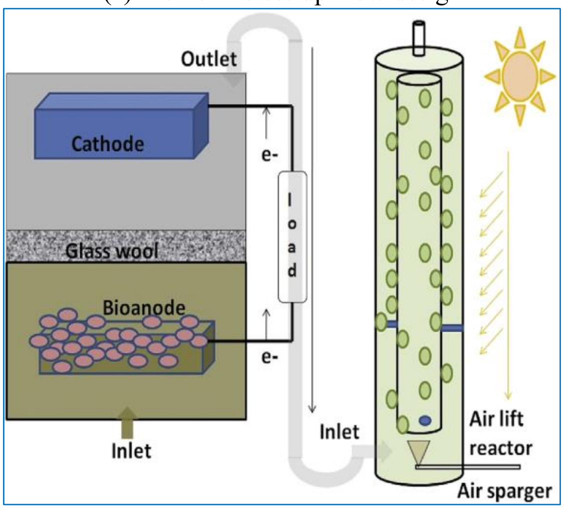
System	Advantages	Disadvantages
Single-chamber	-Scale-up is easier and cheaper due to the simple design. -Internal resistance is lower as there is no membrane presence. -No aeration pump is required in the air cathode.	- Power output is lower due to the possibility of oxygen diffusion to the anode chamber. - Microbial growth conditions are less controlled. -Not suitable and lower efficiency for specific applications such as high salinity wastewater.
Double-chamber	- Separated electrodes lead to higher power output. -More stable in operation and optimization of microbial growth. - More suitable for laboratory studies and scale-up.	- Internal resistance is higher. -Fouling on the membrane reduces the efficiency. - Scaling up is more costly and complex.

4.3 Coupled MFC-PBR system

A coupled MFC-PBR is an integrated system featuring a bioanode chamber MFC that directly pumps carbon dioxide into a connected photobioreactor, as shown in Figure 4(a). This MFC operates without an ion exchange membrane, making it cost-effective and structurally simple. In contrast, an MFC using two electrodes separated by a cation exchange membrane (CEM) is linked to an illuminated photobioreactor, where the air is supplied via a sparger to cultivate algae as shown in Figure 4(b). Under light, the algae perform photosynthesis, resulting in the conversion of energy and the generation of biomass composed of electrochemically active microorganisms in the anode compartment, which in turn produces electricity [17].



(a) Membraneless up-flow design



(b) Up-flow design with the membrane

Figure 4. Coupled MFC-PBR

A coupled microbial fuel cell (MFC) consisted of a photosynthetic cathode using *Chlorella vulgaris* and a yeast-based fermentative anode. The cathode was designed to generate power while metabolizing carbon dioxide emissions from bioethanol plants. In contrast, the anode was illuminated by sunlight and aerated with a feed containing 10% CO_2, enabling electron transfer between the electrode and the yeast.

An MFC integrated with a PBR allows continuous feeding of effluent to the PBR as nutrients for microalgae (Figure 4(b)). Under continuous illumination and nutrition, the rate of algal growth increases tremendously. The lab scale rig was built by combining two plastic cylinders, which were separated by glass beads and wool fibers. Fiber brushes were used as anode and cathode electrodes. An external column, which is an airlift reactor linked with the cathode chamber of up-flow MFC, receives continuous feeding from the effluent and aeration via a sparger located in the middle of the riser. The availability of continuous illumination, nutrients, and air with CO_2 gas supports microalgae growth [18]. The PBR-MFC was fabricated for water treatment and power generation [19, 20].

5. PARAMETERS EFFECT ON THE MFC-PBR PERFORMANCE

Several physical, chemical, and biological parameters limit the MFC-PBR performance. Here, some of the most important parameters are listed and explained.

5.1 Physical parameters

5.1.1 Temperature

In MFC-PBR, the thermodynamics, kinetics, composition, and microbial distributions in the system are affected by temperature variations. Power density and Coulombic efficiency increased with an increase in the temperature of the electrolyte mainly due to improved membrane permeability that reduced Ohmic resistance as well as microbial metabolism resulting from higher liquid solution conductivity [21]. A study in this area proved that the fuel cell could effectively adjust itself to day-night temperature variations. Meanwhile, power generation and nutrient removal increased in algae-cathode MFC when operated at moderate temperatures, and no visible effect was observed between 19℃ and 35℃ [22].

