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Sonargaon University (SU)

সোনারগাঁও ইউনিভার্সিটি (এসইউ)

PERFORMANCE STUDY OF COMPOSITE MEMBRANE IN MICROBIAL FUEL CELL FOR ENHANCED POWER GENERATION AND WASTEWATER TREATMENT

A report submitted to the Department of Mechanical, Sonargaon University of Bangladesh, in partial fulfilment of the requirements for the award of the degree of Bachelor of Science in mechanical engineering

A Project By

Maksudur Rahman Mozumder	**ME2101023146**
Md. Jahangir Alam	**ME2102024468**
Md. Sajal Hossain	**ME2202027212**
Md. Zobayer Hosen	**ME2203028139**

Supervised By

Md. Navid Inan

Lecturer

Department of Mechanical Engineering

Sonargaon University (SU)

Dhaka-1215, Bangladesh

May, 2026

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Approval

This is to certify that the project work entitled, " Performance Study Of Composite Membrane In Microbial Fuel Cell For Enhanced Power Generation And Wastewater Treatment " has been carried out by Maksudur Rahman Mozumder (ME2101023146), Md. Jahangir Alam (ME2102024468), Md. Sajal Hossain (ME2202027212) and Md. Zobayer Hosen (ME2203028139) thereby declared that the work presented here is original work done by me and has not been published or submitted elsewhere for the requirement of a degree of Bachelor of Science (B.Sc.) in Mechanical Engineering in the year of 2026 Program in the Department of Mechanical Engineering, Sonargaon University of Bangladesh (SU) has been carried out under by supervisor.

Md. Navid Inan
Lecturer
Department of Mechanical Engineering
Sonargaon University (SU

DEPARTMENT OF MECHANICAL ENGINEERING

SONARGAON UNIVERSITY (SU)

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DECLARATION

We do hereby solemnly declare that the work presented here in this project report has been carried out by us and has not been previously submitted to any University Organization for the award of any degree or certificate.

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We further undertake to indemnify the university against any loss or damage arising from breach of the foregoing obligation.

[Authors]

Maksudur Rahman Mozumder
ID ME2101023146

Md. Jahangir Alam
ME2102024468

Md. Sajal Hossain
ME2202027212

Md. Zobayer Hosen
ME2203028139

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[Authors]

Maksudur Rahman Mozumder
ID ME2101023146

Md. Jahangir Alam
ME2102024468

Md. Sajal Hossain
ME2202027212

Md. Zobayer Hosen
ME2203028139

NOMENCLATURE

MFC	Microbial Fuel Cells
ETP	Effluent Treatment Plant
PEM	Proton Exchange Membrane
COD	Chemical Oxygen Demand
BOD	Biological Oxygen Demand
EAM	Electroactive Microorganism
AEM	Anion Exchange Membrane
CEM	Cation Exchange Membrane
CNT	Carbon Nanotube
PVA	Poly Vinyl Alcohol

ABSTRACT

Microbial fuel cells (MFCs) are gaining attention as an environmentally friendly technology because they can treat wastewater while simultaneously producing electricity. In this study, a double-chamber microbial fuel cell was developed using textile wastewater as the inoculum and substrate source. A low-cost composite proton exchange membrane (PEM) was prepared using polyvinyl alcohol (PVA), potassium chloride (KCl), and agar, and was chemically crosslinked with glutaraldehyde to improve its mechanical strength and ionic conductivity. The performance of this composite membrane was then compared with that of a conventional membrane under the same operating conditions. The experimental results showed a significant improvement in power generation when the composite membrane was used. The conventional membrane produced a maximum voltage of 0.242 V, whereas the PVA–KCl–agar composite membrane achieved a much higher voltage of 0.467 V. This improved performance is mainly due to the better electrical conductivity, larger surface area, and enhanced electrochemical activity of the composite membrane. These properties helped microorganisms attach more effectively to the electrode surface and allowed faster electron transfer during microbial activity, leading to improved electricity generation. In addition, the composite membrane provided better stability and supported efficient microbial growth and biofilm formation inside the MFC system. The findings clearly indicate that the composite membrane performs more efficiently than the conventional membrane in terms of electrochemical performance and sustainable energy production. Overall, this study demonstrates that the developed PVA–KCl–agar composite membrane can serve as an effective, low-cost, and eco-friendly alternative for microbial fuel cell applications. The system not only enhances bioelectricity generation but also offers a sustainable approach for treating industrial textile wastewater and reducing environmental pollution.

CHAPTER 1

INTRODUCTION

1.1 Microbial Fuel Cell

A microbial fuel cell is a device that uses microorganisms as a biocatalyst and converts chemical energy into electrical energy. This device has attracted a lot of attention recently, due to its ability to generate electricity from various waste materials. A typical dual-chamber MFC consists of an anode and a cathode, which are separated by a proton exchange membrane. [1] These systems are generally considered to be a justifiable new technology. In MFCs, bacterial energy is directly converted to electricity. These types of cells can be used for bio-hydrogen production, wastewater treatment, environmental sensors, and bioremediation. [2] Microbial fuel cells (MFCs), as one type of "green" energy source, have attracted great interest among researchers. In MFCs, the use of entire microorganisms as micro-reactors eliminates the need for isolation of individual enzymes and allows active biomaterials under conditions close to their natural environment to convert organic compounds, from simple carbohydrates to waste organic matter, into electricity at a high efficiency. The specificity of isolated enzymes allows the abandonment of the conventional separation of the anode and cathode compartments and the miniaturization of enzymatic fuel cells. On the other hand, the tendency of the isolated enzymes towards denaturation and deactivation prevents the use of these fuel cells in harsh environments like sewage. [3]

Water is indispensable to all life on earth, playing a pivotal role in maintaining ecosystems and human health. Industrial sectors utilize substantial quantities of water for various purposes, including production processes, cooling, and cleaning. Although industries are crucial for economic growth and technological advancement, their operations can occasionally have adverse effects on water quality. The discharge of diverse by-products and effluents into aquatic systems can compromise the health of these ecosystems and reduce the availability of clean water for communities. To address these challenges, many industries are now implementing systems to treat and recycle wastewater. This has led to the establishment of treatment facilities, known as effluent treatment plants (ETPs), in nearly every industrial setting. Traditional ETPs, however, are known for their high energy consumption in treating wastewater and managing sludge. Consequently, research is ongoing to develop more energy-efficient treatment methods. One promising solution

is the use of microbial fuel cells (MFCs), which leverage the natural processes of microorganisms to treat wastewater while simultaneously generating electricity. MFCs utilize electrochemically active microorganisms, known as exoelectrogens. These microorganisms convert the chemical energy stored in organic matter into electrical energy by transferring electrons from the anode to the cathode. They are capable of treating industrial wastewater while recovering energy. [4]

