

**INVESTIGATION INTO GRAPHENE AS AN ELECTRODE
MATERIAL IN MICROBIAL FUEL CELLS FOR
BIOELECTRICITY GENERATION**

BY

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
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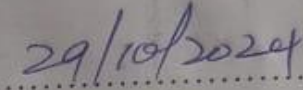
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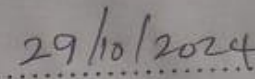
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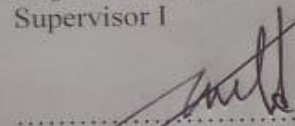
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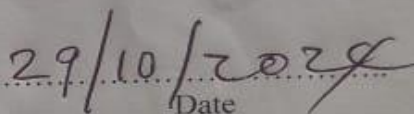

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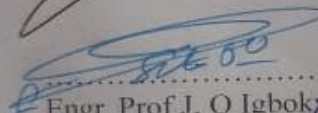

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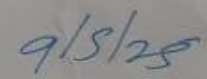

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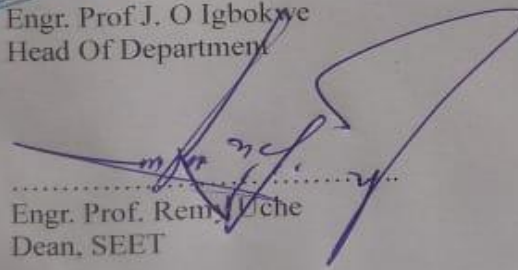

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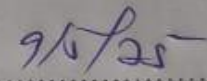

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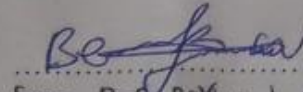

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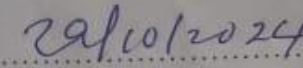

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ABSTRACT

The study investigates the potential of Graphene as an electrode coating material in microbial fuel cells for bioelectricity generation as well as a comparison with other electrode coating materials as copper, oxides, fluorides, carbonates, hydrocarbons, and powdered metal. Driven by the demand for materials with superior mechanical and thermal properties in the realm of advancing technology. Rigorous testing, such as mechanical, physical, chemical, electrical resistance, and defect inspections, were conducted on a Graphene sheet (0.70 x 1200 mm) and compared with copper, carbon isotope values, and NIS standards (NIS-119:1984 and NIS-487:2010). State-of-the-art laboratory equipment, such as an atomic absorption spectrometer, coating thickness gauge, universal tensile machine, and defect inspection system, was employed. The findings indicate that most elements in the graphene material align well with standard values, affirming its suitability for intended applications. However, manganese exceeds the standard limit, necessitating further scrutiny and potential refinement in the production process. In the ultimate tensile strength test, graphene surpasses the NIS requirement of 175, registering an impressive 182. The electrical resistivity values also showcase favorable results, with graphene exhibiting 0.02610^{-6} Ohm/cm compared to the NIS standard of 0.03410^{-5} Ohm/cm. Impact resistance, a critical parameter, demonstrates graphene's robustness with a measured value of 5 J, exceeding the NIS range of 2 J - 5 J. The gloss result for graphene falls within the specified NIS requirement of 40-60%, recording 58%. This research significantly contributes to our understanding of graphene's applicability. It provides valuable insights for optimized production processes and identifies potential applications that demand enhanced mechanical properties. The observed discrepancies, particularly the elevated manganese level, highlight areas for further investigation and process refinement. Overall, the study underscores graphene's promising role in microbial fuel cells and sets the stage for continued advancements in material science and bioelectricity generation technologies.

Keywords: *Graphene Electrode, Microbial Fuel Cells, Bioelectricity Generation, Mechanical Properties, Electrical Resistivity*

CHAPTER ONE

INTRODUCTION

1.1 Background Information

Microbial Fuel Cells (MFCs) represent an innovative and sustainable technology for bioelectricity generation by harnessing the metabolic activities of microorganism.. In recent years, the exploration of advanced materials for MFC electrodes has been identified as a key component in the generation of Bioelectricity. One such material that has emerged as a promising candidate is graphene, Graphene is a single layer of carbon atoms arranged in a hexagonal lattice, forming a two-dimensional structure. It is the basic building block of other carbon allotropes, such as graphite, carbon nanotubes, and fullerenes. Graphene has remarkable properties that make it an exciting material in various fields of science and technology.

These attributes make graphene an attractive material for electrode applications in MFCs, where efficient electron transfer between microorganisms and electrodes is crucial for enhanced bioelectricity generation. (Mirela, O., Iaci, M., Rafael, R., Alessandra, L., Lilian, V., Matheus, P., & Ademir, J. 2022).

This investigation into the utilization of Graphene as an electrode material in MFCs holds great potential for addressing several issues facing the conventional Microbial Fuel Cell (MFC), such as limited conductivity and susceptibility to bio fouling. This study focuses on establishing Graphene as an Electrode material that would significantly contribute to not only the Ecosystem but also National economic development.

In order to establish the above, i explored several methods of confirming the positive properties of graphene as a material some of which include electrical efficiency, chemical composition analysis, weathering and durability testing.

Notably, substantial energy reservoirs lie within organic matter, such as carbohydrates abundantly present in agricultural and municipal waste. Operating as a bio-electrochemical system (BES), MFCs directly convert the chemical energy stored in organic compounds into electrical energy through microbial metabolism, offering advantages such as low maintenance, environmental friendliness, high conversion efficiency, and operation at ambient and low temperatures (Wen & Alatraktchi 2012).

Furthermore, the electricity generated by MFCs can serve various functions, including the production of value-added chemicals like hydrogen in microbial electrolysis cells (MECs) or driving water desalination in microbial desalination cells or MDCs (Wang, 2015). Within the

MFC's anode chamber, bacteria foster growth by oxidizing organic matter, catalyzing fuel oxidation, releasing electrons, and protons. These released electrons and protons subsequently react in the cathode chamber to produce water, thereby generating electricity as the electrons traverse between chambers through an external circuit. (Alatraktchi, 2014).

The efficiency of the anode electrode is pivotal in this process, requiring excellent conductivity for efficient electron transfer and good biocompatibility for microbial inoculum, growth, and adhesion (Wen et al., 2013). The ongoing quest for robust, cost-effective, and highly efficient electrodes is paramount, given that the electrode significantly influences the performance and cost of MFCs (Wei & Logan 2010).

This study therefore investigates graphene use in microbial fuel cells, aiming to provide insightful impact on electron transfer mechanisms, biofilm formation, and overall bioelectricity generation efficiency. Through a comprehensive investigation, we aim to contribute valuable insights that could pave the way for the development of more efficient and robust MFCs for bioenergy applications.

1.2 Problem Statement

While graphene has unique properties that make it a promising candidate for various applications, including electrodes in microbial fuel cells (MFCs), there are challenges and problem statements associated with its use in this specific context. Some of the key issues include:

Limited Biocompatibility: Graphene, especially in its pristine form, may not be inherently biocompatible. The surface properties of graphene can affect the behavior of microorganisms in the microbial fuel cell. Ensuring that the introduction of graphene does not adversely impact the growth and activity of the microorganisms is crucial for the efficiency of the MFC.

Biofouling and Microbial Attachment: Microbial biofouling, the accumulation of microorganisms on the electrode surface, can be a significant problem. While graphene's properties can discourage biofouling to some extent, proper design and functionalization may be necessary to prevent or mitigate microbial attachment, which could degrade the performance of the MFC over time.

Electron Transfer Kinetics: The efficiency of MFCs relies on efficient electron transfer between the microbial biofilm and the electrode surface. While graphene's high conductivity is advantageous, achieving optimal electron transfer kinetics may require further optimization,

such as specific surface modifications or the integration of additional materials to enhance the biocompatibility.

Scalability and Cost: The production of high-quality graphene can be expensive and may pose challenges in terms of scalability for large-scale MFC applications. Researchers need to address the cost-effectiveness and scalability of using graphene as an electrode material for microbial fuel cells.

Long-Term Stability: The long-term stability of graphene-based electrodes in microbial fuel cells needs consideration. Factors such as the potential degradation of graphene over time due to environmental conditions or the accumulation of byproducts on the electrode surface could affect the durability and performance of the MFC.

Addressing these challenges requires interdisciplinary efforts involving materials science, microbiology, and engineering. Researchers are actively exploring ways to overcome these issues through surface modifications, hybrid materials, and improved fabrication techniques to harness the full potential of graphene in microbial fuel cells.

This research seeks to address these critical gaps in knowledge and understanding by thoroughly investigating the role of graphene as an electrode material in MFCs. Also by comprehensively assessing its impact on electron transfer mechanisms, biofilm formation, and overall bioelectricity generation efficiency, the study aims to contribute insights that not only advance the fundamental understanding of MFCs but also guide the development of more efficient and sustainable bioenergy solutions.

1.3 Objective of Study

The main objective of this research is investigation of graphene as an electrode material microbial fuel cells for bioelectricity generation. These specific objectives include:

- i. To establish graphene as an effective and efficient electrode material in MFC's.
- ii. To establish by means of experimentation the percentage efficiency factor and power output and efficiency of a fuel cell with graphene as its electrode material.
- iii. To compare the characterized graphene material with other commonly used electrode materials e.g. copper, Aluminum.

1.4 Justification of the Study

Observing the tendency on optimizing MFC performance, the study addresses the pressing need to enhance the performance of Microbial Fuel Cells (MFCs) by investigating the utilization of graphene as an electrode material. Understanding the electrochemical properties of graphene can potentially overcome the limitations associated with traditional electrode materials, leading to more efficient and sustainable bioelectricity generation.

Based on sustainable energy solutions, as the global demand for sustainable energy solutions intensifies, MFCs offer a unique approach by directly converting organic compounds into electrical energy through microbial metabolism. Investigating graphene's role in MFCs aligns with the broader goal of contributing to sustainable and environmentally friendly energy generation technologies.

In the case of environmental impact of electrode materials, traditional electrode materials may pose environmental concerns during production and degradation. The exploration of graphene, known for its biocompatibility and potential environmental sustainability, aligns with the imperative to adopt materials that have a reduced environmental footprint, especially in the context of renewable energy technologies.

The study also justifies the advancing graphene applications. Graphene with its remarkable electrical, mechanical, and biocompatible properties, has shown promise in various applications. This study contributes to expanding the knowledge base on graphene's application by specifically focusing on its role in MFCs, potentially opening avenues for its use in other energy-related fields.

Based on meeting the energy demand, considering the increasing demand for energy worldwide, particularly from sustainable and renewable sources, optimizing the performance of MFCs becomes critical. By contributing insights into the use of graphene in MFCs, this study aligns with the broader energy transition goals and addresses the need for alternative and efficient energy generation methods.

Another justifiable factor on this study is overcoming electrode material limitations, which the traditional electrode materials often face challenges such as limited conductivity and susceptibility to biofouling. Investigating graphene as an alternative material aims to overcome these limitations, potentially leading to longer-lasting and more efficient MFCs.

1.5 Scope of Study

The scope of this research encompasses a comprehensive investigation into the utilization of graphene as an electrode material in Microbial Fuel Cells (MFCs). The study involves a multi-faceted approach, covering various aspects to evaluate the suitability and efficiency of graphene in comparison to conventional materials. The key components of the scope include:

- Mechanical Analysis of sample specimen: testing of physical properties such as dry film thickness, pencil hardness, impact resistance, and electric conductivity. Comparison with copper (Cu) as the reference element to assess the energy efficiency, lightweight nature, and degradation resistance of graphene when used as an electrode material in MFCs.
- Electrical Analysis of Sample Specimen: The coulombic efficiency of the microbial fuel cell where its electrodes are coated with graphene will be compared to conventional electrode materials.
- Dimensional Properties Analysis: Examination of the size of the specimen in alignment with the Minimum Dimensional Requirements specified by the NIS 199:1984 Industrial Standard. Verification of specimen conformity to the minimum requirements, ensuring it is fit for further laboratory testing.
- Test Result Summary: Compilation and summary of the extensive physical and chemical analysis results. Comparative evaluation of the specimen's properties, emphasizing key aspects such as Electrical Conductivity, Corrosion Resistance, and Chemical Stability in comparison to Copper (Cu) and Iron III Oxide (Fe_2O_3).

CHAPTER TWO

LITERATURE REVIEW

2.1 Overview on Microbial Fuel Cells (MFCs)

The origins of MFC technology can be traced back to the early 20th century, with initial experiments exploring microbial involvement in electricity production. However, significant advancements were made in the late 20th and early 21st centuries, marked by the identification of electroactive microorganisms and the optimization of MFC designs. Over time, MFC technology has evolved from basic laboratory experiments to diversified applications, including wastewater treatment, power generation, and biosensor development {Bi et al. (2018) & Yellappa et al. (2020)}.

(Das et al., 2018) stated that Microbial Fuel Cells (MFCs) represent a groundbreaking bio-electrochemical technology that harnesses the metabolic activities of microorganisms to generate electrical energy from organic compounds. At its core, MFCs operate on the principle of utilizing living microorganisms as biocatalysts for the conversion of chemical energy stored in organic matter into electrical energy. This unique technology holds immense potential for sustainable energy generation due to its ability to directly convert organic substrates, such as wastewater and organic waste, into electricity Cecconet (et al, 2018).

The fundamental principle of MFCs involves the interaction between microorganisms and electrodes within a controlled environment. Microorganisms, commonly bacteria, oxidize organic matter, releasing electrons and protons (Jain et al., 2021). These electrons are then harnessed as electrical energy when they flow through an external circuit towards a cathode, where they combine with protons and oxygen to form water. The anode and cathode constitute the key components, with the anode facilitating microbial metabolism and electron release, and the cathode enabling electron acceptance for the overall electrochemical reaction (Shabani et al 2020).

The significance of MFCs in sustainable energy generation lies in their potential to address pressing environmental and energy challenges. By providing a means to harness energy from organic waste, MFCs contribute to the reduction of pollutants and offer a sustainable alternative to traditional energy sources (Ni et al, 2020). Furthermore, MFCs align with the principles of the circular economy by transforming waste into a valuable resource, exemplifying their role in creating a more sustainable and environmentally friendly energy landscape (Wei et al, 2011; Logan, 2010).

MFCs can be grouped into two general categories, those that use a mediator and those that are mediator-less. A mediator is a chemical that transfers electrons from the bacteria in the cell to the anode in the mediator-less MFC the bacteria typically have electrochemically active redox proteins such as cytochromes on their outer membrane that can transfer electrons directly to the anode (Singh et al 2019). A microbial fuel cell is a device that converts chemical energy to electrical energy by the catalytic reaction of microorganisms. A typical microbial fuel cell consists of anode and cathode compartments separated by a cation specific membrane. In the anode compartment, fuel is oxidized by microorganisms, generating CO₂, electrons and protons. Power production was very low and required the addition of exogenous mediators to shuttle electrons from inside to outside the cell. In new systems, exogenous mediators are not needed, and power production from MFCs has increased dramatically in just the past few years, in part because of designs that lower the reactor's internal resistance (Ivars-Barcdo, Samsundeen & Coedova-Bautista 2017). Extensive optimization is required to exploit the maximum microbial potential for novel wastewater treatment process and biosensor for oxygen and pollutants.

2.2 APPLICATIONS OF MICROBIAL FUEL CELLS

A) WASTE WATER TREATMENT

MFC-based wastewater treatment and energy harvesting research, and analyze various biocatalysts used in MFCs and their underlying mechanisms in pollutant removal as well as energy recovery from wastewater. Lastly, we highlight key future research areas that will further our understanding in improving MFC performance for simultaneous wastewater treatment and sustainable energy harvesting.

B) DESALINATION

Microbial desalination cells (MDCs) with common liquid anodic substrate exhibit a slow startup and destructive pH drop, and abiotic cathodes have high cost and low sustainability. A Bio-cathode MDC with dewatered sludge as fuel was developed for synergistic desalination, electricity generation and sludge stabilization. Experimental results indicated that the startup period was reduced to 3d, anodic pH was maintained between 6.6 and 7.6, and high stability was shown under long-term operation (300d). When initial NaCl concentrations were 5 and 10g/L, the desalination rates during stable operation were 46.37±1.14% and 40.74±0.89%, respectively. The maximum power output of 3.178W/m³) with open circuit voltage (OCV) of 1.118V was produced on 130d. After 300d, 25.71±0.15% of organic matter was removed.

