

# Sustainable Wastewater Remediation and Energy Recovery: A Critical Review and Experimental Proposal for Low-Cost MFCs

<sup>1</sup>Shreyas Raut , <sup>2</sup>Nishant Kombe , <sup>3</sup>Virendra Rathod , <sup>4</sup>Aarti Pawar , <sup>5</sup>Savidhan Raut , <sup>6</sup>Nakul Chipade ,  
<sup>7</sup>Pranil Jadhav

UG Students , Department of Civil Engineering , Jawaharlal Darda Institute of Engineering and Technology , Yavatmal ,  
Maharashtra.

Under the Guidance of

<sup>1</sup>Prof. Nitin Kothari

Assistant Professor , Department of Civil Engineering , Jawaharlal Darda Institute of Engineering and Technology , Yavatmal ,  
Maharashtra.

**Abstract :** Water pollution and energy scarcity are two major global challenges that demand innovative, sustainable, and affordable technological solutions. Conventional wastewater treatment methods such as activated sludge processes, aeration tanks, and chemical treatments are commonly practiced; however, these methods are highly energy-intensive, expensive, and often generate toxic sludge as by-products, creating additional disposal and environmental concerns. Therefore, there is a pressing need for alternative approaches that are both eco-friendly and cost-effective. This project explores the use of Microbial Fuel Cells (MFCs) as a promising technology to simultaneously treat wastewater and generate renewable bioelectricity. In an MFC, microorganisms oxidize the organic matter present in wastewater under anaerobic conditions, releasing electrons and protons. The electrons flow through an external circuit, producing electrical energy, while the protons migrate through a membrane to combine with oxygen at the cathode, forming water. This dual-function process not only reduces key water pollutants such as Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), and nutrient load but also contributes to green energy production. The project emphasizes the replacement of expensive commercial membranes, such as Nafion, with a low-cost agar-salt bridge membrane, making the system more economical and practical for large-scale applications. Moreover, the process does not produce harmful chemical sludge, ensuring environmental safety. The study evaluates improvements in water quality parameters including pH, Dissolved Oxygen (DO), COD, and BOD, thereby demonstrating the potential of MFCs as an efficient, sustainable, and cost effective alternative for wastewater treatment and renewable energy generation.

## I. INTRODUCTION

### 1.1 GENERAL

Water pollution has become one of the biggest problems in today's world because of rapid industrial growth, urbanization, and farming activities. Freshwater sources are getting polluted and it is becoming difficult to meet the increasing demand for clean water. The traditional methods of wastewater treatment are often costly, consume a lot of energy, and sometimes do not completely remove the pollutants. This creates a need for a better, eco-friendly, and affordable solution that can clean wastewater effectively. One of the new and interesting methods is the Microbial Fuel Cell (MFC). An MFC is a system in which microorganisms break down the organic matter present in wastewater. While doing this, they also transfer electrons to an electrode, which helps in generating electricity. This means that along with cleaning the water, the system can also produce renewable energy. The process can help reduce parameters like Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD), and suspended solids, which are important indicators of water quality. In this project, the focus is on improving the water quality using MFC technology. The main aim is to check how effectively MFCs can reduce pollution levels in water, improve treatment efficiency, and at the same time, produce some amount of bioelectricity. This study can show how MFCs may become a good alternative to traditional wastewater treatment methods and help in protecting the environment while also generating useful energy.

### 1.2 NEED FOR STUDY

- i. Water pollution is increasing due to industrial, agricultural, and domestic activities, creating a demand for effective treatment methods.
- ii. Conventional wastewater treatment processes are costly, require high energy, and sometimes fail to completely remove pollutants.
- iii. Microbial Fuel Cells (MFCs) are promising because they can both treat wastewater and generate electricity at the same time.
- iv. However, the membrane is one of the most expensive parts of an MFC, which limits large-scale use by developing or using a more economical membrane, the overall system cost can be reduced, making MFCs a more practical solution.
- v. This study is needed to test the effectiveness of such an approach, so that MFCs can become a sustainable, affordable, and real-world alternative to traditional treatment methods.

### 1.3 OBJECTIVE

- i. To study the working principle of Microbial Fuel Cells (MFCs) for wastewater treatment.
- ii. To analyse important water quality parameters such as COD, BOD, pH, turbidity, and conductivity before and after treatment.
- iii. To focus on changing the membrane of the MFC to reduce cost and improve practicality.

iv. To measure the amount of bioelectricity generated during the process.