The proton exchange membrane (PEM) is a key component that determines MFC performance and capital cost. Protons and cations produced in anode chambers by the bacterial oxidation of organics should be transported to the cathode chamber through an ion exchange membrane while preventing oxygen and substrate crossover. [5] A variety of membrane materials have been researched and employed as separators in MFC systems. A few of the most popular commercial membrane materials are Nafion, but they are often limited by high cost and environmental concerns. Recently, polyvinyl alcohol (PVA)-based polymer membranes have garnered significant interest for their wide range of applications in the medical industry, fuel cells, and other fields. PVA is a biodegradable, non-toxic, and economically viable polymer. Its innate hydrophilicity makes it suitable for wastewater treatment. [6]

Potassium chloride (KCl) is used as an electrolyte-supporting agent within these membranes. Adding KCl enhances ionic conductivity by facilitating ion exchange and reducing internal resistance, which allows more efficient transfer of protons from anode to cathode, increasing power output. Agar, a natural polysaccharide derived from seaweed, creates a porous, ion-conductive matrix when used in membrane synthesis. Studies have demonstrated that increasing agar concentration improves the membrane's ionic conductivity and mechanical stability, which directly impacts MFC efficiency. [7]

In this study, a composite membrane based on Polyvinyl Alcohol (PVA), Potassium Chloride (KCl), and Agar has been developed and investigated as a cost-effective substitute for commercial PEMs in MFCs. PVA is a water-soluble, non-toxic polymer known for its good film-forming ability, mechanical strength, and chemical stability. Agar, a naturally derived polysaccharide, provides a porous and flexible matrix that facilitates proton transfer and enhances membrane hydrophilicity. The incorporation of KCl as an electrolyte salt further improves ionic conductivity by providing mobile ions that promote efficient proton transport across the membrane.

The combined effect of PVA, KCl, and Agar is expected to enhance membrane performance by reducing internal resistance, improving proton conductivity, and maintaining structural integrity during long-term operation. This research aims to fabricate, characterize, and evaluate the electrochemical performance of the PVA–KCl–Agar membrane in MFC applications. Comparative analysis with conventional membranes will highlight its potential as a low-cost, sustainable, and efficient alternative for microbial fuel cell systems.

1.2 Objective of the study

The following objectives will be taken into consideration by the current study:

- To produce electricity by using textile wastewater.
- To remove pollutants from waste waters by decomposing them without any mediators.
- To analyze the voltage produced with respect to time for waste waters and find out the best electricity-producing waste water among them.

1.3 Working Principle of MFC

The classic double-chamber structure of the MFC consists of an anode chamber, an ion exchange membrane, and a cathode chamber (Figure 1a). The principle of electron production is that electroactive microorganisms (EAM) produce electrons and protons by metabolizing the anode substrate. Due to the potential difference between the cathode and the anode, the anode electrons pass through the external circuit to the cathode and supply electron acceptors in the cathode region. [8] The protons migrate through the membrane to the cathode region, combine with the electron acceptors, and accept electrons to produce water, thus forming a circuit and generating electricity [8]. The oxidation of the organic wastes is driven by the anaerobic respiration and metabolism of electrochemically active bacteria.[9] On the other hand, the electron passing through the circuit reaches the cathode, where it is accepted using an electron acceptor (O2 commonly used). MFCs can be termed as a fuel cell that converts the chemical energy of organics to electrical energy, where microorganisms act as the biocatalysts [10]

The reaction associated with MFC can be presented below:

Anodic reaction: $CH_3COO^- + H_2O \longrightarrow 2CO_2 + 2H^+ + 8e^-$

Cathodic reaction: $O_2 + 4e^- + 4H^+ \longrightarrow 2H_2O$

Overall reaction: $12\ C_6H_{12}O_6 + H_2O + 3O_2 \longrightarrow 4CO_2 + 4H_2O$

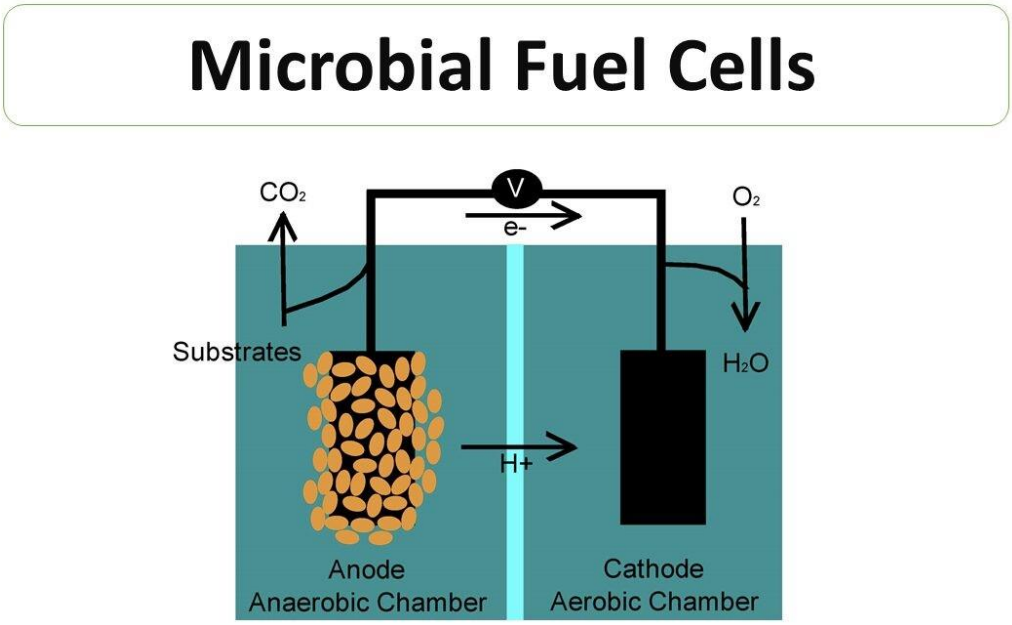

Figure 1: Microbial Fuel Cells

MFCs can use a variety of biodegradable organic molecules from landfill leachates, industrial waste, food waste, municipal wastewater, dairy waste, and other sources. Additionally, MFCs can treat wastewater with a wide COD range, reducing both energy use and greenhouse gas emissions. It has been determined that converting waste directly into high-value energy, clean electricity, or chemical goods is a superior solution for solving the excess sludge and energy problems in traditional wastewater treatment systems. MFC shave been used to produce energy from different wastewater sources, e.g., wastewater from food and food preparation industries, vegetable oil-based wastewater, refinery wastewater, fish handling wastewater, dairy wastewater, slaughterhouse wastewater, cotton industry wastewater, animals, and petrochemical endeavors, as well as from the wastewater of ripe, squeezed apples.[11]