These results demonstrated that dewatered sludge was an appropriate anodic substrate to enhance Microbial Desalination Cells stability for desalination and electricity generation.

C) HYDROGEN PRODUCTION

The primary product of the electrochemical reaction in the organic matter of fuel cells is Hydrogen. Hydrogen from the beginning is known for its ability to produce energy/release of electrons Hydrogen gas has immense potential as an ecologically adequate energy carrier for vehicles. MFC is bio-electrochemical process that utilize microorganism as the impetuses to oxidize organic and inorganic matter and create electricity, whereas MEC are a reactor for bio-hydrogen production by combining MFC and electrolysis. MEC and MFC have been the cleanest, eco-friendly, and efficient method for bio-hydrogen production.

D) REMOTE POWER SOURCE GENERATION

The advancement of microbial fuel cell technologies in the 1980s was largely spurred by the dream of providing cheap, accessible power to remote regions of Africa, where 74% of the population lives without electricity . Although implementation of homemade MFC use in Africa is just beginning, microbial fuel cells that run on manure and dirt have been developed and tested. The electrical current produced by a simple homemade MFC is enough to recharge a cell phone battery, an important communication and lighting tool to rural African communities. . The materials required to construct a simple MFC are soil, manure, copper wire, buckets, and graphite cloth which are relatively accessible.

2.2 Types of MFC Designs

2.2.1. DOUBLE CHAMBER MFC

The double chamber Microbial Fuel Cell (MFC) is comprised of two distinct compartments: the anodic and cathodic chambers, designed to be anaerobic and aerobic, respectively. These chambers are externally connected through a wire and internally linked by a proton exchange membrane. This entire setup completes the circuit, and the membrane facilitates the movement of protons to the cathodic chamber while limiting the diffusion of oxygen into the anodic chamber (Slate & Xia et al. 2018). Submerged electrodes, made of non-corrosive conductive materials, operate in batch mode with a chemically defined medium to generate power. The external resistance directly impacts the output, and optimizing the distance between the electrode and cathode is crucial for maximizing power density (Choi et al 2013). To address

this, internal resistance is minimized, and electrodes are positioned closer to increase power density.

Primarily employed for large-scale wastewater treatment to produce electricity, the double chamber MFC requires consistent solution replacement at the cathode with aeration to supply oxygen. Despite this, power production can be enhanced by controlling cathode pH, introducing fresh O₂, increasing flow rate, adding extra electron mediators, and managing internal resistance.

While typically functioning in the water cathode mode, the dual-chamber microbial fuel cell can be modified into various designs such as single-chamber, stacked, and cylindrical mode MFCs. The configuration of the MFC plays a pivotal role in determining power production efficiency and cost-effectiveness for industrial applications.

2.2.2 SINGLE CHAMBER MFC

The single-chamber Microbial Fuel Cell (MFC) is employed for small-scale power production, offering reduced internal resistance and thus ensuring cost-effectiveness coupled with high efficiency. Derived from the double-chamber MFC design with slight modifications, the single-chamber version features only one defined anodic chamber for wastewater placement. In contrast to the double chamber MFC, the single chamber MFC lacks a defined cathodic chamber and proton exchange membrane (PEM). Instead, it incorporates a porous cathode on one side, allowing protons to pass through while restricting the flow of oxygen toward the anode (Liu & Logan 2014).

On the opposite side, oxygen is obtained from the atmosphere to complete the circuit. Carbon electrodes serve as the anodes, while cathodes can be either PEM fused with flexible carbon cloth or porous carbon electrodes. Graphite covering is commonly used for cathodes. Electrolytes are typically dispensed into the cathode in a steady state, acting as a catholyte to prevent drying out of the cathode and membrane (Cheng *et al.*, 2006).

The single-chamber MFC operates in air-cathode mode, allowing air enriched with oxygen to directly interact with the porous cathode electrode. This design offers several advantages, including less internal resistance, improved proton diffusion, cost-effectiveness, higher oxygen reduction rate at the cathode, simplicity of use, and adaptability to aeration. However, commercial-scale implementation is hindered by challenges such as evaporation, high-rate oxygen diffusion, and liquid outflow (Liu & Logan, 2004).

2.2.3 STACKED MFC

Microbial Fuel Cells (MFCs) can be configured in a stacked arrangement, either in parallel or series, significantly impacting power production. When stacked in parallel, higher current output is achieved, while a series connection results in elevated voltage output. The design does not influence coulombic efficiency, but it enhances the overall battery power (Flimban *et al.*, 2018). Stacked MFCs, which contribute to substantial power generation, necessitate careful consideration of various factors when treating wastewater. These factors include maintaining substrate flow rates, assessing the height of vertically stacked MFCs, monitoring organic concentrations at the end of MFC operation, and determining the reactor volume (An *et al.*, 2015). Stacked MFCs can be categorized into horizontal stacks and vertical stacks.

Horizontal Stacked MFCs are rectangular, parallel-piped double-chambered structures with horizontal stacking. Enclosed within a rectangular frame with two ports (inlet and outlet), they consist of an anode, proton exchange membrane (PEM), and cathode (Wu *et al.*, 2016; Aelterman *et al.*, 2006; Vilajeliu-Pons *et al.*, 2017; Rahimnejad *et al.*, 2012; Jafary *et al.*, 2013; Zhang *et al.*, 2017). Pumps are required to circulate wastewater, and these MFCs are connected to current accumulators with metal wires, forming either parallel or series circuits. Acrylic sheets or rubbers are used to partition the horizontal stacks, preventing catholyte and anolyte sharing within the MFC stack unit.

In a study by Aelterman *et al.* (2006), power density for six horizontally stacked MFC units was evaluated based on polarization curves, reaching as high as 263 W/m³ for parallel connections and 308 W/m³ for series connections. Another pilot project achieved a maximum power density of 51 W/m³ and a COD removal efficiency of 97% from a scaled-up, 72-liter, rectangular, horizontally stacked, parallel-connected MFC (Wu *et al.*, 2016).

Vertical Stacked MFCs operate on parallel electrode connections in series flow mode, utilizing gravity as a cost-effective, self-driven mechanism that eliminates the need for pumps to maintain flow rates. Notable successes have been recorded with vertical stacked MFCs, such as the first self-sustainable MFC stack, a vertical, single-chambered cascade consisting of 40 identical 20 mL units (total volume of 0.8 L) (Ledezma *et al.*, 2013). However, power generation in vertical MFC stacks tends to be lower (110 mW with a maximum power density of 10 W/m³), and challenges such as voltage reversal must be addressed (An and Lee, 2014).

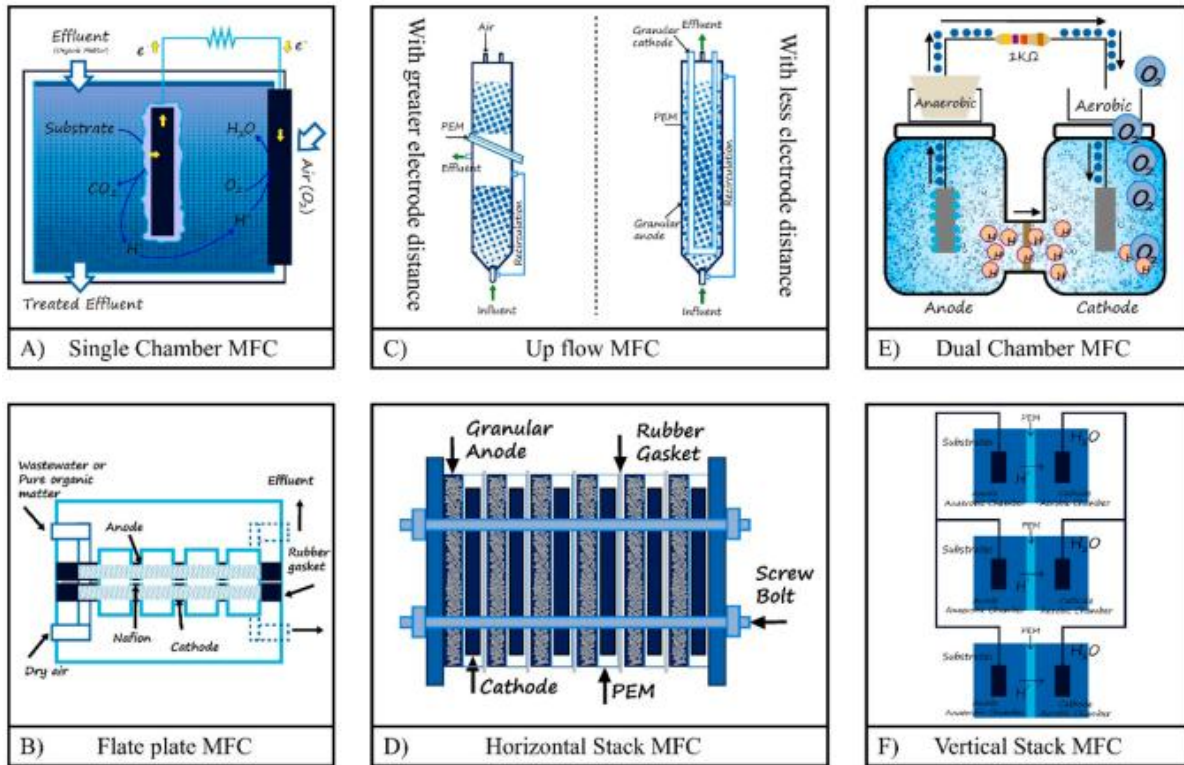


Figure 2.1: **Diagrammatic representation of different types of MFCs.**

Source: Nawaz et al., (2022)

2.2.4 Flat Plate Microbial Fuel Cell (FPMFC)

The FP-MFC, characterized by its cubic, mini-squared flat compact plate design, closely resembles a chemical fuel cell configuration. In this system, the cathode and anode are connected internally through a proton exchange membrane (PEM) and externally via a copper or other conductive material wire. The cathode is hot-pressed onto a Nafion proton exchange membrane, forming a PEM assembly with the anode attached on the opposite side of the membrane. In the cubic FP-MFC, the anodic chamber receives wastewater, while the cathodic chamber is supplied with air without any catholyte. A notable distinction of the cubic MFC from other types lies in its reduced internal resistance, attributed to the smaller distance between components, consequently leading to increased power output (Janicek *et al.*, 2014).

An experiment by Kim et al. (2007) compared the performance of cubic-shaped MFCs with bottle-shaped MFCs. The cubic design exhibited significantly higher power generation,

producing 14 times more power (214 mW/m²) with an internal resistance of 84 Ω, compared to the bottle-shaped MFC (38 mW/m²) with an internal resistance of **1272 Ω**.

2.2.5 Cylindrical Microbial Fuel Cell (MFC)

The cylindrical MFC, also known as Up-Flow MFC, is primarily employed for wastewater treatment rather than large-scale electricity generation. Operated in continuous or series mode to optimize power production, the up flow microbial fuel cell features uniform graphite electrodes alongside a proton exchange membrane (PEM) and functions in a fed-batch mode. Various configurations of the cylindrical MFC have been tested, varying the distance between electrodes, a factor that directly influences internal resistance.



Figure 2.2: Flowchart of parameters depicting MFC performance for bioelectricity generation. Source: Nawaz et al., (2022)

In the operation of the Up-flow MFC, wastewater enters the anodic chamber at the bottom, undergoes processing, and releases electrons to the cathode through an external circuit. The Up-flow MFC requires pumping and fluid recirculation, facilitating the treatment of large volumes of wastewater; however, this comes at the expense of reduced power production due to increased energy loss. To address this, the MFC is utilized in fed-batch or continuous mode to enhance power production, with recirculation mode proving effective for mass transfer and electricity production in fed-batch. In continuous mode, the hydraulic retention time decreases, leading to increased power production, and clogging issues can be mitigated by eliminating suspended solids.

(He et al.2005), presented two configurations of Up-Flow MFC (UP-MFC): one with cathode and anode separated by certain distances, exhibiting an internal resistance of 84 Ω and a maximum power density of 170 mW/m². The other configuration demonstrated lower internal resistance, as electrodes were placed near each other, resulting in a power density of 29.2

W/m². This emphasizes that a smaller distance between electrodes leads to more efficient power generation in a shorter period.

2.3 Electrode Materials in Microbial Fuel Cells

Microbial Fuel Cells (MFCs) have gained significant attention as sustainable bioenergy devices that harness the metabolic activity of microorganisms to generate electricity. Central to the efficiency and performance of MFCs are the electrode materials, which play a pivotal role in electron transfer processes.

The electrodes in MFCs serve as interfaces for electron transfer between microbial biofilms and external circuits. Anode and cathode materials play distinct roles in facilitating the oxidation and reduction reactions, respectively. The efficiency of electron transfer is crucial for maximizing power output in MFCs. Understanding the properties and characteristics of electrode materials is essential for optimizing MFC performance.

2.3.1 Traditional Electrode Materials and Their Limitations

(a) Graphite-Based Anodes: Traditional anodes are often composed of graphite due to their conductivity and stability. Limitations include biofilm fouling, low surface area, and vulnerability to corrosion (Logan et al., 2006); (Cheng & Logan., 2007).

(b) Platinum-Based Cathodes: Platinum and other noble metals are commonly used as cathode materials. High cost and scarcity of noble metals pose economic and sustainability challenges. Liu et al (2008) ; Kim et al, (2018)

2.3.2 Emerging Trends in Advanced Electrode Materials

- Nanostructured Anodes: Recent advancements involve the use of nanostructured materials (e.g., carbon nanotubes, graphene) to enhance surface area and conductivity. Nanostructured anodes mitigate biofilm fouling and improve electron transfer rates Wang et al. (2011) and Santoro et al (2017).
- Non-Noble Metal Cathodes: Exploration of non-noble metal catalysts (e.g., transition metal oxides, carbon-based materials) to replace expensive platinum-based cathodes. Improved cost-effectiveness and sustainability in MFCs. Li et al (2015) and He et al. (2019)
- Bifunctional Electrodes: Development of Bifunctional electrodes that can simultaneously serve as anodes and cathodes. Enhanced compactness, simplified design, and improved overall efficiency (Wu & Xiao, 2020).

2.4 Introduction to Graphene: Properties and Characteristics

Graphene, a single layer of carbon atoms arranged in a hexagonal lattice, has garnered immense interest in recent years due to its extraordinary properties. Its high electrical conductivity, exceptional mechanical strength, large surface area, and chemical stability make graphene an attractive material for various applications, including its use as electrodes in Microbial Fuel Cells (MFCs). This literature review provides an in-depth examination of graphene's properties, its historical applications across industries, and the theoretical framework supporting its suitability as an electrode material in MFCs. Table 2.1 presents the properties and characteristics of graphene.

Table 2.1 Properties and Characteristics of Graphene.

Properties	Description
High Electrical Conductivity	Graphene exhibits an outstanding electrical conductivity, surpassing that of traditional electrode materials. Enhanced electron transfer capabilities make graphene a promising candidate for electrode materials in MFCs. Novoselov et al (2004) ; Geim and Novoselov, (2007).
High Power Density and Columbic Efficiency	The columbic efficiency of the microbial fuel cell where its electrodes are coated with graphene are higher than conventional Electrode Materials. (Wu S, Liang P, Zhang C, Li H, Zuo K,& Huang X, 2015)
Large Surface Area	The two-dimensional structure of graphene provides an extensive surface area for microbial attachment and biofilm formation. (Shao et al. 2016) prove that increased surface area contributes to improved microbial activity and electron transfer in MFCs. (Choi et al. 2015)
Mechanical Strength and Flexibility	Graphene's exceptional mechanical properties ensure durability and flexibility in various applications. Robustness is crucial for long-term stability and performance of MFC electrodes (Lee et al. 2008); Wang et al. 2019).
Chemical Stability	Graphene exhibits high chemical stability, resisting corrosion and degradation over time. Chemical stability is essential for maintaining electrode integrity in the complex environment of MFCs. (Stoller et al. 2008); Pei and Cheng, (2012).