5.1.2 Light

Recent advancements in lighting have led to the appearance of various sources, such as LEDs and textured optical filaments, combined with suitable lenses and wavelengths to create parallel light beams. Light conditions directly affect performance in terms of the release of oxygen into the MFC by the metabolism of the microalgae. Thus, optimal intensity, wavelength, and light/dark cycle are necessary. Optimal intensity and duration of the light are very important to prevent inhibition of growth and photo-oxidation. Increasing light intensity above this level generally improves electricity production; however, where there is too much light, performance decreases, which is mostly reflected in a reduced voltage and peak power output. The production of electricity will be significantly improved with the increase in illumination intensity to facilitate DO formation. There has been some recent progress when using light via different illumination sources, such as LEDs and texturized optic filaments with specific lenses and wavelengths to make the light beam parallel.

In the MFC-PBR, the influence of light intensity on the *Desmodesmus sp. A8* species was assessed as a cathodic microorganism. It was observed that with the increase in light intensity, more electricity and dissolved oxygen were produced [23]. Another research work investigated the impact of light intensity on bioelectricity alongside pigment production in MFC-PBR. It gave the enhancement of current density about six times in response to enhanced illumination, from 26 to 96 μE m^{-2} s^{-1} [24].

5.1.3 Electrodes

The efficiency of MFC-PBR is limited by the nature of electrodes. The electrode characteristics are high conductivity, low resistance, anti-corrosive, large surface area, low fabrication cost, strong biocompatibility, mechanical durability, etc. These restrict its feasibility as a good electrode in anodic or cathodic chambers. Several types of electrodes are currently used, either porous ceramics or modified carbon such as activated carbon, carbon black, graphite, carbon felt, and carbon brush. It sometimes contains some material additives to facilitate electron transport and improve the active sites for redox reactions, such as N doping, -COOH grafting, and acetate pre-treatment [25].

The surface roughness and porosity of the electrode limit even the uniform distribution or formation of the biofilm. A completely smooth electrode hinders the formation of biofilm and hence reduces the electron transfer. On the other hand, mass transfer limitations occur if the highly porous electrode is used, despite it helping to prevent biofilm detachment [26]. Different electrode modifications were studied by Wang et al. using MFC. In this published study, sulfonated cobalt phthalocyanine (SCP) was used as a mediator to oxidize wastewater. The result showed that the power generation of 32.2 mW/m^2 using SCP modification on pre-treated carbon cloth is approximately 6.1 times higher than the plain pre-treated electrode [27]. However, using different electrode modifications and configurations in MFC-PBR and measuring the energy generation and performance is still a good potential area of research.

5.2 Chemicals parameters

5.2.1 Substrate characteristics and loading

Different sources of wastewater have already been investigated to use as ingredients in MFC-PBR. The most important limitations for choosing one are the nature and biodegradability of a substrate. The carbon content in wastewater is crucial for energy generation. Low carbon content can easily be used by microorganisms and enhance system performance. In contrast, wastewater with high carbon content makes it difficult for the microbes to degrade it into smaller compounds and hence reduces the efficiency. Therefore, substrates of MFCs vary based on their type and nature, and that reflects on operational performance. The effect of substrate type and characteristics on MFC performance is significant [28]. Retention time and loading rates influence the electricity production and Coulombic efficiency of MFC-PBR by affecting bacterial growth and biofilm morphology [29]. Electrons can be produced by microorganisms from simple molecule substrates, hence an improvement in the system's functionality. Conversely, some wastewater comprises high levels of organic pollutants that are difficult to degrade into simple molecules. Therefore, the choice of a substrate based on its type and nature is important to reach the maximization of MFC system efficiency [19]. Another study examined how increasing the substrate loading rate from 1.9 to 3.8 g L^{-1} d^{-1} raised electricity generation from 1884 to 2981 mW/m^3 [30].

