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REVIEW

Microbial fuel cell technology: Novelties for a clean future

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Abstract

The degree of civilization exhibited by a society is largely determined by its reliance on energy, and as traditional energy sources such as fossil fuels become scarcer, new technologies will be required to secure sustainable energy. Microbial fuel cell technology is one of the most creative ways to meet humanity's energy demands because it can generate electrical energy from carbon sources. The framework of the limitations limiting the dissemination of this technology has been used to explore in depth new designs and configurations that have been produced recently. Future developments and current applications of this technology in bioremediation investigations are explored. The use of microbial fuel cell technology as a microbial biosensor for the identification of environmental contaminants is particularly significant. However, for a clean and sustainable ecosystem, it is imperative to disclose the challenges associated with the future adoption of this technology.

Keywords: Electricity, microbial fuel cell, microbial electrochemistry, renewable energy

Introduction

Microbial fuel cells (MFCs) have attracted great attention in recent years as an important alternative technology for energy production from renewable sources (Bazina et al., 2023; Catal et al., 2024). These devices, utilize the power of current bioelectrochemical technologies via microorganisms to convert organic carbon resources found in waste materials into electricity (Ishaq et al., 2023). Thanks to this technology, which can be integrated into wastewater treatment facilities, clean energy can be produced and has potential for the future (Bhaduri and Behera 2024). Microbial fuel cells are actually similar to traditional batteries, but unlike batteries, they are open systems and contain biological objects. Although it has various configurations, there are basically two important parts: anode and cathode (Mohyudin et al., 2022). Biological reactions occur mostly in the anode part. Electrochemically active microorganisms break down organic substances as a result of their metabolic activities, and electrons and protons are formed in this process called oxidation (Thapa et al., 2022). Microbial fuel cells can produce electricity by capturing these released electrons (Vidhyeswari et al., 2022). The anode part of the microbial fuel cell attracts electrons from these microorganisms. These electrons pass through an external conductive outer wire, producing an electric current. Then, these electrons reaching the cathode react with oxygen (or another final electron acceptor) and form a water molecule (Zhuang et al., 2010). With these features, microbial fuel cells have the potential to solve two important problems: energy production and wastewater treatment (Gul et al., 2021). As exoelectrogenic microorganisms consume organic compounds, water can become cleaner while simultaneously producing electricity (Suresh et al., 2022). Additionally, microbial fuel cells are a sustainable and renewable energy source (Sorgato et al., 2023). Microbial fuel cells do not require fossil fuels to function and can use various organic substances found in nature as fuel (Apollon 2023). Although it is simple in terms of working principle, this technology is still in the development stage. One of the main challenges is the current levels of power production produced by this technology. Microbial fuel cells generally produce low power, which limits their areas of application. Therefore, research is being carried out on the development of new designs to increase power production (Priya et al., 2022). Additionally, there is a need to develop new electrode and membrane materials for the optimization of microbial fuel cells, as well as to identify the most efficient microbial communities to increase electron transfer and performance (Prathiba et al., 2022). Despite these challenges, the potential applications of this technology are diverse (Zhang et al., 2022a). Perhaps the most important of these application areas is wastewater treatment. Microbial fuel cells integrated into the wastewater treatment plant can both make the wastewater cleaner and contribute to the operating cost of the plant with the electrical energy it produces (Saran et al., 2023). Additionally, in areas where transportation is difficult, environmental sensors and small electronic devices can be powered by microbial fuel cells integrated into the facility (Khan et al., 2020). With extensive research to be carried out, this technology can become an important actor in the field of clean energy in the future. The reduction of fossil fuels already requires renewable energy technologies (Icaza-Alvarez et al., 2023), and as a more sustainable ecosystem element, microbial fuel cells can serve humanity by harnessing the power of microorganisms.