1.4 Characteristics of proton exchange membrane (PEM)

A Proton Exchange Membrane (PEM) is a type of plastic that lets protons (H^+ ions) go through but stops electrons and gases. It's super important in fuel cells, including those that use microbes (MFCs). It gets the reaction going between the positive and negative sides of the cell by moving the protons where they need to be.[12]

The best PEMs should be able to do a few things really well. First, they need to let protons move through them easily ($\geq 10^{-2}$ S/cm). Second, they need to be strong enough to handle pressure without breaking. Third, they need to hold up when it gets hot (usually 60–100°C) and not fall apart when exposed to harsh chemicals.[13]

Also, how much water the membrane holds is key because protons travel through wet spots. The membrane should stay moist enough to keep things moving, but not get so wet that it swells up and gets weak. It also needs to block gases from mixing, which keeps the system working as it should. Ideally, it should last a long time and not cost too much. Nafion membranes are used a lot because they work great, but they're pricey, which is why folks are looking into other options like membranes made from chitosan, PVA, and graphene oxide. These can be cheaper and better for the environment.[14] [15]

1.5 Factors affecting the performance of PEM

A bunch of things can change how well a PEM does its job, both chemical and physical. Temperature is huge. Usually, hotter means protons move faster, but too much heat can dry the membrane out. How humid it is or how much water is in the membrane also matters a lot. Enough water helps protons jump around (Grotthuss mechanism), but too much water makes the membrane swell and fall apart.[13]

The pH of the stuff around it can also mess with the polymer. If it's strongly acidic or alkaline, it can break down the membrane. How thick the membrane is makes a difference, too. A thin one has less resistance but can tear easily, while a thick one has more resistance. How tightly the polymer chains are linked affects how well it holds up chemically and physically, but too much linking can slow down the protons because they can't move through the water as easily.

Also, what the membrane is made of (like Nafion, SPEEK, PVA, Chitosan) and what's added to it (like graphene oxide, SiO_2, TiO_2, ZrO_2, or phosphoric acid) really impacts how well it will work. These added ingredients can help with proton movement, water retention, and staying stable when it gets hot. Lastly, how much pressure you're using, how well it swaps ions, and how it's made all play a role in how long the PEM lasts and how well it works overall. You need to strike a good balance between water, temperature, and linking if you want it to work well for a long time.[12] [15]

CHAPTER 2

LITERATURE REVIEW

2.1 History

Microbial fuel cells can directly produce electricity from wastewater using bacteria and simultaneously remove pollutants from it. The first recorded occurrence of electrochemical activity between bacterial/fungal (yeast) species and electrodes can be traced back to the early 20th century, reported by Potter, were live cultures of Escherichia coli and Saccharomyces spp., produced electricity using platinum macro-electrodes in a battery-type setup with sterile media [16]. This was later confirmed by Cohen in 1931, who reported a voltage of 35 V at a current of 0.2 mA from a stacked bacterial fuel cell system. Some recent thesis papers on microbial fuel cells are described and reviewed below.

According to Hisham et al. [17], an MFC has the ability to generate electricity from the wastewater while simultaneously removing carbon and nitrogen. They have used three wastewaters from different sources and found the most efficient source among them. The finding of the most efficient wastewater source was done depending upon the stable electricity generated and the maximum removal of pollutants. They have used a two-chambered MFC with one-liter wastewater and one-liter phosphate buffer with an unknown size of electrodes. However, phosphate buffer can be replaced by normal water from the point of view of the economic development of MFC. Furthermore, depending upon the size of the electrode, the power produced in the MFC can vary.

Guo et al. [18] stated that while MFCs hold great potential for various applications, major challenges remain for MFCs to be practical. Firstly, the power densities of MFCS must be augmented because they are too low for most envisioned applications. One key bottleneck for MFCs is the electron transfer rate limitation in microbial biofilms. They have focused on microbes in wastewater, the electron transfer mechanism, mediated and direct electron transfer, the construction of MFC, and the materials that can be used in MFC. They also explained the proton exchange membrane and mentioned that Nafion is the most commonly used CEM to allow the passage for ion exchange while partitioning the anode chamber and the cathode chamber. In the case of electricity-producing bacteria, they have mentioned that "There is still a lack of

understanding of electricity-producing bacteria's electron transfer mechanisms, especially in microbial communities involving electrochemically inactive bacteria". It is a fact that to improve MFC performances beyond any conventional approaches could be achieved with a better understanding of how biofilm communities function electrochemically, and new superbug communities can be genetically engineered.

From the point of view of Du et al. [19], energy generation, storage, and consumption are topics that are increasingly prevalent within modern research fields and are of global interest and importance. Microorganisms, such as bacteria, can generate electricity by utilizing organic matter and biodegradable substrates such as wastewater, whilst also accomplishing biodegradation/treatment of biodegradable products, such as municipal wastewater. The structural design of the compartments can vary dramatically to enhance the power outputs of MFCs. Two-compartment MFCs are typically utilized with a defined medium (such as glucose or acetate) and run in batch mode. MFCs can also be operated in a continuous mode and are currently used in laboratories to optimize MFC power outputs.

Wei et al. [20] described that Electrodes utilized in MFCs not only function as conductors, as with traditional fuel cells, but the anode material also acts as a support for bacterial biofilms and therefore must be biocompatible with the bacterial cells present. A high surface area is desirable, and a relatively rough surface is thought to be an ideal surface property in an MFC configuration, as it helps with the retention of the bacteria on the surface. One area which could potentially be explored in order to optimize power output from MFCs is the electrode materials themselves. In order for a material to be effective as an electrode, it should have a number of properties. It should ideally be economical and exhibit beneficial electrochemical properties (i.e., favorable electron transfer) whilst being mechanically stable, in conjunction with a large surface area, giving rise to large current densities.

He and Angenent [21] presented that the use of catalysts and electron acceptors in MFC configurations is non-essential, and their use is often expensive due to the constant need to replenish exhausted materials. In order to avoid the high costs associated with the use of catalysts/electron acceptors in the cathodic compartment, research interest is currently directed to replacing these materials with microorganisms, known as bio-cathodes, which can assist and improve cathodic reactions. Both aerobic and anaerobic biocathodes have been explored; this is of

paramount importance depending on the terminal electron acceptor adopted in the cathode. One example of an aerobic biocathode is Thiobacillus ferroxidase, and this bacterium has been shown to regenerate ferric ions, which have been utilized as electron mediators in the cathodic compartment. An example of an anaerobic biocathode is Geobacter metalloproteins, which have the ability to oxidize ammonia and reduce nitrate (to nitrogen), leading to denitrification in an MFC configuration.

Feng et al. [22] reported that a nitrogen-doped graphene catalyst (of 2-8 layers) gave rise to the oxygen reduction reaction at facile potentials, comparable to that of a platinum catalyst. In an MFC configuration, this could give rise to beneficial outputs of the MFC. The advantages of nitrogen-doped graphene include being less expensive than platinum with improved long-term operational stability in comparison to commercial platinum electrodes as measured within alkaline electrolytes.