5.2.2 pH value

In MFC-PBR, the efficiency of electrochemical reactions and microbial activity is influenced by pH values. Microorganisms in the anode chamber thrive at a near-neutral pH and low ion concentration, and similar optimal pH conditions are necessary in the cathode compartment [31]. Unstable levels of oxygen, protons, and electrons can disrupt the system's pH, impacting power generation, ammonium loss, organic matter removal, and cell physiology. Maximum power generation of 0.66 W/m^3 occurred at pH 9.5; extreme pH levels could harm microbial metabolism and reduce efficiency, halting electricity production [32]. The chemical and physical conditions in MFC-PBR can impact the thermodynamics and kinetics of electrocatalytic oxygen reduction, while alkaline pH also affects reactions at both the cathode and anode in single-chamber MFC-PBR. Proton generation during photosynthesis in MFCs acidifies the anode compartment. This proton accumulation creates pH gradient resistance, contributing to a decrease in pH gradient potential over time, which lowers both current density and electrode potential [33].

5.3 Biological parameters

5.3.1 Type of algal species

The performance of MFC-PBR varies among different algal species, as their photosynthetic rates and times of cell duplication are distinct. Results have proven that Chlorella is much better than Anabaena in capturing CO_2 and producing oxygen photosynthetically to help cathodic reduction. Due to high CO_2 levels, resistance to urban effluent, and good fatty acid composition, *Chlorella sp*. will be preferred for use in biocathodes. On the other hand, microalgae in microbial carbon capture cells produce biodiesel and uptake anodic gas into the cathodic compartment. Thus, it remains critical to identify algae species capable of synthesizing at a pace quick enough to uptake CO_2 and also deliver lipids offering the appropriate unsaturated fats required for the production process of biodiesel [34].

5.4 Material component

5.4.1 Electrode materials

The requirements for the electrodes are inexpensive, highly conductive, long-lasting, stable in response, and compatible with biological systems. The most common materials fulfilling these general requirements are based on non-corrosive metals (e.g., stainless steel and titanium) and carbon materials (e.g., carbon paper, carbon cloth, and graphite sheets).

Anode materials

The necessary anode electrode material requires specific properties for optimizing the performance of microorganism-surface interactions and anode interfaces [35]. Therefore, anode material should possess certain characteristics, for instance, excellent electrical conductivity, corrosion resistance [36], high mechanical strength, surface area, and biocompatibility as well as environmentally benignity and low capital costs [37].

Electrodes are mostly made from carbon material because they can be formulated into different shapes, including graphite rods and plates, fibers, and granules. Most sophisticated materials, such as carbon foam, carbon paper, and carbon cloth, are made from carbon. Graphite rods and plates are used as anode electrodes and have proven to be excellent examples that meet the criteria of high electrical conductivity, inexpensive, ease of handling, and a large surface area. Graphite felt is frequently used in MFC as an electrode because it has a large surface area [20]. The use of reticulate vitreous carbon, which is very dense, has been reported to increase the surface area. Many materials, such as copper, gold, and stainless steel or platinum metals, have good electrical conductivity. Anode materials should own a large surface area, have good electrical conductivity, and strength, and be mechanically stable [38]. Carbonaceous materials, in various forms, have been used most frequently as anode materials in ionic liquid fuel cells. The very simple graphite rods or plates are one of the basic materials used for anode electrodes because they are easy to handle and cheap to produce [39].

Cathode materials

Cathode materials must be active and non-corrosive, similar to the anode. Hence, the same materials may be used for the cathode as used for the anode: carbon sheets, graphite, aluminium, and more typically, platinum as a catalyst to boost the reduction reaction taking place at the cathode. To a greater extent, researchers use a standard carbon cathode in which platinum is loaded on one side that is in contact with liquid water and another side in contact with air [40]. The selection of cathode material influences the maximum performance an MFC can deliver, which is completely determined by its application.

The preferred properties of a good electrode are great biocompatibility, low resistance, high electrical conductivity, corrosion resistance, mechanical durability, large surface area, and low cost of manufacturing. Ferricyanide $[Fe(CN)_6]^{3-}$ has been a widely used electron acceptor in MFCs due to its excellent performance [41]. It has a lower potential than plain carbon when used as a cathode. However, its main drawback is the insufficient reoxidation of oxygen, which necessitates frequent replacement of the catholyte [20]. Graphite, carbon black, carbon brush, carbon felt, and activated carbon are some of the modern electrodes in the form of carbon materials, as shown in Figure 5. In MFCs, oxygen is the ideal electron acceptor due to its high oxidation potential, availability, cost-effectiveness, and the production of water as a byproduct [20].