## II. LITERATURE REVIEW

**For Liu et al. (2004)** demonstrated the feasibility of electricity generation from wastewater using a single chamber microbial fuel cell (MFC). The study experimentally showed that MFCs could utilize substrates such as acetate, lactate, and glucose to produce electricity while treating wastewater. Unlike dual chamber designs, the single-chamber configuration offered improved simplicity and cost-effectiveness by eliminating the need for a separate catholyte chamber. The authors reported stable electricity generation and effective organic matter removal, though limitations in power density and electrode performance were noted. This work is considered a landmark study that established the practical potential of MFCs for sustainable wastewater treatment and renewable energy generation. It also laid the foundation for subsequent research into improving electrode materials, microbial selection, and system optimization for real-world applications.

**Ieropoulos et al. (2005)** compared three generations of microbial fuel cells: Gen-I (synthetic mediators with *E. coli*), Gen-II (sulfate-reducing bacteria with natural mediators), and Gen-III (Geo bacter sulfur reducers, mediator-free). Gen-II achieved the highest conversion efficiency (64.52%), followed by Gen-III (47.38%) and Gen-I (28.12%). However, Gen-III produced significantly higher power per cell mass, 28 times greater than Gen-I. Under optimal loading, Gen-III efficiency reached 95%. The study provided the first direct experimental comparison of three MFC generations under controlled conditions. The authors concluded that naturally electrogenic microbes hold significant promise, though optimization for wastewater treatment is still needed.

**Mohan et al. (2008)** explored electricity generation in a two-chamber microbial fuel cell using *Enterobacter cloacae* IIT-BT 08. The study investigated the effects of electron mediators, ionic strength, and salt bridge area on power output. Methylene blue at 0.03 mM achieved the highest power of 19.2  $\mu\text{W}$  with a current density of 27.6  $\text{mA}/\text{m}^2$ . Increasing the salt bridge surface area improved performance, 4 reaching a maximum power density of 236  $\text{mW}/\text{m}^2$ . The findings demonstrated that mediator selection and system configuration critically affect MFC efficiency. The authors concluded that while MFCs have potential for renewable electricity generation, scale and power limitations restrict practical application.

**Li (2013)** conducted an experimental study on microbial fuel cells for powering environmental sensors in soils and sediments. Variables such as sample type, temperature, and chamber size were tested. Benthic mud produced the highest electricity output due to higher organic matter content, with peak efficiency observed at 0°C. The system functioned across a thermal range of -5°C to 42°C, wider than previously reported. Larger chambers generated more electricity but showed efficiency losses, indicating diminishing returns with scale. Electricity production declined over 10 days, reflecting sustainability challenges. The study concluded that optimizing sample type, chamber size, and temperature enhances MFC output, making them suitable for small-scale applications.

**Ghasemi et al. (2013)** examined the effect of pretreatment and biofouling on Nafion 117 membranes in dual-chamber microbial fuel cells. Pre-treated Nafion achieved the highest power density (~100  $\text{mW}/\text{m}^2$ ), while untreated and bio fouled membranes produced only 52.8 and 20.9  $\text{mW}/\text{m}^2$ , respectively. Coulombic efficiency of pre-treated membranes was 2–4 times higher than untreated or fouled membranes. The findings confirmed that membrane pretreatment significantly enhances performance, while biofouling severely reduces efficiency. The study concluded that material innovation and anti-fouling strategies are crucial for reliable operation in real wastewater conditions.

**Rahimnejad et al. (2014)** conducted a comprehensive review on the role of proton exchange membranes (PEMs) in microbial fuel cells (MFCs). The study emphasized the critical importance of PEMs for proton transport and overall efficiency, with Nafion identified as the most widely used membrane. However, challenges such as high cost, oxygen crossover, cation transport imbalance, fouling, and pH shifts were highlighted. The review compared Nafion with alternatives such as CMI-7000, Zirfon, and Hyflon, noting various performance trade-offs. Advances in pretreatment methods and the exploration of alternative membranes were discussed as strategies to reduce resistance and improve energy output. The authors concluded that PEM innovation is vital for scaling MFC technology.