Although fossil fuels dominate the energy field today (Yildiz 2018), fuel cells are one of the alternative technologies (Chandran et al., 2022). However, microbial fuel cells have some advantages over traditional fuel cells such as operation at low temperatures (Roy et al., 2023). With these features, microbial fuel cells have the potential to revolutionize energy production techniques in the future. While traditional fuel cells require the use of various fuels such as hydrogen (Abdelkareem et al., 2021), microbial fuel cells can use a wide range of organic compounds as fuel, such as wastewater, organic wastes and lignocellulosic materials (Catal et al., 2008a; Catal et al., 2008b; Catal et al., 2011b; Bermek et al., 2014). In this way, they contribute to reducing our need for fossil fuels. They are also important in converting waste into a value-added product. In addition, microbial fuel cells are an environmentally friendly alternative due to their renewable and sustainable nature, as MFCs can significantly reduce methane and N_2O emissions (Wang et al., 2019). While traditional fuel cells focus only on electricity production, microbial fuel cells provide versatile use by performing both electricity production and wastewater treatment simultaneously. While traditional fuel cells require large-scale infrastructures for energy production (Kampker et al., 2020), microbial fuel cells also enable scale-up with their portable designs (Catal et al., 2018). Recently, researchers have been working to increase power output by combining multiple microbial fuel cells (Fan et al 2024). With these portable and scalable features, there are large-scale designs integrated into the wastewater treatment plant as well as small-scale designs for sensor use (Catal et al., 2019a). Although conventional fuel cells have special operational requirements, microbial fuel cells can operate in a wide variety of environmental conditions, including low temperatures and a wide range of substrates (Catal et al., 2011b; Catal et al., 2011c). Thanks to these adaptable features, microbial fuel cells provide the opportunity to operate various devices in regions where the use of traditional technologies is difficult. Ultimately, microbial fuel cells, as an alternative to traditional fuel cells, are promising in the field of clean energy production with features such as versatility, sustainability, scalability and adaptability. However, in order to advance this technology, there is a need to research and understand its working mechanisms, microbial metabolism principles and different configurations.

Essentials of MFCs

Microorganisms function in microbial fuel cells are electroactive (Catal et al., 2024). While these microorganisms produce energy for their own needs by breaking down carbon sources through oxidation reactions, they also release the electrons and protons produced. These released electrons are used to produce electricity (Aiyer 2020). The anode attracts electrons like a magnet. These electrons, transferred to the cathode through an external circuit, flow to the cathode and react with an electron acceptor such as oxygen to produce water (Arkatkar et al., 2021). A membrane is generally used in two-chamber microbial fuel cell configurations. These membranes separate the anode and cathode parts and allow only protons to pass (Kook et al., 2019). However, there is no need to use membranes in single-chamber configurations. Electric current occurs during the transfer of electrons through an external conductive wire.

To increase and optimize power production in microbial fuel cells, it is crucial to understand the energy metabolism, metabolic pathways, and substrate consumption of microbial cells (Thapa et al., 2022). Exoelectrogenic microorganisms are one of the most important components functioning in this technology. These microorganisms can transfer the electrons released during their metabolism to conductive surfaces (Chen et al., 2018). This is just one of the electron transfer mechanisms. These exoelectrogenic microorganisms can use different metabolic pathways while consuming the carbon source in organic substances as a substrate. Fermentation is a common metabolism for many exoelectrogenic microorganisms. In the absence of oxygen, they break down carbon sources and organic molecules and transfer the released electrons to the anode (Georg et al., 2020). Methane (CH_4) and electricity are the end products of ethanol fermentation, for example. First, ethanol is fermented to produce acetate and H_2, and then, on the anode, H_2 and acetate can be immediately oxidized to generate current (Georg et al., 2020). Additionally, some exoelectrogenic microorganisms support the function of the microbial fuel cell by using substances such as nitrate or sulfate as electron acceptors (Fu et al., 2013). Their ability to consume a wide range of substrates is a significant advantage for exoelectrogenic microorganisms. Generally, easily consumable substrates such as sugars are consumed first, followed by complex carbon sources (Catal et al., 2011b). This preference may vary depending on type, energy efficiency and metabolism of microorganisms. Investigating the metabolic pathways and substrate consumption preferences of these microorganisms is essential to increase the performance of microbial fuel cells. Understanding microbial communities, especially those that exhibit high electron transfer rates and efficient substrate consumption profiles, is necessary to develop strategies to increase energy efficiency (Kumru et al., 2012). In this way, optimizing the content of organic substances to be used as fuel seems to be beneficial for encouraging microorganisms that can produce electricity more efficiently. However, a thorough understanding of electron transfer mechanisms in microbial fuel cells is required to achieve efficient electricity production.