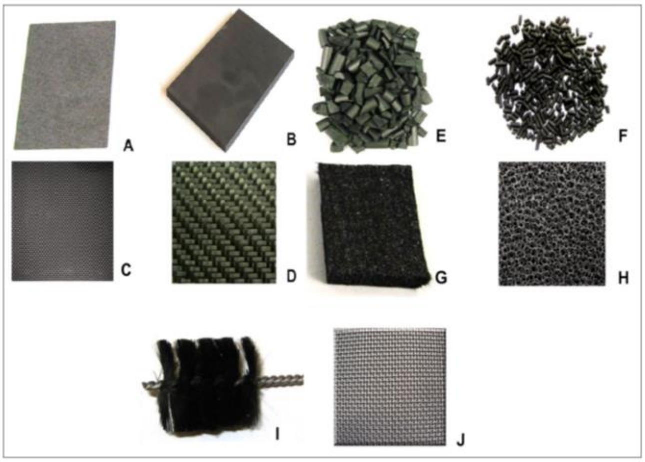


Figure 5. Photographs depicting the electrode materials employed in MFC-PBR: (A) carbon paper, (B) graphite plate, (C) carbon cloth, (D) carbon mesh, (E) granular graphite, (F) granular activated carbon, (G) carbon felt, (H) reticulated vitrified carbon, (I) carbon brush, (J) stainless steel mesh [42]

5.4.2 Membrane materials

The membrane is used as a separator between the anodic and cathodic chambers for the bio-electrochemical reactors. The PEM in MFC-PBR is utilized to separate the anode and cathode chambers and allow the proton to transfer across them. Additionally, the PEM prevents the transfer of oxygen and organic substances between the chambers which could reduce the MET energy recovery [43]. Membranes selectively facilitate the migration of the ion from the anode to the cathode chamber while preventing the liquid of the ion from crossing over into the cathode [44]. In MFC, the mass transport kinetics is enormously affected by the type of membrane material used. The potential gradient across the membrane is the driving force for the protons to migrate from the anode to the cathode chamber [45].

Various membranes, including ceramic barriers, CEM, anion exchange membranes (IEM), and bipolar membranes, are utilized in MFCs. Nafion, polystyrene, bipolar, and microfiltration membranes are types of CEMs, which contain in their structure incorporating groups (COO^-, SO_3^-, PO_3^-) of a negative charge, and these types function as fixed charge cations. The most common membrane used in MFC is Nafion. It has been proven that the coulombic efficiency, proton conductivity, and supporting active microorganisms are improved when the Nafion membrane is utilized. However, the performance of MFC is affected by the thickness and hydration rate of the membrane [46]. High proton transfer rate, resistance to fouling, thermal stability, and low gas permeability are the most important characteristics the membrane has to ensure the high performance of MFC [20].

MFC-PBRs are considered a branch of membrane technologies because they depend on ion exchange membranes that make the anode and cathode chambers apart. In bioelectrochemical reactors, applying an electrical current causes ions to migrate through membranes, resulting in a dipolar reaction. Key challenges for long-term use include biofouling and chemical/inorganic scaling [47]. Furthermore, the thickness and area of the surface of the membrane can be critical parameters affecting MFC-PBR performance [48]. Table 2 outlines the various membrane types, and their pros and cons, of MFC-PBR with different membrane materials.

Table 2. Membrane types, pros and cons, of MFC-PBR with different membrane materials

Membrane	Advantages	Disadvantages
Cation exchange membrane	Lower ohmic resistance leads to reduced internal resistance and increased proton conductivity	pH splitting, oxygen crossover, and biofouling cause reduced ionic conductivity
Anion exchange membrane	Essential for alkaline fuel cells and preventing pH splitting	Substrate crossover and biofouling on the cathode
Porous membrane	Effective for desalination and preventing proton accumulation in the anodic chamber	Water-splitting can increase polarization, resulting in higher internal resistance

5.4.3 Anodic microorganisms

The microbial cultures used in the fuel cell are another significant element affecting fuel cell performance. Certain bacteria in MFCs oxidize organic materials and transport electrons to the electrode surface, making them the common microorganisms used in MFCs. Additionally, the anode microbial population plays a crucial role in MFC-PBR operation by controlling electron transfer rates and determining the types of substrates used, as it utilizes microorganisms as biocatalysts for the biochemical degradation of organic substrates. Several attempts have been adopted to identify the type of microorganisms responsible for generating electricity in the BET system.

