

Microbial Fuel Cells: A Sustainable Solution for Wastewater Treatment and Energy Generation

Arijit Banerjee¹, Kalyani Shao¹, Khondekar Maksuda Begam¹, Katyayini Singh¹, Amima Maswood¹, Aritri Josh¹, Rupesh Dutta Banik^{1*}

*Corresponding Author at: Department of Microbiology, School of Life Sciences, Swami Vivekananda University, Barrackpore, West Bengal- 700121, India

¹Department of Microbiology, School of Life Sciences, Swami Vivekananda University, Barrackpore, West Bengal- 700121, India. Corresponding author email: rupesduttabanik99@gmail.com

ABSTRACT

A novel bio electrochemical technology known as microbial fuel cells (MFCs) offers a decentralized, long-term solution to the world's water and energy problems by treating wastewater and producing renewable electricity simultaneously. In this study, we investigate the possibility of MFCs treating wastewater and producing bioelectricity at the same time, highlighting its dual functioning. Through the optimization of electrode materials, microbial consortia, and reactor layouts, this research primarily aims to enhance the performance and efficiency of MFCs. Using carbon-based anodes, proton exchange membranes, and synthetic wastewater, lab-sized MFCs were constructed in this way to create circumstances as close to reality as feasible. Voltage, current density, and power output were used to quantify bioelectricity generation, while microbial activity was used to measure the breakdown of organic contaminants. In addition to consistent power outputs, the results demonstrated a significant decrease in COD, which is indicative of effective wastewater treatment. Energy recovery was greatly improved by increasing the anodic biofilm and electrode surface area, leading to a dramatic increase in electron transfer rates. Additionally, substrate

utilization rates were enhanced through the employment of mixed microbial consortia, which aided in the breakdown of complex organic molecules. According to these findings, MFCs have a lot of promise as a greener and cheaper substitute for conventional wastewater treatment methods. In light of the foregoing, it is reasonable to conclude that MFCs have the makings of a long-term solution for distributed wastewater management and renewable energy generation, particularly in underserved regions. However, there are still significant obstacles to broad adoption, including issues with scalability, operational stability over the long term, and material prices. In order to make this technology more commercially viable and less harmful to the environment, researchers should work on improving MFC designs, maximizing microbial ecosystems, and finding ways to incorporate it into current wastewater treatment systems.

Keywords: *Microbial fuel cells, bio-electrochemical technology, wastewater treatment, renewable energy production, environmental impact*

INTRODUCTION

Nowadays, wastewater is recognized as an essential resource for conserving energy and facilitating water reuse. Conventional aerobic activated sludge and other traditional treatment technologies, conversely, produce residuals and require significant energy input. The challenge they face includes the insufficient recovery of potential resources from wastewater (HE et al 2017). Concerns regarding clean water represent a significant global challenge, exacerbated by factors such as climate change, population growth, and increasing water consumption (Aghababaie et al. 2015). Anaerobic digester (AD) technology is increasingly recognized as a crucial treatment method, given its remarkable effectiveness in converting organic compounds into methane (CH₄) gas and its potential for energy savings. This can subsequently be transformed into electrical energy through chemical fuel cells or engines that utilize CH₄ as a power source. However, findings indicate that treated wastewater does