Electron transfer processes in MFCs

One of the most important steps in electricity production in microbial fuel cells is electron transfer to the anode. In general, these transfer mechanisms can be grouped under two main headings: direct and indirect electron transfer (Aiyer 2020). In the direct electron transfer mechanism, electroactive microorganisms make physical contact with the anode using structures such as pili or outer membrane cytoplasm (Li et al., 2021a). Electrons are transferred directly from the microorganism to the anode surface (Li et al., 2021a). Since there is no intermediary in this mechanism, electrons are transferred more efficiently. However, some microorganisms do not have the ability to transfer electrons directly and they transfer electrons through indirect electron transfer (Zhang et al., 2022b). In this mechanism, intermediary molecules generally take these electrons from electroactive microorganisms and act as intermediaries in their transfer to the anode surface. Substances such as various quinones, and methylene blue, methyl orange, methyl red can be used as electron mediators (Babanova et al., 2011; Freguia et al., 2009). Although there is a wide range of microorganisms involved in indirect electron transfer, it may be less efficient as electrons and energy may be lost during the shuttle process. The efficiency of electron transfer in microbial fuel cells depends on various factors (Zhao et al., 2009). Electrode materials with larger surface areas increase efficiency because they allow contact with electroactive microorganisms on a larger surface area. Research is being carried out to increase the anode surface with various nanotechnological approaches. By understanding the electron transfer mechanisms that occur with electroactive microorganisms, it may be possible to develop microbial fuel cells with the most appropriate design and configuration to increase power efficiency. New strains reported to be electroactive in microbial fuel cells continue to be identified. Electroactive microorganisms have also environmental protective effects through their interesting abilities (Dong et al., 2024; Sukkasem, 2024). Geobacter bacteria, known to form conductive batteries or adducts to electronically couple to extracellular electron acceptors such as uranium and iron oxide minerals, can be used in microbial fuel cells (Reguera, 2018). Application of magnetic field has been reported to increase the overall energy efficiency of *Geobacter sulfurreducens* and greatly enhance its ability to generate electricity (Zhou et al., 2023). Additionally, some studies have shown that *Geovibrio* species can also be found along with *Geobacter* species (Ait-Itto et al., 2024). Electron uptake from the cathode by *Lactiplantibacillus plantarum*, a predominantly fermentative bacterium found in fermented foods and in the intestines of mammals, has been reported (Tejedor-Sanz et al., 2023). Electricity production was reported with the *Shewanella chilikensis* MG22 strain discovered using 16S rRNA analysis in microbial fuel cells (Efraim et al., 2023). *Shewanella algae*-L3 was isolated from conditioned sludge of brewing wastewater and its role in electricity production was reported (Wu et al., 2024). When we consider how vast the microbial biomass is in our world, it is not surprising that new microorganisms are being discovered. Both the electricity production efficiency and biological remediation properties of microorganisms with this feature can be improved with genetic engineering approaches. However, there may also be microorganisms that are reported to be electroactive and are found in electroactive biofilms containing mixed microorganisms but do not have a direct or indirect function in electron transfer.