Harnisch et al. [23] proposed that factors that can have a detrimental effect on both the power outputs and the efficacy of an MFC are the inactivation of electro-catalysts (if present) and the crossover of organic compounds or electron acceptors from the anode to the cathode (and vice versa). The crossover of electron acceptors from the cathodic compartment into the anode has been shown in a previous study to disrupt biofilm formation and lead to biofilm inactivation, which can considerably decrease MFC performance, due to the flow of internal currents and the formation of mixed potentials.

Deng et al. [24] concluded that the limiting factors of MFCs are reported to be high-associated costs (most notably due to electrode materials and the use of PEMs), low energy outputs, and limited life spans; the key intrinsic factor currently limiting the power output of MFC technologies is the rate of electron transfer to the anode and the electrochemical properties of the material. MFCs are currently unable to attain their theoretical power outputs, and therefore, the implementation of this technology into industry is not yet feasible.

Sun et al. [25] explained that the overall efficiency and performance of an MFC can be affected by a vast array of factors. Other performance-limiting factors have arisen whilst trying to enhance the performance of MFC for industrial and social applications; these include biofouling (leading to electrode surface blockage and ultimately a reduction in surface area), catalyst inactivation (if present), and excessive biofilm growth, possibly leading to the production of non-conductive

debris. The production of non-conductive debris, such as polymeric substances and/or dead cells, can isolate the electrochemically active biofilm from the electrode surface or, with more porous electrodes, become entrapped in the 3D architecture, leading to a potential reduction in available surface area and ultimately a reduction in current generation.

Rabaey and Verstraete [26] stated that MFCs offer a significant advantage over other renewable energy sources, as they can be applied towards wastewater treatment. Another advantage of MFC technologies is that it less dependent in comparison to other renewable energy technologies (i.e., solar and wind) upon geographical location and seasonal change.

Oliot et al. [27] explained that in order to overcome the practical challenges, the reactor should consist of modules involving multiple electrodes and/or multiple MFC units. Division into modules (parts of the whole system) and multiplication of units (MFCs) is one of the necessary means for stepping up the voltage values through the electrical configuration in series, and this is due to short-circuiting between anode and cathode. The modularity is here represented by the components of the module (anodes and cathodes) that can be connected in parallel electrical connection due to the fact that they share the same electrolyte, therefore they form a group of multiple MFC units. The power output generated from an individual MFC unit is insufficient for most practical applications, to increase the power series configuration of individual MFC units needs to be implemented into a stack.

According to Park et al. [28], microorganisms play important roles in the anode chamber and generate electrons. These generated electrons are utilized to reduce electron acceptors in the cathode once they pass through the external circuit. Likewise, to complete the circuit produced protons must pass through the proton exchange membrane (PEM) from the anode to the cathode. It follows logically from what has been mentioned that this process leads to electrical power and organic waste removal contemporarily. As mentioned above, the anaerobic anode compartment is one of the main parts of MFCs. All the essential conditions to degrade the biomass are provided in the anode chamber. This compartment is filled with substrate, mediator (it is optional), microorganism, and the anode electrode as an electron acceptor.

Rozendal et al. [29] clarified that Electrode potential losses for large-scale MFC systems prove to be a major challenge, but can be solved through material selection. Potential losses of bioanodes have consistently been much lower than those observed from traditionally excellent

electrochemical cathodes like platinum. While the reason for the low performance of Pt cathodes, which are very expensive, is not well understood, it may be explained by the relatively mild pH level of wastewater, typically around a value of 7. Other electrochemical systems, such as PEM fuel cells that use Pt catalysts, operate at a very low pH value (<1). This low pH level provides high proton concentrations, a reactant in the cathode reaction, that allows conventional fuel cell systems to sustain much higher current densities. Other cathode materials, such as the MnO2 developed in the NYSERDA/WERF pilot test, provide promise for a low-cost Pt alternative but require further optimization.

Waller and Trabold [30] proposed that, in addition to MFC design challenges, research results based upon actual wastewater treatment are lacking in the open literature. While there have been several studies of MFC applications treating actual wastewater, the overwhelming majority of tested substrates used are synthetic wastewaters or specific chemicals such as acetate and glucose. These studies have been helpful for laboratory-scale MFC development, but often poorly predict real-world results. The most comprehensive list to date of the substrates tested for MFC applications can be found in the paper by Pant et al. (2010). Some of the possible MFC wastewaters on a laboratory scale include: brewery, chocolate industry, domestic, meat processing, paper recycling, protein-rich, and starch processing.

Santoro et al. [31] reviewed a variety of cathode catalyst materials and discussed their performance and reaction mechanisms. These carbonaceous materials were based on metals, and included carbon cloth, carbon paper, carbon felt, carbon veil, stainless steel, titanium, and nickel-chrome mesh as anode materials. Different novel and synthetic materials [such as graphene, platinum, activated carbon, or carbon nanotubes (CNT)] can also positively catalyze the power density of the fuel cell. Nano pores are able to increase the porosity of the surface of the electrode, which may be responsible for maximizing the performance of the MFC because a large surface area also enhances the oxygen reduction reaction in the cathode chamber. Biocathodes are also formulated by microalgae,

Mansoorian et al. [32] and Faria et al. (2017) studied that dairy wastewater can also be used as an MFC substrate because it contains biodegradable organic compounds and nutrients.

Palanisamy et al. [33] reviewed that the highest percentage of carbon removal (>90%) from wastewaters has been observed in MFC. As they have discussed, the MFC technology is used for

wastewater treatment and to generate an electric current. Oxidation of organic matter in wastewater generates electrons and protons in the anode compartment by exaelectrons. The protons and electrons are transferred to the cathode chamber by the membrane and electrodes, respectively. These processes result in the generation of clean water and energy. Wastewater from the food and food-processing, vegetable oil industrial wastewater, refinery and distillery, seafood processing wastewater, dairy wastewater, cassava mill wastewater, swine wastewater, slaughterhouse wastewater, surgical cotton industry wastewater, livestock, and petrochemical industries, as well as from fermented apple juice wastewaters, have been used for the generation of electricity using MFC.

Dong et al. [34], Lu et al. (2017), and Seo et al. (2018) stated that MFCs in wastewater treatment have played a major role in both water treatment and the production of bioenergy. The sustainable credentials of wastewater treatment in MFCs may include: (i) generation of electricity from substrate energy, (ii) operation in the absence of gas, (iii) reduced energy loss during aeration, (iv) operational capability even at low temperatures, (v) low activated sludge associated with anaerobic digestion operation, and (vi) use when electrical power is insufficient.

