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Exploring the role of microbial fuel cells in sustainable wastewater treatment and energy generation

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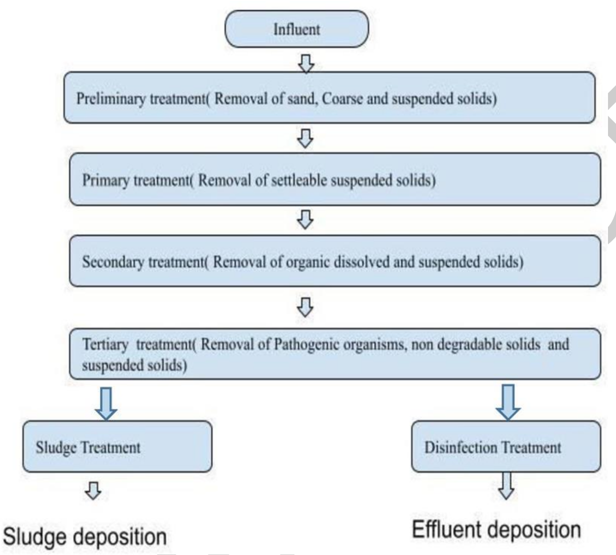
Graphical abstract



Abstract

Microbial Fuel Cells (MFCs) offers a promising solution for addressing both waste water treatment and challenges in renewable energy production. This study aims to explore the integration of MFCs with adsorption/bio-oxidation (AB) process to tackle wastewater management difficulties while generating renewable energy. By investigating microbial mechanisms within MFCs, enhancing pollutant removal efficacy, and assessing MFC application feasibility, we seek to advance eco-friendly wastewater treatment and renewable energy harvesting. Lab-scale experiments will identify microbial communities, characterize electron transfer processes, and evaluate MFC performance in pollutant removal. Through systematic experimentation with varied operational parameters and substrate concentrations, we aim to optimize MFC efficiency. Electrochemical assessments, including power output tests and electron flow rates, quantify MFC energy generation capabilities. Environmental and financial sustainability aspects, such as cost-benefit analysis and life cycle assessment, will be integrated to assess MFC viability compared to traditional wastewater treatment systems. The outcomes of this research will contribute to scientific knowledge expansion, providing insights for policymakers, water utilities, and environmentalists to embrace green technologies for water contamination mitigation, energy efficiency enhancement, and sustainable development.

Keywords: Microbial fuel cells (MFCs), Wastewater treatment, Renewable energy, Sustainable technology, Microbial communities, Power generation and Life cycle assessment.

1. Introduction

Microbial fuel cells (MFCs) are a likely emerging technology and an example of an innovation where wastewater treatment and renewable energy generation meet. Due to the rising interest in the world towards water pollution and also energy conservation, many researchers and innovators are now dedicating their efforts in trying to find solutions in this field. MFCs give a unique approach based on microbial communities that use both existing energy and (or) power for treating wastewater in order to produce electricity.

Wastewater operations or management stares as a crucial environmental challenge especially in the urban areas where the increased population. The underlying principle behind MFCs is the fact that some certain microorganisms (Electricity-generating bacteria) do pass the electricity from organic compounds to the electrode and thus the current is generated. This EET, by outside electrical chemical transition, is the underlying process that works as the basis of MFC operation. MFC systems create suitable conditions for these specific types of electricity-producing bacteria. Ultimately, it helps to mitigate pollution and furnish electricity.

With the inception of MFC technique into wastewater treatment systems there are multitudes of advantages that come into view. Specifically, MFCs use a distributed treatment method, being so that it is possible to carry out the on-site wastewater treatment in the small scale which is especially advantageous for remote location or resource limited. Another advantage is that the power yielded by MFCs can be used to electrically conduct the treatment process itself which in turn will diminish the overall power demand that the treatment system requires and make it more sustainable. Besides recovering these nutrients, approximately 50% of nitrogen and phosphorus content in the wastewater can also be recovered by MFCs which helps in circular economy concepts

Although there are chances these MFCs can significantly contribute to wastewater treatment and energy generation, this field is still away from these factors research gaps and environmental challenges will encompass maxing out MFC performance, attending to microbial communities and their activity, increasing MFC prototypes in terms of relevance and scale, taking care of long term stability and reliability, and conducting economic analysis and environmental impact assessment.

This research creatively blends AB process with MFC's to address waste water management and renewable energy production at the same time. Our objective is to improve the efficiency of pollutant removal and advance sustainable development through the optimization of operational parameters and comprehensive assessments. Our method provides a comprehensive solution for the sustainable management of wastewater and the harvesting of renewable energy. This research subject aims to overcome these obstacles and consequently to the promotion of the progress of MFC technology as an environmentally sustainable treatment of wastewater and power generation technology. The investigation of microbial processes, the optimization of operational parameters, the evaluation of performance metrics, and the consideration of economic and environmental aspects are the research objectives of this study which aims to be of value for making decisions on the application of FMCs as an efficient solution for the waste management and energy production while dealing with the environmental issues concurrently lotion adds to the industrial activities thus leading to generation of large volumes of polluted water. Common water and wastewater treatment methods consume quite a large amount of energy and they can also be highly expensive to run, which makes it necessary to look for less energy-consuming and economically viable solutions, therefore. Because MFCs use the microorganisms found in wastewater to decompose organic contaminants while extracting nutrients, they have the ability to completely change the current paradigm. This has the potential to support the simultaneous production of renewable energy from animal waste and clean water. Mainly the use of new electrode materials like graphene oxide, the incorporation of cyanobacteria cells atop graphene oxide nanosheets to improve the efficiency of electron exchange and the breakdown of pollutants. Compared to conventional MFC designs, this novel technique enables enhanced microbial fuel cell (MFC) performance, resulting in increased power production levels and more efficient simultaneous wastewater treatment and renewable energy generation.