Different MFCs designs and configurations

Although the basic principle is similar in microbial fuel cells, there are designs with different types and configurations (Mohyudin et al., 2022). Depending on their electron transfer mechanism, microbial fuel cells can be divided into two main groups: mediated microbial fuel cells (i) and non-mediated microbial fuel cells (ii) (Moon et al., 2006; Babanova et al., 2011). In mediated microbial fuel cells, electrons are transferred through shuttle molecules that function as intermediaries, and these electrons are transferred to the analyte surface. Some of these intermediary molecules can be produced by electroactive microorganisms. Microorganisms capable of direct electron transfer are used in mediator-free microbial fuel cells (Moon et al., 2006; Catal et al., 2008a). Apart from these two groups, there are microbial electrolysis cells, which are a new type of microbial fuel cell (Kilinc et al., 2023). While microbial fuel cells can be used to produce electricity, microbial electrolysis cells enable the production of hydrogen gas (Cebecioglu et al., 2021). Thanks to this technology, hydrogen gas, which is a carbon-neutral source, is produced while requiring the use of energy as it needs application potential. In recent years, soil microbial fuel cells, in which soil is used in the anode part, have been investigated especially because they also have bioremediation potential (Kilinc and Catal 2023). Microbial fuel cell designs using algae or cyanobacteria capable of photosynthesis use light for electron production and are called phototrophic microbial fuel cells (Strik et al., 2010). Nanoporous membrane microbial fuel cells use nanoporous membranes that separate the anode and cathode parts (Biffinger et al., 2008). Similarly, durable and stable ceramic membranes that allow long-term operation can be used (Merino-Jimenez et al., 2019). The positioning of electrons and, if any, compartments in a microbial fuel cell also affects the configuration. According to their configuration, microbial fuel cells can be grouped as single chamber (i), double chamber (ii), or stacked type (iii) or air cathode (iv) (Santoro et al., 2015; Cebecioglu et al., 2022; Fan et al., 2024). Single-chamber microbial fuel cells have a very simple design (Akagunduz et al., 2022). Depending on its volume, it has advantages such as being portable, cost effective and easy to install. However, diffusion of oxygen into the system negatively affects microbial activity and electron transfer. Two-chamber microbial fuel cells are separated into two chambers using a membrane or salt bridge (Mirza et al., 2022). These components allow the transfer of protons but restrict the passage of other compounds. However, these membranes are mostly quite expensive materials. To increase power efficiency, multiple microbial fuel cells can be connected to each other in series or parallel in a stacked type (Fujimura et al., 2022). This allows for higher energy output. Air cathode microbial fuel cells eliminate the problem of air pumps or pure oxygen supply. In this type of microbial fuel cells, oxygen in the air is used to catalyze the spontaneous reaction and contributes to the operating cost by reducing complexity. The choice of configuration depends on the desired requirements and environmental conditions for the application, and significant advances have been made in this technology in recent years.

