UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Faculty of Electrical Technology and Engineering

DEVELOPMENT OF IOT-MONITORED MICROBIAL FUEL CELL-BASED FOOD WASTE UTILIZATION FOR ELECTRICITY GENERATION

MUHAMMAD AMIRUL AIMAN BIN ROSLAN

Bachelor of Electrical Engineering Technology with Honours

2024

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**A project report submitted
in partial fulfillment of the requirements for the degree of
Bachelor of Electrical Engineering Technology with Honours**

Faculty of Electrical Technology and Engineering

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2024

DECLARATION

I declare that this project report entitled "DEVELOPMENT OF IOT-MONITORED MICROBIAL FUEL CELL-BASED FOOD WASTE UTILIZATION FOR ELECTRICITY GENERATION" is the result of my own research except as cited in the references. The project report has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature	:	
Student Name	:	MUHAMMAD AMIRUL AIMAN BIN ROSLAN
Date	:	5/1/2025

APPROVAL

I approve that this Bachelor Degree Project (PSM) report entitled “DEVELOPMENT OF IOT-MONITORED MICROBIAL FUEL CELL-BASED FOOD WASTE UTILIZATION FOR ELECTRICITY GENERATION” is sufficient for submission.

Signature	:	
Supervisor Name	:	Mohamad Na’im bin Mohd Nasir
Date	:	5/1/2025

APPROVAL

I hereby declare that I have checked this project report and in my opinion, this project report is adequate in terms of scope and quality for the award of the degree of Bachelor of Electrical Engineering Technology with Honours.

Signature :

Supervisor Name : Mohamad Na'im bin Mohd Nasir

Date : 5/1/2025

Signature :

Co-Supervisor Name (if any) :

Date :

DEDICATION

To my beloved mother, Badariah binti Ali Aman, and father, Roslan bin Rohimin,

and

To my supervisor Mohamad Na'im bin Nasir and friends thank you so much for help me to complete my project

ABSTRACT

The research project aims to tackle the issue of effective food waste management by employing microbial fuel cells (MFCs) to turn food waste into electricity. The main goal of the research project is to significantly contribute to waste reduction and the promotion of sustainable energy generation. This aligns with the United Nations Sustainable Development Goals, specifically SDG 7, which aims to attain accessible and environmentally friendly energy for everyone. The objective of the study is to utilise starch, a kind of discarded food, as a substrate in the microbial fuel cell (MFC) to produce renewable energy. The depletion of conventional energy sources has intensified the search for sustainable alternatives, and microbial fuel cells (MFCs) have emerged as a promising technology for clean energy generation. This project, titled Development of IoT-Monitored Microbial Fuel Cell-Based Food Waste Utilization for Electricity Generation, explores the potential of MFCs to convert food waste into electricity while incorporating Internet of Things (IoT) technology for real-time performance monitoring. Potato and rice starch were utilized as microbial substrates to enhance bioelectricity production. Soft carbon graphite felt electrodes were employed for the anode and cathode, while a KCl and agar salt bridge served as the proton exchange membrane.The experimental setup integrated an ESP32 microcontroller and a voltage sensor to monitor system performance, with data transmitted to the Blynk IoT platform. Results demonstrated a voltage range of 54.0 mV to 230 mV, insufficient for standalone IoT operation but providing valuable insights into system optimization. This study highlights the feasibility of coupling microbial fuel cells with IoT for sustainable energy applications and suggests pathways for future improvements in power output and scalability.

ABSTRAK

Projek penyelidikan ini bertujuan untuk menangani isu pengurusan sisa makanan yang berkesan dengan menggunakan sel bahan api mikroba (MFC) untuk menukar sisa makanan menjadi elektrik. Matlamat utama projek penyelidikan ini adalah untuk menyumbang secara signifikan kepada pengurangan sisa dan promosi penjanaan tenaga lestari. Ini selaras dengan Matlamat Pembangunan Mampan Pertubuhan Bangsa-Bangsa Bersatu, khususnya SDG 7, yang bertujuan untuk mencapai tenaga yang boleh diakses dan mesra alam untuk semua. Objektif kajian ini adalah untuk menggunakan kanji, sejenis makanan yang dibuang, sebagai substrat dalam sel bahan api mikroba (MFC) untuk menghasilkan tenaga boleh diperbaharui. Kemerosotan sumber tenaga konvensional telah meningkatkan usaha mencari alternatif yang lebih lestari, dan sel bahan api mikroba (MFC) telah muncul sebagai teknologi yang menjanjikan untuk penjanaan tenaga bersih. Projek ini, bertajuk Pembangunan Sel Bahan Api Mikroba Berasaskan Pemantauan IoT untuk Penggunaan Sisa Makanan bagi Penjanaan Elektrik, meneroka potensi MFC untuk menukar sisa makanan menjadi elektrik sambil mengintegrasikan teknologi Internet Benda (IoT) bagi pemantauan prestasi secara masa nyata. Pati kentang dan beras digunakan sebagai substrat mikroba untuk meningkatkan penghasilan bioelektrik. Elektrod grafit lembut karbon digunakan untuk anod dan katod, manakala jambatan garam KCl dan agar berfungsi sebagai membran penukar proton. Sistem eksperimen ini mengintegrasikan mikropengawal ESP32 dan sensor voltan untuk memantau prestasi sistem, dengan data dihantar ke platform IoT Blynk. Hasil kajian menunjukkan julat voltan dari 54.0 mV hingga 230 mV, yang tidak mencukupi untuk operasi IoT secara kendiri tetapi memberikan pandangan berharga untuk pengoptimuman sistem. Kajian ini menekankan potensi penggabungan sel bahan api mikroba dengan IoT untuk aplikasi tenaga lestari dan mencadangkan laluan bagi penambahbaikan kuasa output dan kebolehskalaan pada masa hadapan.

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First and foremost, I would like to express my gratitude to my supervisor, Sir Na'im bin Mohd Nasir for their precious guidance, words of wisdom and patient throughout this project.

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LIST OF SYMBOLS

%	-	Percentage
Ω	-	Ohms

LIST OF ABBREVIATIONS

V	-	Voltage
P	-	Power
I	-	Current
mV	-	Milivolt
mM	-	Milimeter
nW	-	Nanowatt
uW	-	Microwatt
SDG	-	Sunstainable development goals
MFC	-	Microbial Fuel Cell
WoS	-	Web of Science
MEC	-	Microbial electrolysnthesis cell
MDC	-	Micobial desalination
TKN	-	Total kjeldahl
COD	-	Chemical oxygen demand
LED	-	Light emmiting diode
SMFC	-	Sendiment microbial fuel cell
PMFC	-	Plant microbial fuel cell
WSN	-	Wireless sensor networks
NMPC	-	Nonlinear model prdictive control
IoT	-	Internet of things
RVC	-	Reticulated vitreous carbon

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CHAPTER 1

INTRODUCTION

1.1 Background

The management of food waste presents a significant challenge worldwide, with profound environmental, economic, and social implications. Conventional methods of food waste disposal, such as landfilling and incineration, contribute to greenhouse gas emissions, resource depletion, and land use issues [1]. Simultaneously, the global demand for sustainable energy sources continues to rise, necessitating the exploration of innovative technologies to meet energy needs while addressing environmental concerns. Microbial Fuel Cells (MFCs) have emerged as a promising technology at the intersection of waste management and renewable energy generation. By harnessing the metabolic activity of microorganisms to directly convert organic matter into electricity, MFCs offer a sustainable solution for both food waste utilization and electricity generation. However, challenges remain in optimizing MFC performance, integrating monitoring and control systems, and assessing the feasibility of large-scale deployment. The integration of Internet of Things (IoT) technology with MFCs presents an opportunity to address these challenges by enabling real-time monitoring, control, and optimization of MFC operation. IoT-enabled MFC systems have the potential to improve performance, enhance efficiency, and facilitate remote management, thereby advancing the practical implementation of MFC-based food waste utilization for electricity generation. Against this backdrop, this project aims to undertake the integrated development and performance evaluation of an IoT-monitored MFC-based system for food waste utilization and electricity generation. By combining expertise in microbiology, electrochemistry, engineering, and IoT technology, this research seeks to design and construct an innovative MFC system seamlessly integrated with IoT technology for real-time monitoring and control. Furthermore, it aims to investigate various food waste substrates to identify optimal sources for electricity generation in MFCs, characterizing the performance of the IoT-monitored MFC system utilizing food waste substrates, including power output, efficiency, stability, and longevity. Through interdisciplinary collaboration and systematic investigation, this project aims to contribute to the advancement of MFC technology, waste management practices, and renewable energy generation.

1.2 Problem Statement

The problem statement for this project concerns the efficient management of food waste, which poses significant environmental and economic challenges. Conventional disposal methods contribute to the emission of greenhouse gases and the depletion of resources. Concurrently, there is an increasing demand for sustainable energy sources. Microbial fuel cells (MFCs) offer a promising solution since they convert food waste into power by harnessing microbial activity. This effectively addresses the issue of waste reduction and promotes the generation of sustainable energy. This strategy is in line with multiple United Nations Sustainable Development Goals (SDGs), specifically SDG 7 (Affordable and Clean Energy), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action). It achieves this by advocating for sustainable waste management methods, decreasing dependence on fossil fuels, and addressing the consequences of climate change. However, several challenges must be overcome to fully harness the potential of MFCs, specifically in terms of improving efficiency, scalability, and economic viability. However, several challenges must be overcome to fully harness the potential of MFCs, specifically in terms of improving efficiency, scalability, and economic viability. The low electric power generated by microbial fuel cells presents an important challenge to their widespread use in large-scale or real-world scenarios. Additionally, the inefficiencies and inaccuracies associated with manual data gathering in MFC systems hinder the accurate monitoring and optimization of these systems.

1.3 Project Objective

The main aim of this project is to advance the development, performance evaluation, and integration of IoT-monitored Microbial Fuel Cell-based systems for efficient and sustainable electricity generation from food waste:

a) To develop an advanced Microbial Fuel Cell (MFC) system that is integrated with Internet of Things (IoT) technology, enabling real-time monitoring and control functionalities.
b) To monitor a low voltage output from a microbial fuel cell
c) To assess the practicality and efficiency of including food waste utilization as a sustainable source for generating power in the IoT-monitored MFC system.

1.4 Scope of Project

The scope of this project are as follows:

a) The aim of this study is to utilize starch, a type of food waste, as a substrate in a microbial fuel cell.
b) The voltage sensor is utilized for measuring environmental conditions.
c) The Internet of Things (IoT) is utilized in this research to monitor the output generated by the microbial fuel cell.
d) The electrodes used in this project are made of Carbon Felt, which provides a significant surface area and excellent conductivity.
e) The separators used in this project are salt bridges, which have a straightforward design and are cost-effective.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The literature review stands as a cornerstone in the development of IoT-monitored microbial fuel cell (MFC)-based food waste utilization for electricity generation. It serves as a comprehensive exploration of existing academic discourse, drawing from a diverse array of scholarly sources including journal articles, conference papers, and research theses. Through this review, we aim to delineate the scope of our project and establish the foundational knowledge necessary for its advancement. By examining previous studies and research findings, we endeavor to gain valuable insights into the intricacies of microbial fuel cell technology, food waste management, and the integration of IoT monitoring systems. This exploration not only provides a contextual understanding of the subject matter but also furnishes us with a rich tapestry of methodologies, challenges, and innovations to draw upon in our own endeavors. In the context of this project, the literature review converges on the nexus of sustainable energy production, waste management, and IoT technology. Our primary focus areas encompass the optimization of microbial fuel cells for electricity generation, the valorization of food waste as a renewable resource, and the implementation of IoT monitoring to enhance system efficiency and performance. As we embark on this journey through the literature, we seek to unearth key insights, identify critical gaps in knowledge, and chart a course toward the development of novel techniques and solutions in the realm of IoT-monitored microbial fuel cell-based food waste utilization. Through a synthesis of past research and emerging trends, we endeavor to contribute to the advancement of sustainable energy practices and environmental stewardship.

2.2 Background Study

Background research is an essential part of any paper because it gives the reader the background information they need to comprehend the research topic in a larger context. This section is divided into seven main sections: the history of Microbial Fuel Cell (MFC), concept of Microbial Fuel Cell, Components Microbial Fuel Cell, Substrate material in MFC, electrodes material in MFC, and separators in MFC.

2.2.1 History of Microbial Fuel Cells (MFCs)

In the past decade, microbial fuel cells (MFCs) have garnered significant attention as a technology capable of generating electricity while simultaneously treating wastewater. This study undertakes a quantitative review of MFC literature published between 1970 and 2020, sourced from the Web of Science (WoS) database. For the first time, a comprehensive quantitative review using bibliometric and content analyses has been conducted. A total of 11,397 publications were identified, with research articles comprising 81.6% of this number. The field of MFC has been examined across various dimensions, including publication history, distribution, subject categories, leading journals, countries, and organizations involved in MFC research. Content analysis has also been performed to identify trends and hot topics within MFC research. Findings indicate that 2011-2020 was the most productive period, accounting for 87% of the total publications. The energy fuel and microbiology categories lead with 26.5% each, with energy fuel showing the highest growth in the last decade. Among the 1,147 journals publishing on MFCs, Bioresource Technology is the most prominent. Countries such as China, the USA, and India are the primary contributors, with 26.47%, 16.95%, and 7.69% of publications, respectively. Key research topics include nanoparticles, catalysts, air electrodes, graphene electrodes, power enhancement, air cathodes, and nitrogen removal. The major research areas are engineering, energy fuels, and biotechnology, each contributing 26.5% of the total publications.. Figure 2.1 shows the number of publications and citations in MFCs.

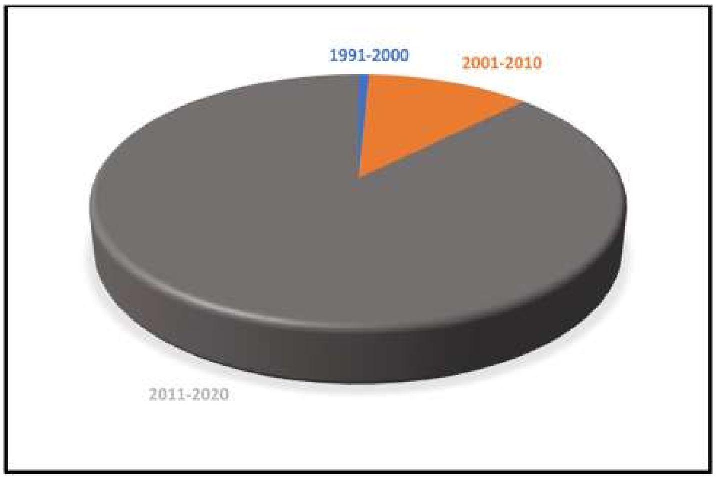

Figure 2.1: Number of publications and citations in MFCs.

2.2.2 Concept of Micobial Fuel Cell

Figure 2.2 shows that Microbial Fuel Cells (MFCs) are bio-electrochemical devices that directly convert organic substrates into electrical energy by taking advantage of microorganisms' metabolic processes [1]. The fundamental working of MFCs is the oxidation of organic compounds by microbes at the anode, which releases protons and electrons. After that, these electrons are moved to the anode electrode, where they produce an electric current. Protons travel to the cathode via the electrolyte in the meantime, where they combine with electrons and an external electron acceptor (such as oxygen) to form reduced compounds, such as water. An electric potential difference produced by this electron flow can be used to generate electricity. Multiple fuel cells (MFCs) present various benefits, such as their versatility in using various organic substrates, low operating temperatures, and low environmental impact. However, challenges such as low power output and long-term stability need to be addressed for practical applications. Figure 2.3 shows the diagram displaying the cathode, which is exposed to dissolved oxygen, and the anode, where bacteria form a biofilm on the surface (with a gas sparger to remove air in the bottle). A cation-exchange membrane (CEM) divides the two chambers, ideally allowing protons to be exchanged through the electrolyte (water) rather than through oxygen or the substrate.

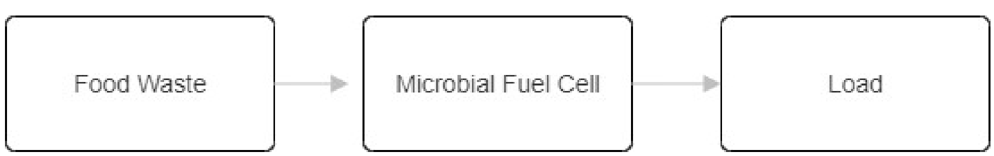

Figure 2.2: Block diagram energy conversion.