Gajda et al. [35] concluded that the greatest challenge for any technology moving into the real world is its suitability for manufacturing, which in turn, drives economies of scale. The same applies to the MFC technology, and this has been part of the challenge in the technology taking off and becoming commercially available. Most of the core parts and components can be bespoke and therefore expensive, even at the prototype level, and there is a scientific challenge in identifying alternatives that would (i) perform equally well and for prolonged periods, but most importantly (ii) be inexpensive and widely available. One of the avenues researchers have explored is the alternative low-cost materials, including ceramic [36,37] or cardboard [38,39] and plant-derived electrodes.[40]

In studies published by Rehman Asghar and Kiani in 2025, Asghar et al. explain how composite membranes with inorganic nanoparticles like TiO_2, SiO_2, and ZrO_2 help further enhance proton transfer while also mitigating methanol crossover. According to Rehman Asghar et al. (2025), the incorporation of nanomaterials in PEMs enhances water retention along the proton conduction pathways. PEMs become ideal for methanol fuel cells (MFCs) and proton exchange membrane fuel cells (PEMFCs). In the same vein, Nafion-TiO_2 composite membranes under high-

temperature, low-humidity conditions also demonstrated high-temperature stability and low-humidity conductivity. The addition of hydrophilic nanoparticles also provides support to the membrane and polymer-complex, by swaying the hydrophilic expansion, increasing the polymer's life, and restricting swelling.[41]

Perhaps one of the most critical areas impacting the performance of MFC is membrane fouling. Membrane fouling lowers the ion exchange capacity and increases internal resistance. The accumulation of biofilm and the deposition of inorganic salts on the surface of the PEM can obstruct the performance by covering active transport sites. PEMs' antifouling strategies include coating PEMs with hydrophobic and biocidal layers [42] and using ceramic or clogging-resistant anion exchange membranes (AEMs). Studies comparing cation exchange membranes (CEMs) and anion exchange membranes (AEMs) have indicated that AEM-based systems have a tendency to yield greater COD removal efficiency and enhanced coulombic yield, likely due to reduced oxygen crossover.[43]

Among the various factors influencing the performance of MFC, membrane fouling holds particular significance. The fouling of membranes decreases exchange capacity and increases internal resistance.[44] The performance of PEM can be affected by the accumulation of biofilm, the deposition of inorganic salts on the surface of the PEM, and the blockage of active transport sites. Strategies PEMs employ to mitigate antifouling include using hydrophobic and biocidal coatings and using ceramic or clogging-resistant anion exchange membranes (AEMs) (Park et al., 2015; Saxena et al., 2024). Several studies comparing cation exchange membranes (CEMs) and anion exchange membranes (AEMs) systems have shown that AEM-based systems tend to achieve higher COD removal efficiency and higher coulombic yield, probably because of reduced oxygen crossover.[43]

PEM material innovation continues to progress toward sustainable, biodegradable, and affordable alternatives. For example, sulfonated polybenzimidazole (S-PBI) membranes have demonstrated impressive proton conductivity and chemical resistance in microbial environments. PVA-Nafion-borosilicate composites [45] and sulfonated lignin-based PEMs have shown better mechanical stability and less crossover. The development of bio-derived PEMs, like chitosan- or cellulose-based membranes, is another new direction for environmentally friendly MFCs.[46]

CHAPTER 3

MATERIALS AND METHODS

3.1 Experimental setup

A basic Microbial Fuel Cell (MFC) consists of an anode chamber, a cathode chamber, a Proton Exchange Membrane (PEM) or salt bridge, and the electrode assembly. MFCs are classified based on their design and operation mode, which include:

- Two-compartment MFCs
- Single-compartment MFCs
- Up-flow MFCs
- Stacked MFCs
- Other designs

For this experiment, one two-compartment MFC was utilized for a conventional membrane(figure-02), and the other is a composite membrane (figure-03). A common configuration for that type is the classic "H" shape [32], which uses two plastic pots connected by a PVC pipe containing a small PEM that separates the anode and cathode chambers.

However, a drawback of that specific “H” design is its tendency toward high internal resistance. This is primarily due to the considerable distance between the two electrodes and the small surface area of the membrane, which ultimately limits the maximum power density output.

Two-chamber MFCs are typically operated in batch mode and are especially well-suited for laboratory research. They are ideal for investigating new variables, such as:

- Power production using novel substrates.
- Performance of different electrode materials or membranes.
- The nature of microbial communities that develop during the degradation of specific compounds.
- Developing MFC-based sensors.

Figure 2: Two-chamber MFCs for composite membrane.

Figure 3: Two chambers of MFCs for a conventional membrane

3.2 Materials

The composite proton exchange membrane used in this microbial fuel cell (MFC) system was made from 10% (w/v) potassium chloride (KCl), 10% (w/v) polyvinyl alcohol (PVA) based on the KCl solution, and 10% (w/v) agar powder. This process involved controlled heating, mixing, and casting. First, KCl was dissolved in deionized water at 90 °C while stirring constantly to create a clear electrolyte solution. Next, PVA was gradually added and stirred at 800 rpm until it fully dissolved, resulting in a thick polymer solution. Then, agar powder was mixed into the hot solution and stirred under the same conditions until a smooth, transparent composite solution formed. After cooling to room temperature, the solution was poured into a PVC pipe mold (12 cm length × 1.91 cm diameter) to shape the tubular membrane. Once gelled, the membrane underwent chemical crosslinking with 2.5% (v/v) glutaraldehyde and 3–5 drops of concentrated HCl for 12 hours to improve its stability and proton conductivity. The MFC assembly included two separate plastic pots that functioned as the anode and cathode chambers. These were connected by the PVC pipe containing the composite membrane, which served as a proton exchange bridge between the two sections. This setup allowed for effective proton transfer while keeping the microbial anolyte and catholyte separate, leading to better power generation and overall system stability.

3.3 Electrodes

Different types of electrodes can be used in an MFC. The electrodes used in this study are Copper (Cu), Aluminum (Al), Carbon (C), etc. As the anodes and the cathodes used in the MFC system have basically the same function, different metals like the electrode materials mentioned above were used to find out the best one that can grow the microbes or have the same ability to take the same electrons. Also, the electrode material for maximum power generation. The primary goal of the electrode selection is to increase the bacterial affinity towards the anode required for the growth of biofilm by providing sufficient support and a conductive surface.