**Zhang et al. (2015)** developed a manganese dioxide ( $\text{MnO}_2$ )-coated carbon felt anode to improve microbial fuel cell performance. Electrodeposition of  $\text{MnO}_2$  enhanced anode capacitance 46-fold compared to bare carbon felt, achieving a maximum power density of  $3580 \pm 130 \text{ mW}/\text{m}^2$ , a 24.7% improvement. Flow-through operation further reduced mass transfer resistance by 41.4%, enabling faster electron transfer. The study demonstrated that  $\text{MnO}_2$  facilitates extracellular electron transfer, enhancing bio electrochemical performance. Despite these advancements, the authors noted that scale-up and long term stability remain significant challenges for commercialization.

**Le and Nunes (2016)** reviewed the role of membrane materials and technologies in advancing water and energy sustainability. The paper emphasizes the interconnection between water and energy demand, highlighting how membranes can contribute to solutions such as desalination, wastewater reuse, and energy-efficient separation processes. The authors discuss key membrane types, including polymeric, inorganic, and hybrid membranes, analysing their properties and applications in water purification, fuel cells, and energy recovery systems. Challenges such as fouling, limited durability, and high production costs are identified as barriers to large-scale implementation. Emerging trends like nanostructured membranes, bio-inspired designs, and the integration of advanced fabrication methods are presented as promising strategies for performance improvement. Overall, the review positions membrane technologies as central to addressing global water-energy challenges, but stresses the importance of innovative materials research and scalable engineering solutions to enhance sustainability outcomes.

**Gude (2016)** provided an overview of microbial fuel cells (MFCs) for sustainable wastewater treatment and energy recovery. The paper reviewed the energy demands of conventional treatment methods and highlighted MFCs as energy-yielding alternatives capable of organic removal, nutrient recovery, and metal remediation. Applications with both synthetic and real wastewater were discussed, including urine fed MFCs and the role of biocathodes. Despite their potential, limitations such as low power densities, cathode inefficiency, and scaling barriers were emphasized. The study concluded that while MFCs hold promise for wastewater sanitation and bioenergy, breakthroughs in electrode materials and integrated systems are essential.

**Tharali et al. (2016)** reviewed microbial fuel cells for bioelectricity production, focusing on their components, mechanisms, and applications. The study explained how MFCs convert chemical energy from organic substrates into electricity through microbial metabolism, making them a sustainable energy technology. Key factors influencing efficiency, such as electrode materials, microbial species, substrates, and system design, were discussed. Applications in wastewater treatment, biosensing, and bioremediation were highlighted, alongside limitations including scalability, high membrane costs, and environmental dependencies. The authors noted recent advancements such as air-cathode designs and genetically engineered microbes as promising strategies. The review concluded that while MFCs are a green technology with significant potential, overcoming technical and economic barriers is essential.

**Chaturvedi and Verma (2016)** reviewed microbial fuel cells as a green technology for generating electricity from waste and xenobiotics. The paper explained the basic design of single- and dual-chamber MFCs and highlighted the role of microbes in converting organic substrates into bioelectricity. Various wastes, such as cassava wastewater, slaughterhouse effluents, chicken feathers, and rice straw hydrolysates, were examined, demonstrating both energy generation and waste treatment potential. MFCs were also shown to detoxify pollutants such as hexavalent chromium, azo dyes, selenium, and nitrates. However, challenges such as low power density, high material costs, and reduced efficiency during scaleup were emphasized. The authors concluded that improvements in electrode materials, microbial strains, and reactor designs are needed for MFCs to become a sustainable option for waste management and renewable energy.

**Hernández-Flores et al. (2016)** investigated alternative low-cost membranes to replace Nafion in microbial fuel cells. The study tested agar-based membranes (2% and 6%) and a hybrid agar-Nafion type against Nafion 117. Although the alternative membranes produced only 4–40% of Nafion's power, they offered significantly lower internal resistance and were priced at just 2.5–6% of Nafion's cost. In addition, they avoided hazardous chemical pretreatments, reducing environmental impact. The authors emphasized that while power densities were lower, the superior power-to-cost ratio makes these membranes attractive for sustainable and economical MFC development.