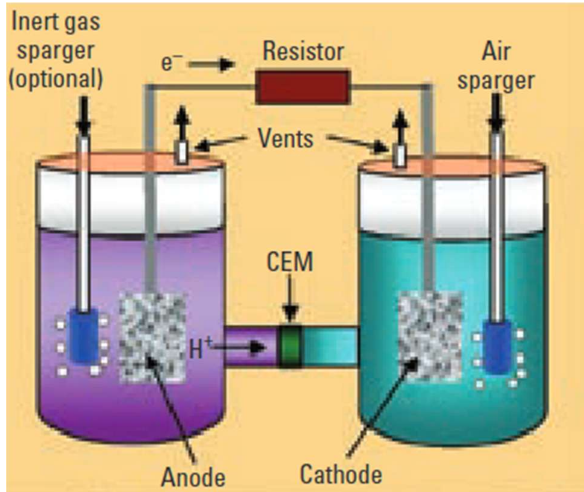

Figure 2.3: Example of an H-type microbial fuel cell [2].

2.2.3 Components of Microbial Fuel Cell

Microbial Fuel Cell have five components which are, the primary components of a Microbial Fuel Cell are anode chamber, which are the organic substrate typically organic matter such as food waste, which serves as the fuel for the microorganisms. While the anode electrode, typically made of conductive materials like carbon cloth or graphite, facilitates the oxidation of the organic substrate, releasing electrons and protons. Next, cathode chamber is a cathode electrode that also made ofconductive materials, where electrons combine with protons and an electron acceptor (usually oxygen) to complete the circuit and generate water. Electron acceptor is typically oxygen, which accepts at the cathode. After that, proton exchange membrane (PEM) is A selective membrane that allows protons to pass from the anode chamber to the cathode chamber while preventing the mixing of the substrates and the electron acceptor. The fourth compenents in MFC are external circuit that Connects the anode and cathode electrodes, allowing the flow of electrons from the anode to the cathode. This circuit often includes a load, such as a resistor or a device that can be powered by the generated electricity. Lastly, microorganisms is a Specific bacteria, such as Geobacter and Shewanella species, which facilitate the transfer of electrons from the organic substrate to the anode. Figure 2.4 shows the example of dual chamber in MFCs using food waste substrate that fulfill the element of the components.

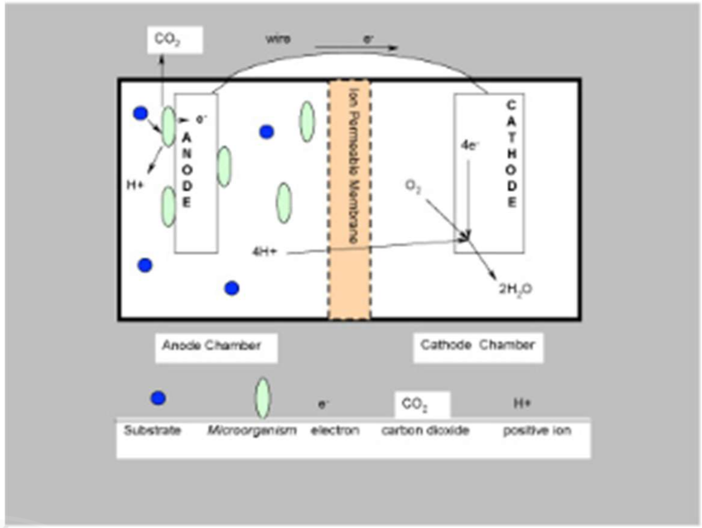

Figure 2.4: The example of dual chamber in MFCs.

2.2.4 Substrate used in MFCs

Substrates in microbial fuel cells (MFCs) are crucial components that drive the biological processes responsible for electricity generation. Microbial fuel cells (MFCs) utilize organic substrates to generate electricity through the metabolic activities of microorganisms. These substrates, typically derived from various types of organic waste, provide the necessary nutrients for microbial growth and energy production. Common substrates include wastewater, food waste, agricultural residues, and other biodegradable materials. By using these organic substrates, MFCs not only offer a sustainable method for generating renewable energy but also contribute to waste treatment and environmental sustainability. The choice of substrate is crucial as it directly influences the efficiency and performance of the MFC, making substrate selection and optimization key areas of research in this innovative technology. Based on the research from internet, theres a lot of substrate that can be use in MFCs. Table 2.1 shows the different substrates used in MFCs with current density at maximum current produced for each substrate.

Table 2.1: Comparison of different substrates used in MFCs with current density at maximum current produced for each substrate[3].

Type of substrate	Concentration	Source inoculum	Type of MFC (with electrode surface area and/or cell volume)	Current density (mA/cm^2) at maximum power	Reference
Glucose	6.7 mM	Mixed bacterial culture maintained on sodium acetate for 1 year (Rhodococcus and Paracoccus)	One-chamber air-cathode MFC (12 mL) with nonwet proofed carbon cloth as anode (2 cm^2) and wet proofed carbon cloth as cathode (7 cm^2)	0.70	Catal et al. (2008a)
Starch	10 g/L	Pure culture of Clostridium butyricum	Two-chambered MFC with woven graphite anode (7 cm^2) and ferricyanide catholyte	1.3	Niessen et al. (2004)
Sucrose	2674 mg/L		Two-chambered mediator-less MFC with stainless steel mesh as anode	0.19	Behera and

		Anaerobic sludge from septic tank	(213.29 cm2) and cathode (176.45 cm2); KMnO4 (0.2 g/L) as catholyte		Ghangrekar (2009)
Acetate	1 g/L	Pre-acclimated bacteria from MFC	Cube shaped one-chamber MFC with graphite fiber brush anode (7170 m2 /m3 brush volume)	0.8	Logan et al. (2007)
Lactate	18 mM	Pure culture of S. oneidensis MR1	Two-chambered MFC with graphite felt electrode (20 cm2)	0.005	Manohar and Mansfeld (2004)

2.2.5 Electrodes material in MFC

Microbial fuel cells (MFCs) rely on electrodes to facilitate the conversion of chemical energy in organic substrates into electrical energy. The electrodes, specifically the anode and cathode, play a crucial role in this process. The anode is where microorganisms oxidize the organic substrate, releasing electrons and protons. These electrons then travel through an external circuit to the cathode, where they combine with protons and an electron acceptor, typically oxygen, to generate water. The materials and design of the electrodes significantly affect the efficiency and performance of MFCs, as they influence electron transfer rates and microbial activity. Therefore, optimizing electrode materials and configurations is essential for enhancing the overall functionality and power output of MFCs. Figure 2.4 shows the material that can be used as electrodes in MFC. The materials selected must be assigned accordingly whether they are anode or cathode. The materials mostly used as electrodes in microbial fuel cell are carbon materials. Such materials include graphite fiber brush, carbon cloth, graphite rod, carbon paper, reticulated vitreous carbon (RVC), and carbon felt [4]. The materials mentioned comes in all shapes and sizes, though regardless of materials, the larger surface area produces more power output. In other cases, metallic-based materials are also used as electrodes for microbial fuel cell. The popular metallic-based materials used are zinc as cathode and copperas anode. These materials are chosen instead of graphite, iron, and carbon due to it being cheap and high electricity conductivity [5]. However, copper and nickel ions in anode chamber can be poisonous to the bacteria and may result in reduced performance[6] . Figure 2.5 shows that material that can be used as electrodes in MFC[7].

Figure 2.5: Material that can be used as electrodes in MFC [7].

To enhance the efficiency of MFC, a thorough evaluation of various designs is crucial. Over time, MFC technology has evolved, giving rise to several new designs each with its own distinct advantages and limitations. Nevertheless, these designs all trace back to the original MFC concept. The MFC designs discussed include standard MFC, Microbial Electrolysis Cell (MEC), Microbial Desalination Cell (MDC), and Microbial Electrosynthesis Cell . MFC represents one of numerous renewable energy sources ripe for further exploration in suitable and efficient applications. It operates predominantly as a self-sustaining system and is environmentally friendly. The mechanism involves microbial respiration within a substrate-filled chamber, leading to electricity production [10]. Simply put, it converts chemical energy into electrical energy. Typically, an MFC comprises two chambers—the anode chamber and the cathode chamber—commonly referred to as a double-chamber MFC. Refer to Figure 2.6 for a schematic of an MFC.

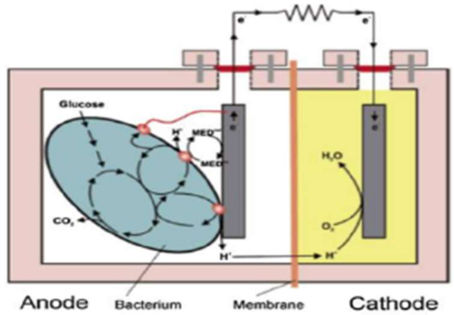

Figure 2.6: The MFC system is consisted of anode and cathode compartments [4].

The anode chamber is hermetically sealed to prevent the ingress of external oxygen. Separating both chambers is a membrane permeable solely to protons. Electrons traverse closed circuits externally connected. Within the anode chamber, microbes or bacteria metabolize substrates and water, yielding hydrogen ions and electrons. Conversely, the cathode chamber receives only hydrogen ions and electrons, reacting with oxygen to produce water . Electron flow between chambers, passing through a load, generates current. The chemical reactions within the anode chamber, cathode chamber, and overall process are delineated by Equations (1), (2), and (3) [4].

Anode reaction: $C_2H_4O_2 + 2H_2O > 2CO_2 + 8e^- + 8H^+$ (1)

Cathode reaction: $2O_2 + 8H^+ + 8e^- > 4H_2O$ (2)

Overall cell reaction: $(CH_2O)n + nH_2O > nCO_2 + 4nH^+ + 4ne-$ (3)

The MFC resembles a battery, comprising two electrodes and electrolyte, similiar to most batteries . Alternatively, MFCs may be configured as single-chamber MFCs, eliminating the need for separators or membranes. Nevertheless, this design necessitates two electrodes due to potential proton accumulation in the anode chamber, lowering substrate pH and impeding microbial activity . Figure 2 illustrates a single-chamber MFC. Unlike MFCs, MECs require external energy for activation and do not generate electrical power. Despite a low power input (>1.2V), MECs yield high concentrations of hydrogen gas. Integration with other renewable energy sources, such as solar or thermoelectric power, is common to achieve self-sufficiency . MEC designs mirror those of MFCs, with single-chambered and two-chambered variations, yielding identical products and necessitating similar conditions.

Disturbances in pH levels within both chambers can adversely affect MEC performance, given their production of copious amounts of hydrogen gas with minimal energy input.

2.2.6 Seperators in MFC

Separators in microbial fuel cells (MFCs) are critical components that play a key role in the cell's efficiency and functionality. These separators, often in the form of proton exchange membranes (PEMs), are placed between the anode and cathode chambers. Their primary function is to allow protons to pass from the anode to the cathode while preventing the mixing of substrates and the electron acceptor, typically oxygen. This selective permeability is essential for maintaining the chemical gradients necessary for electricity generation. The choice of separator material and design significantly impacts the overall performance of an MFC by influencing proton conductivity, durability, and resistance to fouling. Effective separators help in optimizing the power output and longevity of MFCs, making them a vital area of research and development in microbial fuel cell technology. Table 2.2 shows that major advantages and drawbacks of various categories of separators and separator-less setup.
Table 2.2: Major advantages and drawbacks of various categories of separators and separator-less setup [8].

Seperator	Advantages	Drawbacks
None	High proton transfer rate, e, high power density, low-costs, simple configuration	Serious oxygen permeation, high substrate loss, cathode fouling and deactivation, high internal resistance caused by large electrode spacing
Ion exchange membrane	Effective isolation of anodic and cathodic solution/cathode, low oxygen permeation and substrate loss	Constrained proton transfer, pH splitting, membrane fouling, high costs
Microporous filtration membranes	High proton transfer and low pH accumulation, moderate Costs	High oxygen permeation, high internal resistance

Course-pore filters	High proton transfer and low pH accumulation, low-costs	High substrate loss caused by biofilm on filter, inferior durability
Salt bridge	Simple configuration, low-costs	High internal resistance

2.3 Previous Works by Others

This paper will examine the wealth of information provided by past studies conducted by other experts in the field in this section. These studies offer significant perspectives, approaches, and results that will influence the state of knowledge on the subject and form the foundation of this work. This paper aims to contextualize the research within the larger academic landscape and identify potential research gaps or unexplored areas by analyzing these earlier contributions.

2.3.1 An IoT-Enabled Microbial Fuel Cell For Wastewater Treatment And Enhancing Hydroponic Systems : An Eco-Friendly Renewable Energy Development

This previous work has developed IoT Integration for Improved Wastewater Treatment and Energy Production in MFCS to reduce large volumes of wastewater that produced by industrial processes like textile and chemical manufacture, which calls for the use of cutting-edge treatment technologies like Microbial Fuel Cells (MFCs) coupled with Internet of Things monitoring to ensure effective treatment and bioenergy production. To maximise performance, this study investigates an artificially ventilated tidal flow MFC wetland system that makes use of the ESP8266-12 and ADS1115 for real-time data collecting. With TKN and TN removal rates of 65.8% and 76.9%, respectively, and a COD removal rate of 87.5%, the system exhibits notable pollutant removal efficiencies using materials like Jhama brick, brick surkhi, and rubber tyre fragments. In addition, the system attains a maximum voltage of 142 mV, a power density of 3954.03 mW/m^3, and a current density of 27.85 mA/m^3[9]. Notably, Jhama brick offered the best efficiency in terms of generating energy and removing pollutants. Additionally, the wastewater treatment process may be made more environmentally friendly by using the treated wastewater for hydroponic plant growth. This highlights the system's potential for sustainable nutrient recycling. Figure 2.7 show that voltage production with respect to time using three different substrates [9].

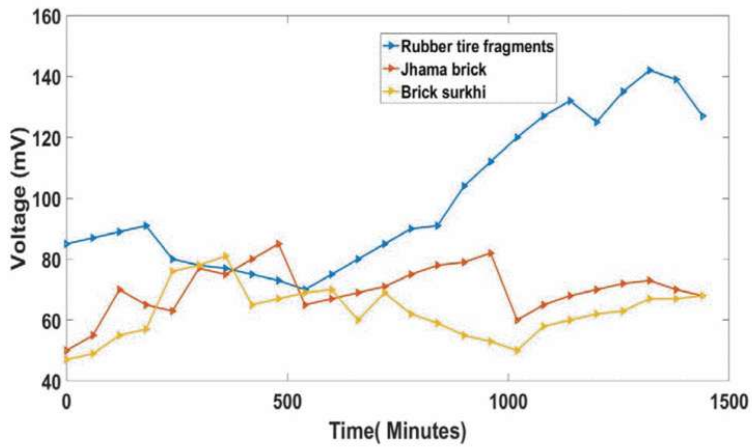

Figure 2.7: voltage production with respect to time [9].

2.3.2 Wastewater Microbial Fuel Cell Stack with the Ability of Driving Low Power Electronic Load

These authors have developed Wastewater Microbial Fuel Cell Stack with the Ability of Driving Low Power Electronic Load. Microbial Fuel Cells (MFCs) employ bio-electrochemical mechanisms to produce electricity, offering a novel method for generating renewable energy and treating wastewater. Despite the potential, the insufficient output voltage and current of MFCs provide a problem to their practical use in powering external loads. The research has primarily concentrated on material analysis, novel MFC designs, and enhancing bacterial activity. However, there is a limited number of studies that investigate power transmission to loads. This study builds three double-chamber microbial fuel cells (MFCs) and two single-chamber membrane-less MFCs. The MFCs are equipped with aluminium anodes and copper cathodes, and wastewater is used as the input. By linking these MFCs in a sequential manner, a peak output voltage of 2.6 V was attained, which is adequate to illuminate a compact LED [10]. This illustrates that the utilisation of series connection can improve the practical usability of microbial fuel cells (MFCs) for low-power applications. To expand energy production and storage, future studies should focus on enhancing cell connections, improving electrode materials, and integrating power management systems. This will facilitate the implementation of microbial fuel cell (MFC) technology in wastewater treatment and renewable energy industries. Figure 2.8 shows that power obtained from proposed microbial fuel cells.