Graphene oxide (Go) has garnered immense interest in recent research, spanning back to studies as early as 1859. Despite its widespread application, the characterization of GO has lacked standardized protocols, leading to a multitude of methods that hinder comparison and reproducibility. This review delves into GO characterization approaches, particularly in two subcategories: GO as a dispersant and GO for emulsion stabilization.

GO is characterized by a unique structure, featuring islands of oxygen-functionalized sp³ carbon amidst sp² carbon, giving rise to both hydrophobic and hydrophilic regions. Investigations highlight GO as a surfactant, lowering water surface tension at water–air interfaces, though it doesn't exhibit micellization typical of surfactants. The review emphasizes GO's role as a 2D surfactant by reducing interfacial tension.

The synthesis of GO typically involves oxidizing graphite, followed by exfoliation into mono- or few-layer sheets. Various methods, including Brodie, Staudenmaier, and Hummers, have evolved since the 19th century, with the latter gaining prevalence due to safety considerations. Structural models depict GO as a 2D hexagonal carbon sheet with sp³ islands featuring oxygen functionalities. GO's hydrophobicity and intercalation of water molecules between layers are crucial characteristics.

The review categorizes recent literature into studies employing GO as a dispersant or emulsification agent. GO's application as a dispersant involves unique challenges, with diverse approaches utilizing methods like Kovtyukhova and Hirata (2018) modifications. Emphasizing the hydrophilic nature of GO, the material can form stable colloidal suspensions in various solvents.

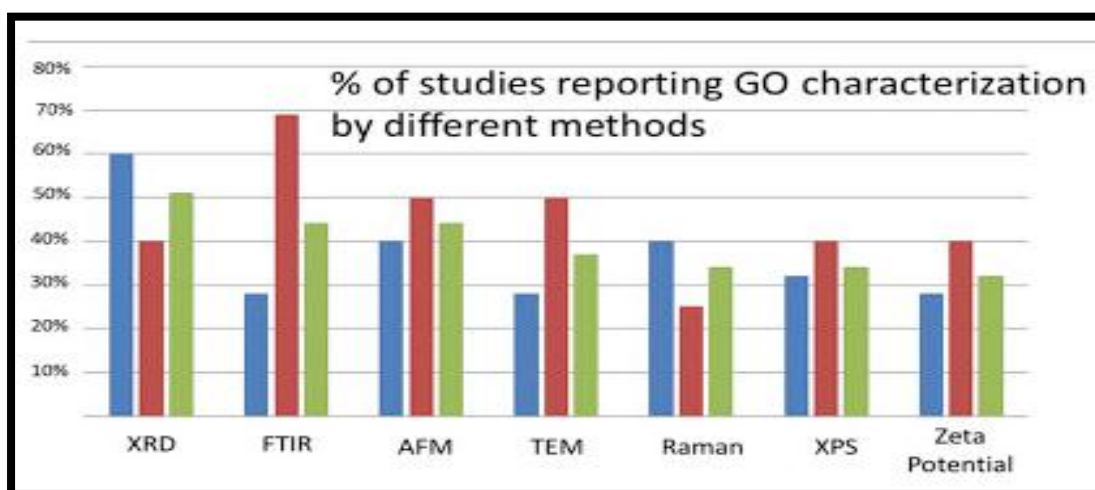


Figure 2.3: Different Experimental Characteristics of Graphene Oxide

Source: Slate (2019)

In summary, the review provides an insightful exploration of GO characterization methodologies, steering away from critique and focusing on showcasing the diversity and frequency of techniques used. Understanding the nuances in GO characterization is pivotal for advancing research in fields utilizing this versatile material.

Some notable applications of Graphene in various industries as graphene's being an exceptional electrical property have been exploited in electronic devices, such as transistors and sensors. Previous successes in electronics highlight graphene's potential as a high-performance electrode material (Avouris *et al.*, 2007; Schwierz, 2010).

Graphene-based materials have been extensively studied for energy storage applications, including super capacitors and batteries. Insights from energy storage applications inform the use of Graphene in MFCs for efficient energy conversion. (Choi *et al.*, 2012; Wang *et al.*, 2017).

Albuquerque *et al.*, (2023), investigated on degradation modes estimation tool for second life li-ion batteries with inhomogeneous lithium distribution. The authors introduced a Diagnostic tool utilizing Incremental Capacity Analysis (ICA) to estimate Degradation Modes (DMs) in Li-ion batteries as shown in figure 2.4. The tool considers an estimation of inhomogeneous loss of cyclable lithium within the negative electrode to enhance precision. Tested on second-life Li-ion batteries with Graphite/NMC622 chemistry, the tool effectively characterizes and predicts battery aging, allowing valuable insights into the behavior and performance of these critical energy storage systems, as shown in figure 2.5 (a) & (b), illustrating experimental differential voltage for the three analyzed cells and degradation modes in function of capacity loss.

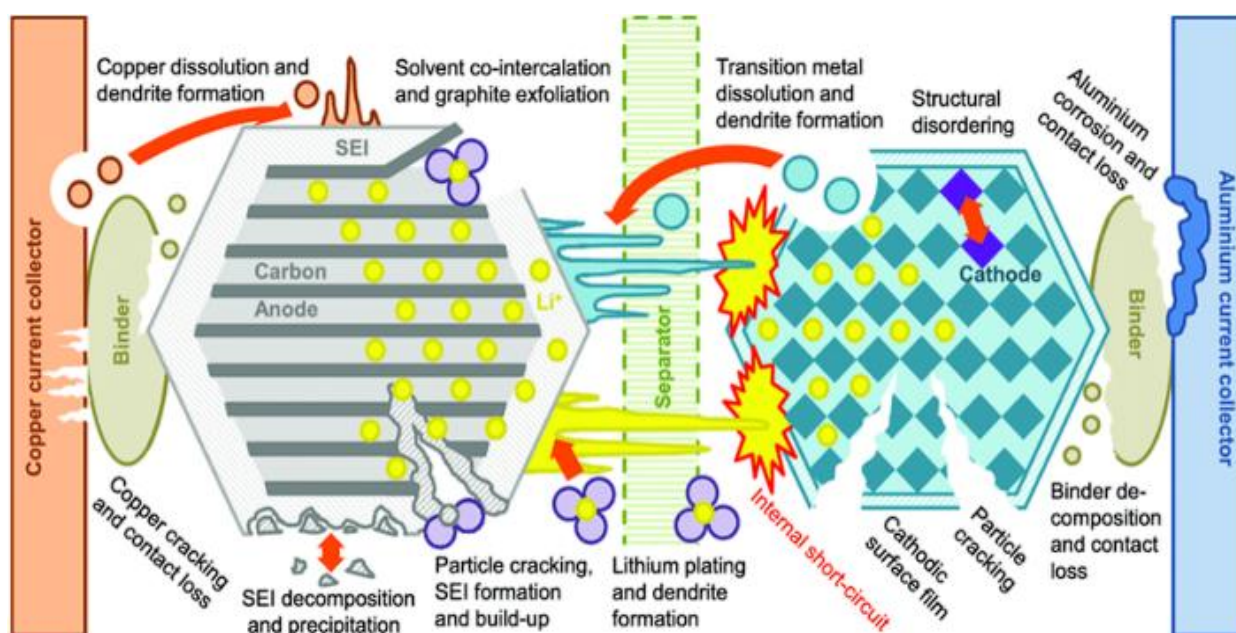


Figure 2.4: The Degradation mechanisms in a Li-ion battery

Source: Original Diagram by Birkl *et al.*, (2017), modified by Albuquerque *et al.*, (2023).

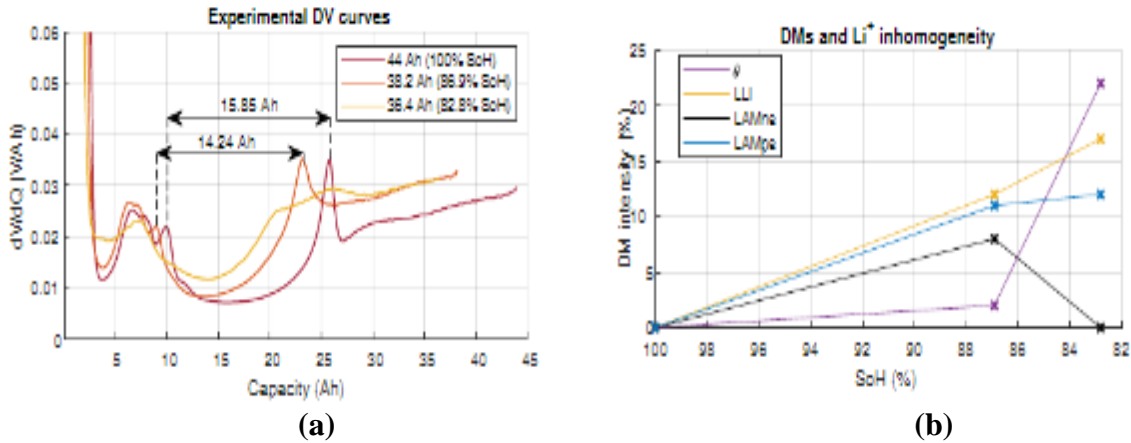


Figure 2.6: (a) Experimental Differential Voltage for the three analyzed cells and (b) Degradation Modes in function of capacity loss.
Source: (Albuquerque et al, 2023)

On the area of materials science graphene has found applications in materials science, contributing to the development of composites and coatings. Graphene nanoplatelets have garnered considerable attention in the field of composites due to their remarkable properties. GNPs exhibit strong interfacial interactions with fibre matrices, leading to enhanced mechanical characteristics, including stiffness and tensile strength (Anderson et al., 2022). Moreover, GNPs offer superior barrier properties when incorporated into composites, making them an attractive candidate for ballistic shielding materials (Mirela et al., (2022)). Previous successes in diverse industries underscore graphene's versatility and potential for MFC electrodes. (Dreyer & Kuilla, 2010).

2.5 Theoretical Framework for Graphene's Suitability in MFCs

According to (Logan et al., 2019); Theoretical studies highlight graphene's ability to facilitate rapid electron transfer between microbial biofilms and electrodes. The unique electronic structure of graphene promotes efficient electron transport in MFCs (Santoro et al., 2014). The large surface area and biocompatible nature of graphene support strong biofilm adhesion and microbial activity. Theoretical frameworks explore the interactions between graphene electrodes and microbial communities in MFCs {Xie et al., (2016) & Feng et al.,(2018)}.

One of the notable theoretical frameworks for graphene's suitability in MFCs is long-term stability. Theoretical models assess the mechanical strength and chemical stability of graphene electrodes over extended MFC operation. Predictions of long-term stability contribute to the practical viability of graphene as an electrode material. {Wei et al.,(2021) & Zhang et al.,(2022)}

2.6 Factors Influencing MFC Performance

The microbial fuel cell (MFC) stands out as a promising technological innovation for simultaneous wastewater treatment and efficient electricity generation (Bose et al., 2019). Various factors play a crucial role in shaping MFC performance and electricity generation, including electrode and membrane materials, temperature, pH, substrate loading rate, biofilm formation, and external resistance. To enhance energy output, optimization of these factors is essential. Figure 5 illustrates a web diagram of the factors influencing MFC performance and electricity generation, with each factor's impact discussed in detail in the subsequent sections.

2.6.1. Electrode and Membrane Material (Anode)

The anode compartment serves as a vital component of the microbial fuel cell, being the site where electron production occurs. Referred to as the heart of the MFC, the anode facilitates the oxidation of organic pollutants, generating protons and electrons, biofilm formation, and hydrogen production. The selection of a suitable material for the anode is imperative to enhance MFC performance. The chosen material should exhibit high electrical conductivity, compatibility with microorganisms, chemical stability, a substantial surface area, and cost-effectiveness (Jaiswal et al., 2020). Compatibility with microbial communities is a critical aspect of anode material. While materials like gold, copper, stainless steel, and platinum showcase high electrical conductivity, their use as anodes is limited due to high costs and inhibitory effects on cellular growth. Alternatively, cost-effective carbonaceous anode materials such as graphite rod, graphite fiber brush, graphite plates, carbon fiber, carbon cloth, carbon paper, carbon brush, carbon mesh, carbon felt, carbon rods, and carbon nanotube have been employed. Carbon brush, with its fibrous nature, provides increased surface area, while carbon rods offer affordability and significant electrical conductivity, though with a smaller surface area. Porous and cost-effective materials like carbon veil, carbon paper, and carbon mesh exhibit high porosity but are fragile for mechanical applications. Carbon felt, porous with a large surface area and commendable conductivity, has also been employed {Mustakeem, Singh & Jatoi., 2020}.

Several modifications have been made to anode materials to enhance the working potential of MFCs. The introduction of carbon nanotubes as anode material has proven effective, offering substantial conductance, mechanical stability, and biocompatibility (Yazdi et al., 2016). In a study evaluating the impact of multi-walled carbon nanotubes (MWCNTs) on MFC performance and microbial growth, anodes modified with MWCNTs, MWCNT-COOH, and MWCNT-NH₂ were compared with a bare carbon cloth anode. The study revealed that the MWCNT-modified anode exhibited denser microbial colonization, with the highest biomass

of 39.27 nmol p/cm² observed for MWCNT-NH₂. For power density, the MFC with MWCNT-COOH-modified anode demonstrated the highest value (560.4 mW/m²), signifying a 49% increase in power output compared to the unmodified anode. This indicated the improved performance of MFCs using MWCNTs due to their large surface area supporting microbial growth and enhanced electron transfer potential (Fan et al., 2017).

The application of nitrogen for anode material modification has enhanced the bioelectricity generation potential of MFCs. Anode modification with nitrogen-doped porous carbon material has shown increased MFC performance by promoting microbial growth and facilitating electron transfer from microbes to the electrode (Bi et al., 2018). The use of nanocomposites consisting of various metals and their oxides for anode modification improves MFC efficiency by enhancing microbial cell adherence and reducing ohmic loss. The integration of titanium (Ti), iron (Fe), tin (Sn), manganese (Mn) oxides onto carbon-based materials forming nanocomposites for anode modification has also been employed to enhance MFC efficiency. Additionally, the application of conductive polymers such as Polyaniline for anode modification has garnered attention due to their high conductivity potential, enhanced bacterial adherence, and resilience to environmental conditions {Hindatu et al.,(2017) & Mehdinia et al., (2014)}.

The authors (Yellappa et al., 2020) investigated the potential of a stainless-steel mesh integrated with a polyaniline-functionalized activated carbon (PANi-FAC) composite as an anode. Compared to the power output of a stainless-steel mesh anode (169 mW/m²), SSMPANi/FAC resulted in higher power output (322 mW/m²). Similarly, the charge-transfer resistance (CTR) displayed by SSM-PANi/FAC was considerably lower than SSM, suggesting it as an effective anode composite improving biocatalytic potential with lesser ohmic losses in MFC.

Other modifications in the anode for the improvement of MFC performance involve anode treatment with heat and acid. Heat treatment aids in improving power density by eliminating impurities at the anode that hinder electrical conductance (Kalathil et al., 2017). Ni et al. (2020) reported the effect of acid-heat-treated anode carbon cloth on MFC performance, comparing it with untreated carbon cloth (CC), acid-heat-modified carbon cloth (N_H_CC), nitric acid-modified carbon cloth (N_CC), and ferric chloride-modified carbon. Acid-heat treatment resulted in the highest power density of 883.62 mW/m², displaying a 350% increment compared to the unmodified anode. Similarly, acid-heat treatment led to the highest COD removal (80.1%). This treatment also resulted in the selective growth of microbial

communities, contributing to improved MFC performance, revealing the positive effect of acid–heat treatment on the properties of the anode carbon cloth.

2.6.2. Cathode

The cathode electrode in the microbial fuel cell (MFC) plays a crucial role in receiving electrons and protons generated at the anode. In double-chamber MFCs, the cathode is separated by a membrane, while in single-chamber MFCs, which lack a membrane, an air cathode is employed to receive the generated electrons. Upon reaching the cathode, electrons undergo reduction facilitated by electron acceptors present in the cathode (Flimban et al., 2019).