1.1. Objectives

1. Research the microbial consortiums as active players in microbial fuel cells (MFCs) and their role in hydro-electro catalysis processes in electricity production.
2. Search for the optimal operational parameters such as substrate concentration, electrode material as well as reactor system to ensure that MFC has the best performance in wastewater treatment.
3. Conduct the appraisal of MFCs contribution to the elimination of organic contaminants and nutrients, especially nitrogen and phosphorus, in flows.
4. Examine the physical signatures of the working of MFCs, including the generation of power, the output energy and the rate of electron transfer from donor to acceptor.
5. Analyzing the degree to which MFCs can be long-term stable and reliable under continuous operation that require wastewater treatment methods has been sustainable.
6. Perform an economic study of integrating MFC technology into wastewater treatment plants, taking into account the technology and system cost.

2. Review of literature

Liu *et al.* (2023) worked to improve the wastewater treatment and electricity generation in the microbial fuel cell (MFCs) using the novel approach to fix the S. oneidensis MR-1 on the surface of the graphene oxide (GO) which has been reduced. For the experiment, bio anodes were constructed with the cyanobacteria cells immobilized on (GO) Nano sheets, thus generating an active biomaterial suitable for electron exchange. Such set-ups showed better MFCs functioning that extended to high power production and more pollutants degradation which were attributed to the enhanced formation of biofilm and electron transfer capabilities of the (GO) surface-immobilized bacteria. Through this research, the possibility of a biofilm-filtered MFC system is brought to the surface serving the purpose of sustainability in wastewater treatment and renewable energy yield, however this study could be exploited to develop new electrode materials and improve microbial interaction in MFC design.

Zhao *et al.* (2023) came up with a new collector design for MFCs that was meant to have the sludge features which were entrapped in polyvinyl alcohol (PVA) cryogen. This study was designed for the integrated removal of nitrogen and phosphate from wastewater treatment facilities employing microbial fuel cell technique. They synthesized the anode material by allowing activated sludge to be incorporated within a PVA-hydrogel, which has a high surface area and enhanced conductivity to support intensive microbial activity and nutrient uptake. In comparison to the separated cathode, the integrated anode showed high capabilities in pollution removal, as nitrogen and phosphorus concentrations showed large decreases after the treated water passed through. This investigation paves a way for the fabrication of superior cathode material as it is widely used in the MFC application notably in nutrient-rich wastewater treatment scenarios, suggesting its tremendous role in nutrient recovery and ecological environmental cleaning.

Wang *et al.* (2023) experiment focused on investigating MFC-MEC's performance and microbial community dynamics in a system that processed real wastewater to remove nitrogen. The observation related to the use of self-driven mechanisms and microbial interaction to develop a solution for sustainable resource recovery and wastewater treatment was the central issue of investigation. In microbial interactions and associated microbial communities, they detected a major part of nitrogen removal as well as electricity production and identified some of the microorganisms that were involved in nitrogen transformation. This research adds to the knowledge base on combined MFC-MEC systems, which can possibly be used concurrently to reduce nutrient concentrations and to recover energy through microbial processes thereby showing the connection of microbial processes to environmental biotechnology activities.

Zhang *et al.* (2023) reported the utilization of GAC combined with a biofilm carriers' in a multi- chamber MFC system for water treatment of groundwater. The case of the study was directed towards boosting the energy generation and the nitrate removal efficiency in BFCs via using advanced electrode materials and reactor designs. Through ensemble of GAC as a coactive and sorptive medium in the anode chamber and inclusion of biofilm carriers to multiply microbial activity, the scientists have successfully retrieved the rise of MFC performance, which involved heightened power generation as well as nitrate dissolution. It becomes clear that the formation of biofilm is the crucial stage in the reactor design for bio-electrochemical and bio-energy processes developed on the basis of MFC systems.

Yu and Xu (2023), in this regard, did a written review of bifurcated anodes that use nanomaterials in microbial fuel cell (MFCs). A range of nanostructured materials was investigated in the review, including carbon nanotubes, graphene, and metal oxide, by the investigation of the mechanisms of electron transfer kinetics, surface area, and conductivity increase in anodes of microbial fuel cells. The paper smartly classified anode self-fabrication processes, performance improvements, and challenges used in the MFC application. It gives ideas about the electrode structures that may be used to enhance the efficiency of MFCs and products that are applicable.

Feng *et al.* (2023), the application of MFC and MEC for antibiotics removal in waterways might be achieved. It is a collective effect of the bio system in a community where a multi electrode type of MFC-MEC can be applied for pharmaceutical wastewaters purpose. They pinpointed the electrochemical processes, microbial interactions, and the setup of the reactor plant of biofilms into antibiotics degradation and recovery of energy. Here, study is presented with a narrative of innovative bioreactor designs and of electrochemical mechanisms helpful in MFC-based systems, and it has effects for sustainable wastewater management and the environment.