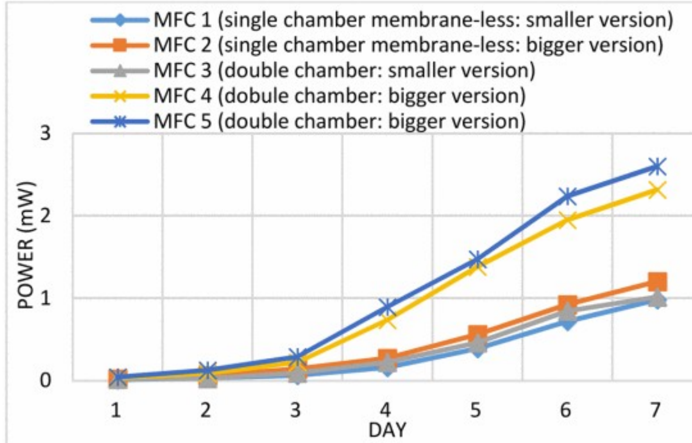

Figure 2.8: Power obtained from proposed microbial fuel cells [10].

2.3.3 Comparison of Current Density and Power Density Obtained from a Double Chamber Microbial Fuel Cell for Different Sludges

This previous study discusses about Microbial Fuel Cells (MFCs) are advanced technologies that utilise the metabolic processes of bacteria to generate power, simultaneously treating wastewater and providing sustainable energy. This study assesses the efficiency of microbial fuel cells (MFCs) by examining their performance when using several types of sludge, including drain sludge, tannery sludge, and Turag sludge. The MFCs operate under aerobic circumstances and utilise starch derived from boiled rice as the carbohydrate source to enhance bacterial growth. Experiments conducted over a period of seven days utilised a salt bridge as the membrane and water in the cathode chamber as the electron acceptor. Fixed volumes of sludge, substrate, and water were employed and monitored. The analysis primarily examined the metrics of current density and power density. It was found that Turag sludge exhibited the highest performance, with a peak voltage of 220.77 mV, a current density of 12.23 mA/m², and a power density of 2.7 mW/m²[11]. The results demonstrate the effectiveness of Turag sludge in generating bioelectricity, indicating its potential for widespread use in large-scale microbial fuel cell applications. Further investigation is needed to examine the capacity to scale up, maintain stability over a long period of time, and optimise the environment for bacterial growth to improve the performance of microbial fuel cells (MFCs). This work highlights the significance of selecting the appropriate substrate to optimise the efficiency of microbial fuel cells (MFCs), providing vital knowledge in the fields of sustainable waste management and energy generation. Figure 2.9 shows that maximum current density and power density obtained from different sludges across 261 Ω.

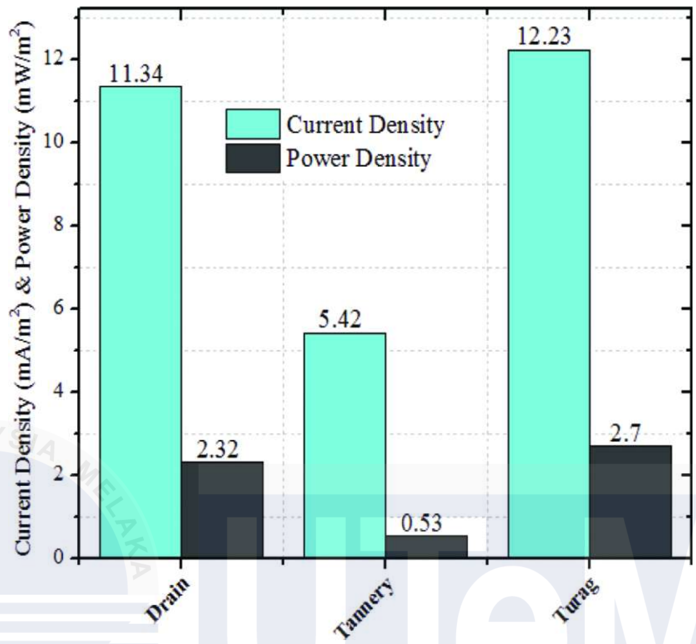

Figure 2.9: Maximum Current Density and Power Density Obtained From Different Sludges Across 261 Ω [11].

2.3.4 Dynamic Analysis of Microbial Fuel Cell Electrochemical Model

This previous study discusses that Microbial Fuel Cells (MFCs) are devices that can directly convert chemical energy into electrical energy. They have shown great promise in the fields of environmental monitoring and new energy development. This study introduces an electrochemical model of a Microbial Fuel Cell (MFC) developed in the MATLAB environment. The focus is on analysing the impact of acetate feed concentration and current density on the dynamic behaviour and performance of the cell. The results suggest that alterations in the concentration of acetate feed result in different changes in cell voltage at different current densities, with higher current densities leading to more significant decreases in voltage. In addition, the rate at which voltage drops follows a discernible pattern: it initially rises, then falls, and ultimately rises again as the current density increases. These findings on the electrochemical behaviour of MFCs in different operating conditions offer valuable guidance for improving MFC performance and efficiency[12]. They highlight the significance of regulating feed concentration and current density to enhance the practical use of MFCs in renewable energy and environmental monitoring applications. Figure 2.10 shows that effect of different current density on MFC power density

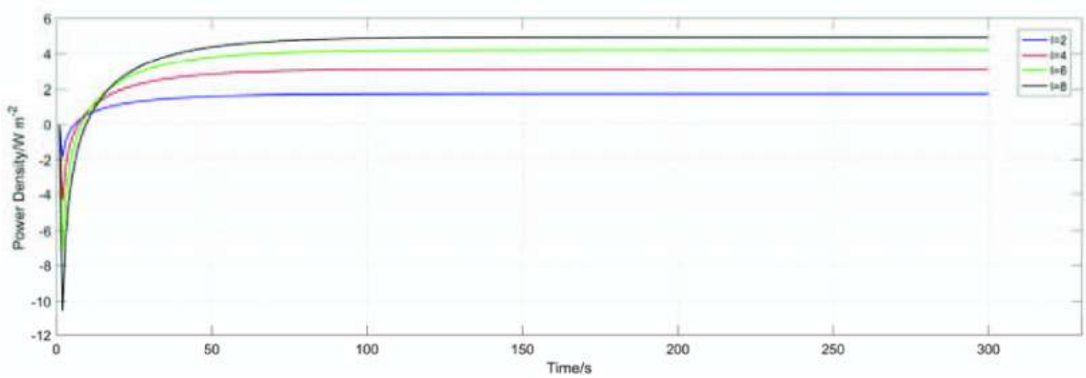

Figure 2.10: Effect of different current density on MFC power density [12].

2.3.5 Voltage Drop Management and Step Up The Voltage of Sediment Microbial Fuel Cells

This previous study develop Voltage Drop Management and Step Up The Voltage of Sediment Microbial Fuel Cells. Sediment Microbial Fuel Cells (SMFCs) are bio-electrochemical devices that produce clean energy by turning organic matter in sediments into electrical energy, figure 2.10 shows that schematic representation of SMFC[13]. Although SMFCs have the capacity for generating electricity, they usually yield low and variable voltages, ranging from 0.982 V to 1.16 V over a span of 60 days. These voltages are inadequate for directly powering electronic equipment. In order to overcome this constraint, the present study introduces an ultra-low voltage DC-DC boost converter specifically engineered to control and amplify the output voltage of SMFCs. The boost converter's performance was verified using both simulation and experimental data. The results demonstrated that a single SMFC discharges within 30 seconds when attached to the boost converter, and it takes 210 seconds for the SMFC to restore its maximum voltage after disconnection. An alternative method for harvesting energy was suggested, involving the use of eight Sequentially Connected Microbial Fuel Cells (SMFCs) in parallel. This setup allows for a consistent output of 2.56 V with an efficiency of 85.46% by supplying power to the boost converter. This boost converter functions efficiently even when the voltage is as low as 20 mV, making it appropriate for SMFC energy harvesting. The suggested system effectively produces a consistent and appropriate voltage for small electronic devices, resolving the issue of low voltage output in SMFCs and improving their practical usability for continuous power supply requirements. Figure 2.11 shows that (a) Block diagram of SMFC energy harvesting system. (b) Simulation results of boost converter. (c) Variation of the output voltage and input voltage of DC-DC boost converter with respect to the time. (d) Variation of the output voltage with respect to the input voltage of boost converter[13].

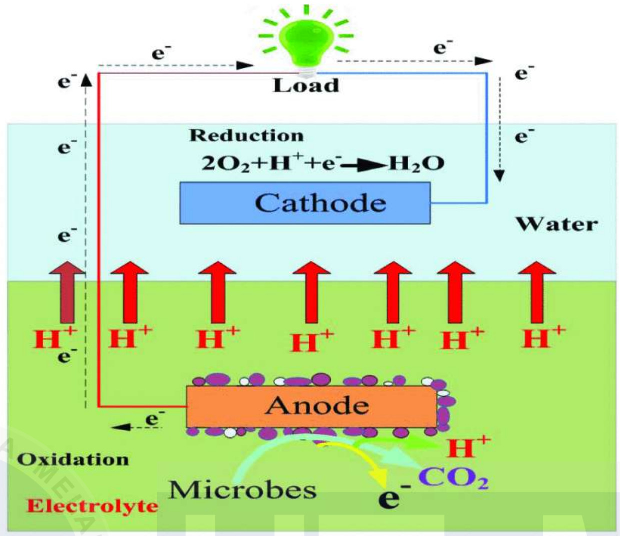

Figure 2.11: Schematic representation of SMFC [13].

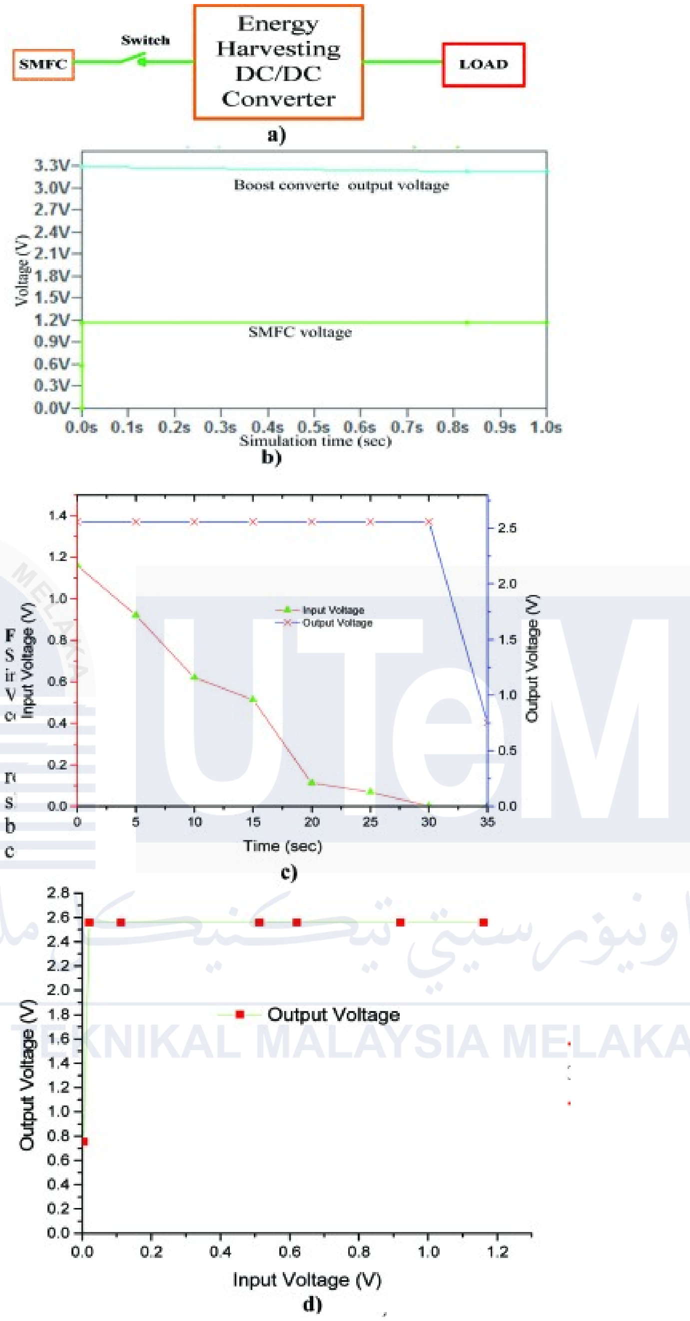

Figure 2.12: (a) Block diagram of SMFC energy harvesting system. (b) Simulation results of boost converter. (c) Variation of the output voltage and input voltage of DC-DC boost converter with respect to the time. (d) Variation of the output voltage with respect to the input voltage of boost converter [13].

2.3.6 Evolution of Construction, Performance and Application of Microbial Fuel Cells Based on River and Acid Mine Drainage Sediments.

This previous project discuss about Evolution of Construction, Performance and Application of Microbial Fuel Cells Based on River and Acid Mine Drainage Sediments. This paper presents a summary of the research undertaken by the team in the area of Microbial Fuel Cells (MFCs), with a specific focus on the development, performance, and application of these cells. The paper details the process of improving MFC performance by carefully designing and constructing it, while also examining the effects of various sediments that contain different microbial populations. Sediment samples were obtained from two specific sites in Serbia: the point where the Sava and Danube rivers meet in Belgrade, and the acidic mine drainage lake called "Robule" in the Bor copper mine. The results indicate that MFCs are effective in treating wastewater, emphasising the impact of various microbial communities in sediments on the efficiency and performance of MFCs. The research highlights the capacity of MFCs in sustainable wastewater treatment and energy generation, emphasising the need of choosing appropriate substrate and promoting microbial diversity to optimise MFC performance. Figure 2.13 shows that power developed at each resistor from the array on each day of measurements for a) MFC-river and b) MFC-lake[14].

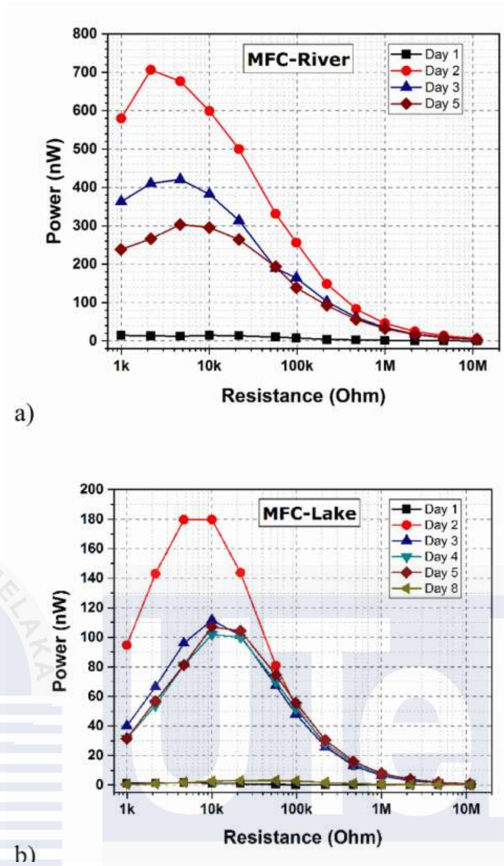

Figure 2.13: Power developed at each resistor from the array on each day of measurements for a) mfc-river and b) mfc-lake [14].

2.3.7 Bioelectricity generation in economic crops at aquaponics system using plant microbial fuel cell.

This previous study investigates the bioelectricity generation in economic crops at aquaponics system using plant microbial fuel cell. The pursuit of sustainability, namely in mitigating global warming and ensuring food security, has prompted the investigation of alternative energy sources to decrease dependence on fossil fuels. Out of these options, the Plant Microbial Fuel Cell (PMFC) has risen as a hopeful renewable energy technology that produces power using living plants, figure 2.14 shows that illustration diagram of PMFC[15]. This study investigates the production of bioelectricity in economically valuable crops grown in aquaponics systems utilising Plant Microbial Fuel Cells (PMFCs). The tests were carried out using single-chamber PMFC setups using graphite felt electrodes, with a specific focus on two crops: chilli and okra. The results showed that both crops could generate bioelectricity, with chilli producing 19.58 nW and okra producing 17.00 nW[15]. This indicates that chilli outperforms okra in terms of power output. The results indicate that combining PMFCs with economic crops in aquaponics systems can be a successful approach for generating sustainable energy and ensuring food security. This emphasises the ability of PMFCs to contribute to renewable energy resources while also promoting agricultural productivity. Figure 2.15 shows that voltage generation of okra and chilli.

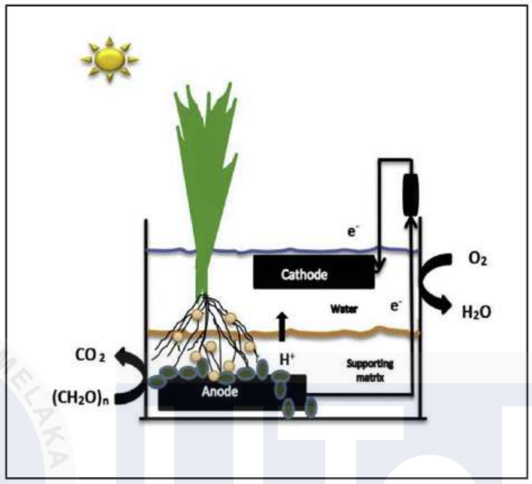

Figure 2.14: 14 Illustration diagram of PMFC [15].