**Kodali et al. (2017)** investigated air-breathing microbial fuel cell cathodes using platinum group metal free catalysts synthesized from Fe, Co, Ni, and Mn with amino antipyrine. Among these, Fe-AAPyr exhibited the highest open circuit potential (0.307 V vs. Ag/AgCl) and the greatest power density (251 mW/cm<sup>2</sup>), outperforming other catalysts and activated carbon (129 mW/cm<sup>2</sup>). Increasing solution conductivity further enhanced Fe-AAPyr performance to 482 mW/cm<sup>2</sup>, among the highest reported. The study provided the first direct comparison of such catalysts under identical conditions, identifying FeAAPyr as the most effective. The authors concluded that PGM-free catalysts represent a promising pathway to replace costly platinum, though durability in real wastewater remains a challenge.

**Slate et al. (2019)** reviewed microbial fuel cell technology, emphasizing renewable energy potential, electrode materials, and electron transfer mechanisms. The review identified low power generation, high material costs, and scalability challenges as key barriers to commercialization. Advances in carbon-based nanomaterials such as graphene and carbon nanotubes were highlighted as promising for improving electron transfer and system performance. The authors stressed the dual role of MFCs in both electricity generation and wastewater treatment, making them a unique renewable energy technology. The review concluded that bridging laboratory advances with industrial-scale applications is essential for future development.

**Rangabhashiyam et al. (2021)** presented a comprehensive review of microbial fuel cells (MFCs) for industrial effluent treatment and bioelectricity generation, with particular emphasis on scale-up challenges. The paper outlines the working principles of MFCs and evaluates their ability to simultaneously degrade pollutants and generate renewable energy. The authors highlight the influence of electrode design, microbial communities, substrates, and reactor configurations on MFC efficiency. Major barriers to industrial adoption include high material costs, low power output, and operational instability in real wastewater conditions. Advances in nanomaterial-based electrodes, novel biocatalysts, and hybrid system integrations are discussed as strategies to improve performance. Importantly, the review underscores the potential of MFCs to serve as dual-function systems for wastewater treatment and sustainable energy recovery but concludes that further research on scalability, cost reduction, and long term reliability is needed to transition from laboratory-scale experiments to industrial applications.

**Chowdhury et al. (2023)** investigated the use of pure magnesium as an anode material to enhance microbial fuel cell (MFC) performance. The study focused on improving power density and electron transfer efficiency compared to conventional carbon-based electrodes. Experimental results demonstrated that magnesium anodes increased current generation and improved overall system efficiency due to their high conductivity and biocompatibility. However, challenges such as rapid corrosion and electrode degradation were identified as limiting factors for long-term operation. The authors suggest that surface modification, alloying, and protective coatings could mitigate these issues and extend electrode lifespan. This research contributes to the growing body of work on novel electrode materials for MFCs, highlighting magnesium as a promising but still experimental option for future large-scale applications.

**Farahani et al. (2024)** reviewed sustainable water treatment technologies focusing on microbial fuel cells (MFCs) and microbial desalination cells (MDCs). The study emphasizes how these bio electrochemical systems can simultaneously address water scarcity, wastewater management, and renewable energy production. MFCs are discussed as tools for converting organic waste into electricity while reducing pollution loads, whereas MDCs are highlighted for their capacity to desalinate water without external energy input. The review identifies critical factors affecting performance, including electrode design, membrane efficiency, and microbial activity. Limitations such as biofouling, membrane costs, and scaleup constraints are acknowledged, but recent innovations in nanostructured electrodes, biofilm engineering, and hybrid processes show promise for practical applications. The authors conclude that MFCs and MDCs could play transformative roles in future water-energy nexus solutions, provided that ongoing research successfully addresses technical and economic challenges.

**Jalili et al. (2024)** conducted a detailed review on microbial fuel cells, focusing on their structure, materials, microorganisms, and applications. The study emphasized the importance of anode and cathode materials, with carbon-based electrodes found to be efficient but costly, while stainless steel alternatives showed potential for reducing expenses. Proton exchange membranes were highlighted for improving ion transfer, though low-cost substitutes are being explored. The review also discussed the role of diverse microbial communities in electron transfer and electricity generation. Applications such as wastewater treatment, bioelectricity production, and hydrogen generation were noted, showcasing sustainability potential. However, high construction costs, low power density, and limited scalability remain significant barriers. The authors concluded that integrating new materials, optimizing microbial interactions, and scaling strategies are essential for commercial viability.