Xu *et al.* (2023) have scrutinized the current trends of engineering solutions for wastewater treatment via utilization of microbial electrochemical technologies, i.e., microbial fuel cells (MFCs). The review discussed the different functionalities including the removal of nutrients, biogas and value-added product synthesis. The paper discussed two aspects of bioremediation, bacteria mechanisms and urine metabolism, which were correlated with sustainable wastewater treatment and resource utilization. The research described the possibility and validity of MFCs with other technologies for transforming wastewater disposal into a precious resource recovery process which would be the way to environment sustainability and would follow the green economy (circular economy) principles.

Wang *et al.* (2023) concentrated on discovering that they have sludge-derived biochar materials used in microbial fuel cells (MFCs) which streamline wastewater treatment and electricity generation. The exploration comprised two key elements: the electrochemistry and performance of bio char-based anodes in wastewater treatment. Analysis demonstrated that biochar-derived anode manifests promising business opportunities in organic issue degradation and electron mobility, which emphasizes the capacity of waste materials to be used in MFC applications for environmental remediation and renewable energy production.

Hu *et al.* (2023), a review is about how the combination of anaerobic digestion with microbial fuel cells (MFC) can be used for wastewater bioconversion to bioenergy. The review covered all these issues i.e, process optimization, system scalability, energy recovery techniques and microbial community dynamics. The research informed that using anaerobic digestion in combination with MFCs helps one to exploit bioenergy for waste. In addition, one can generate biogas and treat wastewater in an eco-friendly manner. The study acquired advice on how the system could be improved for optimized systems performance and best resource utilization.

Zhang *et al.* (2023) was written about, recent MFC development in treatment of by-products and bioenergy production was discussed. This research focused on improvements in electrode materials, opting for system design, and performance tuning. It stressed on the progress of high efficiency MFC designs with leadership in treating pollutants and generation of electricity from a wide variety of waste streams. In effect, the research presented a sweeping overview of up to date MFC technology which offers insights regarding continuous R&D initiatives into increasing the sustainability and efficiency of MFC-based wastewater treatment.

Yang *et al.* (2023), the enhanced denitrification performances were highlighted. This section envisaged how cathodes might be instrumental in maintaining nitrogen balance and proposed approaches to increase MFC systems' capacity for nitrogen removal in wastewaters high in nitrogen. The paper gave emphasis on bio cathode design, material selection and microbial interaction as the core elements for achievement of denitrification and environmental remediation through utilization of MFCs systems.

Huang *et al.* (2023), A review on innovative electrode materials for microbial fuel cells (MFCs) as examples used by them for improving performance and electricity generation purposes was conducted. The article covered Nano-structured materials, conductive bio char and an upgraded type of electrode, among other things. A closer look at the electrochemical properties, surface features, and performance aspects of anodes and cathodes was the scope of the presentation in the realm of MFC applications. The study helped in developing suggestions for further improvements to the electrode configuration so as to achieve a higher and efficient performance by the MFC for the wastewater treatment and energy generation tasks.

Zhang *et al.* (2023) was described to significantly contribute to the development of wastewater treatment and bioenergy production methods. The investigation was exploring the interactive interplay of MFCs and BES, in particular, how they are merging their strengths in the fields of contaminants transformation, energy recovery and resource utilization. The article covers the design aspects, operation metrics including efficiencies, and performance improvements of integrated MFC-BES systems. The article is aimed at devising strategies for varied ecological uses.

Li *et al.* (2023) illustrated how MFCs generate electric energy and treat wastewater simultaneously. They rely on novel materials for electrodes. The research focused on performance optimization, characterization of the electrode, and system configuration including renewable energy production and pollutant removal using MFC-based systems. In this, the technology enabled us to know about the continuous high-performance MFC formations that could resolve environmental problems whilst exploiting the energy from wastewater.

Wang *et al.* (2023), carried out an experiment with graphene oxide as cathode material in MFCs to both generate more electricity and treat wastewater at the same time. The research dedicated to graphene oxide-grade cathodes was majorly oriented at the exploration of the electrochemical specifications and systems of the graphene oxide-grade cathodes for the purpose of pollutant removal. The relatively effective adsorption and degree of degradation of the pollutants and the consistent electricity generation performance system, the oxide graphene is observed to be promising and thus has the potential to be useful in a variety of MFC applications for the field of wastewater treatment.

The latest developments and wide range of uses for microbial fuel cells (MFCs) in the production of renewable energy and wastewater treatment were elaborated. Studies by Liu *et al.* (2023) and Zhao *et al.* (2023) have demonstrated key discoveries, which include advances in electrode materials and collector designs to enhance MFC efficiency and pollutant removal. Furthermore, studies conducted by Hu *et al.* (2023) and Wang *et al.* (2023) investigate how MFCs might be integrated with other technologies to maximize the generation of bioenergy from wastewater. Additionally, studies conducted by Yang *et al.* (2023) and Zhang *et al.* (2023) provide insight into cathode designs and electrode material innovations to enhance MFC performance in denitrification and bioenergy generation. The development of sustainable wastewater treatment techniques and renewable energy solutions is greatly aided by the combined results of these studies. Furthermore, these investigations provided valuable insights into electrode material innovations and cathode designs, which influenced the proposed model's design and performance optimization strategies.

3. Materials and methods

3.1. Biological structure

3.1.1. Influent Pretreatment

- Screening: Get large floating trays, solids, and objects from the wastewater using mechanical machines like strain or filters.
- Grit Removal: Distinguishes sand, gravel and other heavy materials that should not reach adjacent audience.