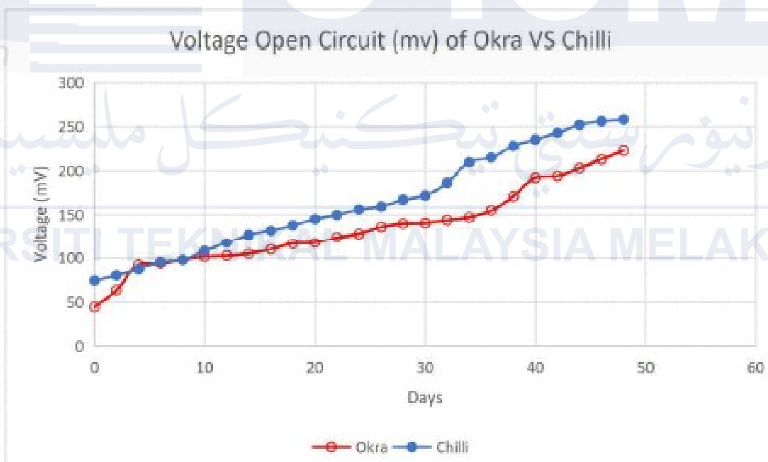

Figure 2.15: Voltage generation of okra and chili [15].

2.3.8 IoT Sensor Network Powered by Sediment Microbial Fuel Cell

This previous work has developed IoT sensor network powered by sediment microbial fuel cell. The IEEE802.15.4/ZigBee standard, renowned for its energy efficiency, encounters the obstacle of battery replacement, a crucial concern in wireless sensor networks (WSNs). Sediment Microbial Fuel Cells (SMFCs) provide a potential answer by utilising renewable energy to support Wireless Sensor Networks (WSNs) without requiring the replacement of batteries, figure 2.16 shows that schematic of the proposed energy harvesting system [16]. Nevertheless, SMFCs, due to their extremely low voltage and current output, are unable to directly supply power to microcontrollers. Furthermore, their expensive materials present further obstacles for their broad use in wireless sensor applications. In order to tackle these problems, this research suggests a new energy harvesting system that combines SMFC sensors with a power management circuit. The goal is to gather enough energy to power the load. This energy harvesting technology enables intermittent data transmission between ZigBee end-devices and coordinators. The experimental results confirm that SMFC-powered ZigBee sensor devices are effective, allowing for intermittent communication and providing a promising alternative to traditional battery-powered solutions for wireless sensor networks. Figure 2.17 shows that evaluation of SMFC[16].

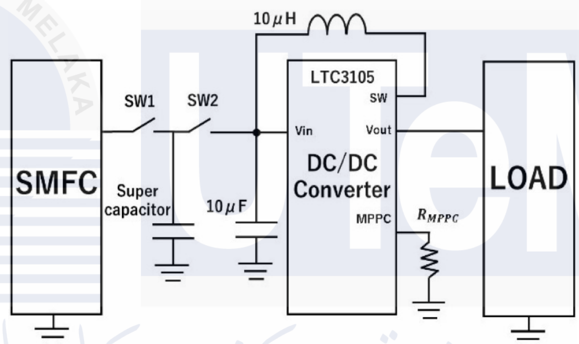

Figure 2.16: Schematic of the proposed energy harvesting system [16].

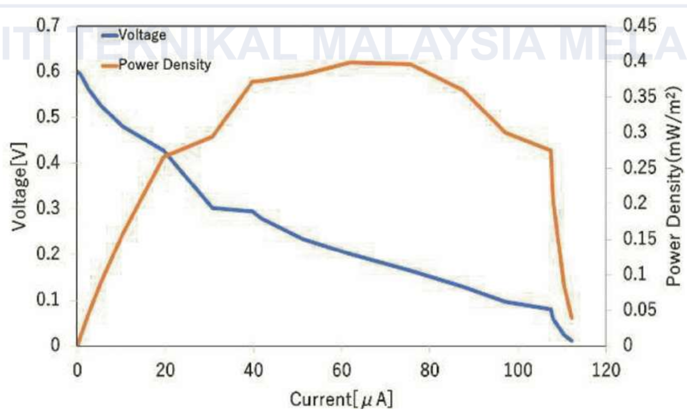

Figure 2.17: Evaluation of SMFC [16].

2.3.9 Energy Harvesting from Beverage Residues using a Microbial Fuel Cells

This previous study discusses Bio electrochemical energy harvesting through the use of Microbial Fuel Cells (MFCs) has emerged as a highly promising method for generating power from organic waste, namely beverage dregs, which are rich in chemical energy. This study examined the efficiency of microbial fuel cells (MFCs) that were inoculated with several types of beverage leftovers, such as coffee, orange juice, soda, milk, yoghurt, energy drinks, and beer. The MFCs exhibited distinct output characteristics across several beverages, indicating variations in the organic constituents that impact microbial activity. Regardless of the differences, all microbial fuel cells (MFCs) effectively produced electrical energy. MFCs inoculated with coffee and energy drinks generated over 50 μW, which is 100 times greater than the control MFC injected with vermicompost[17]. The findings indicate that MFCs can efficiently convert various types of organic waste into energy, implying that this technology has the potential to develop into a sustainable power system that not only produces electricity but also helps in the removal of pollutants. The notable enhancement in output efficiency underscores the practicality of incorporating MFCs into wider renewable energy and waste management plans. Figure 2.18 shows the Maximum power of the beverage-based MFCs.

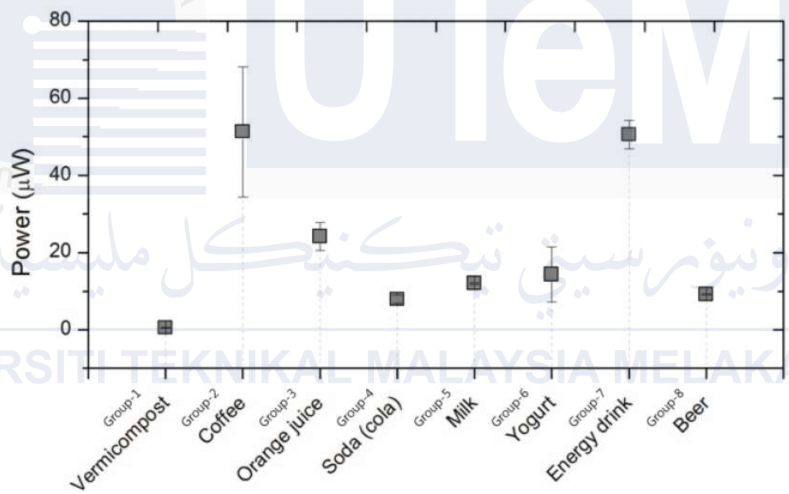

Figure 2.18: Maximum power of the beverage-based MFCs [17].

2.3.10 Biogenic Palladium Nanoparticles for Improving Bioelectricity Generation in Microbial Fuel Cells

This previous work discusses the Biogenic Palladium Nanoparticles for Improving Bioelectricity Generation in Microbial Fuel Cells. The use of electroactive bacteria with in-situ biogenic palladium nanoparticles to improve the performance of microbial fuel cells (MFCs) is a notable progress in the field of bio electrochemical systems. Utilising bio electrochemical reduction by bacteria, palladium nanoparticles were synthesised and attached to the cell membrane. This integration has demonstrated a 75% enhancement in the power density of microbial fuel cells (MFCs). This novel method utilises the inherent metabolic activities of bacteria to produce metallic nanoparticles that enhance the transport of electrons outside the cell, resulting in a more efficient conversion of energy at the interface between the cell and the electrode, figure 2.19 shows the schematic diagram of the paper-based MFC[18]. This discovery enhances our comprehension of how microorganisms produce metallic nanoparticles and presents an innovative approach for constructing microbial electrochemical devices from the ground up. This approach provides a more enduring and economically efficient option for generating renewable energy. It emphasises the possibility of incorporating bio-nanotechnology into microbial fuel cells (MFCs) to improve their effectiveness and environmental sustainability. The results indicate a positive outlook for the advancement of efficient and environmentally friendly microbial fuel cells (MFCs) that utilise natural nanomaterials. Figure 2.20 shows the power outputs and polarization curves of the MFCs powered by the bacteria with Pd-NPs biosynthesized with different bacteria concentrations[18].

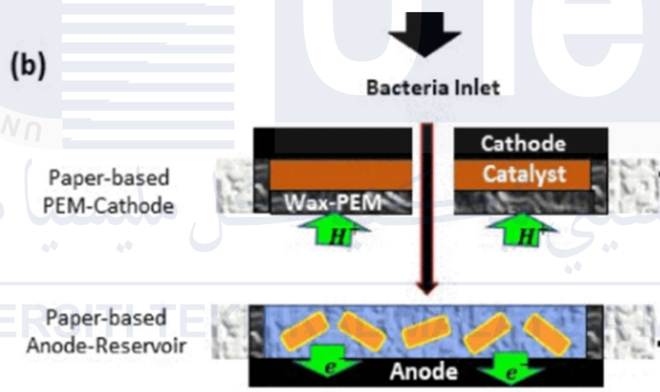

Figure 2.19: Schematic diagram of the paper-based MFC [18].

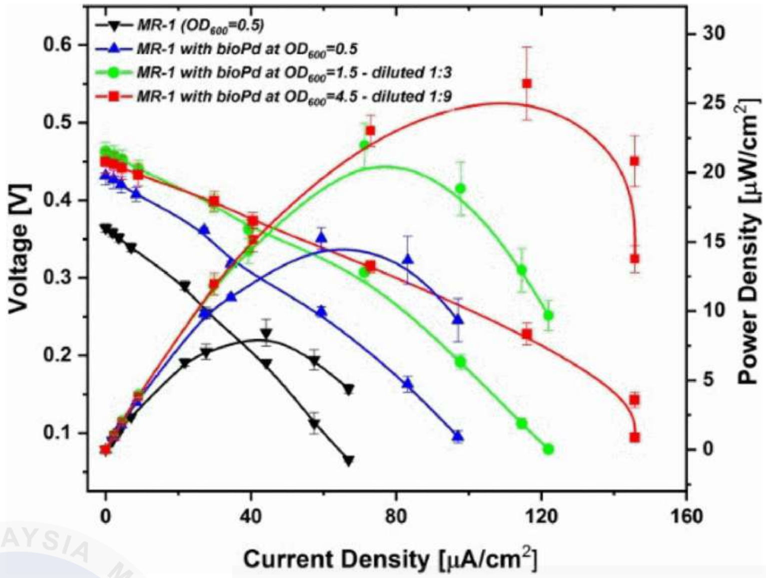

Figure 2.20: Power outputs and polarization curves of the MFCs powered by the bacteria with Pd-NPs biosynthesized with different bacteria concentrations [18].

2.3.11 Energy Harvesting With Microbial Fuel Cell and Power Management System

This study introduces a system capable of extracting energy from water and utilising it to supply power to electrical devices placed in the water. The system comprises a microbial fuel cell (MFC) and a power management system. The MFC employs electrochemical reactions and utilises microorganisms present in the water to extract energy and produce electricity. The power management system, comprised of a charge pump, a super capacitor, two solid-state switches, and a boost converter, collects the energy obtained by the MFC, stores it in the super capacitor, and delivers a sudden surge of power to the load, figure 2.21 shows the power management system block diagram[19].

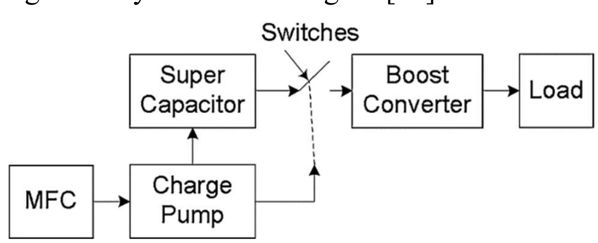

Figure 2.21: Power management system block diagram [19].

The power management system additionally amplifies the voltage of the MFC to an adequate level for the electronic equipment. The energy-harvesting system showcased is self-sufficient, sustainable, eco-friendly, and requires no maintenance. The system has undergone thorough testing and has been validated through empirical experiments. Figure 2.22 displays the power of the MFC and Hydrophone during a four-day duration. Upon startup, the boost converter provided around 95 mW of power to the hydrophone, whereas the MFC consistently supplied only 0.174 mW of electricity to the power management system[19].

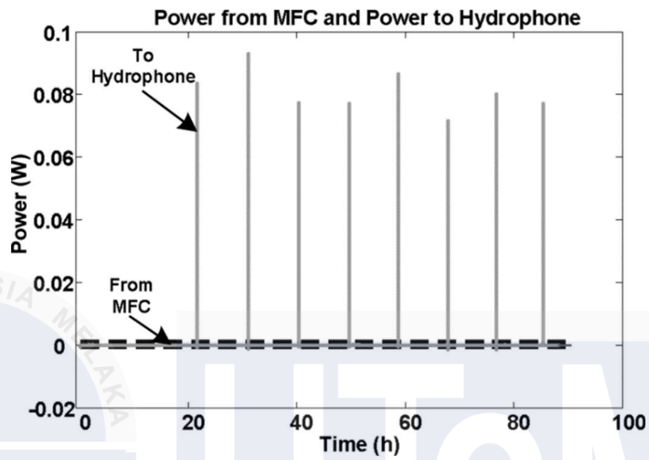

Figure 2.22: Hydrophone and MFC power [19].

2.3.12 Explicit Nonlinear Model Predictive Control of a Two-Chamber Microbial Fuel Cell

This previous work discusses microbial fuel cells (MFCs) are novel pollutants removed from the environment by using microorganisms to oxidise substrates and produce electricity. Because MFCs have a strong inter-variable coupling and are inherently nonlinear and dynamic, advanced control strategies are required for optimal performance. Because of this complexity, Nonlinear Model Predictive Control, or NMPC, is especially well suited for handling these kinds of systems. The use of an approximate multi-parametric nonlinear programming technique to create an explicit NMPC for a two-chamber MFC has been highlighted in recent research. Many benefits come with this explicit NMPC framework, such as simple hardware and software implementation and effective real-time computational performance. This strategy makes use of explicit predictive control to improve MFC operating efficiency while also making control system integration easier. This opens the door to more reliable and scalable bio electrochemical system applications. The development of sustainable technologies for energy generation and pollutant removal is aided by this advancement, which highlights NMPC's potential to enhance the efficiency and dependability of MFCs. Figure 2.23 shows the scheme of two-chamber MFC[20].

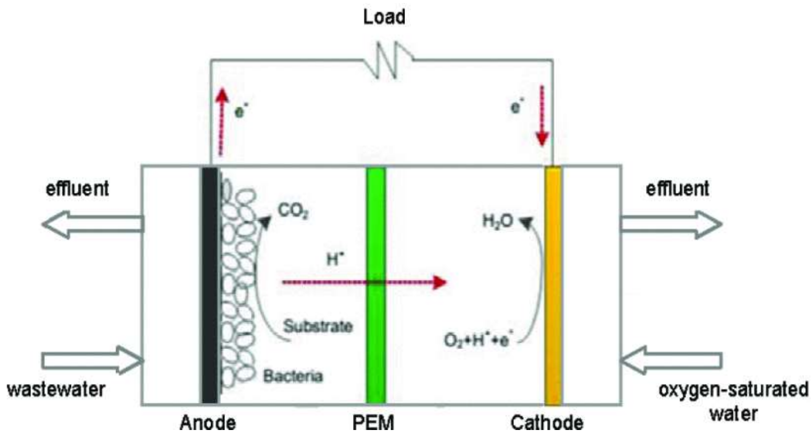

Figure 2.23: Scheme of two-chamber MFC [20].

2.4 Comparison of Previous Works

Table 2.3 The details of the project from different authors.