not consistently meet stringent regulations, highlighting the necessity for additional technological improvements in the post-treatment phase. In light of these challenges, the practice of water reuse has been extensively implemented, especially in certain arid areas. Nonetheless, the elevated standards for water quality in reuse inherently lead to increased energy demands for treatment (Do et al. 2018). Microbial fuel cells (MFCs) represent innovative bioreactor systems that hold the promise of generating such savings. Nonetheless, discussions continue regarding the future of MFC technology, particularly concerning its commercialization and efficiency. The primary advantage of MFCs lies in their ability to lower energy expenses in wastewater treatment. Logan estimated that if all the energy is recovered as electricity, a population of 100,000 people generating 16.4×10^6 (L/year) of wastewater each year could supply enough power for a 2.3 MW power plant through wastewater treatment. Despite the low power density achieved in MFC, utilizing 0.5 MW of power from a wastewater treatment facility is a more practical approach (Aghababaie et al. 2015). This holds particularly true in isolated locations equipped with biosensors, bio hydrogen generators, and local power sources for wastewater treatment and bioremediation (Do et al. 2018; HE et al 2017). This approach facilitates the transfer of electrons to the cathode through electrical flow by oxidizing substrates in an anode chamber with the aid of biocatalyst microorganisms. At the cathode location, reduction processes lead to the formation of water. Microorganisms demonstrate potential as cost-effective substitutes for platinum catalysts, although the latter remains a viable option. Exoelectrogens are microorganisms that function as biocatalysts, possessing unique capabilities such as reducing electron acceptors and facilitating electron transfer to the anode surface. Enhancing MFC technology allows exoelectrogens to be utilized across various applications, particularly in energy generation. The oxidation of organic materials by exoelectrogens generates a redox potential between the electrodes, facilitating the movement of electrons from the anode to the cathode (Jatoi et al. 2021; Enamala et al. 2020; Do et al. 2020). Nonetheless, MFC technology presents a groundbreaking method for improving

energy products and the treatment of waste and wastewater. The mechanisms of electron transfer, the microscale dynamics of biofilm growth and associated transport processes, as well as the macroscale interactions involving electrodes and separators in the bioanode, represent just a fraction of the myriad challenges that require attention (Do et al. 2018; Kim et al. 2015). This article examines MFCs and determines the factors that affect their effectiveness in wastewater treatment and scalable power generation.

MATERIALS AND METHODS

An extensive search was conducted using PubMed, PubMed Central, Google, as well as published research and review articles from various countries. The focus of this review was on the environmental pollutants caused by the leather industries and the microbial bioremediation strategy to eliminate these pollutants. We removed statements of exposure that were too general and only looked at published data. As part of these inclusion requirements, we have included information gathered from credible sources of relevant publications. Other than English, no other languages were considered in the study.

RESULTS AND DISCUSSION

MFCs Configuration

The configuration of a microbial fuel cell Anode and cathode are the two electrodes that make up a microbiological cell, together with a membrane that divides the two compartments. The oxidation of microorganisms at the anode site produces protons and electrons, which initiate the transfer-ring to the cathode. The circuit allows electrons to flow, whereas the membrane allows protons to. When the electrons and protons reach the cathode, they reduce the oxygen to produce water as shown in **Fig. 1**. Mediators facilitate the majority of microbial cells, which are electrochemically inactive. Several operational metrics play a crucial role in evaluating MFC's performance. The current energy landscape clearly indicates a substantial shift towards renewable energy sources is underway. The potential influence of MFC on energy is enormous (Jatoi et al. 2021).

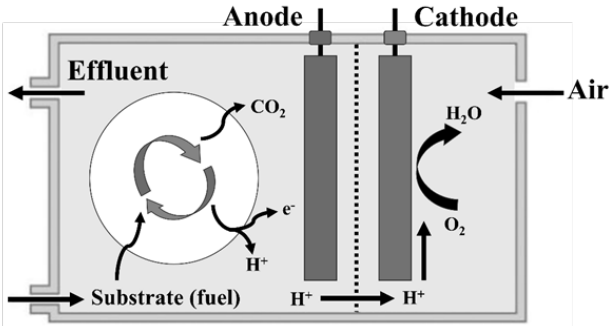


Fig. 1. MFCs Configuration (Schröder 2007)

Elements influencing the efficacy of MFCs

An MFC converts the chemical energy found in organic matter within the substrate into electrical energy. Microorganisms facilitate the oxidation of electron donors such as oxygen, nitrate, or sulphur within the anodic chamber, resulting in the generation of electrons and protons (Jatoi et al. 2021). Countries like the US, Pakistan, China, and India are currently facing an energy crisis, reflecting a global trend. Consequently, technologies rooted in renewable energy sources are crucial for addressing this challenge. The MFC, similar to various other technologies, is shaped by several factors that dictate its performance and efficiency. Multiple parameters can be modified over time, including the cathode, electrolyte, aeration rate, pH, and artificial light, as outlined in Table 1 (Aghababaie et al. 2015).