According to the literature, pure and mixed cultures are the two categories of anodic inoculums. Despite pure cultures requiring high purity and more stringent concentration substrate, pure cultures have proven that can convert substrates more efficiently into electricity due to their straightforward metabolic pathways [49].

Several kinds of microbial strains, such as methanogens, exoelectrogens, and fermentative bacteria, could play distinct in the anode of MFC-PBR. Smaller compounds are produced due to the degradation of organic compounds by fermentative bacteria, while electrons are generated by exoelectrogens, and methane as a byproduct is produced by the methanogen bacteria. Other factors, including substrate type, different microbial species, and pH, can influence the performance and electricity generation in MFC-PBR [38]. Biofilms are formed on the electrodes with varying electrical conductivities by *Geobacter* and *Shewanella* species, and these conductivities are determined by substrate type, pH, and composition of the microbial community [50].

5.4.4 Algal biocathode

MFC-PBR performance varies depending on the algal species type due to the photosynthesis and cell division rates being different. Algae play a crucial role in the cathodic chamber of this type of reactor, which supports the cathodic reactions and stability of the system by supplying sufficient oxygen through photosynthesis. Species like *Chlorella, Spirulina, Dunaliella, and Scenedesmus* excel at absorbing CO_2 and releasing oxygen. They utilize CO_2 from the anode chamber for growth while capturing greenhouse gases. This process generates oxygen for reactions at the cathode, including the oxygen reduction reaction, and enhances electron supply from algal biomass, boosting overall energy production. Harvested algal biomass can be used as biofuel, animal feed, or redirected to the anode chamber. Oxygen absorption can facilitate electron acceptance in biocathode-based biochemical systems, distinguishing them from microbial chemical-catalyzed cathodes [51].

Research indicates that *Chlorella outperforms Anabaena* in CO_2 capture and oxygen production, which supports cathodic reduction. *Chlorella sp*. is the preferred biocathode due to its resilience to high CO_2 concentrations, tolerance to urban effluent, and favourable fatty acid profile. However, increased cell concentration can lead to metabolic losses from excessive metabolite production. Microalgae in microbial carbon capture cells not only synthesize biodiesel but also sequester anodic gas in the cathodic compartment. Thus, selecting algal species with high photosynthesis rates and suitable lipid profiles for biodiesel production is crucial.

6. APPLICATION OF MFC-PBR

Wastewater contains components that can be converted into environmentally friendly energy by using MFC-PBR, this enables these systems to treat wastewater autonomously and sustainably. This method increases the efficiency of energy, reduces the production of sludge, minimizes the adverse effects of byproducts, and extracts resources like nutrients and electricity from the system while still being simple to operate in various conditions. MFC-PBR is different from traditional systems that primarily focus on maintaining a discharge threshold and preserving sludge; instead, it addresses concerns regarding the depletion of fossil fuels and environmental impact by providing a more sustainable and eco-friendly approach to water treatment. It produces electricity via the metabolic processes of electroactive bacteria in organic waste, this method promotes a natural, clean production of energy that lacks hazardous byproducts, and microbes are used as catalysts to convert chemical energy into electrical energy.

Conventionally, sewage treatment processes release significant CO_2 annually to degrade organic pollutants. Utilizing and capturing CO_2 in the MFC-PBR cathodic compartment can lead to substantial algal biomass production, enhancing cost-effectiveness and providing additional benefits. Several approaches to utilizing microbial cells for carbon capture (Figure 6). The most effective method of biological production of biomass and extraction of carbon from wastewater is the utilization of microalgae [12]. However, several factors, including nutrient availability, operational conditions, growth characteristics, light intensity, and other environmental variables, affect the specific algae's biomass production and utilization of carbon efficiency. Other scientists have employed microalgae in anodic oxidation; this has led to an increase in power production.