No.	Authors	Title	Application	Remark
1.	Joy, Upal Barua	IoT Integration for Improved Wastewater Treatment and Energy Production in Microbial Fuel Cell Systems	• The IoT-enabled Microbial Fuel Cell (MFC) system provides a sustainable and effective method for treating wastewater. It achieves high removal rates of contaminants such as nitrogen, COD, and coliforms. • The MFC system has a significant role in generating renewable energy by converting	• The study examines the efficacy of the Internet of Things (IoT)-enabled Microbial Fuel Cell (MFC) system in treating wastewater and generating energy. • The incorporation of IoT monitoring into the MFC system enables the collection of data in real-time and the optimisation of performance, thereby improving the efficiency of the system.

			organic matter in wastewater into electricity, demonstrating its potential as a sustainable energy source.	
2.	Joy, Upal Barua	Wastewater Microbial Fuel Cell Stack with the Ability of Driving Low Power Electronic Load	• The study found that the double chamber microbial fuel cell (MFC) generated significantly greater power than the single chamber MFC, despite using twice the volume. The dual-chamber microbial fuel cell (MFC) exhibited a power output that was 3.66 times greater than that of the single-chamber MFC, demonstrating the superior efficiency of this design.	• Microbial fuel cells (MFCs) offer the advantage of simultaneously producing electricity and purifying water as part of the treatment procedure. MFCs possess a dual functionality that renders them highly valuable for the production of sustainable energy and the preservation of the environment. • Given the imminent energy crisis and the limited availability of fossil fuels, there is a growing significance placed on renewable and eco-friendly energy sources such as MFCs. Microbial fuel cells (MFCs) provide a practical means to decrease reliance on non-renewable

			• MFC technology employs bio-electrochemical mechanisms to transform the chemical energy derived from biological components into electrical energy. It is regarded as a highly promising technology for the production of electricity and the purification of water in wastewater treatment procedures. Due to continuous research and progress, MFCs are becoming more appealing as a viable approach for sustainable energy generation.	energy sources and address environmental deterioration by utilising microorganisms to produce electricity.

3.	Sheikh Shehab Uddin, Kazi Shoffiuddin Roni, Fahmid Kabir	Comparison of Current Density and Power Density Obtained From a Double Chamber Microbial Fuel Cell For Different Sludges	• Microbial fuel cells (MFCs) have the potential to produce electricity from organic waste materials, such as sludge, in wastewater treatment plants. This offers a sustainable energy solution. • The application of MFC technology exhibits potential in effectively purifying wastewater while concurrently generating energy, thereby offering a viable solution to address both environmental and energy-related issues.	• The study determined that Turag sludge exhibited superior performance in terms of current density and power density. This can be attributed to the presence of highly efficient bacteria that contribute to bioenergy production. • The utilisation of chemicals in order to eradicate harmful bacteria in tannery sludge had a detrimental effect on the performance of the microbial fuel cell (MFC), resulting in the poorest outcome.

4.	Fengying Ma, Yankai Yin	Dynamic Analysis of Microbial Fuel Cell Electrochemical Model	• The utilisation of MFC technology in wastewater treatment shows great promise as it has the capacity to transform organic substances into electrical energy, providing a sustainable and environmentally friendly solution. • Microbial Fuel Cells (MFCs) can be employed for the generation of electric energy, which aids in the advancement of novel energy resources and the promotion of environmental sustainability.	• MFC technology is still in the laboratory stage, with challenges such as low output power density hindering its practical application on a larger scale • The relationship between microorganisms and organic matter, which is affected by factors such as acetate concentration and flow rate, can result in an inconsistent output voltage and a longer time to start-up. This emphasises the necessity for additional improvements in the design and operation of microbial fuel cells (MFCs).

5.	Jeetendra Prasad, Ramesh Kumar Tripathi	Voltage Drop Management and Step Up The Voltage of Sediment Microbial Fuel Cells	• Sediment microbial fuel cells (SMFCs) can be utilised in diverse practical applications, such as providing power to small electronic devices like light emitting diodes, wireless sensors, and smart MEMS sensor networks. • Solid oxide fuel cells (SMFCs) can be used in continuous energy harvesting systems to provide a reliable power source for devices that need to operate continuously.	• The proposed boost converter in the research paper effectively steps up the voltage output of SMFCs without the need for an external power source, making it suitable for powering electronic devices requiring higher voltages • The study reported an efficiency of 85.46% for the energy harvester DC-DC boost converter, indicating the effectiveness of the proposed scheme for managing voltage and harvesting energy from SMFCs.

6.	Randjelovi, D. V., Joksimovi, K	Evolution of Construction, Performance and Application of Microbial Fuel Cells Based on River and Acid Mine Drainage Sediments.	• Microbial Fuel Cells (MFCs) have demonstrated potential in the treatment of wastewater, specifically in the process of decolorization. Studies have shown that microbial fuel cells (MFCs) can efficiently cleanse wastewater to meet environmentally acceptable standards within a brief timeframe. This has been confirmed through the use of different analytical methods, including Ultraviolet-Visible Spectroscopy and High-	• Observation: The research carried out on MFCs has emphasised their adaptability and potential in diverse domains including environmental conservation, healthcare, farming, and manufacturing. The paper discusses the evolution of MFC construction and performance, highlighting the ongoing efforts to enhance their efficiency and practicality in real-world situations.

			Performance Liquid Chromatography-Tandem Mass Spectrometry. • Microbial fuel cells (MFCs) show promise for use in self-powered biosensors. Bioelectrochemical systems can be employed to energise biosensors autonomously, eliminating the requirement for external power sources. This provides a sustainable and effective solution for a wide range of sensing applications.	
7.	Lajis, Ghaibulna Abdol, Jasni	Bioelectricity generation in economic crops at aquaponics	• PMFC technology provides a viable and renewable alternative energy source that can be	• In order to improve the performance of PMFC systems, it is necessary to tackle challenges related to electrode

		system using plant microbial fuel cell.	used in a wide range of applications. • The utilisation of plant microbial fuel cells (PMFC) in aquaponics systems demonstrates a novel method for generating green energy through the bioelectricity production capacity of economically valuable crops.	materials, operation structures, plant types, and media types. • Further research and development in the field of bioelectricity generation in economic crops using PMFC is necessary due to the influence of factors such as microbial exudation, root morphology, and biomass on its success.
8.	Masato Niwa, Zhenni Pan, Shigeru Shinmamoto	IoT Sensor Network Powered by Sediment Microbial Fuel Cell	• Environmental Monitoring: SMFC can be used to generate power for IoT sensors that monitor environmental factors like temperature, humidity, and soil conditions. This application demonstrates	• Cost Consideration: One of the challenges of SMFC is the high initial cost of constructing the wireless sensor system, primarily due to material expenses. In order to achieve widespread adoption, it is imperative to address this particular aspect of SMFC to enhance its economic viability.

				the capabilities of SMFC in facilitating the sustainable and battery-free functioning of wireless sensor networks. • Wastewater Treatment: Microbial Fuel Cells (MFC) are frequently employed for wastewater treatment. However, Soil Microbial Fuel Cells (SMFC) specifically harness soil from diverse environments such as gardens, ponds, and sea beds to produce electricity. This application demonstrates the adaptability of SMFC in utilising renewable energy	• Operational efficiency: While SMFC has demonstrated potential in powering IoT devices, there is a requirement for enhancing the energy charging period and power supply duration to enhance its practicality for IoT applications. Improving these aspects will be essential for the effective integration of SMFC in IoT devices.

			sources for environmental objectives.	
9.	Yeo, Jeongjin, Yang, Yoonseok	Energy Harvesting from Beverage Residues using a Microbial Fuel Cells	• Beverage-based microbial fuel cells (MFCs) can be employed to generate sustainable power by converting organic constituents in beverage waste into electrical energy. • These microbial fuel cells (MFCs) possess the capacity to offer a self-reliant and enduring energy supply to uphold Internet of Things (IoT) devices in the foreseeable future.	• The study demonstrates that Microbial Fuel Cells (MFCs) that were exposed to coffee and energy-drink achieved a peak power output of over 50 µW, indicating a substantial enhancement in performance compared to the control group. • Bioelectrochemical energy harvesting technology, such as microbial fuel cells (MFCs), is anticipated to progress towards becoming a sustainable power system that goes beyond merely treating pollutants. This suggests a promising outlook for the future of this technology.
10	Mehdi Tahernia,	Biogenic Palladium	• Electroactive bacteria can synthesise biogenic	• The process of creating palladium nanoparticles using bacterial

	Maedeh Mohammadifar, Shuai Feng	Nanoparticles for Improving Bioelectricity Generation in Microbial Fuel Cells	palladium nanoparticles that greatly increase the power density of microbial fuel cells (MFCs) by up to 75%. This demonstrates their potential in generating renewable energy. • Palladium nanoparticles integrated onto the bacterial cell membrane enhance conductivity and electron transfer rates, showing potential for enhancing the efficiency of microbial electrochemical devices such as MFCs.	metabolism is a new and innovative method for producing environmentally friendly and cost-efficient microbial electrochemical devices. This approach has the potential to transform our understanding of how bacteria can produce metallic nanoparticles during their metabolic processes. • Utilising paper-based microbial fuel cells (MFCs) equipped with biogenic palladium nanoparticles presents a revolutionary opportunity for cost-effective, uncomplicated, and disposable electronic devices, rendering them appropriate for one-time use in environments with limited resources.

11	Meehan, Andrew, Hongwei, Lewandoski	Energy Harvesting with Microbial Fuel Cell and Power Management System	• The suggested power system is appropriate for situations that necessitate self-sufficient, sustainable, low-maintenance, and sporadic power sources in aquatic environments. Illustrative use case: Providing energy to sensors deployed in aquatic environments. • The system is capable of extracting energy from water and utilising it to operate electronic devices that are placed in water, rendering it well-suited for a range of underwater applications.	• The energy-harvesting system described in the paper is autonomous, sustainable, eco-friendly, and requires no maintenance, making it a highly promising solution for fulfilling remote underwater power requirements. • The system has undergone rigorous testing and has been validated through empirical research, demonstrating its dependability and practicality for real-world implementation.

12	Chong Li, Alexandra Grancharova, Liping Fan	Explicit Nonlinear Model Predictive Control of a Two-Chamber Microbial Fuel Cell	• Microbial fuel cells (MFCs) are employed as units for removing pollutants by utilising microorganisms to oxidise substrates, thereby producing electrical energy. • The research paper examines the utilisation of Nonlinear Model Predictive Control (NMPC) to enhance the efficiency of a two-chamber Microbial Fuel Cell (MFC), demonstrating its effectiveness in controlling complex dynamic plants.	• The complexity of MFCs arises from their nonlinear dynamic nature and the strong interdependence between variables. This complexity makes MFCs well-suited for NMPC (Nonlinear Model Predictive Control) due to their intricate characteristics. • The study emphasises the advantages of explicit Nonlinear Model Predictive Control (NMPC), including efficient real-time calculations and easy integration into software and hardware systems, which can improve the control of Model Predictive Control (MPC) systems.

2.5 Summary

This chapter provides a comprehensive analysis of the uses of Microbial Fuel Cells (MFCs) based on the amount of electricity they generate. The document is divided into three primary sections: a study of the background, an examination of past works conducted by others, and a comparison of these previous efforts. The background study section covers the history of Microbial Fuel Cell (MFC), the concept of Microbial Fuel Cell, the components of Microbial Fuel Cell, the substrate material used in MFC, the design of MFC, and the separators used in MFC. The initial portion delves into the core aims of this investigation. The second section explores seminal studies that have shaped the evolution of these technologies. The research provides context by emphasizing features, development processes, techniques, applications, and user interfaces. The comparative section analyses the utilization and attributes of prior literature. This comparison provides a framework for understanding and highlighting the importance and uniqueness of the current study. To summaries, this chapter highlights possible weaknesses and opportunities for development in the existing Microbial Fuel Cells project. As a result, this study suggests new solutions and additions.

CHAPTER 3

METHODOLOGY

3.1 Overview

This chapter will analyze the methodologies and instruments employed in the project, along with the necessary hardware and software for its implementation. This section outlines the experimental methodologies utilized to design and evaluate the Internet of Things-monitored microbial fuel cell (MFC) system for electricity generation from food waste. The methodology integrates IoT, electrical, and biological technologies to achieve this. The IoT integration enabled real-time monitoring via the Blynk app, while the MFC construction focused on enhancing the anode and cathode arrangement. This section outlines the components, construction technique, data collecting, and system validation to assure the system's effectiveness and functionality. Figure 3.1 illustrates the complete project flow in a sequential format. A flowchart enhances understanding of the processes and implementation of a process. This strategy was utilized to outline the execution process for the project.

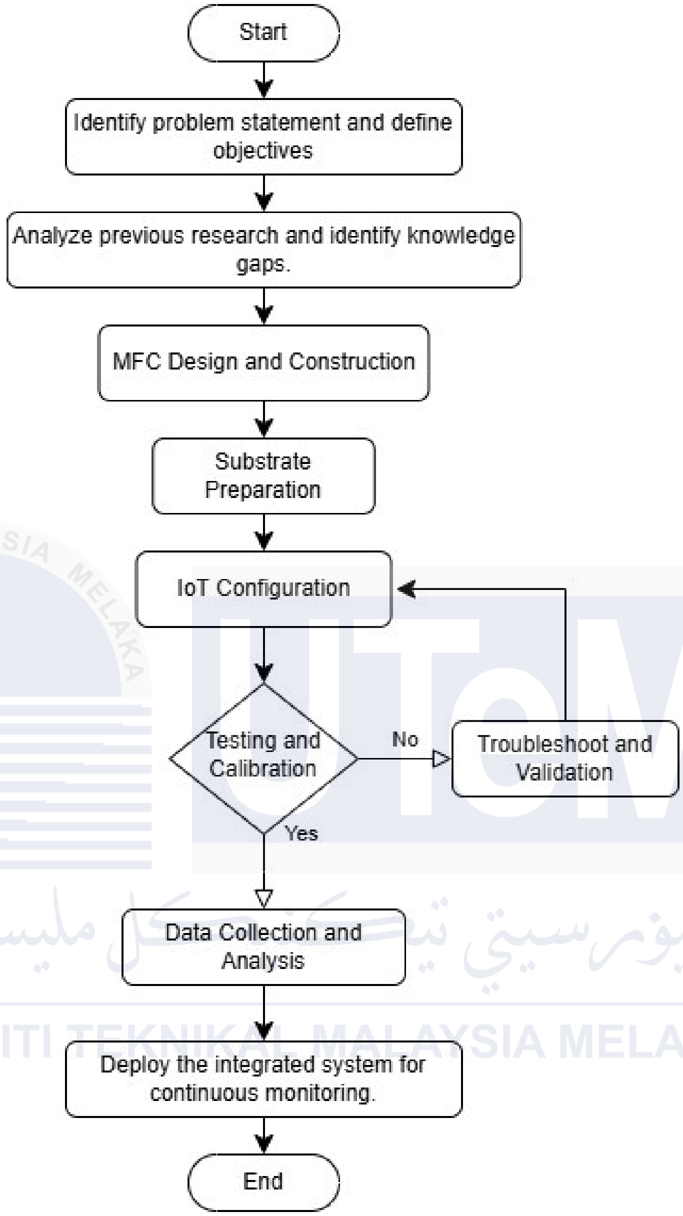

Figure 3.1: Overall project flowchart

3.2 Materials and Equipment

The equipment and materials were carefully chosen to satisfy the project's criteria. The MFC employed soft carbon graphite felt as the anode and cathode to facilitate effective electron transfer. 500 mL of rice water and 500 mL of potato water were combined to create the microbial substrate, owing to their high organic content, which boosted microbial activity. The salt bridge, consisting of agar and potassium chloride, enabled ionic conductivity between the anode and cathode sections. Electrical parameters were evaluated using a voltage sensor, and IoT connectivity was enabled with the ESP32 Wi-Fi module. The Blynk program, equipped with widgets for displaying voltage, current, and power, enabled real-time monitoring.

3.3 Experimental Design

The MFC was constructed, sensors were incorporated, and IoT connectivity was established as a component of the experimental design. Electrodes composed of soft carbon graphite felt were utilised in the fabrication of the MFC. They were situated in separate sections and interconnected by a salt bridge. The anode chamber was filled with a mixed substrate solution to enhance microbial activity. The ESP8266 module was programmed to transmit data in real time to the Blynk application, while the voltage sensor was interfaced with the MFC to assess output parameters. The WiFi connectivity of the ESP32 was validated, and the voltage sensor was calibrated during the design process. The relationship between microbial activity and electricity generation was regularly monitored for system performance. Figure 3.2 illustrates the configuration of the MFC system integrated with the ESP32.