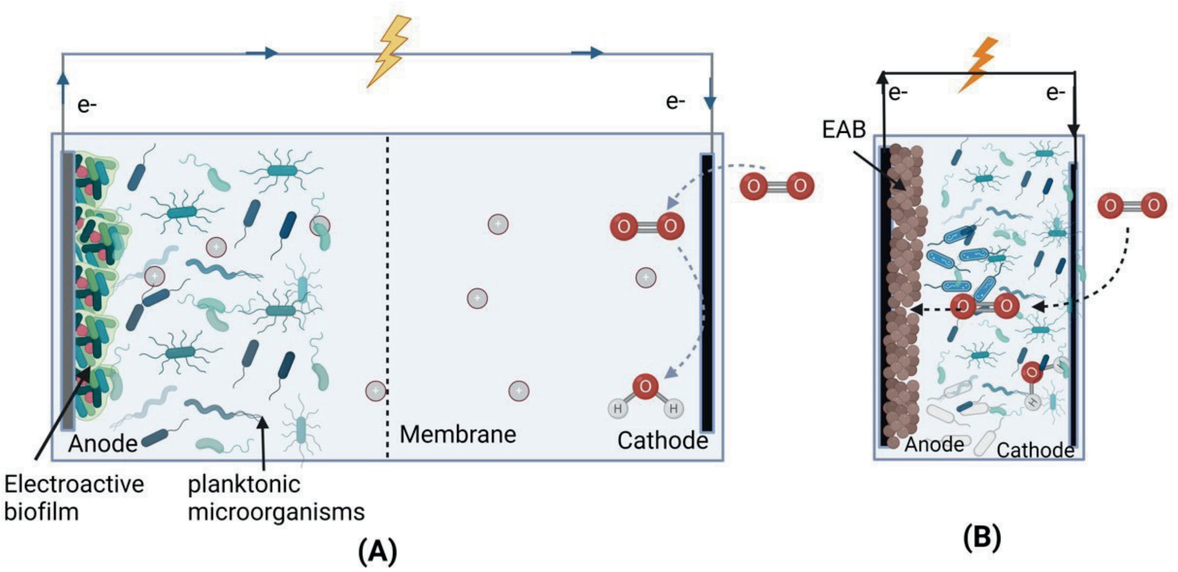

Figure 1. A dual chamber MFC (A) and a single chamber MFC configurations. EAB: electroactive biofilm (Created with BioRender.com).

Latest Advances in MFC Technology

One of the most important parameters affecting energy efficiency in microbial fuel cells is the anode material used. A suitable anode material must have various properties. A good anode electrode should easily receive electrons from microorganisms and transfer them effectively to the external circuit (Kang et al., 2015). In addition, it must provide a suitable environment for the growth of electroactive microorganisms and must be biocompatible (Tahir et al., 2021). In this way, it should allow microorganisms to form biofilm. Materials that provide a large surface area are especially preferred because they provide more effective electron transfer (Walter et al., 2020). It is important in terms of cost that the material to be used as the anode material be durable and stable for a long time and also be cheap (Zhu et al., 2022). So far, different materials have been researched and used with various advantages and disadvantages. One of the most used anode materials is carbon-based materials, which have a large surface area and high conductivity (Akul et al., 2021). Graphite felt, carbon fibers, activated carbon, carbon cloth are examples of commonly used anode materials (Wang and Feng 2017; Delord et al., 2017; Gajda et al., 2020; Sen et al., 2020). Some carbon materials can negatively affect energy production performance because they allow undesirable microorganisms to grow on the anode surface. However, metallic materials can also be used as anode due to their high conductivity and durability (Wang et al., 2016). However, they have disadvantages in terms of bioavailability. Recently, various composite materials that provide advantages in terms of biocompatibility and catalytic activity have also been investigated as anode materials (Roh and Woo 2015). Studies are being carried out on these composite materials, the composite of carbon materials, which have certain properties of different materials, with metal oxides. Conductive polymers such as polypyrrole and polyaniline have been proposed as anode materials because they have advantages in terms of bioavailability (Jia et al., 2020). Selection of a suitable anode material depends on the area of application, cost and desired properties. Extensive research is being carried out on anode materials with optimized properties, which can pave the way for cost-effective bioelectrochemical systems.

Cathode development

Although the anode has an important place in the performance of microbial fuel cells, the cathode is equally important. In order to produce electricity, electrons coming from the anode must react at the cathode with the help of cathode, usually in the presence of oxygen (Chen et al., 2023). The cathode material used significantly affects electricity generation performance. The most important element that a good cathode material should have is high oxygen reduction reaction activity. This reaction must be catalyzed efficiently (Zheng et al., 2022). When oxygen reduction reaction activity is slow, it causes performance loss. Additionally, its high electrical conductivity is important for efficient electron transport. It must be resistant to long-term operations and be able to maintain its function stably for a long time. Being cheap and competitive in terms of cost is also one of the reasons for choosing cathode materials (Behera et al., 2010). Air cathodes, one of the most commonly used cathode types, use the oxygen present in the air and do not require additional oxygen supply. These designs are generally simpler and can be said to be cost effective. In addition, since it requires oxygen in the air to operate, it may have a slower kinetic activity, resulting in lower power output. To increase catalytic activity, carbon materials treated with catalysts such as cobalt, iron and platinum are used (Mahmoud et al., 2011; Ozdemir et al., 2019; Yu et al., 2021). In recent years, biofuels that use microorganisms' own enzymes or biomimetic catalysts have come to the fore. Biocathodes can provide advantages in terms of high catalytic activity and compatibility (Qiu et al., 2021). Although metal-based cathodes are expensive, they are very advantageous in terms of high efficiency (Mahmoodzadeh et al., 2023). Composite cathodes also stand out as alternative materials in that they contain the desired properties of different materials (Antolini 2015). In selecting the most suitable cathode material, factors such as the area of application, desired efficiency and performance parameters, and cost are important. As microbial fuel cell technology develops, it will require the development of new and innovative cathode materials with high catalytic activity, cost-effectiveness and durability.