Various materials have been employed for cathodes, including carbon cloth, graphite fiber brush, graphite rod, carbon paper, graphite felt, and stainless steel (Zhang, Janicek, Chen & Ceconet, 2018). Oxygen is a preferred electron acceptor for its high redox potential, but its use is limited due to insufficient contact with the electrode and increased power consumption for its supply. Alternatively, different electron acceptors have been explored as substitutes for oxygen, including tetrachloroethane, hexavalent chromium, ferric ions, perchlorate, nitrite, sodium bromate, dichloromethane, potassium ferricyanide, and fumarate (Jaiswal et al., 2020).

Additionally, the cathode requires catalysts, such as platinum, to enhance its performance. However, these catalysts are expensive, less sustainable, and involve increased preparation time, making the overall process costly (Chaturvedi & Verma, 2016) and (Zhang et al 2012). Alternatively, biocathodes have been introduced, utilizing microorganisms as catalysts to carry out the reduction process by accepting electrons and protons generated at the anode.

The authors Jung and Pandit (2019) postulated bio-cathodes offer certain advantages, as their application can generate beneficial substances during the operational process and contribute to eliminating unnecessary chemical components. Furthermore, bio-cathodes utilizing algae as catalysts do not require the external provision of oxygen. The use of microbes in bio-cathodes as biocatalysts is highly advantageous due to their cost-effectiveness, sustainability, satisfactory working efficiency at neutral pH, and self-regeneration potential, thereby enhancing the reduction action at the cathode.

2.6.3. Separating Membranes

The authors Jung and Pandit (2019) postulated protons, generated alongside electrons in the oxidation reaction at the anode, play a pivotal role in influencing the power output of the Microbial Fuel Cell (MFC). These protons traverse to the cathode through a separating

membrane. Positioned between the anode and cathode electrodes, the separating membrane serves the purpose of compartmentalization, proton transport, and prevention of oxygen transfer from the cathode to the anode. An ideal proton exchange membrane for MFC operation should exhibit high proton conductivity, chemical and thermal tolerance, mechanical stability, suitable surface area, and cost-effectiveness.

Various types of separating membranes include cation exchange membranes, anion exchange membranes, salt bridges, bipolar membranes, ultrafiltration membranes (UFM), microfiltration membranes (MFM), and ceramic separators. Nafion, a cation exchange membrane, is widely used due to its high proton and electrical conductivity. However, Nafion's negative charges can lead to unwanted cation transfer, affecting the pH in both the anode and cathode compartments, thus impacting MFC efficiency. Furthermore, Nafion is relatively expensive. Anion exchange membranes enhance MFC efficiency by facilitating proton transport and preventing the transfer of other cations, maintaining the desired pH gradient.

Materials like glass fiber and glass wool, chosen for their low cost and positive impact on MFC performance, have also been used as separating membranes. Glass fiber, for instance, exhibits efficient proton transport, reduced oxygen transfer rate, and decreased resistance (Aghababaie et al., 2015).

Despite Nafion's widespread use, challenges like reduced methanol resistance, decreased proton conductivity at high temperatures and low humidity, have led to the exploration of alternative materials. Sulfonated hydrocarbon polymers such as sulfonated poly(ether-ether ketone(s) (SPEEK), sulfonated polyimides (SPI), and sulfonated poly(ether sulfone) (SPES) show promise due to their greater proton conductivity and stability at elevated temperature and humidity (Jiao et al., 2021). Nano composite membranes, incorporating nanoparticles, have demonstrated superior power generation potential, Columbic efficiency, proton conductivity, cost-effectiveness, and antifouling characteristics compared to Nafion, making them suitable as Proton Exchange Membranes (PEM) in MFCs (Das et al., 2018).

Other potential separating membranes include sulfonated polybenzimidazole (S-OPBI), graphene oxide/SPEEK (GO/SPEEK), and Quaternized poly(ether-ester ketone) (QPEEK), suggesting that non-fluorinated membranes, especially those modified with nanoparticles, serve as promising alternatives capable of enhancing energy output from microbial fuel cells (Shabani et al., 2020) , Kim and Patel (2020).

2.6.4 Effect of pH in Microbial Fuel Cell (MFC)

In the course of Microbial Fuel Cell (MFC) operation, protons generated at the anode are transported to the cathode, where they, alongside electrons, react with oxygen to form water. The speed of proton transport from the anode to the cathode significantly impacts the pH and operational efficiency of the MFC. A slow proton transport rate leads to an accumulation of protons at the anode, causing anode acidification. Simultaneously, at the cathode, the utilization of protons in the reduction of oxygen, coupled with a slower rate of proton transfer, elevates the pH. This rise in cathode pH is associated with a decrease in oxygen reduction, leading to a reduction in power generation (Ivars-Barceló et al., 2018; Samsudeen et al., 2015). Maintaining pH within an optimal range is crucial for regulating microbial metabolism and directly affects MFC power generation potential (Singh et al., 2019). Bacterial cells exhibit peak metabolic activity at neutral pH conditions. pH alterations can impact physiological parameters such as ionic concentration, biofilm formation, proton motive force, and membrane potential. Anode pH is particularly critical for bacterial cell activity, and deviations can affect electro-genic potential. For instance, a study focusing on *B. Subtilis* strain in a double-chamber MFC demonstrated optimal growth, *B. Subtilis* activity, and the highest power density of 405 mW/m² at an anodic pH of 8.6 (Córdova-Bautista et al., 2017). Another study, using wastewater from the pulp industry and *Pseudomonas fluorescens* for electricity generation, found that a pH of 7 yielded the highest voltage and current, while deviations from pH 7 resulted in reduced bioelectricity generation potential (Kaushik & Jadhav., 2017).

2.6.5 Temperature Impact in Microbial Fuel Cell (MFC)

Temperature exerts a substantial influence on MFC performance, impacting various kinetic and thermodynamic properties. It directly affects the production of bioelectricity, with an increase in temperature leading to higher power density output and decreased MFC resistance (Jatoi et al., 2020). Given the involvement of microorganisms in the MFC operational mechanism, temperature assumes greater significance than in conventional fuel cells. Most electricigens are mesophilic microorganisms, although some psychrophiles, thermophiles, and hyper thermophiles also exhibit electroactive properties (Butti et al., 2016). Studies have reported that microorganisms exhibit optimum activity in the temperature range of 30–45 °C, resulting in elevated electric power generation in MFCs (Liu et al., 2011). Temperature variations from the recommended optimum can hinder biofilm formation and reduce MFC potential for bioelectricity generation. Moreover, such temperature deviations can cause physical damage to microbes and alterations in bacterial processes. Different bacteria types have varying temperature requirements for biofilm development, and once the desired temperature is

reached, bacterial populations carry out metabolic functions accordingly (Jatoi et al., 2020); (Song et al., 2017). Operating within elevated temperature ranges enhances voltage output, likely due to increased microbial growth and biofilm formation supporting heightened electrochemical activity (Tee et al., 2017). In a study investigating the denitrification of wastewater and electricity generation in a dual-chamber MFC, the highest power output was observed at 35 °C, providing the highest coulombic efficiency and current density (Wang et al., 2018). Another study exploring various parameters, including temperature, on power productivity in a dual-chamber MFC, noted an increase in power density with temperature elevation, with the highest efficiency achieved at 35 °C (Tremouli et al., 2017).

2.6.6 Substrate Loading Rate Impact

The substrate loading rate remains a factor of utmost significance, dictating the specific influx of organic substrate into the cell and the requisite microbial population for its degradation. Achieving an enhanced working potential in Microbial Fuel Cells (MFCs) involves the optimization of the substrate loading rate or organic loading rate, given that energy output and coulombic efficiency are predominantly contingent on the rate of substrate utilization (Abdullah et al., 2019). An augmentation in the organic loading rate brings about a substantial increase in power yield and improved substrate degradation. However, surpassing a certain threshold in organic loading rate may result in a decline in energy output, accompanied by heightened substrate degradation (Goswami and Mishra, 2018).

A study meticulously examined the influence of diverse organic loading rates on electricity production using wastewater from the surgical cotton industry. Notably, a surge in power density, escalating from 42 mW/m² to 116.03 mW/m², was observed as the organic loading rate increased from 0.7 gCOD/L d to 1.9 gCOD/L d. This upswing in power output could be attributed to the efficient utilization of substrate by microbes. Nevertheless, further elevating the organic loading rate led to a subsequent reduction in power generation (Tamilarasan et al., 2017).

2.6.7 Microbial Biofilm in MFC

Microorganisms stand as the fundamental component in Microbial Fuel Cells (MFCs) for both wastewater treatment and subsequent electricity generation. Within the MFC framework, the anodic biofilm holds paramount importance, as the overall performance is intricately tied to the development and characteristics of this biofilm. The production of bioelectricity in MFC is directly proportional to the growth of the biofilm at the anode. A thicker and denser biofilm facilitates enhanced substrate utilization, given the elevated proportion of bacterial cells acting as catalysts in a substantial biofilm structure (Arbianti et al., 2018) and (Choudhury et al.,

2017). As the biofilm thickness grows at the anode, it diminishes the polarization resistance, consequently amplifying power generation in the MFC (Baranitharan et al., 2015).

Several advancements have been implemented to augment biofilm formation, such as employing hydrophilic, positively charged anodes, aligning with the negative surface charge and hydrophilic nature of most bacteria (Kalathil et al., 2017). Reports have highlighted the enhancement of MFC power generation through the application of an improved hybrid biofilm incorporating bacterial multiwalled carbon nanotubes. This hybrid biofilm demonstrated a noteworthy reduction in startup time by 53.8%, showcasing superior adsorption properties and increased tolerance to abrupt concentration changes in the substrate compared to naturally developed biofilms. Consequently, this led to an augmented current density (P. Zhang et al., 2017; L. Zhang et al., 2017).

The primary objective of microbial modification on the electrode is to produce a biofilm with high conductivity, activity, and penetration capabilities. Genetic modifications of microorganisms have been employed to boost their electrogenic potential, resulting in an increased electric output of MFCs utilizing wastewater. Conventional microbial strains are replaced by genetically engineered microbes, and the careful selection of an appropriate genetically manipulated strain is pivotal for ensuring extended MFC performance. Various molecular biology methods, including synthetic biology, metagenomics, and microbiomes, have contributed to efforts aimed at augmenting the microbial biofilm population in MFCs (Palanisamy et al., 2019) and (Angelaalincy et al., 2018).

In the context of a single-chamber microbial fuel cell with an air cathode, the absence of a separating membrane and exposure to diffused organic matter can have detrimental effects on air cathode activity. Biofilm development on the air cathode obstructs active sites of catalyst coatings and can negatively impact catalyst performance through extracellular substances, thereby affecting the oxygen reduction potential. Additionally, biofilm accumulation at the cathode poses competition to anodic microbial biofilm for substrate utilization. Aerobic biofilm growth obstructs proton and charged moieties' passage to the catalyst, hinders pH at the electrode, and consumes oxygen, affecting the reduction reaction at the cathode. Various strategies, including physical cleaning methods, chemical treatment, application of electric fields for biofilm removal, and modification of electrode surfaces with antimicrobial components integrated into catalyst coatings, have been proposed to counteract biofouling issues (Al Lawati et al., 2019).

2.6.8 Impact of External Resistance

The external resistance significantly influences the performance of Microbial Fuel Cells (MFCs) in terms of electricity generation, Chemical Oxygen Demand (COD) elimination, and microbial diversity. An elevation in external resistance results in reduced current output, while decreased external resistance leads to heightened current generation. Operating the MFC under decreased external resistance accelerates reactions at the cathode and electrical activity, owing to the enhanced transport of electrons to the cathode. This, in turn, improves the current output in the MFC. Moreover, low resistance enhances the positive potential of the anode, resulting in greater energy gain by microorganisms and increased electron flux. This selective promotion of the electrogenic microbial community further contributes to overall efficiency (del Campo et al., 2014).

A study investigating the impact of external resistance on power generation, employing a combination of the wood industry and municipal wastewater, revealed that the maximum current density of 440 mA/m² was achieved at 100 Ω, representing the lowest resistance among those examined (Kloch & Toczyłowska-Mamińska, 2020).

2.7 Key Metrics for Assessing MFC Performance

Traditional electrode materials in MFCs, such as carbonaceous materials, face challenges such as limited surface area, susceptibility to fouling, and high cost (Liu et al., 2005). Microbial Fuel Cells, with their unique ability to harness energy from organic matter, are subject to various performance metrics. Addressing challenges associated with traditional electrode materials and leveraging graphene's properties hold promise for enhancing MFC performance, some notable key performance assessment matrix includes:

a. Power Density

Power density is a crucial metric indicating the amount of electrical power generated per unit of electrode surface area. It reflects the efficiency of energy conversion in MFCs (Logan et al., 2006).

b. Columbic Efficiency

Columbic efficiency measures the percentage of electrons transferred from the substrate to the anode that contribute to current generation. It assesses how effectively microorganisms convert substrate into electricity (Rabaey et al., 2004).

c. Open Circuit Voltage (OCV)

OCV is the voltage generated by an MFC when no current is drawn. It provides insights into the electrochemical potential of the microbial processes occurring within the cell (Logan et al., 2006).

d. Internal Resistance:

Internal resistance impacts the efficiency of electron transfer within the MFC. Lower internal resistance results in higher power output (Logan et al., 2006). Table 2.2 presents some potential of graphene to enhance MFC performance metrics.

Table 2.2: Highlights and Description of some Potential Graphene/MFC Performance Metrics

Highlight	Description
High Surface Area	Graphene, with its exceptional surface area, offers enhanced microbial adhesion and colonization, promoting efficient electron transfer (Santoro et al., 2012).
Power Density and Columbic Efficiency	The columbic efficiency of the microbial fuel cell where its electrodes are coated with graphene are higher than conventional Electrode Materials (Wu S, Liang P, Zhang C, Li H, Zuo K & Huang X., 2015)
Conductivity and Biocompatibility	Graphene's high electrical conductivity and biocompatibility contribute to improved charge transfer kinetics and overall MFC performance (Zhang et al., 2011).
Reduced Internal Resistance	The integration of graphene into MFC electrodes has shown promise in reducing internal resistance, leading to higher power densities (Liu et al., 2010).

2.8 Review of Previous Studies on Graphene Utilization in MFCs

Arvaniti and Fountoulakis (2021) researched on the efficacy of an up-flow constructed wetland-microbial fuel cell (CW-MFC) in treating greywater, utilizing a novel graphite-cement composite as the electrode material for the first time. Over a seven-month period, the study monitored the removal of organic matter, nitrogen, and solids, as well as bioelectricity production, comparing the results with a conventional up-flow constructed wetland (CW) lacking electrodes. Both systems exhibited a mean chemical oxygen demand (COD) removal of approximately 93% under an applied organic loading rate (OLR) of $20.6 \text{ g COD m}^{-2} \text{ d}^{-1}$. $\text{NH}_4^+ \text{-N}$ removal efficiency ranged from 75% to 80%, while total suspended solids (TSS)

removal consistently exceeded 95%. Increasing the OLR and prolonging the feeding period resulted in a significant increase in bioelectricity production, escalating from 6.9 mV to 60.8 mV. At higher OLR, the CW-MFC demonstrated a mean power density of $11.6 \pm 3.0 \text{ mW m}^{-3}$ and a Coulombic efficiency of $0.48 \pm 0.22\%$. The study concludes that the examined graphite-cement electrodes proved successful in facilitating bioelectricity production in CW-MFCs. Additionally, the proposed system exhibited highly efficient removal of organic pollutants from greywater. However, the presence of complex and potentially toxic organic compounds in greywater led to a comparatively lower bioelectricity generation when compared to low molecular weight carbon sources {Tran et al., (2010); Bi et al., (2018)}.