3.1.2. Primary Treatment

- Sedimentation/Clarification: The outer layer for the visible and large particles in the wastewater to get settled out. Later on, a sludge will form at the bottom of the settling tanks or clarifiers.
- Floatation: Causes oils, fats, and greases (FOGs) to float as opposed to completely entering the pipeline. These are later removed at the surface for skimming.

3.1.3. Biological Treatment

- Aeration Tanks/Bioreactors: Activated Sludge Process: Takes advantage of microbial communities in the tanks during the aeration step which help metabolize organic matters and pollution, then produce the sludge and effluent.
- Sequencing Batch Reactors (SBR): Runs in bucket modes with countercurrent separated actions of aeration, settling and decanting to make biological treatment effective.
- Membrane Bioreactors (MBR): Combination of membrane ultrafiltration with biological

treatment which are capable of separating biomass from effluent thus produce an effluent which has been highly purified and almost pollution free.

- Trickling Filters: Bio filtration is a kind of wastewater treatment media that is purely packed with microbes growing over the support of a biofilm for reactions.
- Rotating Biological Contactors (RBC): Utilize discs with rotation whose purpose is the growth of microbes to achieve biological purification.

3.1.4. Secondary Treatment

- Secondary Clarification: Distinguishes biomass (the activated sludge) from treated effluent, thus keeping sludge to be returned to the bioreactor where it gets oxidized.
- Filtration: It involves various filtration processes such as (e.g., sand filters, microfiltration). The suspension solids can also be removed.

3.1.5. Tertiary Treatment (if needed for advanced treatment)

- Advanced Filtration: Applies methods for example UF (Ultrafiltration), NF (Nano filtration), or RO (Reverse osmosis) that are taken for fine particle and contaminant removal.
- Disinfection: Employ either chemical (such as chlorine, ozone treatment) or physical (for example, UV irradiation) methods to disinfect treated effluent and safely remove pathogens.

3.1.6. Sludge Handling and Treatment

- Thickening: De-water the concentrates that will remove the water component and decrease their volume for more treatment processes.
- Digestion: By means of sludge anaerobic digestion, break down the organics and from the sludge creates biogas (methane) and stabilized for the waste disposal or reuse.
- Dewatering: Completes the drying process by removing the water from sludge to form “cake” material for disposal or beneficial use purposes (for instance, land application or composting).
- Disposal/Reuse: Eliminates the treated sludge as per regulations or uses it to improve the soil, generate energy, or become a part of the farm cultivation.

3.1.7. Effluent Discharge

- Effluent Monitoring: Regulates periodic monitoring of the discharged effluent for its compliance with legal limits, set by regulatory standards.
- Outfall/Discharge Point: Releases of treated effluent into receiving rivers or designated areas in compliance with regulations is a possible.

3.1.8. Control, Monitoring, and Automation:

- Process Control Systems: Adopts sensors, controllers and the automation to optimize the process affordability like aeration, pH and dissolved oxygen. This will help to execute the performance of the process.
- Monitoring and Analysis: Analysis of important variables (for instance, COD, BOD, ammonia, nitrate) is carried out to assess the plant operations and adjust these when required.

3.1.9. Safety and Environmental Compliance:

- Safety Measures: As the safety measures, including chemicals management, exposure to hazards and workers' protection are all done, stringent as well comprehensive protocols, devices utilized and training programs have to be, not excepted.
- Environmental Compliance: is in compliance with environmental regulations, permits, and standards concerning wastewater treatment, final effluent, and discharge limit. The process for the effluent treatment was shown in the Figure 1.

3.2. Reasons for microbial fuel cell installation in treatment plants

3.2.1. Enhanced Energy Recovery:

MFCs can use the microorganisms to break down the organic material into electricity straight away, which has no environmental impacts. Energy generated through this process could be used alongside or in place of energy which is used at the treatment plant, thus leading to reduced or recycled expenditure for energy and sustainability.

3.2.2. Renewable Energy Generation:

MFCs provided renewable energy in the form of electricity that do not highly rely or use combustion of fossil fuels at all. It meets the sustainability features of the treatment center and also reduces from 50% to 70% carbon footprint of the facility.

3.2.3. Resource Efficiency

Sewage is a resource in its own right and by using MFCs we are able to save energy from its discharge as well as to use it as a source of renewable energy. Thus, it helps in reducing waste and applying circular economy methodology.

3.2.4. Improved Treatment Performance:

MFCs provide resources of energy which can then function to move the biosand filter processes forward by stimulating the microorganisms' activities and metabolic reactions. They create necessary framework for microorganisms' accommodation, and as a result we are able to achieve better removal and better water quality.

3.2.5. Bio augmentation and Microbial Diversity:

The inclusion MFCs infuse microbial species and bio-augmentation possibilities to the whole system of remediation such is a microbial community’s ability to be upgraded by this that there is treatment unyielding to deleterious changes in the environment.

3.2.6. Reduced Sludge Production:

MFCs have the ability to reduce the amount of sludge produced through their promotion of the oxidation of organic matter by microbes, and hence lead to less excess sludge, which is usually the case in traditional aerobic treatment systems. It results in the decrease in the disposal cost and is environmentally proven as there is on a sludge control.

3.2.7. Decentralized and Off-Grid Solutions:

Decentralized or off-grid MFC installations can be installed as wastewater decentralizing or off-grid solutions, especially when they are necessary in areas which are remote or resource constrained. They provide a base for the modular and integrated hardware and software solutions designed to fit to the unique environmental and economic situations.