Table 1. Factors that affect the performance of MFCs (Khan et al. 2019; Jatoi et al. 2018; Jatoi et al. 2020; Rozendal et al. 2006; Choudhary et al. 2017; HE et al 2017; Arun et al. 2020).

Factors	Effects
Cathode	• When scaling up MFC, the cathode determines the maximum power density. • Due to inadequate oxygen transfer crossover, comparatively large amounts of MLC are needed in the lab. • Low cathode liquid Because of the materials used and aeration, a cathode-specific surface area is usually expensive, especially for large-scale MFC. • Power rises from 660 to 1114 MW/m² when carbon paper is replaced with carbon cloth electrodes, a 69% upgrade. The main reason for this gain is a change in cathode material. • Performance is impacted by the cathode's potential since a higher potential cause both more power to be produced and more energy to be lost.
Electrolyte	• Wastewater and distilled water were used in the control experiment; the pH shift was shown to be substantially less than in the non-control experiment. • The temperature of the electrolyte has a significant impact on microbial activity. The ideal temperature varies according to the microbial colony and might range from 20 to 40 degrees Celsius • The pH of the fuel cell's cathode compartment gradually increased to 9.5 following the fuel delivery, whilst the anode's pH dropped. These findings demonstrate the slower rate of proton transfer across the membrane compared to the anode's generation, which the buffer can counteract. • A fuel cell needs a neutral pH to function at its best; hence, buffer is necessary to preserve the ideal microbial environment. • Electrolytes with strong ionic conductivity function better when utilized in MFCs.

Aeration rate	• Ideal aeration increases microbial growth and metabolism it leads to increase in electron transfer and generates power • Regulated aeration leads to an improved current yield. The maximum current increased with an aeration rate of 100 mL min⁻¹, but decreased at 200 mL min⁻¹, likely due to disruption from the sheer force exerted by immobilized microorganisms on the anode. • Control eration minimizes energy loss and regulates oxygen supply • Power generation increased with air flow rate but decreased after it hit a threshold of 150 mL/ min. This indicates a reduced capability for MFC generation at air flow rates over the threshold value, most likely due to oxygen blocking microbial anaerobic activity. • It enhances oxygen transport to cathode supporting efficient oxygen reduction reaction.
pH	• An increase of pH in the cathode compartment decreases the current generation; hence, it is beneficial to reduce operational pH for achieving higher power output. • pH ranging from 7 to 8 suppose the increases power density, growth and activity of microbes, it improves electron transfer and generates power. PH exceeding that can reduce electron transfer and decrease power generation • Additionally, the growth of bacteria is crucial for adjusting pH levels. Bacteria typically thrive at a pH level that is near neutral. Variations in pH that facilitate bacterial growth can lead to alterations in other parameters, including ion concentration, proton motility, membrane potential, and biofilm formation. • The enzymatic activity of most prokaryotes is significantly influenced by pH levels. The pH level significantly influences the activity of prokaryotes. • Regular pH monitoring detects fluctuations and adjustments necessary to maintain optimal pH conditions, effectively eliminating acidic or basic components.

Artificial light	• Artificial light, such as light emitting diodes (LEDs), can greatly increase algal growth, which often improves MFC performance. Compared to traditional light sources such compact fluorescent bulbs, the performance and efficiency of MFCs were improved when LEDs were employed as the light source. • Artificial light in waste water accelerates the decomposition of organic contaminants, helping to improve treatment efficiency. • Under blue (0.156-4.741 mW/m²) and red (1.525-12.947 mW/m²) light conditions, power density rises with light intensity (100-900 lux). • Growing algae may cause competition with microorganisms and reduce the efficiency of MFCs. • Using red LED light enhances electron transport from the algal cell to the electrode due to the photosynthetic system's high absorption of light energy at this wavelength.
------------------	---