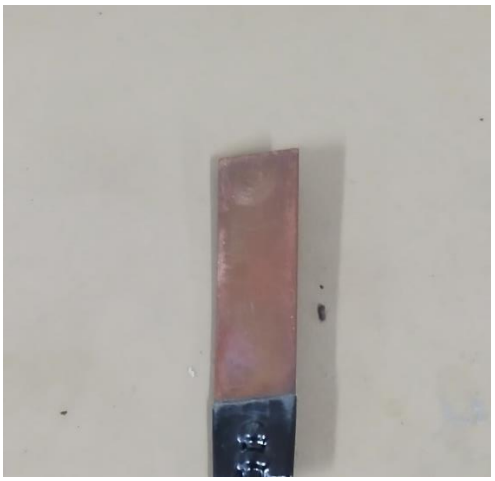

Figure 4: Copper electrode

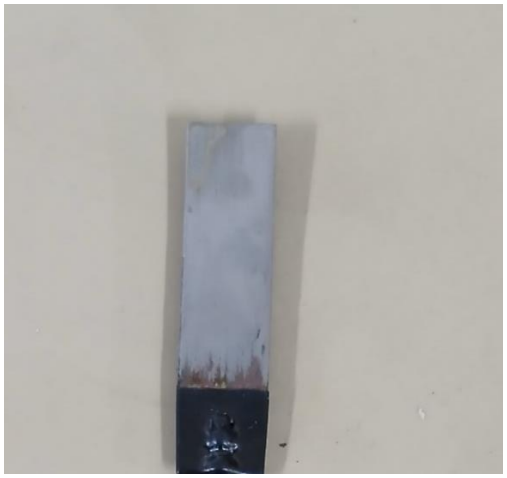

Figure 5: Iron electrode

3.4 Fabrication of Membrane

The proton exchange membrane for the microbial fuel cell was made using a blend of polyvinyl alcohol (PVA), potassium chloride (KCl), and agar powder. This involved controlled heating, mixing, casting, and chemical crosslinking. In the first step, 10 g of KCl was dissolved in 85 mL of deionized water. The mixture was stirred at 90 °C for 15 minutes at 500 rpm to ensure the salt fully dissolved. Next, 10 g of PVA was slowly added to the hot KCl solution. It was stirred at 90 °C and 800 rpm until the PVA completely dissolved, forming a clear, thick polymer solution. Once the PVA was dissolved, 10 g of agar powder was added. This mixture was stirred continuously at 90 °C and 800 rpm until it became a uniform, transparent, and bubble-free gel-like mixture. The prepared polymer solution was cooled to room temperature to avoid thermal degradation and to encourage gelation. After cooling, the homogeneous solution was cast into a clean PVC pipe mold sealed at one end to create a tubular membrane.

Figure 6: Crosslinking of PEM by glutaldehyde (2.5% v/v)

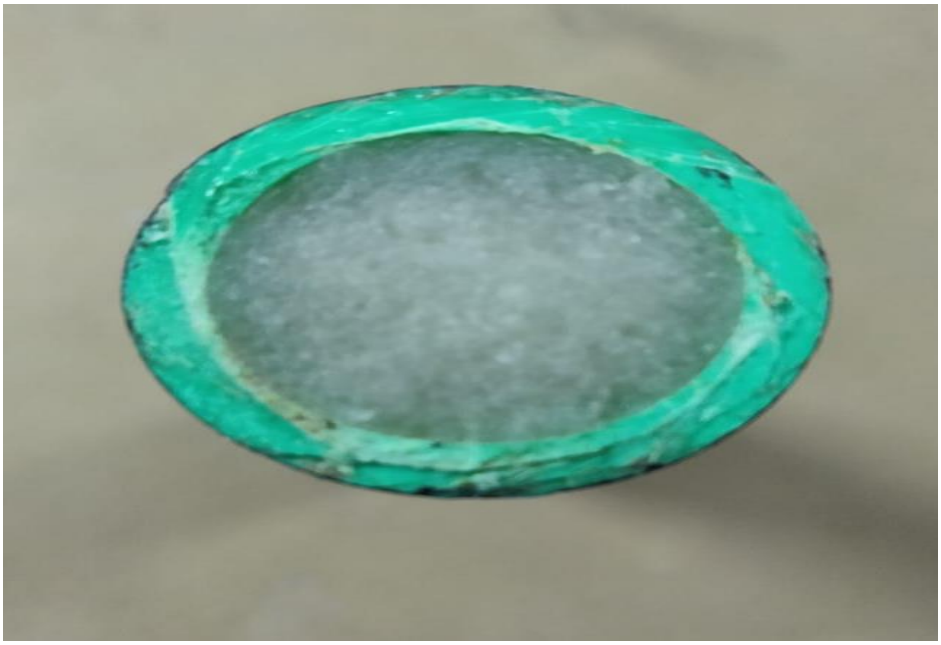

Figure 7: Cross-sectional view of PEM.

The pipe was gently rotated to ensure an even layer on the inner surface. It was then left undisturbed at room temperature for slow gelation and partial drying. Once the membrane formed, it underwent chemical crosslinking (figure-)by being immersed in a 2.5% (v/v) glutaraldehyde solution. Three to five drops of concentrated hydrochloric acid (HCl) acted as a catalyst, and the reaction lasted for 12 hours at room temperature. This crosslinking improved the membrane's mechanical strength, water stability, and proton conductivity by creating covalent linkages between the PVA and agar chains. Following crosslinking, the membrane was washed several times with deionized water to clear any unreacted glutaraldehyde or acid residues. It was then soaked for 24 hours in deionized water or 0.1 M KCl to reach equilibrium before use. The resulting PVA–KCl–agar membrane was flexible, mechanically stable, and showed good ionic conductivity, making it suitable for use as a proton exchange membrane in the microbial fuel cell system.

3.5 Fabrication of Microbial Fuel Cell

The microbial fuel cell (MFC) was built as a two-chamber tubular reactor. It used two identical plastic pots for the anode and cathode compartments, connected by a PVA-KCl-agar proton-exchange membrane cast inside a PVC tube (12 cm × 1.91 cm). To prepare the membrane, we mixed 10% w/v KCl, 10% w/v PVA, and 10% w/v agar. This mixture was cast into the PVC mold, demolded, and chemically crosslinked using 2.5% (v/v) glutaraldehyde with 3–5 drops of concentrated HCl for 12 hours. After that, it was thoroughly rinsed and equilibrated in 0.1 M KCl.

One electrode was placed in the anode chamber, and an identical one went in the cathode chamber facing the membrane to reduce the ionic path length. The anode chamber was filled with textile wastewater, filtered to remove large solids if needed. This served as both substrate and inoculum. The cathode chamber contained fresh water and was either aerated or exposed to air to provide the electron acceptor. We covered both chambers to limit evaporation while allowing gas exchange at the cathode.

To assess how well the composite membrane performed, we later built another MFC using a conventional membrane, with copper in the anode chamber and steel in the cathode chamber, all under similar operating conditions. We then compared the performance of both systems based on power density, internal resistance, and COD removal efficiency. This side-by-side analysis helped us understand the real benefits that it brought compared to the conventional membrane setup.