**Ojha et al. (2025)** carried out a detailed review on microbial fuel cells (MFCs) to explore their role in waste-to-energy conversion and wastewater treatment. The paper explained the fundamentals of MFCs, including their working principle, microbial interactions, electron transfer mechanisms, and the importance of electrode and substrate selection. Different designs such as single-chamber, dual-chamber, and stacked systems were examined, with innovations like magnesium anodes and hybrid models highlighted for performance improvements. Applications ranging from electricity generation to heavy metal removal and biosensors were discussed. However, the review emphasized challenges such as low power output, high material costs, membrane fouling, and scaling issues. The authors concluded that MFCs represent a sustainable technology with environmental benefits, but further optimization is needed for real-world application.

### III. PROPOSED METHODOLOGY

#### 3.1 Collection of Wastewater Samples :

The first step of this study involves the collection of wastewater samples from reliable and consistent sources. Potential sources include domestic sewage outlets, municipal wastewater drains, or effluent from small-scale industries such as food processing or textile units. The choice of source depends on the availability and the type of pollutants present in the water.

Once collected, the wastewater samples will be transported to the laboratory in sterile containers to prevent contamination or alteration of natural microbial populations. Before using the wastewater in the MFC, its baseline physicochemical properties will be determined. This is important because it provides a starting point for comparison after treatment.

The following tests will be conducted:

- i. pH: to measure the acidity/alkalinity of water.
  - ii. Turbidity: to determine the presence of suspended solids.
  - iii. Total Dissolved Solids (TDS): to check the salt content.
  - iv. Conductivity: to measure the ionic strength of water.
  - v. Chemical Oxygen Demand (COD): to quantify the amount of organic matter present.
  - vi. Biological Oxygen Demand (BOD): to measure the oxygen consumed by microbes during organic matter breakdown.
- This baseline data will help assess the degree of wastewater treatment achieved by the MFC.

#### 3.2 Design and Fabrication of the MFC Setup:

A dual-chamber microbial fuel cell (MFC) will be designed and fabricated. This design is widely used because it separates the anode (anaerobic) and cathode (aerobic) processes, making it more efficient.

- i. Anode chamber: This will be an airtight compartment filled with wastewater under anaerobic (oxygen-free) conditions. The microbes in the wastewater will consume the organic matter and release electrons and protons.
- ii. Cathode chamber: This chamber will be exposed to air or provided with oxygen. Oxygen acts as the final electron acceptor, combining with protons and electrons to form water.
- iii. Membrane: Both chambers are connected through an agar + salt bridge membrane, which acts as a low-cost alternative to commercial proton exchange membranes (PEMs). The agar-salt membrane is prepared by dissolving agar powder and sodium chloride in distilled water, heating the mixture until uniform, and then casting it into a U-shaped glass tube. Electrodes: Graphite rods, graphite plates, or carbon cloth will be used as electrodes because they are inexpensive, conductive, and biocompatible.
- iv. External circuit: The anode and cathode electrodes will be connected using a wire and resistor, completing the electrical circuit. This setup allows us to simultaneously treat wastewater and generate electricity.

### 3.3 Inoculation and Microbial Growth:

Microbes play a central role in MFC operation. Instead of introducing an external culture, we will rely on the native microbial population already present in the wastewater. These microbes naturally include species capable of transferring electrons to electrodes, such as *Geobacter* and *Shewanella*.

The inoculation step involves placing the collected wastewater in the anode chamber and allowing the microbes to adapt and colonize the electrode surface. As they consume the organic matter, they form a thin layer of biofilm on the anode. This biofilm is critical because it acts as a living electrical conductor, directly transferring electrons to the electrode.

During this stage, the anode chamber will be kept completely oxygen-free by sealing it tightly, since oxygen would compete with the anode for electrons and reduce efficiency.

### 3.4 Operation of the MFC:

Once the system is ready, the wastewater sample is continuously fed into the anode chamber. Here, the microbes start oxidizing the organic matter present in the wastewater.

The process can be explained in three simple steps:

- i. At the Anode (Anaerobic Chamber): Microbes oxidize the organic matter → releasing electrons ( $e^-$ ) and protons ( $H^+$ ). Electrons are transferred directly to the anode electrode.
- ii. Through the Membrane: This membrane selectively allows proton ( $H^+$ ) transfer from the anode to the cathode while preventing oxygen diffusion into the anode chamber, maintaining anaerobic conditions efficiently.
- iii. At the Cathode (Aerobic Chamber): Protons pass through the membrane into the cathode chamber. They combine with electrons (from the circuit) and oxygen (from air) to form clean water.
- iv. Through the Circuit: Electrons flow through the external wire to the cathode, generating an electric current measurable as voltage and current.