Electron transfer mechanism in MFCs

The mechanism of electron transfer formed the basis of the operation of the microbial fuel cell (Jatoi et al. 2021). A variety of studies have elucidated the mechanism by which electrons move between microorganisms and the anode/cathode in MFCs. Considering this, direct electron transfer and mediated electron transfer represent two crucial pathways for extracellular electron transfer. The majority of publications indicate that electron transfer in the MET, DET mode takes place between microorganisms and the anode material (Prathiba et al. 2022). Microscopic examinations demonstrated the presence of a significant biofilm layer on the anode of the fuel cell. The generation of power is influenced by various factors, including the kinetic reaction of oxygen, the surface area of the electrodes, electrolytic resistance, and the ability of microorganisms to transfer electrons. Aiyer (2020) examined the impact of operating conditions on a mediator-less microbial fuel cell. The pH must be 7, and the resistance needs to exceed 500 Ω , based on the conclusions drawn from the study. However, inadequate proton and oxygen supply

was seen when the resistance was less than 200 V; hence, a fuel cell must have a strong reducing activity in order to be effective (Jatoi et al. 2021).

Direct electron transfer (DET)

The bacterial cell membrane or a membrane organelle physically contacts the fuel cell anode to initiate the direct electron transfer. The microorganisms must have membrane-bound electron transport protein relays that move electrons from the inside of the bacterial cell to the outside, ending in an outer-membrane (OM) redox protein that permits the electron transfer to an external, solid electron acceptor (a metal oxide or an MFC anode) (Schröder 2007).

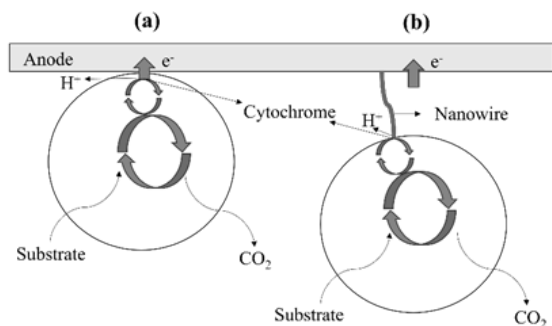


Fig. 2. (a) Membrane-bound cytochrome and (b) Electrically conducting nanowires are used to demonstrate the DET (Schröder 2007).

Mediated electron transfer (MET)

A non-conductive lipid membrane, comprising peptidoglycans and lipopolysaccharides, surrounds various microorganisms, including *Saccharomyces* species and *E. coli*, which are utilized in some MFCs. This membrane slows down the direct electron transmission to the anode. Hence, the need arises for shuttles or electron mediators which act as carriers for moving the electrons generated in the anodic chamber to

the anode. The ability to pass through the bacterial membrane is necessary for mediators to reach the reductive species within the bacteria and undergo reduction during microbial metabolism. Certain bacteria can use nanowires and pili, or microbial compounds known as endogenous mediators, to move electrons from the substrate to the anode. We refer to these types of bacteria as electrogenesis bacteria (Aghababae et al. 2015).

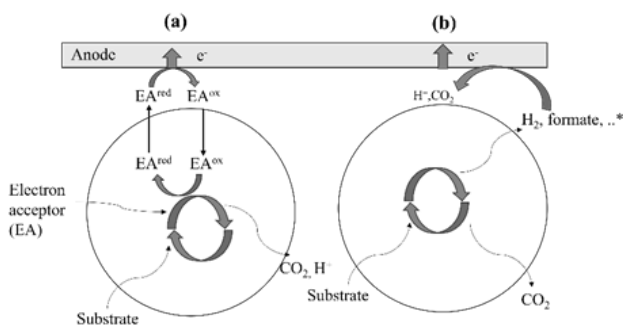


Fig. 3. MET is shown schematically in two simplified ways: (A) through reduced terminal electron acceptors (anaerobic respiration), and (B) by oxidation of reduced fermentation products (Schröder 2007).