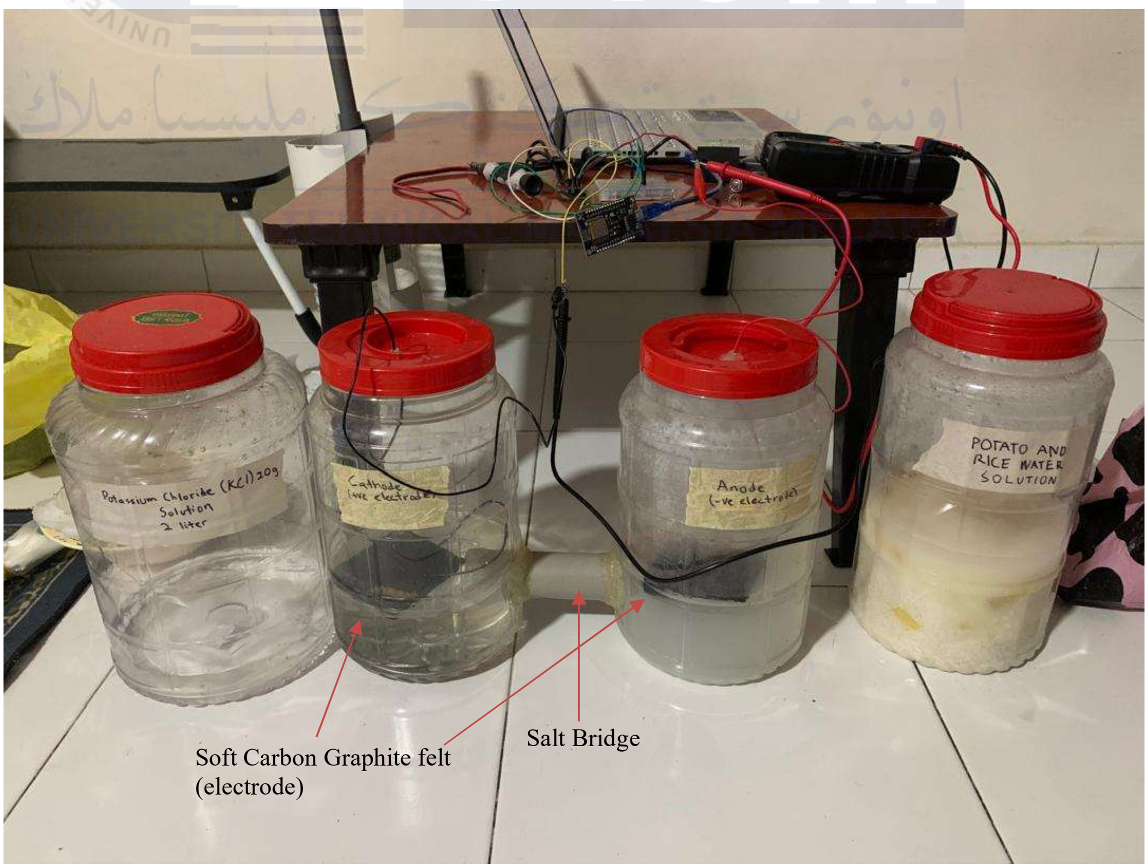

Figure 3.2 MFC system integrated with esp8266

3.4 Circuit Design

Figure 3.3 shows the voltage monitoring circuit utilising an ESP32 incorporates a voltage sensor module, an LED, and a 220Ω resistor to guarantee precise and effective voltage measurement. The voltage sensor scales the input voltage to a level suitable for the ESP32's ADC pin, which can interpret analogue signals within a 0–3.3V range. The ESP32 analyses the analogue signal from the sensor to ascertain the voltage levels in real time. An LED is linked to one of the ESP32's digital pins via a 220Ω resistor, which limits the current and safeguards the LED from damage, thereby offering a visual indicator of the voltage condition. When the measured voltage resides within a specified threshold, the ESP32 illuminates the LED to indicate that the voltage is within the acceptable range. The system is specifically engineered to oversee the output voltage of a microbial fuel cell (MFC), which serves as the principal power source. For preliminary testing and calibration, a 5V power bank will serve as a stable and dependable input voltage source. This dual testing methodology guarantees the system functions correctly in both controlled and real-world environments, rendering it appropriate for assessing the MFC's electricity generation performance.

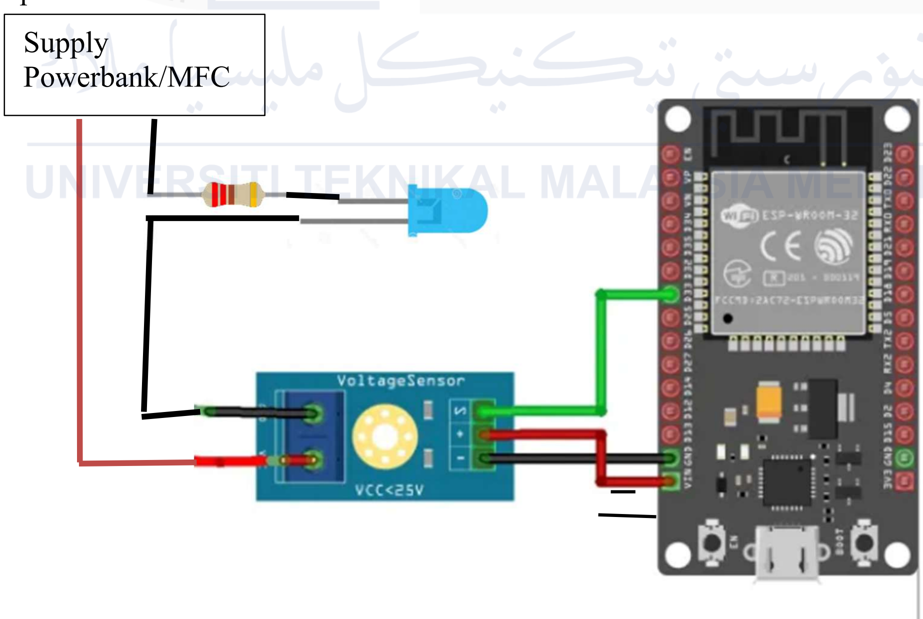

Figure 3.3 IoT Circuit

3.5 Troubleshooting and Validation

Efficient troubleshooting and validation are crucial to guarantee the reliability of the Blynk-integrated voltage monitoring system. The procedure commences with the verification of hardware connections, confirming that the ESP32, voltage sensor, and LED with the 220Ω resistor are correctly configured as per the circuit diagram. Verify the power supply, confirming that the 5V power bank or microbial fuel cell (MFC) provides a consistent input voltage. Should the LED fail to illuminate as anticipated, examine the resistor and the LED polarity, as improper connections may hinder functionality. Verify that the ESP32 is programmed with the appropriate firmware, incorporating the Blynk Auth Token, Wi-Fi credentials (SSID: Manlan, Password: kacang09), and pin configurations. To address software-related issues, verify that the ESP32 establishes a successful Wi-Fi connection by examining the Serial Monitor output.

3.6 Testing and Validation

The evaluation and verification of the Blynk-integrated voltage monitoring system entail a thorough procedure to guarantee precision, dependability, and peak performance. The process commences with hardware evaluation utilizing a 5V power bank to verify the voltage sensor, ESP32, and LED indicator. Sensor voltage measurements are verified with a multimeter for accuracy, and the data is transmitted to the Blynk App for real-time monitoring. Software validation include confirming the ESP32's WIFI connectivity with the designated SSID (Manlan) and password (kacang09), in addition to validating that Blynk widgets exhibit precise data and react appropriately to voltage fluctuations. Following preliminary testing, the system is authenticated in real-world conditions by substituting the power bank with the microbial fuel cell (MFC) and assessing its output. The voltage measurements on the Blynk App are verified with a multimeter, and alert thresholds are evaluated to confirm that notifications are activated correctly. Ultimately, long-term stability testing is performed by operating the system constantly to monitor voltage trends and verify consistent data transmission, thereby affirming the system's reliability for practical applications.

3.7 Project Architecture

This is a block diagram depicting the operation of the project. According to the Figure 3.2, For real-time monitoring, the system architecture combines IoT components with the microbial fuel cell (MFC). Microbial activity, which is detected by sensors and sent to a mobile app via Internet of Things protocols, powers the MFC. The architecture guarantees smooth communication between the Blynk platform and hardware components.

Figure 3.4: Block diagram of the project.

3.7.1 Hardware of the project

The hardware architecture includes the following components:

1) Microbial Fuel Cell (MFC): The MFC consists of an anode and a cathode chamber connected by a salt bridge. The anode chamber contains the food waste substrate (a mixture of potato and rice water), which supports microbial activity and electricity generation.
    - Anode and Cathode: Made from soft carbon graphite felt to ensure efficient electron transfer.

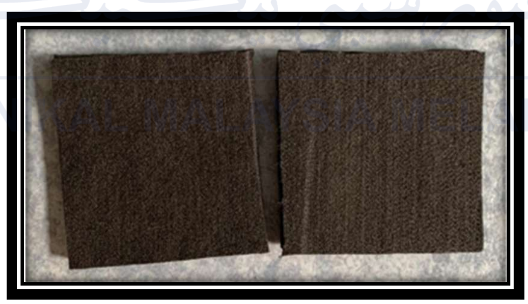

Figure 3.5: Soft Carbon Graphite Felt

- Salt Bridge: Composed of agar and potassium chloride to allow ion exchange between chambers.

Figure 3.6: Agar-agar Salt Bridge

2) Voltage Sensor: Measures voltage generated by the MFC.

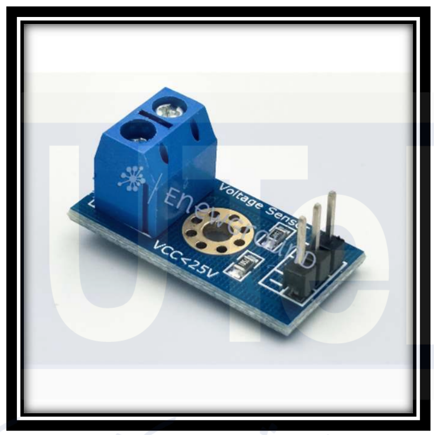

Figure 3.7: Voltage Sensor

3) ESP32 WiFi Module: Collects data from the voltage sensor and transmits it to the Blynk platform.

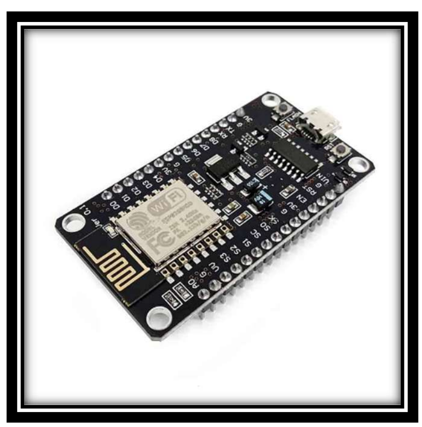

Figure 3.8: ESP32 WiFi module

4) Load Circuit: An LED and a 220 Ω resistor act as a test load to validate the system's electrical output.

Figure 3.9: LED

Figure 3.10: 220 Ohm Resistor

5) Power Supply: A 5V, 2.4A power bank provides consistent power to the IoT components.

Figure 3.11: Powerbank

3.7.2 Software of the project

The software architecture focuses on data acquisition, communication, and visualization:

1) Arduino IDE: Used to write and upload the firmware for the ESP32 module. The voltage sensor library is integrated for accurate sensor readinngs.

Figure 3.12: Arduino IDE

2) IoT Communication: Data is sent from the ESP8266 to the Blynk cloud server via Wi-Fi, enabling real-time updates.
3) Blynk App: Configured to display voltage, current, and power using widgets. A graph widget visualizes trends over time for better analysis.

Figure 3.13: Blynk App

3.8 Procedure

The project commences with the preparation of the salt bridge and substrate, which are critical elements of the microbial fuel cell (MFC). The salt bridge, usually composed of a KCl and agar solution, is designed to function as a proton exchange membrane, facilitating ion transfer between the anode and cathode while preserving electrical neutrality. The substrate, composed of a blend of potato and rice water, is formulated to supply the microbial fuel cell with organic matter, promoting microbial proliferation and enabling energy generation via microbial metabolism. Following the preparation of the MFC, the subsequent step is IoT integration via an ESP32. This entails linking the ESP32 to the microbial fuel cell to assess critical parameters including voltage, current, and power production. The ESP32 is configured to connect with sensors and relay data to a cloud-based platform such as the Blynk App for real-time surveillance. The ESP32's Wi-Fi functionality transmits data from the MFC to the Blynk App, facilitating remote monitoring and control. This integration offers critical insights into the MFC's performance, allowing users to monitor its energy generation and implement adjustments for optimisation.

3.8.1 Salt Bridge

Introduction

This section outlines the procedure for building a salt bridge, a crucial element for sustaining ion flow in a microbial fuel cell (MFC). The salt bridge maintains electrical neutrality between the anode and cathode compartments by facilitating ion passage while inhibiting the mixing of distinct electrolytes. The salt bridge was constructed with agar-agar as the gelling agent and potassium chloride (KCl) as the electrolyte.

Materials

1. Agar-agar powder: 5 grams

Figure 3.14: Agar-Agar

2. Potassium chloride (KCl): 1 gram

Figure 3.15: Potassium Chloride (KCl)

3. Distilled water: 150 ml
4. Plastic tube (15 cm long, 3.5 cm diameter)

Figure 3.16: Plastic Tube

5. Heat source
6. Stirring rod

Procedure

1. Preparation of Agar-Agar Solution:

- Measure 150 ml of distilled water and add 5 grams of agar-agar powder to it.

- Stir the mixture thoroughly to ensure the agar-agar is evenly distributed.

2. Addition of Potassium Chloride:

- Add 1 grams of potassium chloride to the agar-agar solution.

- Stir the solution until the potassium chloride is completely dissolved.

3. Heating the Mixture:

- Place the mixture on a hot plate and gently heat it while stirring.

- Continue heating until the agar-agar fully dissolves and the solution becomes clear. Avoid boiling.

4. Molding the Salt Bridge:

- Pour the hot solution into a glass or plastic tube, ensuring no air bubbles form.

- Allow the solution to cool at room temperature until it solidifies.

5. Installation:

- Once set, carefully remove the salt bridge from the tube and install it in the MFC, connecting the anode and cathode chambers.

3.8.2 Substrate Preparation for Microbial Fuel Cell (MFC)

Material and Equipment

The following materials and equipment were used in the preparation of the substrate for the microbial fuel cell (MFC):

- **Materials**:

  1) Potatoes (sufficient to extract starch-rich water)
  2) Rice (sufficient to extract starch-rich water)
  3) Potassium chloride (KCl)
  4) Distilled water

- **Equipment**:

  1) Cooking pots
  2) Stove
  3) Sieve
  4) Measuring cylinder (1 L capacity)
  5) Storage containers

Procedure

1. Preparation of Combined Potato and Rice Water Substrate (Anode chamber)

To prepare a nutrient-rich substrate solution, potato and rice starch were extracted and combined into a single solution. The steps involved are as follows:

1. **Cleaning**: The potatoes and rice were thoroughly washed under running water to remove dirt and other impurities. This step ensured no contaminants would interfere with the microbial processes.
2. **Cooking the Potatoes and Rice**:

    - Potatoes were diced into small pieces to facilitate faster cooking, while the rice was left as-is.
    - Both the diced potatoes and rice were boiled together in 1 L of distilled water for 15 minutes. During this process, starch from both components leached into the water, forming a rich substrate solution.

3. **Filtration**: The boiled mixture was filtered using a sieve to separate the solids (potato pieces and rice grains) from the liquid. The resultant solution, rich in starch, was collected into a clean container.
4. **Cooling**: The combined potato and rice water solution was allowed to cool to room temperature before further use. Cooling is essential to prevent adverse effects on the microbes during the MFC setup.

2. Addition of Potassium Chloride, KCl (Cathode Chamber)

To enhance the ionic conductivity of the substrate solution, potassium chloride (KCl) was added:

1. **Measurement**: The required amount of KCl was 1.5 gram for 1 liter of water.
2. **Mixing**: The KCl was dissolved into the cooled potato and rice water substrate by stirring until fully dissolved. This ensures uniform distribution of ions, which is critical for the MFC's electrochemical processes.

3. Storage

1. If the substrate was not used immediately, it was stored in an airtight container to prevent contamination or unwanted microbial activity.