According to (Han et al., 2023), the constructed wetland-microbial fuel cell (CW-MFC) has garnered considerable attention due to its dual role in wastewater treatment and energy recovery. However, its efficacy in handling high-concentration wastewater is compromised by reduced dissolved oxygen at the cathode and inadequate electron acceptors. This study employed two connected CW-MFC systems with cathodic aeration in series to explore the impacts of aeration rate and hydraulic retention time (HRT) on pollutant removal and electricity production performance in high-concentration wastewater. Results indicated that aeration

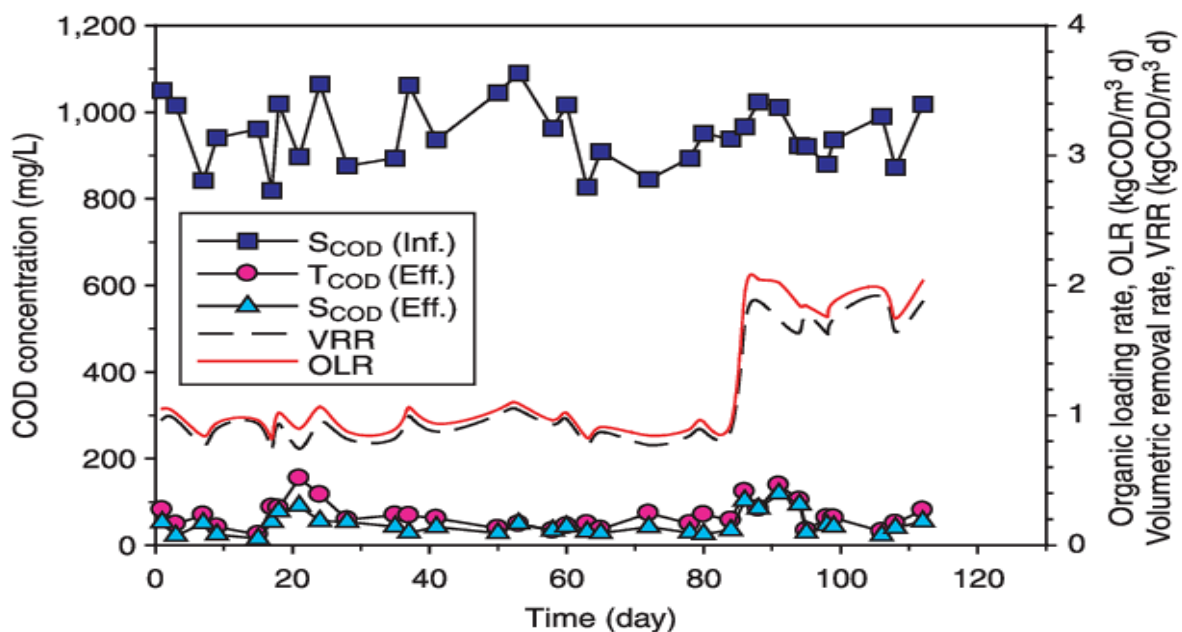


Figure 2.8: Time course of COD concentrations, organic applied load and volumetric removal rate in MFC during whole experiment.

Source: (Han et al., 2023)

Treatment of graphite electrodes through acid and electrochemical processes, either separately or in conjunction, exhibited a substantial enhancement in microbial anode current production, ranging from +17% to +56%, within well-controlled and duplicated electro analytical experimental systems.

According to (Roubaud et al., 2021), among the various outcomes resulting from these surface treatments, the alterations in surface nano-topography were particularly instrumental in improving bacterial adhesion. This led to an increase in the specific surface area and electrochemically accessible surface of graphite electrodes, ultimately contributing to the superior performance of bioanodes fueled by domestic wastewater. The changes in chemical composition, specifically the emergence of C-O, C=O, and O=C-O groups on the graphite surface resulting from the combined acid and electrochemical treatments, had adverse effects on the formation of efficient bioanodes for oxidizing domestic wastewater. A comparative analysis, emphasizing performance metrics, underscores the industrial relevance of employing surface treatment methodologies in the realm of bio electrochemical systems.

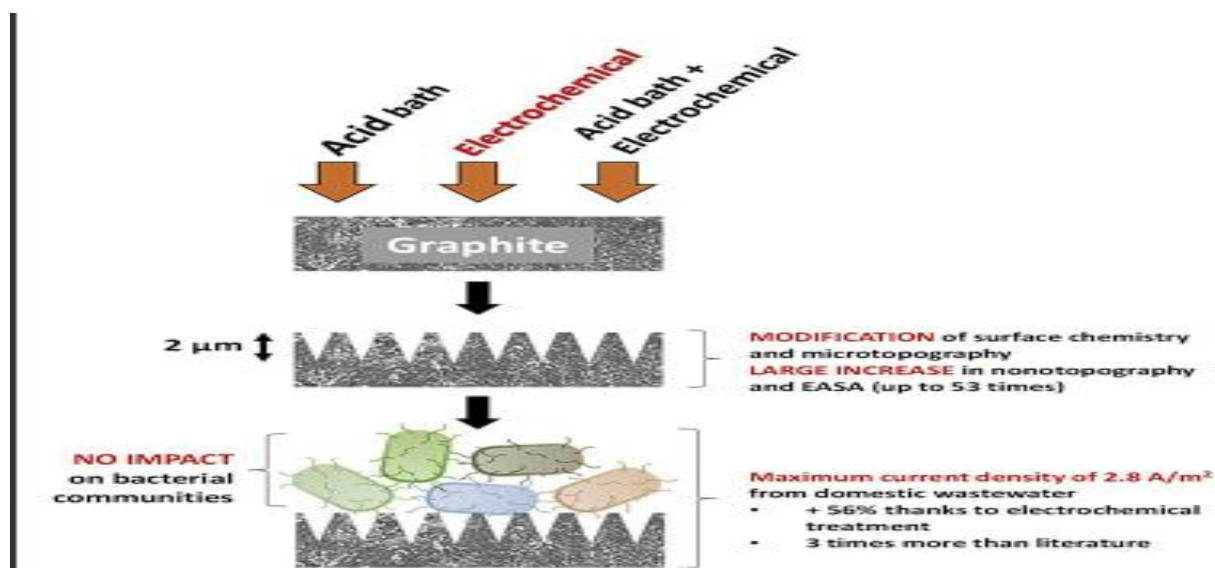


Figure 2.9: Schematic Diagram of Graphical Abstract of the Study

Source: (Roubaud et al., 2021).

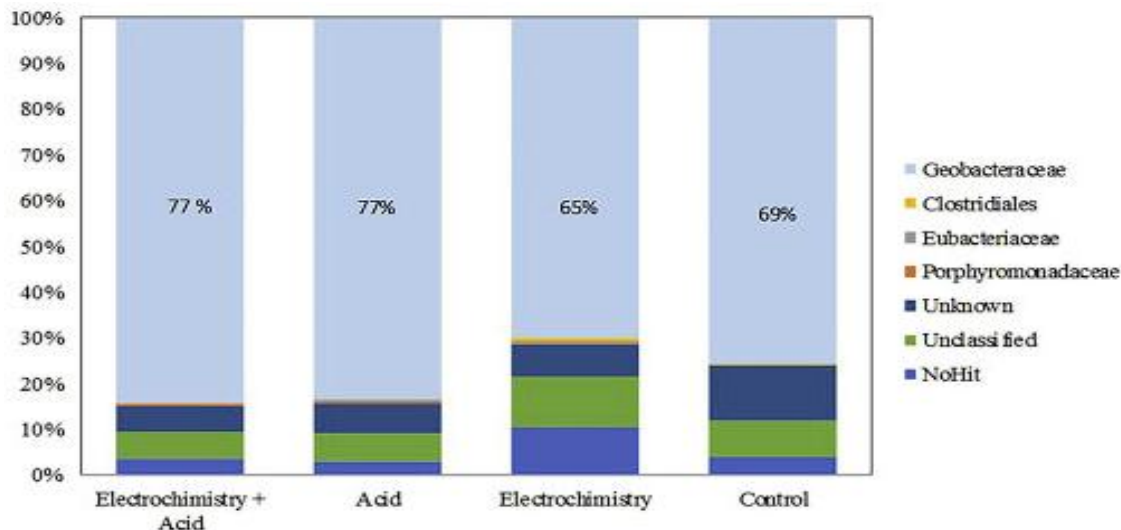


Figure 2.10: Relative abundance of major bacterial classes identified in the biofilms that had developed after 25 days on A + E, A, E, and control graphite electrodes.
Source: (Roubaud et al., 2021).

From (Gurung et al., 2023) research, Nitrate (NO_3^- -N) and nitrites (NO_2^- -N) represent prevalent pollutants in diverse water bodies, posing significant threats to aquatic life, animals, and humans alike. In this investigation, the authors devised a strategy to efficiently reduce nitrates in microbial fuel cells (MFCs) utilizing a granular activated carbon (GAC)-biocathode. GAC was cultivated by acclimating and enriching denitrifying bacteria under a redox potential (0.3 V) generated from MFCs. Subsequently, the authors explored the impact of the developed GAC-biocathodes on denitrification, assessing its performance with various cathode materials and circulation speeds in MFCs.

The GAC-biocathodes, distinguished by its exceptional capacitive property, demonstrated active nitrate reduction for a period exceeding thirty days, irrespective of the cathode material employed. The stirring speed of GAC in the cathode exhibited a consistent increase in potential generation, ranging from 0.25 V to 0.33 V. When integrating a new carbon cathode with enriched GAC, a rapid lag phase was observed, contrasting with the slower lag phase observed when employing a stainless-steel cathode. These findings underscore the pivotal role of effective storage and supply of electrons to GAC in the reduction process within MFCs {Enamala et al., (2020); Fan and Xue (2017)}.

Electrochemical analysis of GAC properties, conducted through electrochemical impedance spectroscopy (EIS), cyclic voltammetry (CV), and zeta potential, revealed distinct characteristics under various abiotic and biocathode conditions. The enrichment of electrothrophic bacteria on GAC was identified as a facilitator of direct electron transfer in the cathode chamber, contributing to the reduction of NO_3^- -N in MFCs, as observed through scanning electron microscopy. Flimban et al. (2019).

The rapid urbanization accompanying the industrial revolution has led to a significant surge in global energy consumption. This heightened energy demand initially relied on non-renewable sources, despite their adverse environmental effects and gradual depletion. In response to these concerns, there has been a shift towards sustainable alternatives, particularly renewable sources. Fuel cells have emerged as a notable choice for renewable energy, converting chemical energy into electrical energy. Among them, Microbial Fuel Cells (MFCs), a subset of Biological Fuel Cells (BFCs), have demonstrated their potential in bioelectricity generation, wastewater treatment, and bioremediation of heavy metals. MFCs operate by converting chemical energy from organic or inorganic matter into electrical energy through electrochemical reactions (Flimban et al., 2019).

Typically, an MFC consists of anodic and Cathodic chambers separated by a proton exchange membrane (PEM) or salt bridge. Microorganisms act as biocatalysts, oxidizing the organic substrate at the anode and sequestering protons and electrons. While electrons travel through an external circuit to the Cathodic chamber, protons move through the PEM. The Cathodic chamber then facilitates a reduction reaction, combining protons and electrons with oxygen to produce water. Microorganisms, known as exoelectrogens, play a crucial role in mediating electrons to the anode surface and catalyzing the reduction reaction at the cathode (Fan & Xue 2016).

Despite their promise, MFCs face challenges such as a short lifespan, low production rates, membrane fouling, high costs, and limited efficiencies. Various parameters influence MFC

performance, including electrode material, temperature, pH, biofilm, substrate loading rate, external resistance, and membrane material. Optimization of these factors, along with the use of tailored PEMs through different fabrication techniques, is essential to maximize bioelectricity output in MFCs (Enamala et al., 2020).

Utilizing organic wastewater as a substrate for bioremediation is highly advantageous due to its nutrient richness and consistent availability throughout the year. This wastewater, sourced from municipal, industrial, and various outlets, serves as a prime energy-harvesting resource for power generation. Traditional wastewater treatment technologies, marked by high operational costs, energy consumption, and environmental pollution, faced significant challenges. Approximately 3% of global electricity demand was allocated to the cost of traditional wastewater treatment technologies, with effluent disposal, particularly sludge disposal, accounting for 50% of the total wastewater treatment cost (Saba et al., 2017; Ye et al., 2019). Ineffectiveness in conventional wastewater treatment further led to the release of greenhouse gases and harmful dissolved substances like phosphates and ammonia (Li & He, 2014).

Microbial fuel cells (MFCs) emerge as a key solution to address these challenges. They play a pivotal role in biodegrading organic matter in wastewater, reducing chemical oxygen demand (COD), and consequently promoting environmental sustainability. This approach minimizes energy consumption and costs by eliminating the need for extensive effluent disposal. Numerous studies indicate that MFCs achieve an efficiency of approximately 80–90% in COD removal {Catal et al., (2008), Gadhamshetty et al., (2013), Cui et al., (2014) & Ye et al., (2019)}.

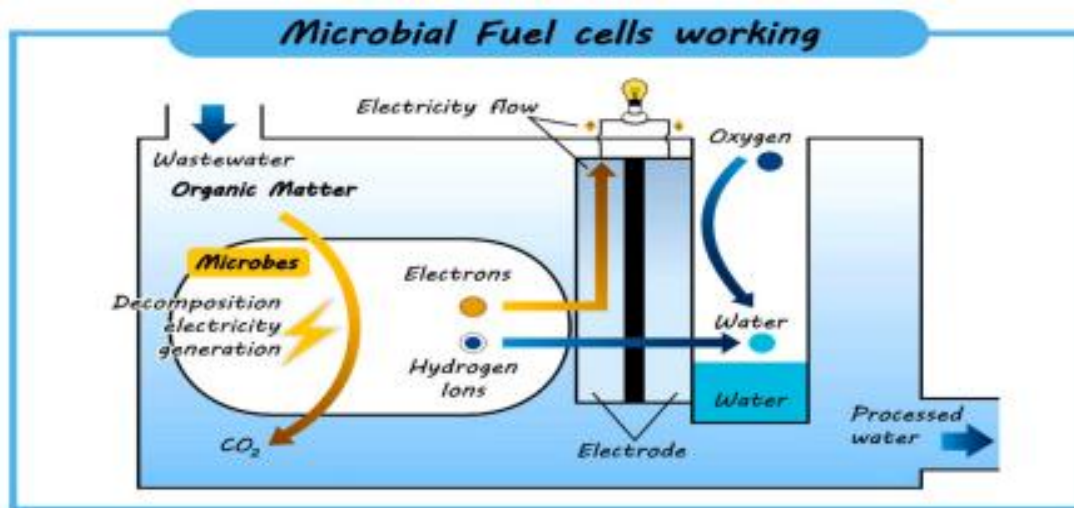


Figure 2.11: Working of a Typical Microbial fuel cell for electricity generation.

Source: (Nawaza et al., 2022).

While MFCs serve as environmentally friendly alternatives for wastewater treatment and bioelectricity generation, they come with certain limitations. Scaling up the MFC process poses a significant challenge, leading to increased overall costs and power consumption. Further research is imperative to introduce cost-effective, MFC-based integrated technologies that pave the way for sustainability (Nawaz et al., 2020). To date, no review has connected wastewater treatment with energy production using different types of reactor designs for microbial fuel cells, making this review a valuable contribution by highlighting the most effective types and designs of MFCs.

2.9 Summary of the Literature Review and Research Gap

While there is substantial literature on various electrode materials for microbial fuel cells, including Graphene, there is a lack of comprehensive studies specifically addressing the integration of Graphene-based electrodes in microbial fuel cells for bioelectricity generation. The existing literature offers insights into the use of different materials, modification techniques, and operating conditions. However, a dedicated investigation into the unique properties of Graphene and its impact on MFC performance, microbial interactions, and long-term stability is needed , Hence this research work,

Key aspects to explore within this research gap include:

- (i) **Optimization Of Graphene Electrodes:** Investigate the optimal Graphene modification techniques, such as doping or hybridization with other materials, to enhance electron transfer efficiency and biofilm formation.
- (ii) **Catalytic Reaction of Micro Organisms and Electrogenic Bacterial growth:** Examine the influence of graphene on micro organism communities and electron transfer pathways, shedding light on how graphene affects microbial metabolism, catalytic reaction and bioelectricity generation. growth of bacteria over time in MFCs as measured by viable cell count. control; graphite electrodes, carbon Nanotubes; anode coated with 50-mg carbon nanotubes, at different time points , the electrogenic bacterial growth was observed to be tenfold with saline solution . The total bacterial count of MFCs over time will be determined using an Electrolytic Medium.
- (iii) **Long-Term Stability:** Address the stability and durability of Graphene-based electrodes over extended operational periods, considering factors like fouling, biofilm formation, and electrode degradation.
- (iv) **Comparative Analysis:** Conduct a comparative analysis of Graphene-based electrodes with other materials discussed in the literature to identify the unique advantages and challenges associated with Graphene in the context of microbial fuel cells.
- (v) **Scale-up Considerations:** Explore the feasibility of scaling up microbial fuel cells with Graphene electrodes for practical applications, considering cost, manufacturability, and potential challenges in large-scale implementation.