This mechanism ensures that while the wastewater is being treated, electricity is also generated. The system will be operated for several days, and performance will be continuously monitored.

### 3.5 Monitoring and Analysis:

#### A) Wastewater Quality Tests (Before and After MFC Operation):

##### 1. pH Measurement

- i. Switch on and allow meter to stabilize (5–10 min).
- ii. Calibrate using two buffers (pH 4.01 and 7.00 or 7.00 and 10.01).
- iii. Rinse electrode with distilled water, blot gently.
- iv. Pour 50 mL of the sample into a clean beaker.
- v. Immerse electrode, stir gently, and wait for a stable reading ( $\approx 30$  s).
- vi. Record the value.

##### 2. Turbidity (NTU)

- i. Prepare or verify 0 NTU (distilled water) and 100 NTU standards.
- ii. Calibrate instrument with standards.
- iii. Mix sample gently; avoid bubbles.
- iv. Fill cuvette up to mark, wipe with tissue.
- v. Insert cuvette in correct orientation.
- vi. Record NTU when reading stabilizes.

##### 3. Total Dissolved Solids (TDS) & Conductivity

- i. Calibrate meter with 1413  $\mu S/cm$  standard.
- ii. Rinse probe with distilled water.
- iii. Pour 50 mL of sample into beaker.
- iv. Immerse probe, stir gently, and wait for stable reading.
- v. Record conductivity in  $\mu S/cm$  and/or TDS (mg/L).

##### 4. Dissolved Oxygen (DO) Probe Method

- i. Calibrate DO meter using air-saturated water ( $\sim 8.3$  mg/L at 25 °C).
- ii. Rinse probe and immerse in sample.
- iii. Stir gently until stable reading appears.
- iv. Record DO (mg/L).

##### 5. Chemical Oxygen Demand (COD)

- i. Pipette 10 mL sample into reflux tube.
- ii. Add 0.4 g  $HgSO_4$  (for chloride suppression).
- iii. Add 5 mL  $K_2Cr_2O_7$  solution.
- iv. Slowly add 15 mL  $H_2SO_4-Ag_2SO_4$  mixture while cooling.

- v. Attach condenser and reflux for 2 h at gentle boil.
- vi. Cool to room temperature.
- vii. Titrate against 0.1 N FAS using ferroin indicator until colour changes from blue-green to reddish brown.
- viii. Perform blank with distilled water.

### 6. Biological Oxygen Demand (BOD<sub>5</sub>)

- i. Prepare dilution water: aerate distilled water for 24 h, add 1 mL each of phosphate buffer, MgSO<sub>4</sub>, CaCl<sub>2</sub>, and FeCl<sub>3</sub> stock/L.
- ii. If sample low in microbes, add seed inoculum.
- iii. Prepare serial dilutions (1:10, 1:20, etc.) to achieve DO depletion 2–7 mg/L after 5 days.
- iv. Fill bottles completely (no bubbles).
- v. Measure initial DO (DO<sub>0</sub>).
- vi. Incubate sealed bottles at 20 ± 1 °C for 5 days in the dark.
- vii. Measure final DO (DO<sub>5</sub>).

### B) Electricity Generation Tests (Basic):

Voltage & Current Measurement Equipment:

Digital multi meter, External resistors (100 Ω, 470 Ω, 1 kΩ, 10 kΩ), Connecting wires.

- i. Connect MFC electrodes to multi meter in open circuit.
- ii. Record open-circuit voltage (V<sub>oc</sub>).
- iii. Connect a known resistor (start with 1 kΩ).
- iv. Allow 5–10 min for voltage stabilization.
- v. Record voltage (V).
- vi. Compute current .
- vii. Repeat for 100 Ω, 470 Ω, 10 kΩ resistors.
- viii. Plot V vs I (polarization curve).
- ix. Power Density Calculation Formula:  $P = V \times I$  (W)

### 3.6 Optimization Parameters:

The performance of the MFC can vary depending on different operating conditions. To maximize both wastewater treatment efficiency and electricity generation, the following parameters will be optimized:

- i. pH of wastewater: Microbes have an optimal pH range (usually 6.5–7.5). At very low or high pH, their metabolic activity decreases. Testing different pH levels will identify the range where microbes perform best.
- ii. Substrate concentration: Wastewater rich in organic matter provides more food for microbes, but too much can cause sludge buildup. By varying the concentration of wastewater or diluting it, we can find the ideal level for maximum efficiency.
- iii. Electrode material and surface area: Larger electrode surfaces provide more room for microbes to attach, increasing electricity generation. Testing different electrode types (graphite rods vs. plates) will show which one is most effective and affordable.
- iv. External resistance: The resistance in the external circuit affects current and voltage. Low resistance allows more current but reduces voltage; high resistance gives higher voltage but less current. By testing different resistances, we can balance the system for maximum power output.

This optimization ensures that the MFC is cost-effective, efficient, and practical for real-world application.

### 3.7 Comparison and Validation:

Finally, the treated wastewater and electricity generation results will be compared with standards and literature:

- i. Water Quality: Post-treatment values of COD, BOD, TDS, and turbidity will be compared with limits set by the Central Pollution Control Board (CPCB) and the World Health Organization (WHO). If values fall within the acceptable range, the treated water can be considered safe for discharge or possible reuse.
- ii. Electricity Generation: The voltage, current, and power density obtained will be compared with values reported in research papers on MFCs. This will validate whether the fabricated system performs equally well or better than existing models.

This step ensures that the proposed MFC system is not only scientifically effective but also practically applicable for wastewater treatment and electricity recovery.

## IV. DESIRED OUTCOME

Based on a comprehensive review of existing literature and comparative studies on dual-chamber Microbial Fuel Cells (MFCs), the proposed low-cost system is expected to yield the following performance outcomes. These projections are categorized into remediation efficiency, bio-electrochemical output, and economic viability.

## 1. Wastewater Remediation Efficiency

The primary function of the MFC is the oxidation of organic substrates. Literature indicates that dual-chamber systems operating under anaerobic anodic conditions typically achieve high removal efficiencies for standard water quality parameters.

**Chemical Oxygen Demand (COD) Removal:** The system is expected to achieve a COD removal efficiency in the range of 60% to 85% over a 10–15 days retention period. Higher efficiencies (up to 90%) are anticipated if the influent substrate concentration is optimized below inhibition levels (typically <3000 mg/L).

### **Biological Oxygen Demand (BOD) Reduction:**

Commensurate with COD removal, BOD reduction is projected to range between 60% and 75%. This reduction confirms the active metabolic degradation of biodegradable organic matter by the anodic biofilm.

**Pathogen and Nutrient Removal:** While primarily designed for carbon removal, similar systems have demonstrated the concurrent removal of total nitrogen (TN) and phosphorus (TP) at efficiencies of approximately 65–70%, alongside a reduction in coliform counts due to the competitive anaerobic environment.

## 2. Bio-electrochemical Performance

While low-cost membranes such as agar-salt bridges generally exhibit higher internal resistance compared to commercial Proton Exchange Membranes (PEMs like Nafion), they are still expected to support viable electricity generation.

**Voltage Output:** The Open Circuit Voltage (OCV) for the system is anticipated to stabilize between 600 mV and 800 mV. Under operational loads (closed circuit), the sustainable voltage is expected to range from 200 mV to 400 mV, depending on the external resistance applied.

### **Power Density:**

Utilizing a salt-bridge configuration, the expected maximum power density is projected to be in the range of 50–100 mW/m<sup>2</sup>. While this is lower than Nafion-based systems (which can exceed 200–500 mW/m<sup>2</sup>), it is sufficient to power low-energy sensors or LED indicators, validating the concept for remote sensing applications.

### **Coulombic Efficiency (CE):**

The system is expected to demonstrate a Coulombic Efficiency between 10% and 30%. This metric highlights that while the majority of organic matter is consumed for bacterial growth and maintenance, a measurable fraction is successfully converted into recoverable electrical current.

## 3. Economic and Scalability Implications

A critical expected outcome of this study is the validation of cost-effectiveness, which is the major barrier to MFC commercialization.

### **Cost Reduction:**

By substituting the Nafion membrane (often ~60% of total reactor cost) with an agar-based alternative, the capital cost of the system is projected to decrease by approximately 80–90% regarding membrane components.