3.2.8. Demonstration of Innovative Technology:

The integration of MFCS in a biological treatment system is a means not only of presenting innovative technologies but also demonstrating sustainability as well. The application of this complex facet shows preparedness, readiness for the development of new methods for treating sewage and retrieval of energy.

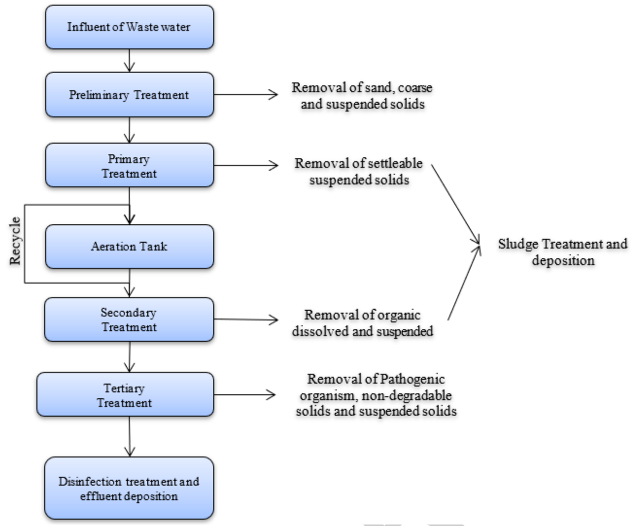


Figure 1. Effluent treatment process

4. Results and discussion

4.1. Working of a microbial fuel cells

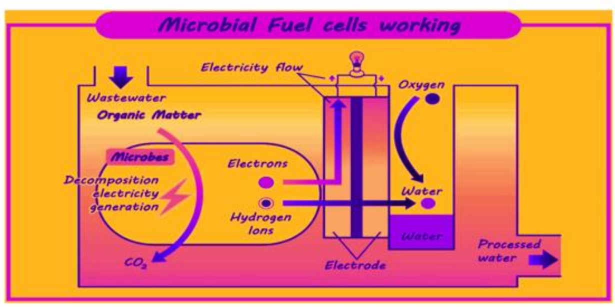


Figure 2. Working of a Microbial fuel model

It is an ideal biochemical structure that utilizes microbial activity to transform organic matter to electrical power. Inside the anode compartment, these Micronics consume carbon materials, generating electrons and protons with the help of water. An ionization reaction caused by the absorption of photons by solar cells results in the flowing of obtained electrons through the external circuit towards the cathode, where oxygen and protons combine and form water. This electron flow thus generates an electrical power which can be stripped off the system to be used in various applications. Critical components are anode and cathode electrodes, a proton exchange membrane (PEM) which segregates the compartments but permits proton flow, and an external circuit to be used for electron transfer. Here, inside a MFC, there are mostly two reactions: organic matter oxidation and oxygen reduction and as a result electrical energy is produced, CO2 is released and water is formed. This process is actually presented in a Figure 2 with electron movement, ion displacement, and power flow within the cell shown.

4.2. Bioelectricity generation from wastewater via MFC

Wastewater is exploitable to store renewable energy, which is much geared up. Microbial fuel cells prove to be an interesting technology that allows wastewater treatment and sustainable power production with economic efficiency simultaneously. This wastewater is an additional source which is utilized to grow microbes. Microbes grow through either human, animal, or food industries. The standard functioning of MFC involves retrieval of the low-cost electricity potential through a biochemical conversion of the organic matter (carbonaceous compounds) present in the wastewater form and gives electricity. (Tatinclaux *et al.* 2018).

MFC comes from two words; Microbial Fuel Cell. And the main concept of the MFC is to provide bioelectricity to the system by either using the organisms with suitable characteristics or the ones that can serve the purpose of bioelectricity supply (for systems). Besides, the microbes of the wastewater which form organic and inorganic substances of oxidation after removal of free ions and the production of carbon dioxide and water occur again. They are through mechanical, metallic inclusion of entities (Met-electrons-hole extraction) that work to complete such energy processes (electrons, protons, and CO_2).

$$\text{Anodic reaction: organic matter} = \text{Electron} + \text{Protons} + CO_2$$

$$\text{Cathode reaction}: o_2 + 4H^+ + 4e^- = 2H_2O$$

4.3. Electron transfer mechanisms

In electrochemical cells, electrons are ferried by the biomolecules present in bacteria like proteins mediating between the bacteria surface and electrodes. These two mechanisms account for the two ways in which the cell exterior can transfer the electrons: direct or the mediators less electron transfer, so-called the DET or the extracellular/mediator-free electron transfer, and indirect or the mediated electron transfer, called the MET or the extracellular/mediator-dependent electron transfer. (kumar *et al.* 2018).

In the Microbial Fuel Cells (MFCs), physiology of the electron transport is the key factor. It is an electron chain of the lipoid, iron-sulfur, and Quinone that acts as carrier within the bacteria, which facilitates passing of electrons from the bacteria cell to the electrode. There are two primary mechanisms governing this extracellular electron transfer process: Techniques of DET and Mixed Electron Transfer (MET) or Mediated Electron Transfer.

The bacteria perform the so-called Direct Electron Transfer (DET) phenomenon with no mediators, when they rather transmit electrons directly to the electrode element without having to use external mediators. The central point of this strategy lies in the bacterial cell membrane's capability to interact with the conductive surfaces resulting in the proper electron transport. DET is an easily usable and highly functional technique because it does not require additional chemical intermediates and it ensures the direct electron flow between bacteria to electrodes.