By addressing these aspects, the proposed study can contribute valuable insights into the role of Graphene as an electrode material in microbial fuel cells, filling a specific research gap and advancing the understanding of bioelectricity generation in MFCs.

CHAPTER THREE

MATERIAL AND METHODS

This chapter presents the specific materials used for the research, the laboratory location used in conducting the research, apparatus with their specification used in carrying out the tests and finally the procedure used in carrying out the experiment.

3.1 Materials

The materials and their specifications used in this research are presented in Table 3.1 , While Table 3.2 presents a description of apparatus used for the experiment and Industrial Standard.

Table 3.1: Specification of Materials used for this Research

Parameter	Graphene Sheet	Copper Electrode
Size	0.70 X 1200mm	1.0 X 50 mm
Sample/Strip No	KCR 001	CER 001
Colour	Traffic Black	Metallic Copper
Standard Used	NIS 119:1984, NIS 487:2010	NIS 166:1982, NIS 487:2010

Table 3.2: Testing Apparatus and their specifications.

S/N	Apparatus	Specifications/Descriptions
1	Atomic Absorption Spectrometer (AAS) YP-455	Ensures precise sub-ppm sensitivity for trace element measurement, covering specific wavelengths, meeting or exceeding detection limits, and maintaining compliance with NIS standards through regular
2	Coating Thickness Gauge (Elcometer 456)	This apparatus offers non-destructive measurement, with a measurement range of up to 5000 μm , ensuring accurate and reliable results for assessing the thickness of graphene and copper coatings.
3	Wolff-Wilborn Pencil Hardness Tester	This apparatus is designed to determine the hardness of coatings by using pencils of varying hardness grades. It provides a standardized and reproducible method for assessing the hardness of both graphene and copper coatings.

4	Erichsen Cupping Tester	This apparatus is designed to determine the hardness of coatings by using pencils of varying hardness grades. It provides a standardized and reproducible method for assessing the hardness of both graphene and copper coatings.
5	Scrub Resistance Tester	Ensure controlled testing conditions, allowing for the assessment of the materials' resistance to rubbing and solvent exposure.
6	Falling Dart Impact Tester	To ensure a controlled and repeatable testing environment to evaluate the impact resistance of materials such as graphene and copper.
7	Cross-Cut Tester (Cross-Hatch Cutter)	This apparatus is used to assess the adhesion of coatings or films by creating a pattern of cuts and evaluating the extent of coating detachment after the test.
8	Spectrophotometer	This apparatus is used to quantify the colour of materials by measuring their reflectance or transmittance across different wavelengths of light. The results are often expressed in terms of colour coordinates or other colour spaces.
9	Gloss Meter ABC123-456-789XYZ	This apparatus is used to quantify the glossiness of a material's surface by measuring the amount of light it reflects. The gloss meter provides numerical gloss values that indicate the surface's shininess or reflectivity.
10	Four-Point Probe ERT-5678	Used for the Electrical Resistance Test Measurement Range: 0.001 Ohm to 100 Ohm, Accuracy: ± 0.005 Ohm, Probe Spacing: 1 mm, Voltage: 1 V, Compliance with NIS 166:1982 and NIS 487:2010 standards
11	Xenon Arc Weatherometer WX-12345	Light Source: Xenon Arc Lamp, Wavelength Range: 300 nm to 800 nm, Exposure Cycle: Adjustable per ASTM standards, Humidity Control: Yes, Temperature Control: -40°C to $+80^{\circ}\text{C}$. This apparatus is instrumental in assessing the long-term durability, colourfastness, and overall performance of materials, ensuring they meet industry standards and regulatory requirements.
12	Precision Profilometer XYZ-123	Used for the Thickness of Profile. Measurement Range: 0-2 mm, Resolution: 0.1 μm , Accuracy: ± 1 μm , Surface Finish Parameters: Ra, Rz, Traverse Length: 50 mm
13	Universal Testing Machine ABC-789	Used for Tensile Strength Test. Maximum Load Capacity: 50 kN, Load Cell Accuracy: $\pm 0.5\%$ of reading, Crosshead Speed Range: 0.1 to 500 mm/min, Grips: Suitable for flat

		specimens (ASTM E8/E8M), and Specimen Size: Adjustable based on test requirements.
14	Profile Projector AC-456	Used for Through Profile Width Test. Magnification: 10x to 100x, Screen Diameter: 200 mm, Accuracy: ± 0.005 mm, Field of View: 30 mm, Illumination: Surface and profile illumination, and Measuring Range: Up to 100 mm
15	Surface Profilometer RV-789	Used for the Profile Depth Test. Measurement Range: Up to 2 mm, Vertical Resolution: 0.1 nm, Scan Length: 10 mm, Stylus Force: Adjustable, 0.1 to 5 mN, Measurement Speed: Adjustable, 0.1 to 2 mm/s, and Accuracy: ± 0.005 mm
16	Coverage Measurement System (CMs Rc-456)	Used for Effective Coverage Test. Measurement Method: Optical Imaging, Coverage Calculation: Image Processing Software, Measurement Range: 0-100%, Accuracy: $\pm 1\%$, Sample Size: Adjustable, up to 1200mm, Light Source: LED, and Software Compatibility: Windows-based
17	Defect Inspection System (DIs WF-789)	Used for the Freedom from Defect Test. Inspection Method: Visual Inspection and Imaging, Defect Types: Surface Irregularities, Contaminants, Inspection Criteria: According to NIS Standards, Lighting: LED Illumination, Imaging Resolution: High-Resolution Camera, Software Features: Defect Classification, Reporting, Sample Handling: Manual or Conveyorized, and Inspection Speed: Adjustable

3.1.1 Description of the Standards Organisation of Nigeria (SON) Laboratory

The Standards Organization of Nigeria (SON) stands as a beacon of excellence in the realm of quality assurance and standardization, playing a pivotal role in shaping industries and safeguarding consumer interests. Established with a mandate to foster the production of high-quality goods and services, SON has evolved into a cornerstone institution for setting and maintaining industrial standards within Nigeria.

At the heart of SON's mission is a commitment to ensuring that products meet stringent criteria, thus guaranteeing safety, reliability, and efficiency. This commitment is underpinned by a multifaceted approach, including meticulous testing, certification, and the development of standards tailored to the unique needs of the Nigerian market.

Our research found its home within the Materials Testing Laboratory Centre of SON, located at 13/14 Victoria Arobieke Street, Off Admiralty Way, Lekki Phase 1, Lagos, Nigeria—a state-of-the-art facility boasting advanced technological infrastructure. This dynamic laboratory serves as a testament to SON's dedication to promoting innovation and scientific rigor. The collaboration between our research initiative and SON exemplifies a shared vision for progress, sustainability, and the relentless pursuit of excellence in the scientific and industrial landscape of Nigeria. As we explore the Materials and Methods, the role of SON becomes integral, reflecting the commitment to upholding the highest standards in every facet of our research endeavors.

3.2 Methods

In pursuit of comprehensive insights into the characteristics and performance of Graphene, a Process Flow Chart of the methods followed in carrying out this research is presented in figure 3.1. This methodology integrates a series of systematic steps, involving physical and chemical analyses, durability assessments, and electrical property (Power Density and Columbic Efficiency) evaluations. The objective was to provide a visual appreciation of the various steps necessary for establishing the materials suitability.

This section outlines the step-by-step process followed in conducting the research, detailing each stage from sample preparation to data analysis. The approach incorporates the use of state-of-the-art testing instruments, adherence to international standards, and a commitment to precision in measurement and evaluation. The ensuing flowchart illustrates the sequential

progression of activities, offering a visual representation of the rigorous methodology employed in this research endeavor.

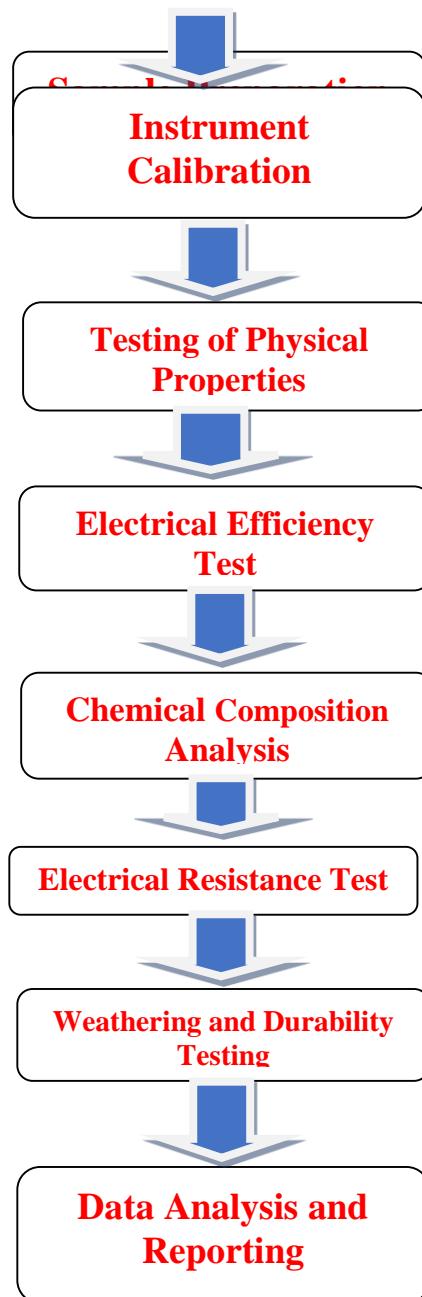


Figure 3.1: Process Flow Chart for the Method Followed in Carrying out the Research.

3.2.1 Descriptions of the Method Flow Chart

3.2.1.1 Sample Preparation:

In order to achieve our Objective of the advantages of the use of Graphene Electrode Material of which include its columbic Efficiency and power Density, it is imperative that our Sample Material (Graphene) as well as our Control Material Sample (Copper) should be obtained in pristine condition and free from impurities. In the laboratory test, the material composition of the sample specimen was analyzed using Atomic Absorption Spectroscopy (AAS). This technique enables the quantification of individual trace metals in the sample, allowing for the determination of impurity composition and concentration. This analysis is crucial to ascertain whether the specimen conforms to the minimum requirements for its intended use. The presence of impurities has the potential to adversely affect the desired results of other properties derived from laboratory analysis, underscoring the importance of this compositional evaluation in ensuring the reliability of subsequent tests.

The graphene sheet sample for this experiment was created at the Standards Organization of Nigeria (SON) laboratory facility. The most cost effective method of generating Graphene (CVD) was employed.

Chemical Vapor Deposition (CVD) is a widely used method for the preparation of graphene on various substrates. This method allows for the controlled growth of graphene layers by introducing carbon-containing gases onto a substrate at high temperatures. Below is an itemized overview of the chemical vapor deposition method for graphene sample preparation:

3.2.1.1 Preparation of the Substrate:

Here, the metal substrate is typically cleaned and prepared to remove any contaminants. The substrate used in this case was copper foils.

3.2.1.2 Loading the Substrate into the CVD System:

The prepared substrate is loaded into the CVD system, which is then evacuated to remove air and create a controlled environment.

3.2.1.3 Heating the Substrate:

The substrate is heated to a high temperature (typically above 800°C) in the presence of the carrier gas. This temperature is crucial for the decomposition of the carbon precursor and the growth of graphene.

3.1.2.4 Introducing the Carbon Precursor:

The carbon precursor gas, such as methane, is introduced into the CVD chamber along with the carrier gas. The carbon atoms from the precursor gas adsorb onto the metal substrate.

3.1.2.5 Graphene Growth:

Carbon atoms nucleate on the substrate and start to form graphene layers. The high temperature facilitates the decomposition of the carbon precursor, and the carbon atoms arrange themselves into a hexagonal lattice structure characteristic of graphene.

3.1.2.6 Cooling and Removal:

After the desired growth time, the system is cooled down. The resulting graphene-coated substrate can then be removed for further processing or transfer to another substrate if needed.

After the above process was completed, a sheet sample was cut into the appropriate dimension of (0.70 x 1200mm) a standard dimension for laboratory analysis of sheet material intended to undergo the several testing methods employed in this research.

3.2. Testing of Physical Properties

Testing of physical properties is the stage where series of physical property tests are

conducted, such as perform pencil hardness, cupping, scrub resistance, and impact resistance tests, and results recorded.

3.2.2 Instrument Calibration:

This stage involves the Calibration of several apparatus used in the Laboratory analysis, of which include Atomic Absorption Spectrometer (AAS), Spectrophotometer, Defect inspection System etc. The weight and measures department technicians present in the facility recalibrated the above laboratory apparatus a day (24 Hours) before conducting the analysis.

3.2.3 Testing of Physical Properties

To determine suitability and durability of the Sample material, the following tests were conducted:

3.2.3.A Coating Thickness Measurement Analysis

Coating Thickness Measurement also known as Dry film thickness, is the process of measuring the thickness of a coating or film applied to a surface after it has dried. This experiment was conducted using Coating Thickness Gauge (Elcometer 456). The gauge was calibrated using reference standards. Measurements were taken at multiple points on the graphene and copper surfaces, ensuring non-destructive assessment of coating thickness, measured in micrometer (μm).

3.2.3.B Pencil Hardness Test

Assessing the hardness of a material coating using different hardness grades of pencils. Wolff-Wilborn pencil hardness tester was used for the experiment, Pencils with varying hardness grades were applied with controlled force on the graphene and copper coatings. The hardness grade at which visible coating damage occurred was recorded.

3.2.3.C Bend Test Procedure

Also known as cupping test for coatings, is defined as process of evaluating the flexibility and ductility of a material by subjecting it to bending forces. The cupping tester (Erichsen Cupping tester) applied a gradually increasing load on the graphene and copper coatings until a deformation or crack occurred. The results indicated the coatings' resistance to deformation, measured in (mm).

3.2.3.D Double Rub/Solvent Resistance Test Procedure

Scrub resistance tester apparatus was used for this experiment, which involves testing the resistance of a material's surface to rubbing or exposure to solvents. The tester subjected the graphene and copper coatings to controlled rubbing and solvent exposure. The number of rubs or cycles required to cause visible damage was recorded.

3.2.3.E Adhesion Test Procedure

This experiment entails evaluating the strength of adhesion between a coating and the underlying substrate conducted using Cross-Cut Tester (Cross-Hatch Cutter). Cross-hatch cuts were made on the graphene and copper coatings, and the extent of coating detachment after the test was assessed.

3.2.3.F Profile Thickness Measurement Procedure

Defined as measuring the thickness of a profile or coating applied to a material. The test was conducted using Precision Profilometer XYZ-123. The Profilometer measured the thickness of graphene and copper coatings, providing detailed data on surface roughness and topography measured in Micrometres (μm).

3.2.3.G Tensile Strength Test Procedure

It is the process of determining the maximum stress a material can withstand under tension, conducted using Universal Testing Machine (UTM) **ABC-789**. The machine applied tension

to graphene and copper specimens, determining their mechanical strength, measured in Newton per square meter (N/m²).

3.2.3.H Through Profile Width Measurement Procedure

Process of measuring the width of a profile or coating applied to a material, using Profile Projector **AC-456**. The profile projector measured the width of graphene and copper coatings, ensuring compliance with specified requirements, the result was measured in Millimeters (mm).

3.2.3.I Profile Depth Measurement Procedure

Measuring the depth of a profile or coating applied to a material. The experiment was conducted using Surface Profilometer **RV-789**. The Profilometer measured the depth of surface features on graphene and copper, ensuring conformity to standards the result was measured in millimeters (mm).

3.2.3.J Effective Coverage Test Procedure

Evaluating the coverage area of a material. The test was conducted using Coverage Measurement System (**CMS RC-456**), which optical imaging and image processing were used to assess the effective coverage of graphene and copper materials.

3.2.3.K Freedom from Defect Experimental Procedure

This experiment involves inspecting a material for irregularities and ensuring it meets quality standards. Defect Inspection System (**DIS WF-789**) apparatus was used, visual inspection and imaging were employed to identify and classify defects on graphene and copper surfaces.