MFC configurations with improved efficiency

There are some limiting factors in the widespread use of microbial fuel cells. In order to overcome these limiting factors, innovative approaches have been demonstrated in recent years to increase power efficiency. Stacking approach has recently been used to increase the power efficiency of microbial fuel cells (Fan et al., 2024). This approach is based on the principle of stacking multiple microbial fuel cells in series or parallel (Estrada-Arriaga et al., 2018). When microbial fuel cells are connected in series, voltage production is increased. However, when connected in parallel, the current output increases. Various microbial fuel cells can be stacked in series or parallel depending on the purpose of the application. Modular microbial fuel cells allow the preparation of scale-up systems by assembling smaller units (Liang et al., 2018). This type of microbial fuel cells can be used especially for bioremediation purposes. Microfluidic microbial fuel cells have some advantages as they allow faster electron transfer (Ouyang et al., 2023). Particularly for biosensor applications, such microfluidic microbial fuel cells offer opportunities for integration. Bipolar plate-electrode assembly (BEA) design, which significantly increase the performance of microbial fuel cells, is also an innovation (An et al., 2014). New strategies are being developed within the scope of the development of electrode materials that encourage the growth of microorganisms and the formation of biofilms. By adding polyquaternium-7, the surface hydrophilicity was enhanced and the composite electrode's biocompatibility for bacterial attachment, colonization, and substrate diffusion was improved in a previous paper (Li et al., 2021b). Additionally, microbial fuel cells can be integrated into other systems. Table 1 shows recent advances in MFC performances. This technology can be integrated with other technologies for desalination (Aber et al., 2023). In addition, the salt water formed in this process can also serve as a food source for microorganisms. Bioremediation offers a wide range of research and application opportunities as an application area (Li et al., 2015). Thanks to their integration with microbial electrolysis cells, the microbial fuel cell produces electricity, while the microbial electrolysis cell can use this power to produce hydrogen gas.

Application areas of MFCs

MFCs in wastewater treatment and bioremediation

Microbial fuel cells have a wide range of applications in bioremediation and wastewater treatment. In this way, sustainable energy production can be obtained from renewable sources. Traditional water treatment technologies require high energy input. Microbial fuel cells offer an alternative paradigm as they use waste as an energy source. One of the most important parameters determining the effectiveness of microbial fuel cells in wastewater treatment is chemical oxygen demand (Yao et al., 2023). With this technology, a significant reduction in chemical oxygen demand, which is an important parameter of pollution, can be achieved. In addition, various heavy metals and pharmaceutical wastes found in wastewater can be bioremedied (Abourached et al., 2014; Catal et al.,, 2015; Akagunduz et al., 2022; Pugazhendi et al., 2022). In this regard, microbial fuel cell technology has an important potential for bioremediation. These environmental pollutants mixed into wastewater from various industries negatively affect not only humans but also other living elements of nature in our ecosystem (Ozdemir et al., 2019). In order to guarantee environmental health, these pollutants need to be removed, especially before releasing wastewater to nature. Exoelectrogenic microorganisms in microbial fuel cells can remove and detoxify these pollutants by various methods. Microbial fuel cells can function in environments with low oxygen levels. In addition, voltage data processed as signals during the electricity production process also has potential applications in the biosensor field (Adekunle et al., 2021). In addition, the energy produced can also be used to operate other devices used in a wastewater treatment plant. In the real field of application, there are still obstacles to be solved in terms of microbial fuel cells. Especially large-scale wastewater treatment and scale-up remain a significant obstacle. However, studies are continuing to adapt it to biosensor technologies, which are still very popular as a research field.