Cathodic electron transfer mechanism

There is a relative scarcity of studies that focus on comparing cathodic electron transfer techniques, specifically from cathode material to microbiological cells, with anode electron transfer mechanisms. A study indicates that electrons can transfer from cathode material to the outer cell of bacteria through two distinct pathways: direct and indirect (Kumar et al. 2016). The most prevalent use of cathode electron transfer to microbial cells is for bioremediation of environmental pollutants. Bio-cathodic microbial fuel cells produce methane, other carbon-containing molecules, and hydrogen via the mechanism of electron transfer from the cathode material to

the bacteria (Cheng et al., 2009; Rozendal et al., 2008; Prathiba et al. 2022).

Applications of MFCs

Production of bioelectricity

The chemical energy contained in the chemical components of biomass can be transformed into electrical energy by microorganisms using microbial fuel cells. It has been demonstrated that *R. ferrireducens* can produce energy with an electron yield of up to 80%. The oxidation of formate using Pt black as a catalyst was reported to have an exceptionally high Coulombic efficiency of 97%. For the purpose of sending signals, like temperature, to receivers in remote locations, MFCs are particularly well-suited for powering wireless sensors and compact telemetry systems with low power requirements (Chaudhuri et al. 2003; Do et al. 2018)

Hydrogen bioproduction

It is easy to modify MFCs so that they produce hydrogen rather than electricity. It is possible to store hydrogen for use at a later time. Protons released by the anodic reaction move to the cathode under typical working circumstances, where they mix with oxygen to generate water (Du et al., 2007; Do et al. 2018).

Biosensor

Sensor pollutant analysis, along with in situ process monitoring and control, are further applications for MFC technology. Biosensors for immediate BOD estimate have been constructed utilizing MFC technology, which comprises a transducer with a biological sensing element. The MFC-based sensors have applications for online wastewater monitoring because they are robust over the long term and can potentially use frequently (Feng et al., 2013).

Treatment of wastewater

Studies have demonstrated that biological treatment is a widely utilized, dependable, and very economical method for removing nitrogen and organic debris from leachate. The unique capacity of MFCs employing certain microorganisms to

eliminate sulfides as needed for wastewater treatment. MFCs can confirm that bio electrochemically active microorganisms have strong operational stabilities by promoting their growth during wastewater treatment. There have been reports of a colonic efficiency of up to 80%, and in specific circumstances, up to 90% of the COD can be abolished (Ramadan et al. 2017).

Drawbacks

MFCs present a range of advantages and disadvantages in their field applications. Prior to the commercialization of MFC technology, it is essential to address the operational challenges, such as inadequate power output and elevated running costs. The capital cost of the MFC is generally 30 times higher than that of traditional activated sludge treatment systems for household wastewater, as noted by Rahimnejad et al. in 2014. While MFC technology has seen diverse applications, several challenges remain that need to be addressed for the technology to achieve profitability. Identifying an effective strategy to enhance the MFC represents the initial significant challenge. In evaluating the potential for scaling up previous designs for sustained operations, we identify several constraints, including elevated internal resistance, the distance between electrodes, and the exchange of anolytes and catholytes across the PEM, among others. However, some concepts have been demonstrated but remain unexamined in an industrial context. The second challenge involves the development of cost-effective electrode materials and, if relevant, PEM for MFCs. The electrode materials currently accessible, including carbon paper and carbon cloth, are likely to incur significant costs (Liu et al. 2013).

Activation losses (AL)

Decreases in Activation (AL) Multiple electrochemical processes take place at the electrode surface during the operation of the MFC. An activation energy is necessary for these electrochemical redox processes. This activation energy is essential for facilitating electron transport to the electrolyte/feed oxidation at the anode or for the reduction of O₂ as a terminal acceptor at the cathode. Increasing the process temperature to a specific level may lead to a reduction in the

AL. In a similar manner, it can be minimized by improving electrode catalysis through the incorporation of a catalyst into the electrode material. Conversely, the development of biofilm on the electrode surface, along with the expansion of the electrode surface area, can lead to suboptimal AL (Do et al. 2018).

Concentration polarization (CP)

When the electrode side oxidizes the substrate more quickly than it could be transported towards the electrode (anode) surface, CP occurs. The greater oxidative strength of the anode in MFCs is generally thought to be the cause of this. This phenomenon might be troublesome, though, in situations when flow is significantly slowed down, such as in dense, non-conductive anodophilic bacterial biofilms, hydrodynamics, and geometrical characteristics (Do et al. 2018).