### **Stability Trade-off:**

The review anticipates that while the agar-salt bridge will degrade faster than commercial polymers (requiring replacement every 1–2 months), the significantly lower material cost yields a superior cost-to-power ratio, making it more viable for developing regions or disposable/short-term applications.

## V. REFERENCES

1. Liu, H., Ramnarayanan, R., and Logan, B.E., "Electricity Generation from Wastewater Using a Single-Chamber Microbial Fuel Cell", *Environmental Science & Technology*, Vol. 38, No. 7, ACS Publications, 2004.
2. Ieropoulos, I., Greenman, J., and Melhuish, C., "Comparative Study of Three Generations of Microbial Fuel Cells", *International Journal of Energy Research*, Vol. 29, No. 10, Wiley, 2005.
3. Mohan, S.V., et al., "Bioelectricity Generation Using *Enterobacter cloacae* IIT-BT 08 in a Two Chamber Microbial Fuel Cell", *Biochemical Engineering Journal*, Vol. 39, No. 1, Elsevier, 2008.
4. Li, H., "Microbial Fuel Cells for Powering Environmental Sensors in Soils and Sediments", *Journal of Power Sources*, Vol. 221, Elsevier, 2013.
5. Ghasemi, M., et al., "Effect of Pretreatment and Biofouling on Nafion 117 Membranes in Microbial Fuel Cells", *International Journal of Hydrogen Energy*, Vol. 38, No. 26, Elsevier, 2013.
6. Rahimnejad, M., et al., "Microbial Fuel Cell as New Technology for Bioelectricity Generation: A Review", *Alexandria Engineering Journal*, Vol. 53, No. 3, Elsevier, 2014.

7. Zhang, Y., et al., “Manganese Dioxide-Coated Carbon Felt Anode for Enhanced Performance of Microbial Fuel Cells”, *Journal of Power Sources*, Vol. 274, Elsevier, 2015.
8. Le, N.L., and Nunes, S.P., “Membrane Materials and Technologies for Water and Energy Sustainability”, *Environmental Science: Water Research & Technology*, Vol. 2, No. 1, Royal Society of Chemistry, 2016.
9. Gude, V.G., “Microbial Fuel Cells for Wastewater Treatment and Energy Recovery – A Review”, *Journal of Environmental Chemical Engineering*, Vol. 4, No. 1, Elsevier, 2016.
10. Tharali, A.M., Sagadevan, V., and Muniyandi, K., “Microbial Fuel Cells for Bioelectricity Production – A Review”, *Journal of Cleaner Production*, Vol. 221, Elsevier, 2016.
11. Chaturvedi, V., and Verma, P., “Microbial Fuel Cells: A Green Technology for Generating Electricity from Waste and Xenobiotics”, *Journal of Cleaner Production*, Vol. 112, Elsevier, 2016.
12. Hernández-Flores, G., et al., “Alternative Low-Cost Membranes to Replace Nafion in Microbial Fuel Cells”, *Electrochemical Acta*, Vol. 213, Elsevier, 2016.
13. Kodali, M., et al., “Air-Breathing Microbial Fuel Cell Cathodes Using Platinum Group Metal-Free Catalysts”, *Journal of Power Sources*, Vol. 366, Elsevier, 2017.
14. Slate, A.J., et al., “Microbial Fuel Cells: An Overview of Technology, Materials, and Mechanisms”, *Energies*, Vol. 12, No. 20, MDPI, 2019.
15. Rangabhashiyam, S., et al., “Microbial Fuel Cells for Industrial Effluent Treatment and Bioelectricity Generation: A Comprehensive Review”, *Environmental Research*, Vol. 194, Elsevier, 2021.
16. Chowdhury, [First Name Initials], et al., “Pure Magnesium as an Anode Material to Enhance Microbial Fuel Cell Performance”, [Journal Name], Vol. [12], No. [194], 2023.
17. Farahani, H., et al., “Sustainable Water Treatment Technologies: Microbial Fuel Cells and Microbial Desalination Cells”, [Journal Name], Vol. [215], No. [17], 2024.
18. Jalili, H., et al., “Microbial Fuel Cells: Structure, Materials, Microorganisms, and Applications – A Review”, [Journal Name], Vol. [20], No. [18], 2024.
19. Ojha, P., et al., “Microbial Fuel Cells for Waste-to-Energy Conversion and Wastewater Treatment: A Review”, [Journal Name], Vol. [69], No. [12], 2025.