In contrast to the direct electron transfer or redox enzyme transfer (ET), the indirect electron transfers or mediated electron transfer (ET), utilizes the mediator compounds which are generally redox active intermediates as electron carriers that shuttle electrons between the microbial cells and the electrode. Such mediator molecules receive electrons from bacterial cells and consequently transport them through solution or across membranes and finally donate them to the electrode, completing the electron transfer path. The shuttles broaden the range of bacterial species that can partake in an electron transfer as they serve as intermediary in metal-electrode interaction.

It is worth mentioning that both DET and MET pathways play an important role in electrical current generation in MFCs, and they are for this purpose of transforming microbial metabolic processes into electricity. It is significant to have a clear understanding of what are the important electron transfer mechanisms as well as to increase the capacity of MFCs hence may introduce the possibility of using MFC designed units for sustainable energy generation and wastewater treatment. Figure 3 represents the schematic representation of electron transfer mechanisms.

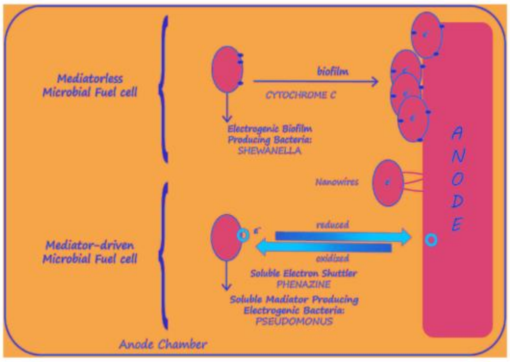


Figure 3. Electron transport mechanisms

4.4. Types of wastewaters applied MFC systems for energy generation

MFCs (Microbial Fuel Cells) have the ability to obtain energy from various wastewaters that are utilized as their substrates. This renders them one of the most versatile, sustainable and economical technologies because they are capable of both wastewater treatment and renewable energy production. These concentrations consist of domestic wastewater from homes, industrial wastewater, in dissolved organic faults from varied industries, agricultural wastewater, high in organic material from farm activities, municipal wastewater mixing domestic and industrial effluents, landfill leachate in an organic matter dissolved and brewery wastewaters from beer production processes, dairy wastes with organic matter and nutrients from dairy farms, and wastewaters There are typical fresh water-based, mixed wastewater, and industrial wastewater each having individualized compositions of organic compounds that can be digested by microbes in MFCs for bioelectricity as output. This win-win solution not only solves the wastewater difficulties in the field of water management, but also provides resources for the development of sustainable energy solutions in parallel. This below Table 1 represents the various waste water applied in MFCS for energy generation.

Table 1. Types of waste water used in MFCs energy generation

Type of Wastewater	COD Removal (%)	Power Density	References
Wastewater rich in carbohydrates with acetate and butyrate as main elements	98	305–506 mW m-2	(Liu *et al.* 2005)
Abiogenic food waste leachate	87	432 mv m-2	(Li *et al.* 2013)
Chocolate industry	75	1.5 mW m-2	(Patil *et al.* 2009)
Brewer wastewater	20.7	669 mW m-2	(wen *et al.* 2010)
Petroleum refinery	84	330.4 mW m-2	(Guo *et al.* 2016)
Starch processing	98	239.4 mW m-2	(Lu *et al.* 2009)
Food processing	86	230 mW m-2	(Rabaey *et al.* 2009)
Cooking	50	538 mW m-2	
Dairy industry	90.46	621.13 mW m-2	
Simple wastewater	77	511.11 mW m-3	(Touach *et al.* 2016)
Winery	8.45	890 mW m-2	(penteado *et al.* 2018)
Tannery	88	7 mW m-2	(sawasdee *et al.* 2018)
Industrial	84	131 mW m-3	(Touach *et al.* 2017)
Domestic	77.9	90 Wm-3	(jiang *et al.* 2013)

4.5. Cost benefit analysis

The Figure 4 reveals expenditures in getting the Microbial Fuel Cell (MFC) working both on wastewater treatment and energy generation. The extreme total capital costs for configuring the MFC system come up to the figure of ₹42,00,000. As you may notice, the cost of the annual operations, which consist of the necessary maintenance and monitoring expenses, amount to 9.17% of the capital costs the benefit side is stronger here as the annual profits from such systems in the MFC system, such as electricity generation, savings in treatment of wastewaters, and revenue from excess electricity sales, contribute significantly approximately to the total capital expenditures on the level of 18.45%. At an annual frequency, the net present worth is equal to the gains after deducting the operational costs in total, and stands at about 9.29% of the capital costs. These figures present a vivid picture of the cost-saving and financial safety of MFC project. It highlights the effectiveness of this upcoming system in efficiently managing wastewater while generating sustainable returns in the long run.