Before starting, we gently purged the MFC with N_2 to create anoxic conditions in the anode (this step was optional). We conditioned the membrane and electrodes by soaking them in electrolyte, and then connected the cell across an external resistor. We continuously monitored the electrical output (voltage across the resistor) with a data logger, recording at regular intervals, such as every 5 minutes. From this data, we calculated current ($I = V/R$), power ($P = V \cdot I$), and power density (normalized to electrode/projected area).

For performance assessment, we measured open-circuit voltage (OCV), polarization, and power curves by changing external resistance. We also looked at internal resistance from the V-I slope or EIS, if available, and conducted long-term stability tests. We periodically sampled the water quality (COD) of the anolyte and catholyte to assess substrate removal. The system was operated until we achieved steady power output before collecting final data.

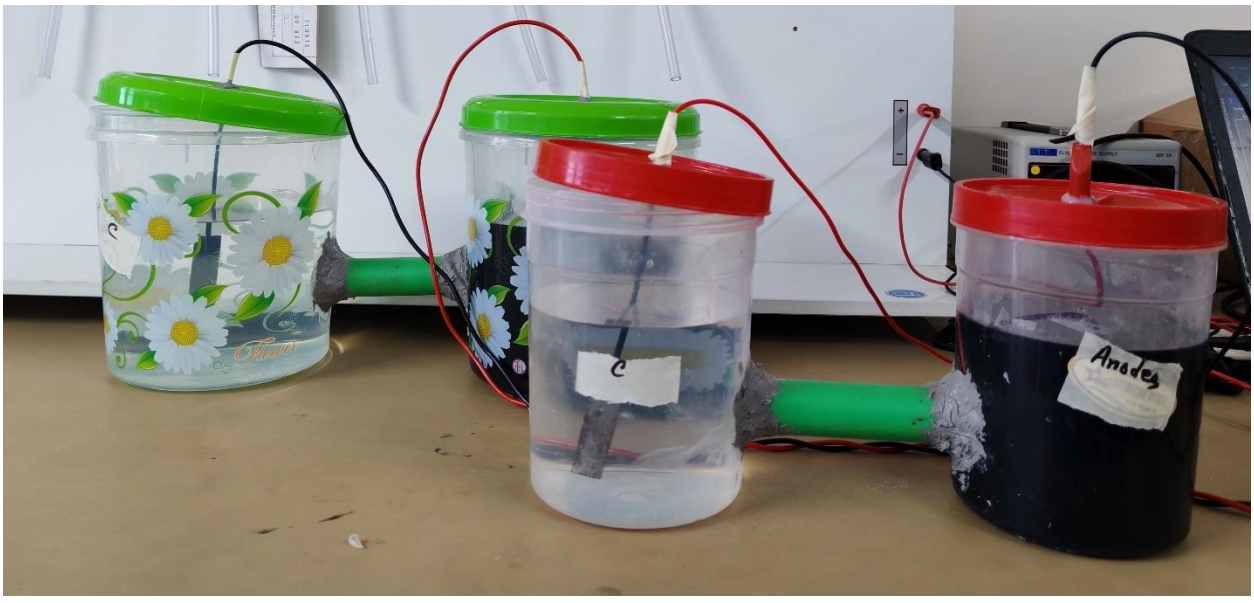

Figure 8: Two chambers of MFCs

CHAPTER 4

RESULT AND DISCUSSION

4.1 Results and Discussion:

In this study, we took a closer look at how two different types of membranes perform and how they impact the overall efficiency of microbial fuel cells (MFCs). The conventional membrane, which served as our control, produced a maximum output voltage of just 0.242 V. This result highlights its limited electrochemical activity and relatively poor electron transfer ability between the microorganisms and the electrode surface. On the other hand, the composite membrane made from PVA–KCl–agar membrane delivered a much more impressive voltage output of 0.467 V. This significant boost in performance can be linked to the enhanced structural and electrical properties of PVA–KCl–agar membrane. By co-doping with nitrogen and sulfur atoms, we improved its electrical conductivity, increased the surface area, and created more active sites for microbial attachment and biofilm development. These features allowed for quicker electron transfer from the microorganisms to the anode, ultimately enhancing the overall power generation of the MFC. The comparison clearly shows that the composite membrane outperforms the conventional electrode in terms of electrochemical performance and stability, making it a more promising option for efficient and sustainable bioelectricity generation in microbial fuel cell applications.

Table 1: Electricity production from textile wastewater (conventional membrane) with respect to time

Time(min)	Voltage(V)	Time(min)	Voltage(V)
0	0.208	170	0.241
10	0.211	180	0.24
20	0.214	190	0.239
30	0.225	200	0.238
40	0.228	210	0.24
50	0.23	220	0.239
60	0.235	230	0.238
70	0.24	240	0.237
80	0.242	250	0.235
90	0.242	260	0.234
100	0.242	270	0.233
110	0.242	280	0.232
120	0.242	290	0.23
130	0.242	300	0.228
140	0.242	310	0.225
150	0.241	320	0.223
160	0.242	330	0.22

Table 2: Electricity production from textile wastewater (composite membrane) with respect to time

Time(min)	Voltage(V)	Time(min)	Voltage(V)
0	0.466	170	0.456
10	0.467	180	0.455
20	0.448	190	0.451
30	0.457	200	0.447
40	0.459	210	0.446
50	0.462	220	0.448
60	0.465	230	0.452
70	0.463	240	0.451
80	0.457	250	0.445
90	0.461	260	0.442
100	0.46	270	0.449
110	0.459	280	0.447
120	0.465	290	0.449
130	0.456	300	0.448
140	0.455	310	0.445
150	0.457	320	0.443
160	0.457	330	0.443