Ohmic losses (OL)

Interconnections, resistance to ion transfer via membranes, and resistance to ion transfer through electrolyte were the primary causes of OL in MFC. But, because of poor connections or decreased electrolyte conductivity, the resistance across the MFC may increase quickly. The electrolyte's free stream, bacterial biofilm growth, high conductivity, and adequate turbulence for adequate H^+ flow towards the separator and cathode electrode materials must all be maintained by the anode material arrangement. To reduce cathode resistance (CR), active exoelectrogenic microorganisms or materials can be used as a biocatalyst or catalyst. Increases in the cathode's specific surface area and mass transport rate may also result in a reduction in the CR (Do et al. 2018).

Potential losses (PL)

The thermodynamically predicted potential, or cell electromotive force (Ethermo), is always higher than the operating voltage (Vop) produced by MFC. There is no way to reverse these possible losses. Energy loss in MFCs can happen in a number of ways, including activation loss (perhaps for starting the reactions on both electrodes and extracellular electron transfer to the anode), bacterial metabolism loss

(because bacteria get energy by oxidizing the substrate), mass transfer loss (because of the reactants' restricted flow to the electrode), and ohmic losses (because of charge transfer resistance and proton diffusion resistance) (Du et al. 2007)

CONCLUSION

Wastewater is acknowledged as a significant factor in environmental pollution. The current energy and economic constraints of modern wastewater treatment technology make it challenging to achieve and maintain wastewater recovery. Microbial fuel cells (MFCs) have undergone extensive investigation and are now acknowledged as a groundbreaking technology, especially notable for their benefits in the wastewater treatment field. This study outlined the essential architecture and design characteristics of microbial fuel cells. A notable characteristic that sets MFCs apart from other wastewater treatment techniques is anaerobic digestion (AD). MFCs improve energy generation, reduce sludge buildup, and promote energy conservation. The main MFCs used for wastewater treatment were contaminated with anaerobic or aerobic sludge, thereby eliminating the need for a mediator. Optimal pH and temperature, akin to other microbial systems, promote bacterial proliferation and thereby increase MFC effectiveness. Salinity and ionic strength represent additional essential factors. Elevated salinity and ionic strength can improve the conductivity of the substrate and boost MFC performance, despite the negative impacts of salt on microbial growth. The composition and design of the anode, cathode, and membrane play a crucial role in determining the cost and efficiency of MFCs and should be carefully evaluated throughout their development process.

FUTURE SCOPE

MFCs demonstrate effectiveness in addressing hazardous wastewaters, particularly those from industrial sources that are laden with heavy metals and toxic compounds. Saline wastewaters can be processed in this way, depending on their compatibility with the salinity levels of the anode chamber. As a result, MFC could be considered promising systems for addressing various forms of wastewater treatment.

The electricity generation from MFC is minimal; however, wastewater treatment remains a primary focus in this area. Taking into account the previously discussed factors is essential for attaining the best outcomes in wastewater treatment and energy production. Metabolic engineering can be utilized to enhance bacterial metabolism, thereby boosting cell potential when energy generation is desired. The combination of electricigenic bacteria with fundamental substrates such as acetate, considering the design factors, could yield a higher potential. In wastewater treatment processes, the use of modified bacteria is impractical; consequently, activated sludge is often used as the inoculum for microbial fuel cells (MFC). The expansion of MFC is a debated issue, and there is a lack of comprehension surrounding it. The creation of innovative materials and technologies for MFC production, coupled with an examination of the elements affecting MFC performance, will enhance the implementation of MFCs in extensive wastewater treatment processes. In the construction of an MFC, it is essential to take into account the material and surface area of the anode, cathode, and membrane, along with the distances between electrodes and the potential for scalability. In summary, developing a cost-efficient MFC for scalable wastewater treatment that also boasts significant power generation potential is beneficial.

Conflict of Interest

There is no conflict of interest related to the study.