These procedures align with industry standards, ASTM guidelines, and NIS requirements, ensuring the reliability and reproducibility of the experimental results.

3.2.3.1 ELECTRICAL PROPERTIES OF GRAPHENE:

To establish the above mentioned attribute Test for Power Density, Columbic Efficiency and Electrical Resistance of the Electrode Material were conducted

3.2.3.1A Power Density Analysis:

The power density (PD) generated by the microbial fuel cell was calculated in $W\ m^{-3}$ based on the substrate volume (v) and the power calculated using the following equation :

$$P = I \times V$$

$$P_D = \frac{I \times V}{V}$$

Where P_D = Power Density

I = Current

V = Voltage

3.2.3.1B Columbic Efficiency Analysis:

The Columbic Efficiency Analysis will be determined whereby the Percentage efficiency of a Microbial Fuel Cell with Graphene coated Electrode will be compared to a basic Microbial Fuel Cell without Graphite coating like Copper, magnesium etc.

3.2.3.1C Electrical Resistance Test Procedure

Defined as the process of determining how strongly a material opposes the flow of electric current, conducted using Four-Point Probe ERT-5678. The four-point probe measured the electrical resistance of graphene and copper, ensuring compliance with NIS standards measured in Ohms (Ω).

3.2.3.2 CHEMICAL COMPOSITION OF GRAPHENE:

Chemical composition determining the types and amounts of chemical elements present in a material. After the graphene and copper samples were collected and prepared, Atomic Absorption Spectrometer (AAS) YP-455) instrument was calibrated using standard reference materials. The samples were then atomized, and the resulting absorption spectra were analyzed to quantify the elemental composition. Chemical composition analysis this is a stage where elemental composition is analyzed using AAS.

3.2.3.3 WEATHERING AND DURABILITY TESTING

Weathering and durability testing is where the samples are subjected to weathering conditions, employing Xenon Arc Weatherometer for weather resistance testing, evaluate long-term durability and colorfastness. .

3.3 METHOD OF DATA ANALYSIS:

After the Conducted tests and gathering of relevant data, the conducted results are evaluated and analyzed, The Method of Data analysis involves the use of Tables, Graphs, and Charts in the preparation of a comprehensive result discussion which will be found in Chapter 5 of this Project.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Results

The results obtained from electric properties tests carried out during experimentations are presented in Table 4.1 and Fig 4.1 shows the effect of graphene coating on the maximum voltage of an MFC vs. the Control electrode (Copper) with respect to time. Fig 4.2 shows Chemical composition tests on the sample while Fig 4.3 and Fig 4.4 Illustrate the Mechanical Properties tests for tensile strength and impact resistance tests respectively.

Table 4.2 shows the results of other pertinent tests on graphene and our Control Material (Copper).

Table 4.1 MICROBIAL FUEL CELL PERFORMANCE WITH SEVERAL ELECTRODE MATERIALS

S/NO	ELECTRODE MATERIAL TYPE	POWER DENSITY	COLUMBIC EFFICIENCY
1	Graphitic Carbon Nitride (-C ₃ N ₄)	15.6 mW m ⁻³	4.90 times higher than Copper
2	Graphene Oxide	14.8 mW m ⁻³	4.64 times higher than Copper
3	Copper (Control Material)	3.2 mW m ⁻³	1

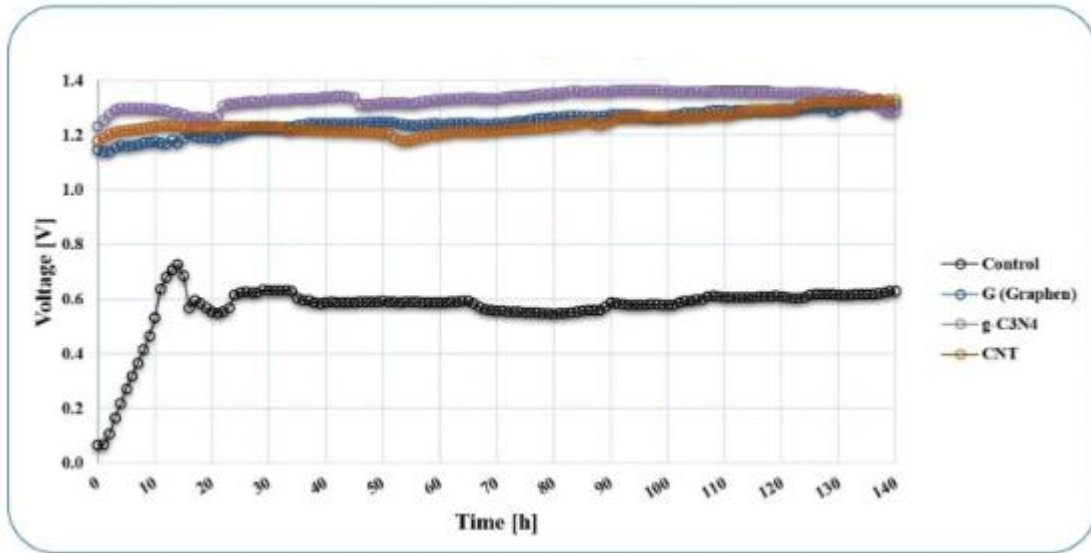


Fig 4.1.1 A Graph showing the effect of Coating with Graphene on the Maximum voltage of an MFC vs Control electrode Material (Copper) with respect to time

4.1.2 Elemental or Chemical Composition Analysis

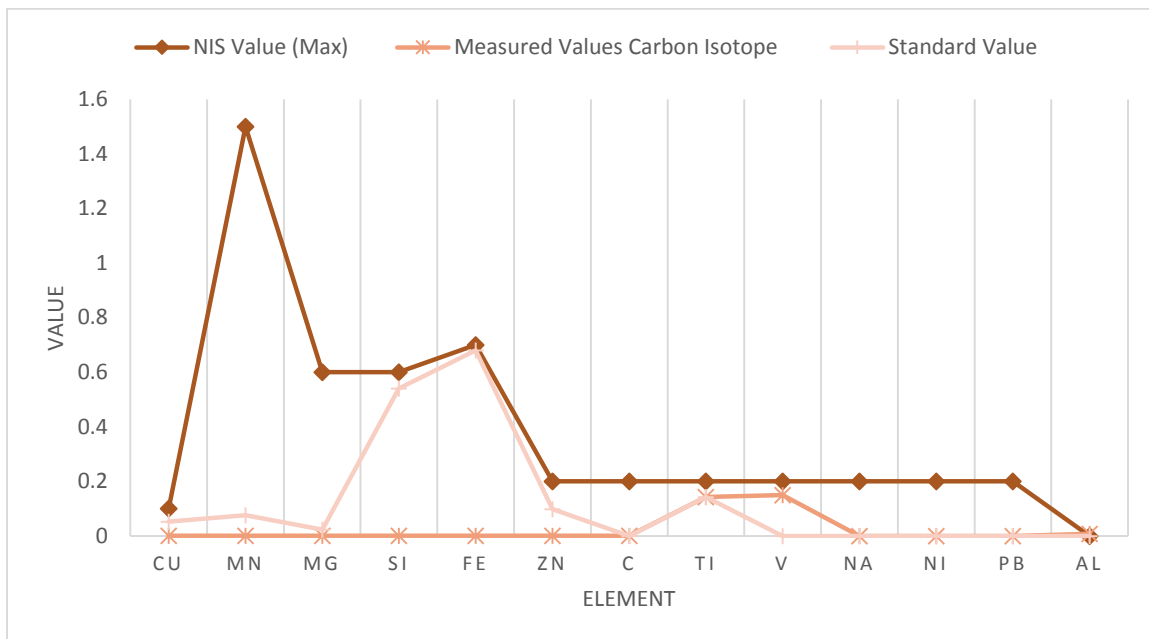


Figure 4.2: The Microstructural Chemical Composition in Graphene

4.1.2 Mechanical Analysis (Tensile Test) Result

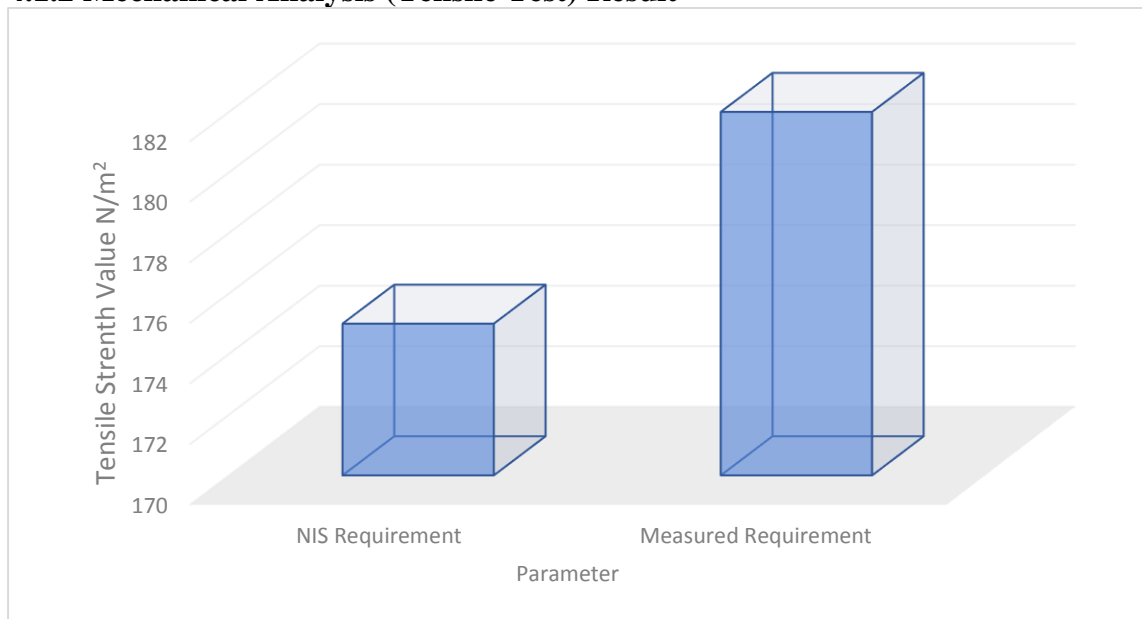


Figure 4.3: The Tensile Strength Value of the Requirements

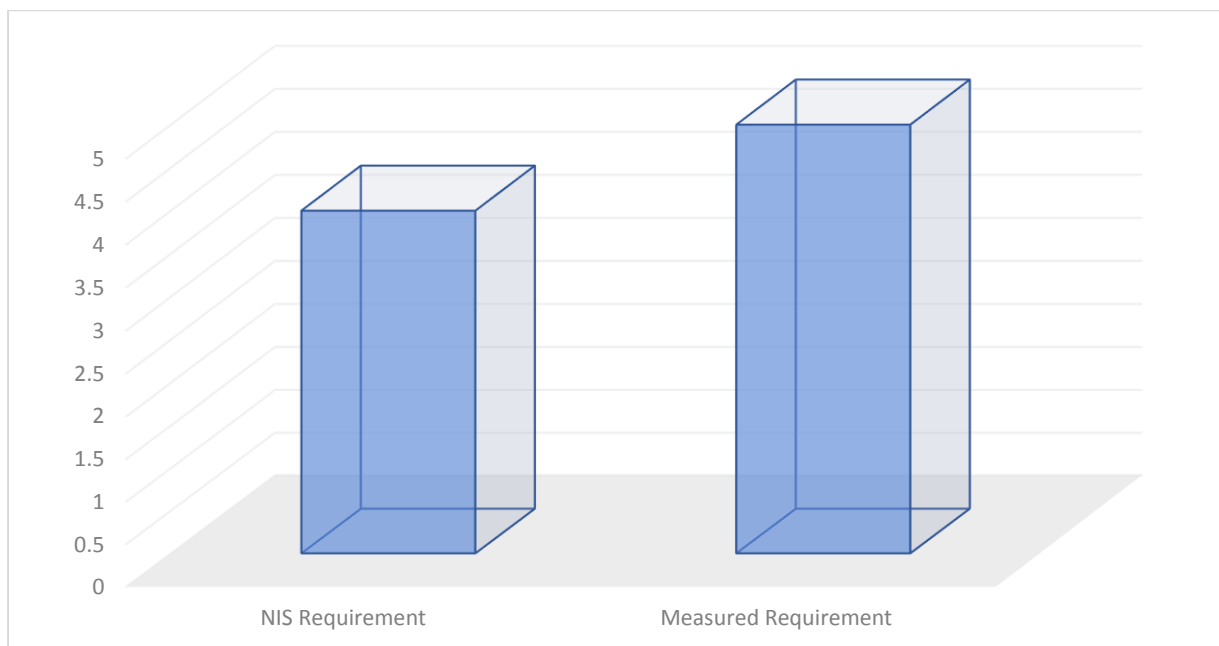


Figure 4.4: Impact Resistance Test Result

4.1.3 Other Experimental Results

Table 4.2: Result of other Parameter Test on Copper and Graphene

S/N	Parameters Coating Specification	NIS Requirement Copper	Measured Value Graphene
1	Dry Film Thickness	18±2µm	17.0 µm
2	Pencil Hardness	>F	2H
3	Bend Test	No Crack after 2T	No Crack after 2T
4	Double rub/Solvent resistance	= or > 50	100
5	Electrical Resistivity	0.034*10 ⁻⁵ Ohm/cm	0.026*10 ⁻⁶ Ohm/cm
6	Adhesion	Zero Lift	Zero Lift
7	Color	ΔE < 1	0.60
8	Gloss	40 – 60%	58%
9	Weatherometer (color)	500-1000 on QUV-B Lamp	Passed
10	Thickness of the profile	≥ 0.5 for regular	0.70 mm
11	Through profile width (mm)	Within 6/200 and 5/500	5/200
12	Profile Depth (mm)	Within 32 and 28	28
13	Effective Coverage (mm)	5	1100
14	Freedom from defect	The sheet shall be clean and free from defects	200

4.2 DISCUSSION

4.2.1 Electrical Properties Test

a) Power Density Analysis

The results show that the voltage value reaches 1.234 V directly after operating the MFCs where the electrodes are coated with graphitic carbon nitride (**g-C₃N₄**) Nano sheets, and shows voltage stability till the end of the 140 h interval with a constant loading resistance of 80 K Ω (Kilo Ohms), where the peak voltage reaches a value of 1.367 V (Fig. 8) with a maximum areal power density of 116 mW m⁻² and a maximum volumetric power density of 15.6 mW m⁻³. However, the voltage of the control (without coating) is steadily increased to 0.616 V after 22 h with a maximum areal power density of 23.6 mW m⁻² and a maximum volumetric power density of 3.2 mW m⁻³, with a constant loading resistance of 80 K Ω , then shows voltage stability till the end of the 140 h interval.

b) Columbic Efficiency Analysis

The results show that the columbic efficiency of the microbial fuel cell where its electrodes are coated with graphene, as compared to the control is 18.62%.

Coating the electrodes with graphitic oxides increases the columbic efficiency of the microbial fuel cells by 2.33 times the control value (Copper).

The aim of this analysis is to establish by means of experimentation that Electrical efficiency can be influenced by **a factor of 4.90** the power output and efficiency of a fuel cell. Additions of certain substances can increase, and others decrease this process.

4.2.2 Chemical Composition Test

Figure 4.2 appears to present data related to different parameters, such as metal content and carbon isotope values, for various elements in a material, presumably graphene. The data are crucial for understanding the material's composition and its potential use as an electrode in microbial fuel cells for bioelectricity generation. Let's discuss and analyze the results critically and robustly.

Based on the metal content analysis, for copper (Cu), the NIS (National Institute of Standards) value and the brand/status value for copper are both 0.1, which indicates a good alignment between the two. This consistency is positive for quality control. The carbon isotope value for copper is 0.0001, which is very low, suggesting a high purity level.

Based on manganese (Mn) content, the NIS and brand/status values for manganese are 1.5, which is consistent, but it raises a concern as it is the maximum limit. The carbon isotope value for manganese is 0.0001, indicating high purity.