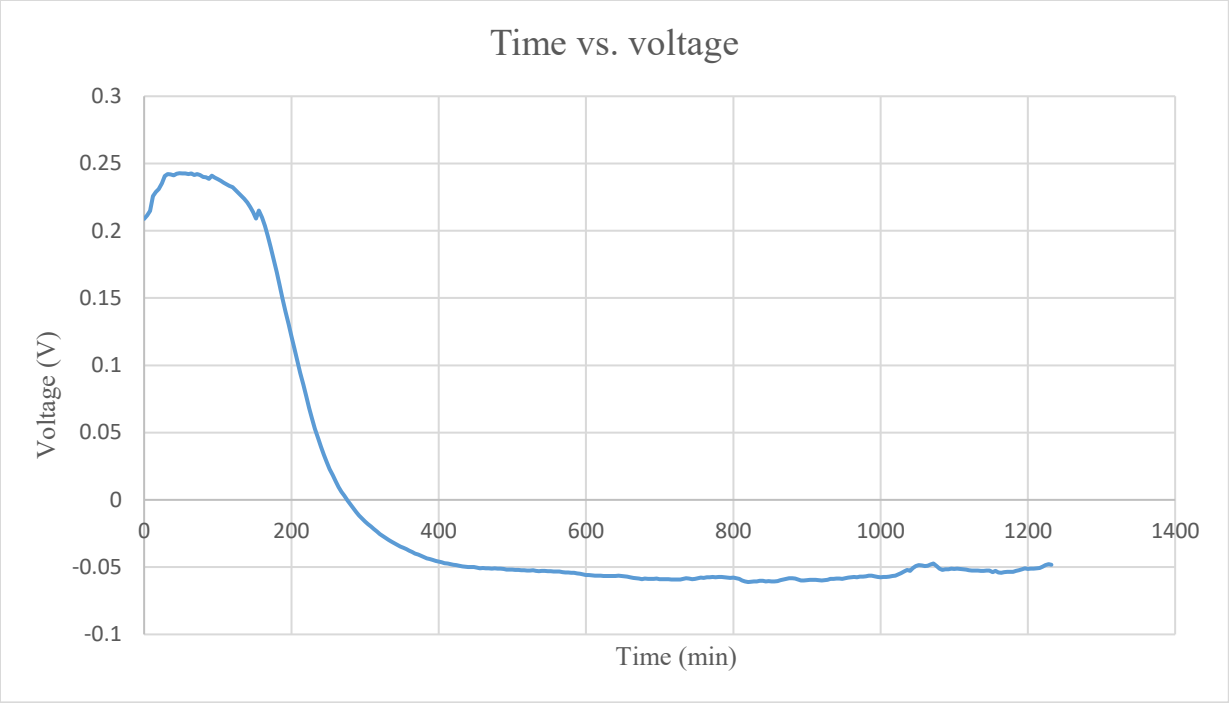

Figure 9: Time vs. Voltage for conventional membrane

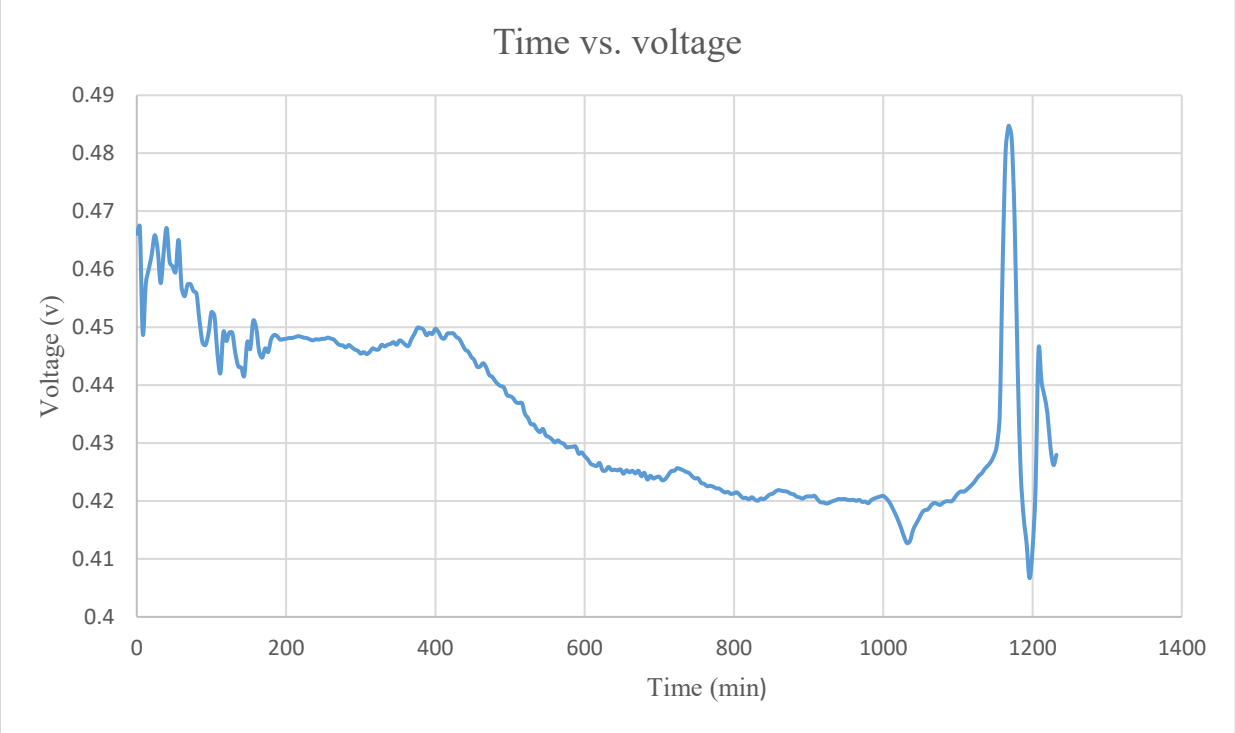

Figure 10: Time vs. Voltage using PVA–KCl–agar membrane

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

In this study, a double-chamber microbial fuel cell (MFC) was successfully designed and fabricated using a low-cost, eco-friendly proton exchange membrane (PEM) composed of polyvinyl alcohol (PVA), potassium chloride (KCl), and agar powder, chemically crosslinked with glutaraldehyde to improve its mechanical and ionic properties. The membrane showed good flexibility, stability, and ionic conductivity, making it an effective alternative to expensive commercial membranes like Nafion. Textile wastewater served as the substrate in the anode chamber, providing both organic matter and microorganisms necessary for bioelectricity generation, while fresh water was used in the cathode chamber as the electron acceptor medium. The system configuration, using a PVC pipe (12 cm × 1.91 cm) as a membrane housing between two plastic chambers, proved simple and efficient for laboratory-scale operation. Continuous monitoring through a data logger confirmed stable voltage generation, demonstrating the feasibility of wastewater-to-energy conversion. The results indicate that the synthesized PVA–KCl–agar composite membrane can effectively facilitate proton transport and electron flow, achieve satisfactory electrochemical performance while contributing to wastewater treatment. Therefore, the developed microbial fuel cell presents a sustainable and cost-effective approach for simultaneous energy generation and environmental remediation, offering significant potential for future scale-up and optimization in renewable bioenergy systems.

5.2 Recommendations

Recommendation for Future Research

- To increase the efficiency of the MFC and economical implementation, the following recommendations are proposed:
- Finding out the cheap and efficient material for the electrode which doesn't affect by microorganisms or has a negligible effect of bacteria on it.
- Finding out the PEM with an optimum surface area at a lower cost so that it can efficiently transfer protons to the cathode side.

- Providing sufficient agitation on the cathode side will produce more voltage, depending upon the amount of water production.
- Providing a non-porous membrane such as nylon, cellulose, or polycarbonate will provide the more power density.
- The production of hydrogen gas is possible by this system with the generation of electricity.
- Finding another cathodic solution instead of water, which is more feasible and economically can generate more power output.
- Economic development of MFC so that it can produce electricity with simultaneous removal of pollutants, depending upon the quality and quantity of wastewater.

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