3.8.3 IoT Integration Using Blynk, ESP32, and voltage sensor

The implementation of the IoT system with the ESP32 commences with the hardware configuration. The essential components comprise the ESP32 microcontroller, a voltage sensor, a reliable power supply (such as a power bank), and any supplementary sensors or actuators needed for monitoring. The ESP32 is powered via a USB connection, power bank, or the microbial fuel cell (MFC), contingent upon the particular system configuration. The voltage sensor is linked to the ESP32's analogue input pin for voltage measurement, ensuring the sensor's VCC is connected to either the 3.3V or 5V pin on the ESP32, while the GND pin is attached to the ESP32's ground. Supplementary sensors, including current sensors, may be integrated when necessary to monitor other parameters such as current or power. The configuration of the Blynk App is finalised. A new project is initiated on the Blynk App, with ESP32 designated as the device. The Blynk Auth Token, created upon project initiation, is documented for implementation in the ESP32 code to facilitate communication between the ESP32 and the application. Multiple widgets have been incorporated into the application to monitor system characteristics, including a Gauge Widget for voltage, a Label Value Widget for displaying exact numbers, and an LED Indicator Widget for visual feedback. These widgets are designed to connect with virtual pins, such as V1 for voltage, and are tailored with suitable range settings and display formats according to the anticipated sensor outputs.The ESP32 firmware development entails the installation of the Blynk library and the ESP32 board library within the Arduino IDE. The WiFi credentials (SSID: Manlan, Password: kacang09) are set to enable the ESP32 to connect to the local network. The Blynk Auth Token is integrated into the code to facilitate the connection between the ESP32 and the Blynk App. The code is designed to read data from the voltage sensor utilising functions such as analogRead(), and the detected voltage is adjusted to a suitable range. The voltage data is transmitted to the Blynk App using the Blynk.virtualWrite() function, associating it with the app's virtual pins V0 for voltage. When an LED widget is incorporated into the application, the ESP32 is configured to activate or deactivate the LED according to voltage thresholds, serving as a visual representation of the system's condition. Testing and calibration are essential procedures for ensuring the system operates correctly. Upon uploading the code to the ESP32, the Serial Monitor is employed to confirm the connectivity between the ESP32, the WiFi network, and the Blynk App. The system is evaluated with a reliable 5V power supply, such as a power bank, and the data shown in the Blynk App is juxtaposed with the readings from a multimeter to verify precise voltage measurement. Sensor calibration is accomplished by modifying the code's scale factors to align with the actual measurements. After the system is validated with a 5V power bank, integration with the microbial fuel cell (MFC) is executed. The power bank is substituted with the MFC, and the system is monitored to assess its response to the MFC's output voltage. The voltage measurements from the Blynk App are verified against a multimeter to ensure accuracy. In the Blynk App, predetermined voltage thresholds are established to activate notifications or alerts when the voltage surpasses or drops below specified values. This stage guarantees the system's ability to deliver real-time feedback and notifications on voltage fluctuations. Ultimately, prolonged testing is performed to assess the system's stability and performance over an extended duration. The system's capacity to sustain steady communication between the ESP32 and the Blynk App is evaluated, while voltage monitoring data is consistently recorded. Upon successful validation, the IoT system is prepared for deployment in the MFC configuration. The system is now capable of monitoring the energy generation of the MFC, offering real-time performance insights, and facilitating remote control and modifications via the Blynk App.

3.9 Summary.

The project entails the incorporation of an IoT system utilizing the ESP32 to oversee and regulate the functionality of a microbial fuel cell (MFC) by detecting voltage and relaying data to the Blynk App. The technique commences with the construction of the MFC, involving the preparation of a salt bridge composed of KCl and agar, alongside the creation of a substrate from potato and rice water to supply the microbial fuel for electricity generation. The anode and cathode of the MFC are interconnected, and a salt bridge is employed to facilitate ion transfer, while the prepared substrate is introduced to stimulate microbial activity that produces electricity. After the MFC configuration, the hardware assembly for the IoT system entails linking the ESP32, voltage sensor, and power supply (either a power bank or the MFC). The Blynk App is configured by establishing a new project, producing a Blynk Auth Token, and connecting the app to the ESP32 using WiFi credentials. The application incorporates various widgets, such as a Gauge Widget for voltage measurement and an LED Indicator for visual alerts, to facilitate real-time system monitoring. The ESP32 firmware development entails programming the microcontroller to acquire voltage sensor data and transmit it to the Blynk App via virtual pins. Upon uploading the code to the ESP32, the system undergoes testing and calibration using a 5V power bank to ensure precise readings and dependable communication. The system is subsequently integrated with the MFC by substituting the power bank with the MFC to evaluate its output. Voltage measurements from the Blynk App are juxtaposed with those from a multimeter, and voltage thresholds are established within the app to activate alarms if the voltage surpasses or drops below specified limits. Ultimately, long-term stability assessments are conducted to guarantee reliable performance. Upon successful validation, the IoT system is implemented for ongoing monitoring of the MFC, delivering real-time performance data and facilitating remote management and modifications via the Blynk App.

CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

This chapter will offer a detailed account of the project's advancement, highlighting the results attained. The amalgamation of microbial fuel cells (MFC) with an IoT-based monitoring system is an innovative method for harnessing microbial activity for sustainable energy production and real-time performance assessment. Evaluating the outcomes of such a system is essential for comprehending its efficacy and pinpointing opportunities for enhancement. This analysis concentrates on three primary aspects: the electrical performance of the MFC, the functioning of the IoT monitoring system, and the system's behavior under load situations. The electrical performance underscores the MFC's capacity to produce voltage and current, together with the temporal trends in power generation. The analysis of the IoT system assesses the dependability of data transmission and visualization through the ESP8266 and Blynk platform. The load behavior analysis evaluates the MFC's ability to support and energies modest loads, offering insights into its practical utility. Collectively, these evaluations provide an in-depth insight of the system's performance and facilitate potential improvements.

4.2 Result and Analysis

For this section, this project is carried out to measure voltage and current after finishing preparing the material and completing the positive terminal and negative terminal parts. After that, this section will provide the results and analysis of the results from the organic material according to the name of this project.

4.2.1 Voltage and Current profile analysis

Table 4.1 shows that the MFC generated a voltage that increased from 54 mV initially to 230 mV over time, as measured with a multimeter. This augmentation signifies enhanced microbial activity and substrate consumption. Current measurements were recorded using the multimeter, revealing trends that align with the reported voltage. The results, together with power estimates, validated the low energy density of the MFC, a prevalent constraint in such systems. The findings highlight the necessity of enhancing the microbial ecosystem and investigating methods to amplify the system for increased yields.

Table 4.1 MFC data for 60 second using potato and rice water solution substrate.

Time (s)	Voltage (V)	Resistance (k Ω)	Current (mA)(I=V/R)	Power (mW)
0	0.260	4.44	0.0586	0.015236
10	0.263	4.48	0.0587	0.015438
20	0.266	4.52	0.0588	0.015641
30	0.269	4.56	0.0590	0.015871
40	0.272	4.60	0.0591	0.016075
50	0.275	4.67	0.0589	0.016198
60	0.280	4.75	0.0589	0.016492

Time(s) vs Voltage (V)

Figure 4.1 representing Time (s) vs Voltage (V) demonstrates a steady increase in voltage over time, indicating a positive correlation between time and the voltage output of the microbial fuel cell (MFC). The voltage increases from 0.260 V to 0.280 V during a duration of 60 seconds. During the initial phase (0–10 seconds), the voltage rises consistently from 0.260 V to 0.263 V, signifying the commencement of microbial activity and the electrochemical response. The intermediate phase (10–40 seconds) exhibits a consistent increase from 0.263 V to 0.272 V, indicating the stabilisation of the reaction as microorganisms acclimatise and effectively transform the substrate into electrical energy. In the last phase (40–60 seconds), the voltage rises to 0.280 V, indicating the system's capacity to maintain and marginally improve its performance when microbial activity reaches its zenith. The consistent increase indicates the MFC's dependability and the substrate's efficacy in facilitating microbial activity, underscoring its potential for reliable energy production in short-term applications. Subsequent testing may investigate whether this growth persists, stabilises, or diminishes because of substrate depletion.

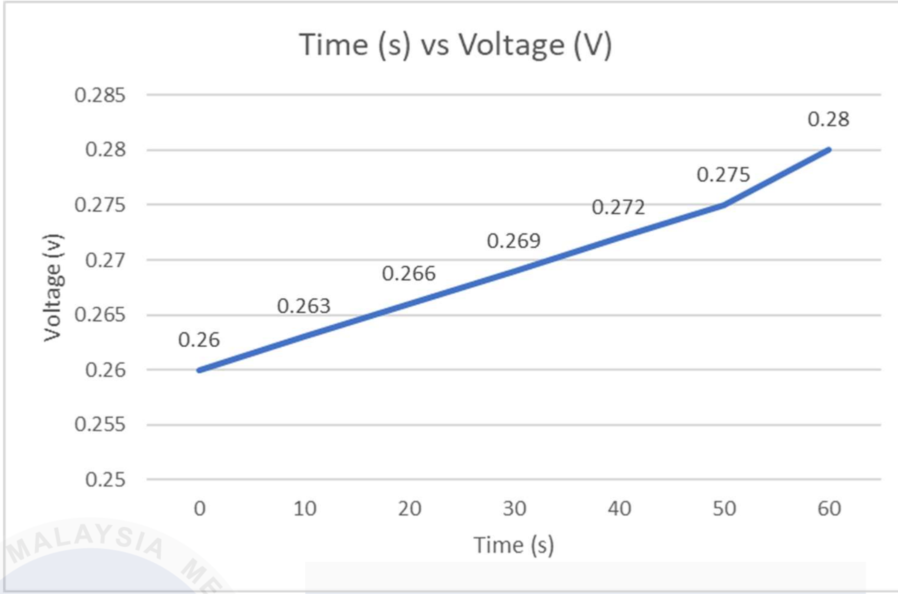

Figure 4.1: Time vs voltage for potato and rice water solution

<u>Time (s) vs Resistance (kΩ)</u>

The graph depicting Time (s) versus Resistance (kΩ) illustrates a consistent rise in resistance over time, signifying a positive link between time and resistance in the microbial fuel cell (MFC). The resistance escalates from 4.44 kΩ to 4.75 kΩ over a period of 60 seconds. In the initial phase (0–10 seconds), the resistance steadily increases from 4.44 kΩ to 4.48 kΩ, indicating the onset of microbial activity and its influence on the system's conductivity. The intermediate phase (10–40 seconds) demonstrates a steady rise from 4.48 kΩ to 4.60 kΩ, signifying the stabilisation of microbial activity and the possible formation of biofilms influencing electron transmission. During the concluding phase (40–60 seconds), the resistance escalates to 4.75 kΩ, signifying the system's ability to sustain its operation despite possible polarisation effects or electrolyte exhaustion. The steady growth emphasises the MFC's performance traits and indicates the necessity for additional research into long-term trends to ascertain if resistance stabilises or persists in increasing due to system constraints.

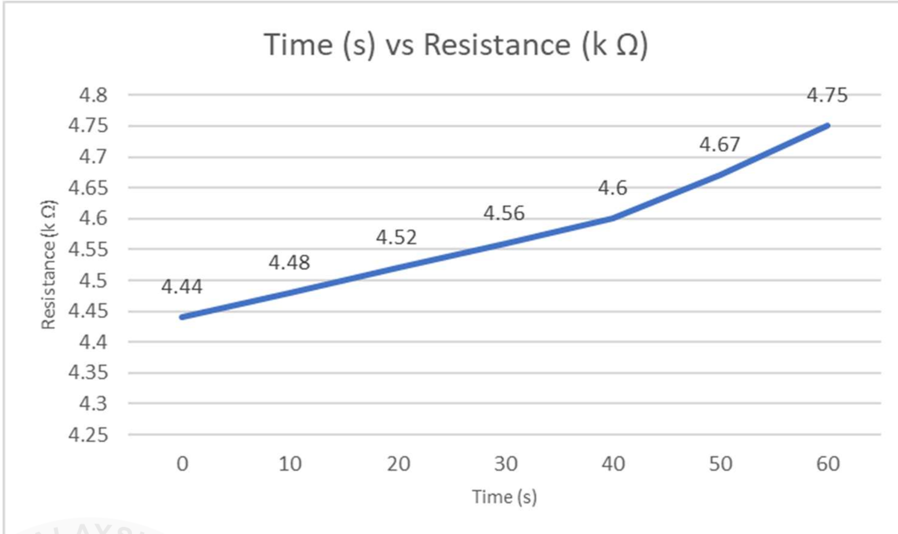

Figure 4.2: Time vs resistance for potato and rice water solution

<u>Time (s) vs Current (A)</u>

Figure 4.3 shows the graph illustrating Time (s) vs Current (mA) exhibits an early rise followed by a minor decrease, signifying fluctuations in current output over time in the microbial fuel cell (MFC). The current rises from 0.0586 mA to a maximum of 0.0591 mA during the initial 40 seconds, subsequently experiences a minor decline, and stabilises at 0.0589 mA by the conclusion of 60 seconds. In the early phase (0–20 seconds), the current increases from 0.0586 mA to 0.0588 mA, indicating the onset of microbial activity and electron transfer mechanisms. The middle phase (20–40 seconds) demonstrates a sustained increase from 0.0588 mA to 0.0591 mA, indicating the stabilisation and optimisation of microbial activity as the system effectively transforms substrate into electrical energy. During the concluding period (40–60 seconds), the current diminishes somewhat and stabilises at 0.0589 mA, suggesting potential polarisation effects or a little reduction in microbial efficiency when the system attains a stable state. The trend emphasises the MFC's capacity to generate a consistent current and indicates the necessity for additional research into substrate availability and system optimisation for enduring performance.

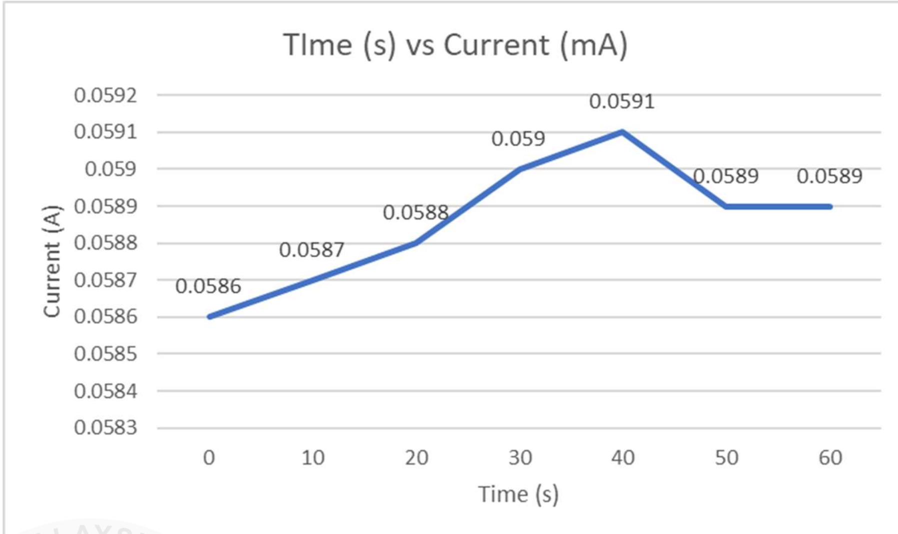

Figure 4.3: Time vs current for potato and rice water solution

Time (s) vs Power (mW)

The graph illustrating Time (s) vs Power (mW) exhibits a consistent rise in power output over time, signifying a favourable link between time and power generation in the microbial fuel cell (MFC). The power increases from 0.015236 mW to 0.016492 mW during a period of 60 seconds. In the early phase (0–20 seconds), power rises steadily from 0.015236 mW to 0.015641 mW, indicating the onset of microbial activity and the commencement of energy conversion processes. The intermediate phase (20–40 seconds) demonstrates a sustained increase from 0.015641 mW to 0.016075 mW, indicating the stabilisation of microbial activity as the system enhances substrate utilisation for energy production. During the last phase (40–60 seconds), the power escalates to 0.016492 mW, signifying the system's ability to sustain and augment performance as microbial activity attains an optimal condition. This continual rise underscores the MFC's dependability and capacity for persistent energy generation, while forthcoming research may investigate whether power output stabilises or declines due to prolonged substrate depletion or system constraints.