Table 1. Recent MFC performances.

MFC type	**Electron donor (substrate)**	**Cathode**	**Power density**	**Reference**
Multiple cloth electrode assemblies internally connected in series	Sodium acetate (5.9 g/L or 100mM)	Air cathode	3.5 W/m^2	Fan et al., 2024
Single chamber	Sodium acetate (1 g/L)	Air cathode	303 mW/m^2	Sonmez et al., 2024
Single chamber scaled-up (2 L)	Sodium acetate (850 mg/L)	Air cathode	7.87 ± 2.72 mW/m^2	Sorgato et al., 2023
Bio-anode microfluidic	Sodium acetate (4.65 g/L)	Potassium ferricyanide	1.05 W/m^2	Ouyang et al., 2023
A single-chamber with a ceramic membrane separator	Synthetic potato-process wastewater	Synthetic potato-process wastewater using submerged carbon cloth	130.2 ± 45.4 mW/m^2	Sato et al., 2023
Single chamber	Molasses	Air cathode	169.86 mW/m^2	Hu et al., 2023
Two chamber	Glucose (0.5 g/L)	Buffer using air pump	130.72 mW/m^2	Mahmoodzadeh et al., 2023
Soil-based	Sodium acetate (1.2 g/L)	Air cathode	227 mW/m^2	Kilinc and Catal 2023
Single chamber	Sodium acetate (30 mM)	Air cathode	6840 mW/m^2	Catal et al., 2024
Two chamber	LB + M9	Potassium ferricyanide (50 mM)	3366 ± 42 Mw/m$^{2.}$	Kirubaharan et al., 2023
duckweed composite constructed wetland	Domestic wastewater containing sucrose	Free water layer	42.93 mW/m^2	Jain et al., 2023
Dual-chamber MFC	Distillery wastewater and domestic wastewater	50 mM sodium phosphate solution using air pump	162.5 ± 2 mW/m^2	Jaswal et al., 2023

Biosensors and environmental monitoring

Microbial fuel cells have the potential to be used not only in electricity generation but also as biosensors. The voltage data resulting from the transfer of electrons released as a result of the metabolic activities of microorganisms to the anode surface and the production of electricity can function as a signal for detection of various compounds such as bisphenol A (Zhu et al., 2023). Microbial fuel cells can function as biosensors by exploiting the complex interaction between microorganisms and target compounds. However, there are some obstacles to overcome before microbial fuel cells can function as biosensors. The most important of these are sensitivity and selectivity (Zhu et al., 2023). The basic principle of using microbial fuel cells as biosensors is the interaction between the target molecule and the exoelectrogenic microbial community. The target molecule can often be a contaminant. This pollutant may be a heavy metal in the wastewater system or a waste drug molecule such as antibiotics (Catal et al., 2015). In the presence of the contaminant molecule, the metabolism of microorganisms is affected, which can cause measurable differences in voltage data that serve as signals. For the optimization of the system, researchers continue their research to correlate the chemical power with the concentration of the target molecule. However, one of the main problems here is that molecules other than the target molecule or physical or chemical factors may interfere with the interaction between the microorganism and the target molecule. Therefore, there is a need to investigate new approaches to increase specificity in the future. Various organic pollutants, heavy metals, biomolecules and pathogenic microorganisms can be detected with microbial fuel cells (Ma et al., 2022). While there are studies on the detection of organic pollutants such as pesticides and herbicides, heavy metals such as lead, zinc, mercury and various pathogenic microorganisms that are a threat to public health can also be detected by microbial fuel cells (Abourached et al., 2014; Chouler and Di Lorenzo 2019; Adekunle et al., 2023). In order to customize this microbial response, studies have been carried out to design microbial communities, and by using microorganisms known to sequester certain pollutants, it has become possible to develop more sensitive biosensors against these pollutants. There are still challenges to be overcome before they can be used as biosensors. Such application-oriented new designs and the development of easy-to-transport and inexpensive systems are approaches that can help microbial fuel cells become widespread. Despite all these difficulties, with the development of optimized microbial fuel cells in the future, molecules and compounds that pose a threat to environmental health can be monitored and even find a place in wide application areas such as food safety and biosecurity. Therefore, microbial fuel cells, which are a clean production technology, can also reach wide use in the field of biosensors in the future.