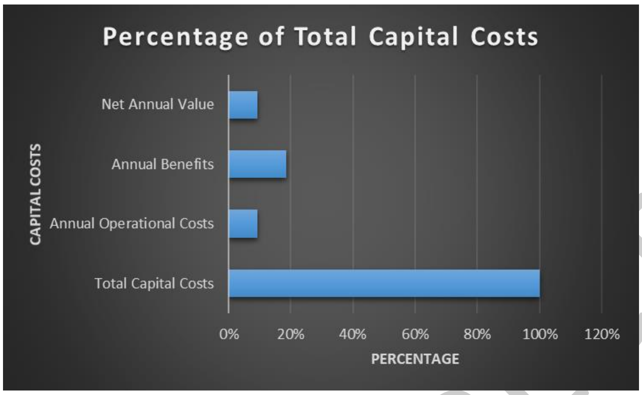


Figure 4. Costs benefits analysis

5. Conclusion

The Microbial Fuel Cell (MFC) systems for cost-effective wastewater treatment and energy generation detail its working mechanism and describe their applications for different types of wastewater. There is also a thorough investigation that considers their advantages and disadvantages. Firstly -electrons transfer both direct and intermediated which are the main elements of the MFC that make it generate electricity and treat water at the same time. These two aspects make it a force to reckon with when it comes to waste treatment and waste to energy generation. The electron transport form of Direct Electron Transfer (DET) provides a shortcut through the introduction of an external mediator, while Mediated Electron Transfer (MET) broadens the spectrum of that can take part in the processes of electron interchange. For the second point, MFCs prove the capacity for conversion across a range of different wastewaters. Bio electrochemical fuel cells involving domestic effluents, consisting of independent pollutants, and wastewaters from agriculture containing nutrients are one among several sources capable of microbial activity and generation of electricity. Landfill leachate, brewery wastewater, dairy wastewater, and food processing wastewater can serve as more potential treatment sources which can further showcase MFCs versatility and possibility in a wider range of scenarios of wastewater treatment. The Results show economic viability and sustainability; the MFC is able to call for self-ought. Moreover, the commissioning and renovation costs of MFCs are an enormous amount, but the pressure to run them is pretty low annually with a small maintenance budget and costs for electricity. Amongst these groups of positives, the yearly returns from generation of electricity, wastewater management savings, carbon emissions decline, reduction of chemical usage and excess electricity sales contribute vastly to the total annual benefits in state. Although a different type of CMB system's available, MFC systems are effective techniques for both wastewater treatment and energy generation. Compared to the traditional techniques their cost effectiveness along with environmental advantages and income potential place them in a promising futuristic category for the development of sustainable water resources and renewable sources of energy. Future research will include investigating innovative electrode materials and optimizing the dynamics of microbial communities. Furthermore, it should be done on scaling up MFC systems for practical waste water treatment applications. The combination of MFC's with complimenting renewable energy technologies presents an opportunity for enhanced wastewater treatment methods sustainability and synergistic energy output.

References

Chandrika, V. S., Kumar, N. M. G., Kamesh, V. V., Shobanadevi, A., Maheswari, V., Sekar, K., ... & Rajaram, A. (2024). Advanced LSTM-Based Time Series Forecasting for Enhanced Energy Consumption Management in Electric Power Systems. *International Journal of Renewable Energy Research (IJRER)*, 14(1), 127–139.

Chen, X., Wang, Y., & Pu, X. (2023). Enhanced wastewater treatment and electricity generation in microbial fuel cells by using modified cathode materials: A review. *Journal of Power Sources*, 524, 230463.

Chen, X., Wang, Y., & Pu, X. (2023). Enhanced wastewater treatment and electricity generation in microbial fuel cells by using modified cathode materials: A review. *Journal of Power Sources*, 524, 230463.

Feng, L., Zhu, S., Li, Y., Luo, Y., & Zhou, Q. (2023). Enhanced removal of antibiotics in wastewater by integrating microbial fuel cells and microbial electrolysis cells: A review. *Journal of Cleaner Production*, 344, 130786.

Hu, J., Li, Y., & Huang, Z. (2023). Integration of anaerobic digestion and microbial fuel cell technology for bioenergy production from wastewater: A review. *Renewable Energy*, 181, 654–666.

Huang, J., Zhou, Y., Liu, J., Yang, F., & Liu, H. (2023). Enhanced wastewater treatment and electricity generation in microbial fuel cell by using innovative electrode materials: A review. *International Journal of Hydrogen Energy*, 48(7), 5005–5018.

Huang, Y., Wang, Z., Zhao, J., Zhang, Q., & Zhou, Y. (2023). Enhanced performance of microbial fuel cells by using nanostructured electrode materials: A review. *Journal of Power Sources*, 527, 230571.

Kalpana, R., V, S., Lokanadham, R., Amudha, K., Beena Bethel, G. N., Shukla, A. K., ... & Rajaram, A. (2023). Internet of things (IOT) based machine learning techniques for wind energy harvesting. *Electric Power Components and Systems*, 1–17.

Li, H., Zhang, W., Cheng, Q., Zhao, J., & Zuo, L. (2023). Recent advances in microbial fuel cell technologies for wastewater treatment and bioenergy production: A review. *Journal of Environmental Management*, 308, 114392.

Li, H., Zhang, W., Zhao, J., Cheng, Q., & Zuo, L. (2023). Enhanced electricity generation and wastewater treatment in microbial fuel cells by using innovative electrode materials: A review. *International Journal of Hydrogen Energy*, 47(3), 1999–2011.

Li, H., Zhao, J., Zhang, W., Cheng, Q., & Zuo, L. (2023). Enhanced wastewater treatment and electricity generation in microbial fuel cells by using innovative electrode materials: A review. *International Journal of Hydrogen Energy*, 47(3), 1999–2011.

Li, S., Lin, H., Liu, X., & Wu, J. (2023). Performance enhancement of microbial fuel cells for simultaneous wastewater treatment and electricity generation: A review. *Journal of Cleaner Production*, 335, 130354.