Author contributions

Acquisition and interpretation of data is done by Arijit Banerjee, Kalyani Shao, Khondekar Maksuda Begam, Katyayini Singh, Amima Maswood and Aritri Josh. Conception, design and revising of the article are done by Rupesh Dutta Banik.

Acknowledgement

I would like to express my special thanks of gratitude to the higher dignitaries of Swami Vivekananda University for allowing me to carry out the study.

REFERENCES

- Aghababaie, M., Farhadian, M., Jeihanipour, A., & Biria, D. (2015). Effective factors on the performance of microbial fuel cells in wastewater treatment—a review. *Environmental Technology Reviews*, 4(1), 71-89, <https://doi.org/10.1080/09593330.2015.1077896>
- Aiyer, K. S. (2020). How does electron transfer occur in microbial fuel cells?. *World Journal of Microbiology and Biotechnology*, 36(2), 19, <https://doi.org/10.1007/s11274-020-2801-z>
- Arun, S., Sinharoy, A., Pakshirajan, K., & Lens, P. N. (2020). Algae based microbial fuel cells for wastewater treatment and recovery of value-added products. *Renewable and Sustainable Energy Reviews*, 132, 110041, <https://doi.org/10.1016/j.rser.2020.110041>
- Chaudhuri, S. K., & Lovley, D. R. (2003). Electricity generation by direct oxidation of glucose in mediatorless microbial fuel cells. *Nature biotechnology*, 21(10), <https://doi.org/10.1038/nbt867>
- Cheng, S., Xing, D., Call, D. F., & Logan, B. E. (2009). Direct biological conversion of electrical current into methane by electromethanogenesis. *Environmental science & technology*, 43(10), 3953-3958, <https://doi.org/10.1021/es803531g>
- Choudhury, P., Prasad Uday, U. S., Bandyopadhyay, T. K., Ray, R. N., & Bhunia, B. (2017). Performance improvement of microbial fuel cell (MFC) using suitable electrode and Bioengineered organisms: A review. *Bioengineered*, 8(5), 471-487, <https://doi.org/10.1080/21655979.2016.1267883>
- Do, M. H., Ngo, H. H., Guo, W. S., Liu, Y., Chang, S. W., Nguyen, D. D., ... & Ni, B. J. (2018). Challenges in the application of microbial fuel cells to wastewater treatment and energy production: a mini review. *Science of the Total Environment*, 639, 910-920, <https://doi.org/10.1016/j.scitotenv.2018.05.136>
- Do, M. H., Ngo, H. H., Guo, W. S., Liu, Y., Chang, S. W., Nguyen, D. D., ... & Ni, B. J. (2018). Challenges in the application of microbial fuel cells to wastewater treatment and energy production: a mini review. *Science of the Total Environment*, 639, 910-920, <https://doi.org/10.1016/j.scitotenv.2018.05.136>

Do, M. H., Ngo, H. H., Guo, W., Chang, S. W., Nguyen, D. D., Liu, Y., ... & Kumar, M. (2020). Microbial fuel cell-based biosensor for online monitoring wastewater quality: a critical review. *Science of The Total Environment*, 712, 135612, <https://doi.org/10.1016/j.scitotenv.2019.135612>

Du, Z., Li, H., & Gu, T. (2007). A state of the art review on microbial fuel cells: a promising technology for wastewater treatment and bioenergy. *Biotechnology advances*, 25(5), 464-482, <https://doi.org/10.1016/j.biotechadv.2007.05.004>

Enamala, M. K., Dixit, R., Tangellapally, A., Singh, M., Dinakarrao, S. M. P., Chavali, M., ... & Chandrasekhar, K. (2020). Photosynthetic microorganisms (Algae) mediated bioelectricity generation in microbial fuel cell: Concise review. *Environmental Technology & Innovation*, 19, 100959, <https://doi.org/10.1016/j.eti.2020.100959>

Feng, Y., Barr, W., & Harper Jr, W. F. (2013). Neural network processing of microbial fuel cell signals for the identification of chemicals present in water. *Journal of environmental management*, 120, 84-92, <https://doi.org/10.1016/j.jenvman.2013.01.018>