Challenges

Although microbial fuel cells can be used practically on a laboratory scale, there are some challenges when it comes to scale-up. The efficiency achieved with microbial fuel cells, which are mostly used at laboratory scale, decreases as the scale is increased (Selvasembian et al., 2022). In large-scale microbial fuel cells, the interaction between microorganisms and electrodes is negatively affected. This negatively affects microbial activity and productivity. Another problem is that as the scale increases, the internal resistance in microbial fuel cells also increases (Motos et al., 2017). Increasing internal resistance also causes ohmic losses to increase and power output to decrease. Pilot-scale microbial fuel cells studied before the development of microbial fuel cells suitable for wastewater treatment plants have shown promising results. Microbial fuel cells at laboratory and pilot scale also provide prototypes for larger-scale designs and provide preliminary data to understand the functioning of the system. Apart from laboratory applications, scale-up seems feasible, especially for use in remote areas. These scale-up studies require both cost and financial funding to sustain the research. Optimizing designs, investigating cost-effective materials, and creating proficient microbial fuel cell operation and support conventions are pivotal steps. In any case, the potential benefits of microbial fuel cells (wastewater treatment, bioremediation, and clean vitality generation) make overcoming these challenges beneficial. As investigate advances, microbial fuel cells can be anticipated to develop as a reasonable and economical innovation for a cleaner, more energy-independent future.

The type and concentration of organic matter found in wastewater significantly affects the power output of microbial fuel cells (Catal et al., 2008b). The abundance of substrates that can be degraded quickly and easily is also a disadvantage. It is also directly related to the metabolic activities of the microorganisms used in this technology. The efficiency of electron transfer is also related to the electrode materials used in the system. Increasing internal resistance due to increase in size also poses a problem in microbial fuel cells. It is especially important to implement new approaches that can positively affect the interaction between the electron surface and microorganisms with the developments in nanotechnology. Additionally, when it comes to wastewater, there are also factors that cause pollution and can accumulate or cause corrosion in microbial fuel cells. The fact that the cathode section requires additional ventilation to increase efficiency in most cases increases the cost and makes operations difficult.

Conclusion

In the future, it is very likely that wastewater treatment plants that can generate electricity on their own will be developed and microbial fuel cells that can work to detect targeted molecules remotely will be implemented. With this innovative and clean technology, converting organic waste materials into added value can be achieved with the help of exoelectrogenic microorganisms. Microbial fuel cells work like biological batteries, but unlike batteries, they are open systems. Since microorganisms are already living beings, they require the use of an open system and can break down the organic materials provided and convert them into electricity. This technology is versatile in many aspects. While it allows wastewater treatment, it can simultaneously produce clean energy. Since they work naturally with the help of microorganisms, they have many advantages in terms of renewable and sustainability. However, considering the research conducted and the field of application, it is safe to state that this technology is yet at the age of infantry. Efficiency values in power output are still a limiting factor for large-scale applications. There is also a need to develop appropriate optimized microbial fuel cell designs and discover suitable microbial communities. Achieving an increase in energy efficiency through research carried out despite all these difficulties can revolutionize power resources. With the widespread use of this innovative technology, the way can be paved for a cleaner and more environmentally friendly way that meets and supports humanity’s energy needs.

Conflict of interest

The authors declare no conflict of interest.

Data availability statement

Data sharing is not applicable to this review article as no datasets were generated or analyzed during the current study.

Ethics committee approval

Ethics committee approval is not required for this article.

Authors’ contribution statement

Tunc Catal and Hong Liu designed this article. Tunc Catal and Hong Liu wrote and revised the paper.

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