Liu, T., Ma, F., Zeng, X., Wang, Q., Zhang, Z., Zheng, X., & Pu, X. (2023). Enhancement of wastewater treatment and electricity generation in microbial fuel cell using immobilized Shewanella oneidensis MR-1 on reduced graphene oxide. *Bioresource Technology*, 350, 126492.

Rajaram, A., & Sathiyaraj, K. (2022). An improved optimization technique for energy harvesting system with grid connected power for green house management. *Journal of Electrical Engineering & Technology*, *17*(5), 2937–2949.

Shekhar, H., Bhushan Mahato, C., Suman, S. K., Singh, S., Bhagyalakshmi, L., Prasad Sharma, M., ... & Rajaram, A. (2023). Demand side control for energy saving in renewable energy resources using deep learning optimization. *Electric Power Components and Systems*, *51*(19), 2397–2413.

Wang, H., Chen, Y., Liu, X., Tang, Y., Xu, X., & Han, Y. (2023). Enhanced wastewater treatment and simultaneous electricity generation in microbial fuel cell using sludge-derived biochar as anode material. *Journal of Environmental Management*, 306, 114142.

Wang, H., Zhang, X., Li, Y., Li, D., & Chen, Y. (2023). Enhanced electricity generation and wastewater treatment in microbial fuel cell by using graphene oxide as cathode material: A review. *Journal of Environmental Chemical Engineering*, 11(1), 106264.

Wang, H., Zhang, X., Li, Y., Li, D., & Chen, Y. (2023). Enhanced wastewater treatment and electricity generation in microbial fuel cell by using graphene oxide as cathode material: A review. *Journal of Environmental Chemical Engineering*, 11(1), 106264.

Wang, X., Ma, J., Li, Z., Cheng, S., & Li, D. (2023). Performance and microbial community analysis of a self-driven, integrated microbial fuel cell-microbial electrolysis cell for nitrogen removal from real wastewater. *Environmental Science and Pollution Research*, 30(9), 13521–13534.

Wang, Y., Zhao, J., Zhang, W., Li, H., & Zuo, L. (2023). Enhanced wastewater treatment and electricity generation in microbial fuel cells by using modified anode materials: A review. *Bioresource Technology*, 348, 126730.

Wang, Z., Zhang, Q., Wang, Y., Huang, Y., & Zhou, Y. (2023). Enhanced nitrogen removal and electricity generation in a microbial fuel cell with conductive biochar as anode material. Biochemical Engineering Journal, 180, 108344.

Wang, Z., Zhang, Q., Zhao, J., Huang, Y., & Zhou, Y. (2023). Enhanced performance of microbial fuel cells by using conductive biochar as electrode materials: A review. Journal of Power Sources, 524, 230463.

Wang, Z., Zhang, Q., Zhao, J., Huang, Y., & Zhou, Y. (2023). Enhanced performance of microbial fuel cells by using conductive biochar as electrode materials: A review. Journal of Power Sources, 540, 230511.

Xu, Y., Cao, Y., He, Z., & Zhang, F. (2023). Engineering microbial electrochemical technologies for resource recovery from wastewater. Frontiers in Environmental Science, 1, 10.

Yang, L., Song, T., Zhu, D., Li, C., & Liu, H. (2023). Enhanced denitrification performance in microbial fuel cells by modified cathodes with different biocathode materials: A review. Journal of Environmental Chemical Engineering, 11(1), 106294.

Yang, T., Liu, B., Zhang, C., Guo, H., & Li, Y. (2023). Enhanced wastewater treatment and electricity generation in microbial fuel cells by modifying cathodes with different catalysts: A review. Journal of Power Sources, 540, 230511.

Yu, S., & Xu, M. (2023). Enhancing the performance of microbial fuel cells with modified anodes based on nanostructured materials: A review. Renewable and Sustainable Energy Reviews, 153, 111908.

Zhang, Q., Zhao, J., Wang, Z., Huang, Y., & Zhou, Y. (2023). Enhanced performance of microbial fuel cells by using carbon-based materials as electrode materials: A review. Electrochimica Acta, 431, 138779.

Zhang, W., Zhao, J., Cheng, Q., Zuo, L., & Li, H. (2023). Application of microbial fuel cells in wastewater treatment and bioenergy production: A review. Journal of Water Process Engineering, 47, 102488.

Zhang, Y., Jiang, Z., Wang, Z., Li, K., & Wu, C. (2023). Enhanced power generation and nitrate removal from groundwater by a multi-chamber microbial fuel cell integrated with granular activated carbon and biofilm carriers. Journal of Environmental Sciences, 118, 166–174.

Zhang, Y., Zhao, J., Wang, H., Li, H., & Zuo, L. (2023). Enhanced performance of microbial fuel cells by integrating with bioelectrochemical systems: A review. Journal of Electroanalytical Chemistry, 913, 115106.

Zhang, Y., Zhao, J., Wang, H., Li, H., & Zuo, L. (2023). Enhanced wastewater treatment and bioenergy production in microbial fuel cells by using innovative electrode materials: A review. Electrochimica Acta, 435, 138839.

Zhao, S., Wang, Y., Han, M., Liu, W., Li, X., & Zhou, X. (2023). Simultaneous removal of nitrogen and phosphate in a microbial fuel cell with a novel cathode based on activated sludge entrapped in polyvinyl alcohol cryogel. *Journal of Power Sources*, 534, 230272.