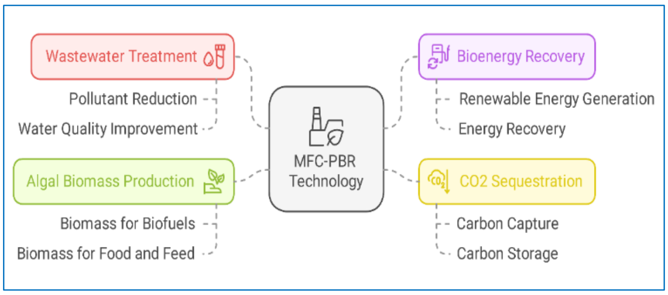


Figure 6. MFC-PBR applications

The electricity produced by MFC-PBR is capable of powering various electronic biosensors and devices. Additionally, treated effluent from the anode chamber can have further filtrating before discharge, this is done through the algae in the cathode chamber because it consumes nutrients from the anodic flow. During photosynthesis of microalgae, biomass is generated and served as a feedstock, which is considered valuable byproducts for other products such as bioethanol, biodiesel, methane, and fertilizers [52].

7. LIMITATIONS AND FUTURE CHALLENGES

MFC-PBR has significant benefits, but the scaling and performance limitations are still the bottlenecks that prevent successful commercialization. The high cost of infrastructure and high energy requirements associated with microalgae harvesting are major disadvantages of the bio-electrochemical system. Furthermore, it is necessary to provide an ideal ratio of surface area to volume and sufficient light intensity for microalgae photosynthesis by ensuring adequate light distribution, and that is another challenge with this technology. In addition, cell voltage and power output are declined by the pH variations across the membrane due to acidification and alkalization, which occur at the anode and cathode chambers. The transfer of protons across the membrane to the cathodic chamber is essential to sustain the redox reactions. Permeable membranes in MFC-PBR are usually used but expensive; therefore, proton permeable membranes at low cost, less tendency of oxygen and acetate diffusion, and high proton conduction are crucial to investigate by the researchers. Oxygen diffusion to the anodic chamber reduces the MCF-PBR performance because the activity of anaerobic microorganisms deteriorates when oxygen is available.

Coupling wastewater treatment and energy recovery can be achieved by integrating MFC and PBR technologies. However, this required sophisticated design and harmonizing the operating parameters of the two systems, which is still a big challenge. Routine maintenance is required for long-term operation through minimizing fouling, equipment wear, and scaling. Also, in fluctuating wastewater conditions, the stability of microbial and algae communities remains a major challenge. The integration of MFC with PBR presents an alternative and suitable solution for traditional wastewater treatment by simultaneously generating energy, treating water, mitigating CO_2 emissions, and producing biomass. However, a comprehensive economic cost analysis, including the capital, fabrication, operation, and maintenance costs of MFC-PBR, must be conducted to compare it with conventional methods of wastewater treatment. Therefore, the major key factors need to be considered to evaluate the revenue potential of using MFC-PBR, such as energy production and consumption, biomass utilization, membrane fouling, and low sludge formation.

Optimizing the energy obtained from MFC and biofuel from PBR is significant for the integrated system to be economically viable. Improving the overall efficiency is required by utilizing more advanced electrode materials and reactor design. Continuous investigation for low maintenance and less corrosive electrode materials is significant for long-term operation. Maximizing system efficiency and energy recovery by exploring synergies with other renewable energy resources, like solar panels. Using a diverse microbial community in MFC and keeping optimal algal species in PBR under dynamic environmental and certain operating conditions is challenging.

8. CONCLUSIONS

MFC-PBR is an innovative and sustainable solution for wastewater treatment, CO_2 sequestration, bioenergy recovery, and biomass production. This integrated approach offers two key benefits, namely, improving the efficiency of wastewater treatment and reducing environmental impact through the simple extraction of electrical power and enhanced organic productivity. Compared to conventional wastewater treatment methods, the integrated system offers several economic and environmental benefits: simultaneous wastewater treatment and electricity production, reduced sludge generation, lower reliance on external energy, and decreased biofouling on membranes. This technology shows promising potential for applications in bioindustries and wastewater treatment, supporting sustainable development goals. However, further research is needed to optimize its overall performance and improve its technical feasibility and financial viability.

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