He, L., Du, P., Chen, Y., Lu, H., Cheng, X., Chang, B., & Wang, Z. (2017). Advances in microbial fuel cells for wastewater treatment. *Renewable and Sustainable Energy Reviews*, 71, 388-403, <https://doi.org/10.1016/j.rser.2016.12.069>

Jatoi, A. S., Akhter, F., Mazari, S. A., Sabzoi, N., Aziz, S., Soomro, S. A., ... & Ahmed, S. (2021). Advanced microbial fuel cell for waste water treatment—a review. *Environmental Science and Pollution Research*, 28, 5005-5019, <https://doi.org/10.1007/s11356-020-11691-2>

Jatoi, A. S., Tunio, M., Riaz, S., Abro, R., Wajahat, M. H., Qureshi, K., ... & Mubarak, N. M. (2018). Utilization of distillery effluent as substrate for power generation with optimized parametric conditions using microbial fuel cell. *Eurasian J. Anal. Chem*, 13, 94978, <https://doi.org/10.29333/ejac/94974>

Khan, A., Chen, Z., Zhao, S., Ni, H., Pei, Y., Xu, R., ... & Li, X. (2019). Micro-aeration in anode chamber promotes p-nitrophenol degradation and electricity generation in microbial fuel cell. *Bioresource technology*, 285, 121291, <https://doi.org/10.1016/j.biortech.2019.03.130>

Kim, B., An, J., Fapyane, D., & Chang, I. S. (2015). Bioelectronic

platforms for optimal bio-anode of bio-electrochemical systems: from nano-to macro scopes. *Bioresource Technology*, 195, 2-13, <https://doi.org/10.1016/j.biortech.2015.06.061>

Kumar, R., Singh, L., & Zularisam, A. W. (2016). Exoelectrogens: recent advances in molecular drivers involved in extracellular electron transfer and strategies used to improve it for microbial fuel cell applications. *Renewable and Sustainable Energy Reviews*, 56, 1322-1336, <https://doi.org/10.1016/j.rser.2015.12.029>

Liu, J., Liu, L., Gao, B., & Yang, F. (2013). Integration of bio-electrochemical cell in membrane bioreactor for membrane cathode fouling reduction through electricity generation. *Journal of Membrane Science*, 430, 196-202, <https://doi.org/10.1016/j.memsci.2012.11.046>

Prathiba, S., Kumar, P. S., & Vo, D. V. N. (2022). Recent advancements in microbial fuel cells: A review on its electron transfer mechanisms, microbial community, types of substrates and design for bio-electrochemical treatment. *Chemosphere*, 286, 131856, <https://doi.org/10.1016/j.chemosphere.2021.131856>

Rahimnejad, M., Bakeri, G., Najafpour, G., Ghasemi, M., & Oh, S. E. (2014). A review on the effect of proton exchange membranes in microbial fuel cells. *Biofuel Research Journal*, 1(1), 7-15, <https://doi.org/10.18331/BRJ2015.1.1.4>

Ramadan, B. S. (2017). Challenges and opportunities of microbial fuel cells (MFCs) technology development in Indonesia. In *MATEC Web of Conferences* (Vol. 101, p. 02018). EDP Sciences, <https://doi.org/10.1051/mateconf/201710102018>

Rozendal, R. A., Hamelers, H. V., & Buisman, C. J. (2006). Effects of membrane cation transport on pH and microbial fuel cell performance. *Environmental science & technology*, 40(17), 5206-5211, <https://doi.org/10.1021/es060387r>

Rozendal, R. A., Jeremiasse, A. W., Hamelers, H. V., & Buisman, C. J. (2008). Hydrogen production with a microbial biocathode. *Environmental science & technology*, 42(2), 629-634, <https://doi.org/10.1021/es071720&plus>

Schröder, U. (2007). Anodic electron transfer mechanisms in microbial fuel cells and their energy efficiency. *Physical Chemistry Chemical Physics*, 9(21), 2619-2629, <https://doi.org/10.1039/B703627M>