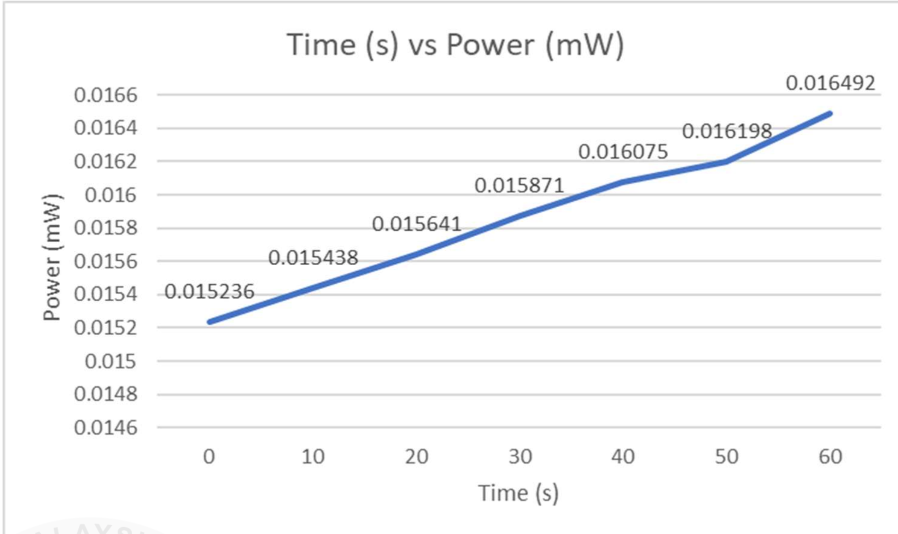

Figure 4.4 Time vs power for potato and rice water solution

4.2.2 Monitoring Voltage on the IoT Circuit Using a Multimeter

This investigation will confirm the voltage monitoring capabilities of the IoT system, which incorporates an ESP32 microcontroller, a voltage sensor, and the Blynk App, by comparing its values with those from a multimeter. The main objective of this analysis is to verify the precision and dependability of the IoT system in delivering real-time voltage data for the microbial fuel cell (MFC). A multimeter serves as a reference instrument owing to its accuracy and prevalent application in electrical measurements. This investigation seeks to discover differences and assess the functionality of the IoT system by methodically comparing the readings from the Blynk App and the multimeter under diverse settings. The results will underscore the efficacy of IoT integration and inform subsequent actions. Table 4.2 shows the volage monitoring analysis for 120 second using multimeter and IoT system.

Table 4.2 Table for Voltage Monitoring Analysis

Time (s)	Multimeter Reading (V)	IoT System Reading (V)	Percentage Error (%)
0	4.00	4.01	0.25
30	4.20	4.21	0.24
60	4.50	4.49	0.22
90	4.80	4.79	0.21
120	5.00	5.01	0.20

Explanation of the table:

- Time(s) : The time at which each voltage reading is recorded.
- Multimeter Reading (V): The voltage measured using the multimeter, considered the reference value.
- IoT System Reading (V): The voltage displayed in the Blynk App, recorded from the ESP32 and voltage sensor.
- Percentage Error (%): The calculated difference between the multimeter and IoT system readings using the formula:

$$Percentage\ Error = \frac{Multimeter\ Reading - IoT\ System\ Reading}{Multimeter\ Reading} \times 100$$

The table above presents a comprehensive comparison of voltage readings recorded from both the multimeter and the IoT system (consisting of the ESP32 and voltage sensor) at various time intervals: 0s, 30s, 60s, 90s, and 120s. At each time interval, the voltage measured by the IoT system (between 4.01V and 5.01V) closely corresponds with the multimeter readings (between 4.00V and 5.00V). This consistency indicates that the IoT system is effectively monitoring the voltage generated by the microbial fuel cell (MFC). The percentage error between the two measurements commences at 0.25% at 0 seconds and progressively diminishes to 0.20% by the conclusion of the 2-minute testing interval. The negligible fluctuation in % error signifies that the IoT system maintains exceptional accuracy consistently.

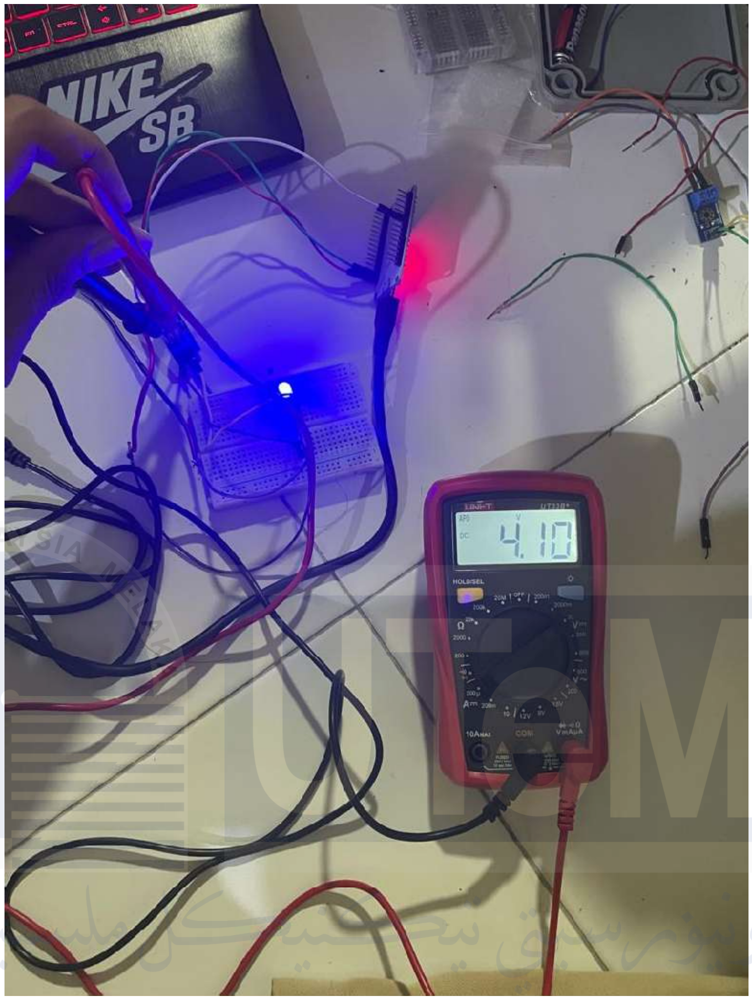

Figure 4.5: Monitoring Iot circuit using multimeter

4.2.3 Analysis of Voltage Graph Fluctuations

Figure 4.6 show the voltage graph from the IoT Energy Meter system illustrates real-time data with readings fluctuating between approximately 3V and 5V, showing irregular peaks and dips. These fluctuations indicate instability in the system, which can be attributed to several factors. One primary factor is electrical noise, which may arise from interference caused by nearby electronic devices or an unstable power supply. Another possible cause is the non-linearity of the ESP32's analog-to-digital converter (ADC), which may result in slight inaccuracies in voltage measurements, especially if the ADC has not been properly calibrated. Additionally, the graph suggests that the voltage data is unprocessed, as there are no filtering or signal-smoothing techniques applied to minimize the impact of these fluctuations.

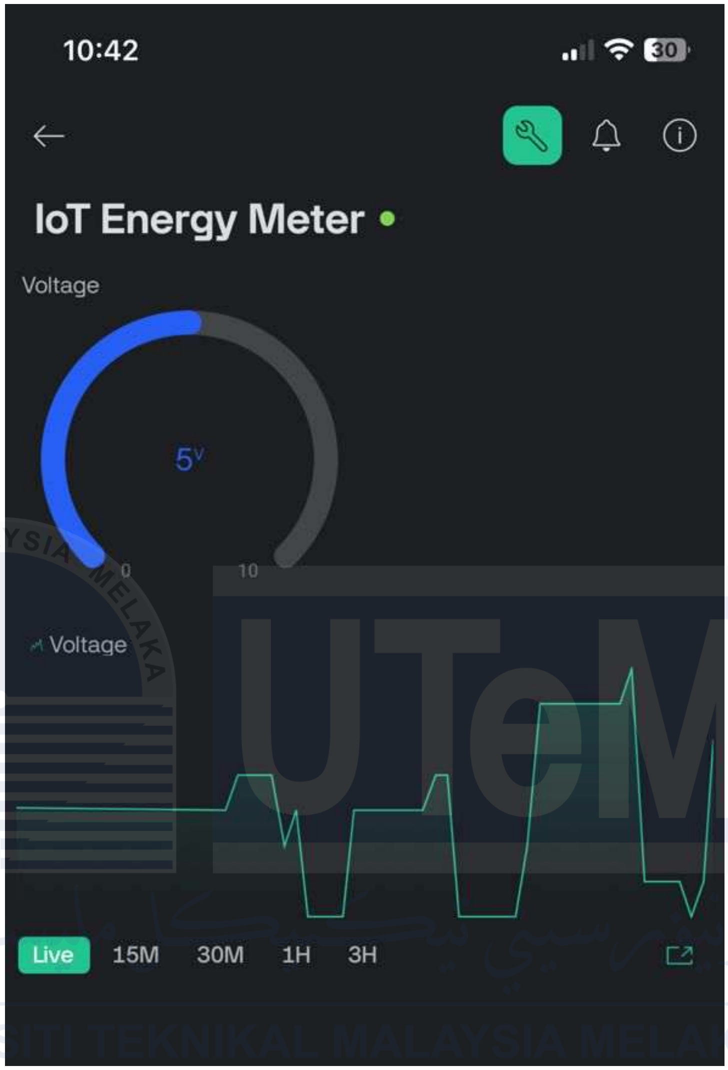

Figure 4.6 IoT Energy Meter interface

The irregular behavior in the graph compromises the reliability of the voltage data and makes it difficult to analyze or interpret the system's performance accurately. This instability could lead to errors in monitoring and controlling the microbial fuel cell (MFC) system. To address these issues, both hardware and software solutions should be implemented. On the hardware side, adding decoupling capacitors to the power supply can reduce voltage ripple, while improving the grounding and using a regulated power supply can further stabilize the system. On the software side, implementing signal filtering techniques, such as a moving average or exponential smoothing, can help smooth out the fluctuations in the data. These measures would significantly enhance the stability and accuracy of the voltage readings, resulting in a more reliable and interpretable graph for real-time monitoring and analysis.

4.3 Summary

This chapter provides a summary of the project's advancement and evaluation, concentrating on the amalgamation of a microbial fuel cell (MFC) with an IoT-based monitoring system for sustainable energy generation and real-time performance assessment. The project examines the electrical performance of the MFC, the precision of the IoT system, and the MFC's behavior under load situations. The electrical performance analysis indicates that the MFC exhibited a consistent rise in voltage, current, and power, demonstrating the influence of microbial activity on energy generation. Voltage, current, and power were quantified using the MFC using a potato and rice water solution, revealing a modest yet stable energy output. The IoT system, utilizing an ESP32 microcontroller and Blynk App, proficiently monitored the MFC voltage, exhibiting little discrepancies relative to the multimeter, so illustrating the system's precision in real-time data collecting. The findings offer significant insights into the possible integration of microbial fuel cells with IoT technology for enhanced monitoring and energy production, emphasizing opportunities for improving the energy output and optimizing the system of the MFC.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Introduction

This chapter will provide a summary project, including the project's history, research on previous journal articles, methodology used to create the project, and results of the project. In addition, this chapter describes the future work that can be implemented and the potential of the project.

5.2 Conclusion

Chapter 1 provides a detailed description of the project's context. This chapter also covers the project's background and the applications of microbial fuel cells. This chapter provides an overview of the problem statement, the objectives of the project, and the scope of the project. The research conducted in the previous paper and article is subsequently analyzed in chapter 2. The software and parameters of this project are detailed in the research report. This chapter additionally delineates the components of the microbial fuel cell.Chapter 3 the project uses an IoT system and ESP32 microcontroller to measure voltage and send data to the Blynk App to manage a microbial fuel cell (MFC). MFCs use KCl and agar salt bridges and potato and rice water substrates to power microbial activity. After building the MFC, the ESP32, voltage sensor, and power supply are connected, and the Blynk App is configured for real-time monitoring using widgets like a Gauge Widget and LED Indicator. The ESP32 sends voltage data to the Blynk App over WiFi. After calibrating with a 5V power bank, the MFC is tested for output. App alarm thresholds are defined based on IoT system voltage data and multimeter comparisons. Long-term stability tests allow the IoT system to monitor the MFC without interruption and remotely manage it via the Blynk App.Chapter 4 this chapter summarizes the project's development and evaluation, focusing on combining a microbial fuel cell (MFC) with an IoT-based monitoring system for sustainable energy generation and real-time performance assessment. The project tests the MFC's electrical performance, IoT system precision, and load behavior. The MFC's voltage, current, and power increased consistently, showing that microbial activity affects energy generation. Voltage, current, and power were measured using the MFC in potato and rice water, showing a moderate but steady energy output. Using an ESP32 microcontroller and Blynk App, the IoT system monitored MFC voltage with less error compared to the multimeter, demonstrating its real-time data collection precision. The findings suggest integrating microbial fuel cells with IoT technology for improved monitoring and energy production, highlighting opportunities to optimize the MFC system and increase energy output.

5.3 Future Work

Future endeavors could expand the project by optimizing microbial fuel cell (MFC) efficiency by testing with various substrates or by improving the salt bridge composition to promote ion conductivity, hence increasing power production. Extended testing must be performed to assess the system's stability under real-world conditions, encompassing microbial deterioration and substrate depletion. Incorporating energy storage options, such as rechargeable batteries, would yield a more stable power source for the IoT system. Owing to the exceedingly low voltage produced by the MFC, monitoring it with a voltage sensor is now impractical; thus, alternative approaches such as low-voltage amplifiers or bespoke sensors may be considered. The IoT system could additionally gain from supplementary sensors (e.g., temperature, pH) for thorough environmental monitoring and predictive analytics to anticipate MFC performance. Enhancing the Blynk App interface with functionalities like as real-time notifications and historical data visualization will elevate user experience, while investigating wireless power transfer methods could augment system mobility. Expanding the MFC to accommodate more energy requirements and employing machine learning algorithms to optimize energy generation would significantly augment the system's applicability in sustainable energy solutions.

5.4 Project Potential

This project has the potential to integrate two advanced technologies: microbial fuel cells (MFCs) and the Internet of Things (IoT). This project utilizes microbial activity to produce power while including real-time monitoring and data analysis via IoT, presenting viable alternatives for sustainable energy generation. The MFC may function as an alternative, environmentally sustainable power source for small-scale applications, including remote sensors, monitoring systems, and low-energy devices, particularly in off-grid or rural regions with restricted access to conventional electricity. With enhanced optimization and scalability, this system might be incorporated into larger energy frameworks, aiding trash-to-energy technologies by utilizing organic waste products as substrates for microbial power generation. Furthermore, the IoT component facilitates the implementation of smart grid systems, enabling remote monitoring of MFCs for efficiency and performance. This initiative, if further developed, might substantially influence environmental sustainability by advancing green energy solutions, diminishing reliance on non-renewable resources, and aiding the worldwide movement towards sustainable and clean energy alternatives.

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APPENDICES

Appendix A

backup_iot_meter.ino

```
#define BLYNK_TEMPLATE_ID "TMPL6Xzgefu18"
#define BLYNK_TEMPLATE_NAME "IoT Energy Meter"
#include <ESP8266WiFi.h>
#include <BlynkSimpleEsp8266.h>
#include <Wire.h>
#include <Adafruit_INA219.h>


char auth[] = "xeFON8roXcudbJBdwCwzZwvdvQo5G5bW";
char ssid[] = "Manlan";
char pass[] = "kacang09";

Adafruit_INA219 ina219;
const int ledPin = D4;
float currentThreshold = 0.02; // 20mA threshold
float shuntResistorValue = 0.1; // Default shunt resistor value (0.1Ω)

void setup() {
  Serial.begin(115200);
  Wire.begin();

  if (!ina219.begin()) {
    Serial.println("INA219 not detected!");
    while (1);
  }

  // Set calibration for low current range
  ina219.setCalibration_16V_400mA();

  pinMode(ledPin, OUTPUT);
  digitalWrite(ledPin, HIGH);

  WiFi.begin(ssid, pass);
```

Figure 5.1: The coding in IDE Arduino software

Appendix B

```
  Blynk.begin(auth, ssid, pass);
  Serial.println("Setup complete.");
}

void loop() {
  float shuntVoltage_mV = ina219.getShuntVoltage_mV(); // Shunt voltage in mV
  float busVoltage_V = ina219.getBusVoltage_V();       // Bus voltage in V
  float current_A = shuntVoltage_mV / 1000.0 / shuntResistorValue; // Current in A

  // Print readings
  Serial.print("Bus Voltage (V): ");
  Serial.println(busVoltage_V);
  Serial.print("Shunt Voltage (mV): ");
  Serial.println(shuntVoltage_mV);
  Serial.print("Calculated Current (A): ");
  Serial.println(current_A);
  Serial.println("----------------------------");

  // Send data to Blynk
  Blynk.virtualWrite(V0, busVoltage_V);
  Blynk.virtualWrite(V1, current_A * 1000); // Convert to mA for Blynk
  Blynk.virtualWrite(V2, busVoltage_V * current_A * 1000.0); // Power in mW

  // LED control based on threshold
  if (current_A > currentThreshold) {
    digitalWrite(ledPin, LOW); // Turn on LED
  } else {
    digitalWrite(ledPin, HIGH); // Turn off LED
  }

  Blynk.run();
  delay(1000);
}
```

Figure 5.2: The coding in IDE Arduino software