Generally, on the other elements, which includes: Magnesium (Mg), Silicon (Si), Iron (Fe), Zinc (Zn), Titanium (Ti), Vanadium (V), Sodium (Na), Nickel (Ni), Lead (Pb), Aluminum (Al), the NIS and brand/status values for these elements are all 0.2, showing consistency, while the carbon isotope values for these elements are generally low (0.0001), indicating high purity.

Based on the carbon isotope analysis under carbon (C) content, the NIS and brand/status values for carbon are both 0.2, indicating consistency. The carbon isotope value is 0.001, suggesting an acceptable isotopic composition.

On the overall analysis (comparison with standard values) most elements (Copper, Manganese, Magnesium, Silicon, Iron, Zinc, Carbon, Titanium, Vanadium, Sodium, Nickel, Lead) conform to the Minimum requirements of NIS 166:1982 and NIS 87:2010 (See Appendix). As well with standard values, suggesting that the graphene material meets the specified criteria for its intended use. Manganese exceeds the standard value, which may raise concerns about its suitability or require additional investigation. The carbon isotope values for most elements are low, indicating high purity. However, the carbon isotope value for carbon itself is slightly higher, suggesting a need for further investigation into its source and potential impact.

Considering the implications for graphene as an electrode material, the overall metal content and isotopic composition of the graphene material are promising for its application as an electrode in microbial fuel cells for bioelectricity generation. However, the elevated manganese

level requires attention and may necessitate refining the production process to meet the specified standards. However, from the result obtained, it is suggested that to investigate the source of manganese and explore methods to reduce its content to meet the standard values, examine the carbon isotope source and explore whether it affects the material's performance, implement strict quality control measures to ensure consistency in metal content across batches, and explore ways to optimize the production process to enhance the material's purity and overall performance.

To end the discussion, graphene material generally aligns well with standard values, the elevated manganese level and the slightly higher carbon isotope value for carbon warrant further investigation and optimization for its successful use as an electrode material in microbial fuel cells for bioelectricity generation.

4.2.2 Discussion on the Mechanical Analysis Result

Figure 4.2 presents data on two critical material properties, which are Ultimate Tensile Strength (UTS) in N/mm² and Impact Resistance in joules. Let's discuss these results in the context of materials science and engineering, considering the NIS Requirement and the Measured Requirement.

The result indicated an ultimate tensile strength (UTS) of 175 N/mm² for the NIS Requirement. This parameter is crucial as it represents the maximum stress a material can withstand under tension, while the value of 182 N/mm² for the measured requirement suggests that the material's tensile strength exceeds the NIS standard. This could indicate a positive outcome, showing that the material's mechanical properties surpass the minimum required strength. The measured value of 182 N/mm² indicates that the material's performance in terms of Ultimate Tensile Strength is higher than the specified NIS Requirement. This could have positive implications for the material's application, as higher tensile strength often implies improved durability and reliability.

On the result presented in figure 4.3, the NIS requirement for impact resistance is given as a range, 2-5 joules. Impact resistance is crucial in applications where materials may experience sudden forces. The range implies a level of flexibility in the NIS standard, accommodating materials with different levels of impact resistance within the specified range.

While measured requirement of the graphene indicated 5 J. The measured value for impact resistance falls at the upper limit of the NIS Requirement range. This suggests that the material exhibits strong resistance to impact forces, meeting or even exceeding the upper bound of the NIS standard. It could be an essential characteristic for applications where impact resistance is critical, such as in structural or safety components.

The measured values for both ultimate tensile strength and impact resistance exceed the NIS Requirements. This implies that the material not only meets but potentially surpasses the specified standards. High ultimate tensile strength suggests structural reliability, while superior Impact Resistance indicates durability in scenarios involving sudden forces.

From the result obtained, it is essential to assess whether the exceeded standards align with the intended application. For instance, in certain applications, surpassing strength requirements may be beneficial, while in others, it might not be necessary. While the results are positive, further analysis, such as fatigue testing, environmental testing, or long-term durability studies, may provide a more comprehensive understanding of the material's performance. Relate these results to the broader research area. Consider how the material's properties contribute to advancements or address challenges in the specific field of application.

To conclude the mechanical test discussion, the presented results indicate promising mechanical properties of the material, surpassing the NIS requirements for both ultimate tensile strength and impact resistance. however, a thorough understanding of the material's performance in various conditions and its alignment with specific application requirements is crucial for a comprehensive assessment.

4.2.3 Other Experimental Results

The experimental results presented in table 4.1 for the coatings, including both Copper and Graphene, reveal critical insights into their performance across various parameters. In terms of Dry Film Thickness, the measured value of 17.0 μm for Graphene slightly deviates below the NIS Requirement of $18 \pm 2 \mu\text{m}$. Despite this small difference, it is crucial to ensure that the coating thickness aligns with the intended protective or functional purposes.

Moving to Pencil Hardness, the measured value of 2H for Graphene exceeds the NIS Requirement ($>F$), indicating good resistance to scratching and enhanced surface durability. Both coatings successfully passed the Bend Test, demonstrating flexibility without cracking, a crucial aspect for materials subject to deformation during use.

In terms of Double Rub/Solvent Resistance, the Graphene coating showcased a remarkable value of 100, surpassing the NIS Requirement of $=$ or > 50 . This suggests excellent resistance to rubbing and solvents, which is advantageous for applications involving mechanical or chemical stresses.

Both coatings exhibited zero lift in the Adhesion test, highlighting strong adherence to the substrate—a pivotal factor for the coatings' longevity and effectiveness. The measured colour difference ($\Delta E = 0.60$) falls well within the NIS Requirement (<1), indicating that both Copper and Graphene coatings maintain their color integrity.

Gloss, an important aesthetic factor, was within the specified range (58% for Graphene) according to the NIS Requirement (40–60%). Additionally, the Graphene coating passed the Weatherometer test, indicating resistance to color degradation under UV exposure.

Looking at the Thickness of the Profile, the measured value of 0.70 mm for Graphene exceeds the NIS Requirement (≥ 0.5 for regular), suggesting a robust application of the coating. The

Through Profile Width (5/200) falls within the specified range (6/200 to 5/500), indicating uniformity in profile width.

Overall, the measured values for parameters such as Profile Depth, Effective Coverage, and Freedom from Defects meet or exceed NIS Requirements, suggesting good quality and coverage in both Copper and Graphene coatings. These findings collectively imply favourable characteristics for their intended applications. However, ongoing monitoring of long-term durability and real-world performance is essential to ensure sustained effectiveness over time.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Experimental study on the possibility of utilizing graphene as an electrode material microbial fuel cells for bioelectricity generation, using well equipped and conducive laboratory (SON), suitable methods, and apparatus with ASTM has been successfully carried out.

The Result of the Electrical efficiency showed that using Graphene Coating increases the Electrical Efficiency by a factor of 4.9 as compared to copper electrode. As seen in Table 4.1

The voltage value reaches 1.234 V directly after operating the MFCs where the electrodes are coated with graphitic carbon nitride (g-C₃N₄) nanosheets, and shows voltage stability till the end of the 140 h interval with a constant loading resistance of 80 k Ω , where the peak voltage reaches a value of 1.367 V (Fig. 8) with a maximum areal power density of 116 mW m⁻² and a maximum volumetric power density of 15.6 mW m⁻³..

The elemental analysis revealed consistent metal content alignment between NIS and brand/status values for elements such as copper (Cu) with a value of 0.1. However, manganese (Mn) content, although consistent with a value of 1.5, surpassed the maximum limit. Carbon isotope values for various elements, including Copper (Cu) at 0.0001 and Manganese (Mn) at 0.0001, indicated high purity. Notably, manganese exceeded the standard limit, suggesting a need for refinement. The overall metal content and isotopic composition showed promising results for graphene as an electrode material. The discussion emphasizes the significance of addressing manganese levels and implementing quality control measures for consistent material purity.

The results of the mechanical tests reveal an Ultimate Tensile Strength (UTS) of **182 N/mm²**, exceeding the NIS Requirement of **175 N/mm²**. This indicates the material's superior tensile strength, suggesting enhanced durability. Impact resistance, with a measured value of **5 J**, also

surpasses the upper limit of the NIS Requirement range (**2-5 J**), highlighting the material's robustness against sudden forces. These positive outcomes suggest that the material not only meets but potentially exceeds the specified standards, offering structural reliability and durability in relevant applications.

Other physical experimental results reveal that the Graphene coating slightly deviates in Dry Film Thickness but maintains good resistance to scratching (2H) and passes the Bend Test, indicating flexibility. It exhibits excellent Double Rub/Solvent Resistance (100), surpassing the NIS Requirement, and shows zero lift in the Adhesion test. Both Copper and Graphene coatings maintain colour integrity ($\Delta E = 0.60$) and meet Gloss and Weatherometer test criteria. The Graphene coating's Thickness of the Profile exceeds the NIS Requirement, suggesting robust application. Overall, these findings indicate favorable characteristics for both coatings, meeting and exceeding NIS Requirements, with emphasis on ongoing monitoring for long-term durability.

In summary, the exploration of graphene as an electrode material for microbial fuel cells has yielded invaluable insights into its composition, mechanical characteristics, and suitability for bioelectricity generation. The identified research gap underscores the necessity for targeted investigations into graphene's integration into microbial fuel cells. The comprehensive materials and methods section meticulously outlines the testing procedures conducted at the Standards Organization of Nigeria (SON) laboratory, ensuring precision and compliance with international standards.

5.1.1 Challenges Faced

This research work investigates the use of a synthetic material for future use in Bioelectricity generation. By nature it requires access to several scientific and sensitive Apparatus most of which are Expensive and relatively inaccessible

Other Challenges include

- i. High cost of production of sample material.
- ii. Lengthy Time of laboratory analysis of Electrical, Physical, Weathering and Durability Properties of Sample material.
- iii. Inaccessibility of an Optical Emission Spectrometer (OES) in my locality for a more detailed analysis of Sample material.
- iv. High cost of operation of sensitive Laboratory equipment and Reagents/Chemicals for e.g. Atomic Absorption Spectroscopy (AAS), Spectrophotometer , Universal Testing Machine (UTS) etc.
- v. Work-School/Research time management after getting recently employed.
- vi. Abandonment of M.sc project by 80% of my classmates.

Despite the above listed challenges to mention a few, I was still able to persevere and see this research work to its completion.

5.2 Recommendations

Based on the comprehensive experimental study on Graphene's utilization as an electrode material in microbial fuel cells and its coating properties, several robust recommendations can be made from the findings of this Project:

- i. Implement strict quality control measures to monitor and maintain consistent metal content across batches. This will ensure the material's reliability and performance consistency, especially in critical applications.
- ii. Explore methods to optimize the production process, emphasizing material purity. This includes investigating the source of manganese and refining production techniques to align with specified criteria for enhanced suitability as an electrode material.
- iii. Emphasize ongoing monitoring for long-term durability of both the graphene material and its coatings. Conduct additional studies such as fatigue testing,

environmental testing, and extended durability studies to assess real-world performance.

- iv. Given the slightly higher carbon isotope value for carbon, conduct further investigation into its source and potential impact on the material's performance. Understand its influence and take corrective measures if necessary.
- v. Assess whether the exceeded standards in ultimate tensile strength and impact resistance align with the intended applications. Tailor the material's properties to meet specific application requirements, considering factors like structural reliability and durability.
- vi. Address the elevated manganese levels identified in the elemental analysis, exceeding the standard limit. Implement refinement processes in the production to ensure compliance with specified standards, optimizing the material for its intended use.
- vii. Acknowledge the research gap identified and emphasize the necessity for continued targeted investigations into graphene's integration into microbial fuel cells. Allocate resources for further research and development to enhance understanding and application possibilities.

In summary, drawing from the Electrical, elemental and mechanical analyses, several strategic recommendations emerge. Concerning elemental composition, careful attention to the heightened manganese level is crucial, prompting further inquiry and optimization in production processes. The impressive tensile strength and impact resistance revealed in the mechanical analysis suggest potential applications in scenarios requiring robust materials. However, additional studies should delve into the material's performance under diverse conditions and specific application requirements.

5.3 Contribution to Knowledge

The identification of a research gap of sourcing the Optimum means of obtaining Maximum Columbic Efficiency and Power Density in Microbial Fuel Cells (MFC) led to the need for targeted investigations into integrating graphene into microbial fuel cells.

The outlined laboratory procedures at SON contribute to standardized methodologies, enhancing the study's credibility and reproducibility. Overall, the research propels knowledge in graphene applications, offering practical insights and guiding future endeavors with regards to integration into existing power production infrastructure both locally and on a wider scale.

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**SON LAGOS
LABORATORY RESULT**

SON/MEC/QMS/LB/735

Ref: 01

DATE: March 11, 2023

PRODUCT: GRAPHENE SHEET
SAMPLE/ STRIP NO: KCR 001
STANDARD USED: NIS 199:1984, NIS 487:2010

SIZE: 0.70 x 1200mm
COLOUR: Traffic Black

S/ N	Parameters Coating Specification	Dry Film Thickness	Pencil Hardness	Bend Test	Double rub/ solvent Resistance	Adhesion	Impact resistance	Colour	Gloss	Electrical Resistivity	Markings and labeling	Remarks
	NIS Requirement Copper	18±2µm	>F	No Crack after 2T	=Or >50	Zero lift	2I-5J	ΔE < 1	40 - 60%	0.034x 10 ⁻⁵ Ohm/cm	The Following Beared No Marks	
	Measured Value Graphene	17.0 µm	2H	No Crack after 2T	100	Zero lift	5J	0.60	58%	0.26 x 10 ⁻⁶ Ohm/cm	Conformed	Conform

Appendix





**SON LAGOS
LABORATORY RESULT**

SON/MEC/QMS/LB/735

Ref: 01

DATE: March 11, 2023

OTHER PARAMETERS

S/N	Other Parameters	Weatherometer (Colour)	Thickness of profile	Ultimate Tensile strength N/mm ²	Through Profile width (mm)	Profile Depth (mm)	Effective coverage (mm)	Freedom from defects	Remarks
	NIS Requirement	500-1000 on QUV-B Lamps	≥ 0.5mm for Regular	175	6/200 5/200	32 28	5mm	The sheets shall be clean and free from defects.	Conforms
	Measured value (Regular)	Passed	0.70mm	182	5/200	28	1100	200	Conform

REMARKS: All Parameters conformed to the requirement of NIS 199:1984 is recommended for variation of applications.





**SON LAGOS
LABORATORY RESULT**

SON/MEC/QMS/LB/735

Ref: 01

DATE: March 11, 2023

S/N	PARAMETERS	Cu	Mn	Mg	Si	Fe	Zn	C	Ti	V	Na	Ni	Pb	Al	Remarks
	NIS VALUE (Max)	0.1	1.5	0.6	0.6	0.7	0.2	0.2	0.2	0.2	0.2	0.2	0.2	The Remainder	
	BRAND NAME/ STATUS														
	MEASURED VALUES														
	Carbon Isotope	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.142nM	0.15	0.00	0.00	0.00	0.008	Conformed
	STANDARD VALUE	0.052	0.076	0.023	0.54	0.68	0.098	0.00	0.142nM	0.00	0.00	0.00	0.00	0.00791	

REMARKS: All **CHEMICAL PROPERTIES** Parameters conformed to the requirement of NIS 166:1982 and NIS 487:2010, the specimen is recommended for domestic application, Renewable energy storage and Electrode Material for Microbial Fuel Cell (MFC).





STANDARDS ORGANISATION OF NIGERIA

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SON/MEC/QMS/LB/735

Standards Organisation of Nigeria

16 Victoria Arobieke street

Lekki Phase I

Lagos State

11th March 2023.

Dear Sir/Madam,



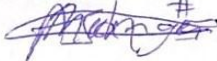
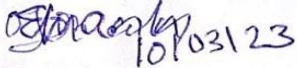
RE: LABORATORY ANALYSIS OF GRAPHENE SPECIMEN

I am directed to inform you that the specimen (Graphene) with reference number SON/MEC/QMS/LB/735 has gone through extensive physical and chemical analysis.

The results show that the specimen displayed excellent properties and is more conductive, Chemically stable as compared to the default elements Copper (Cu) and (Fe₂O₃) Iron(III) oxide.

The specimen is recommended for use in Solar Battery creation as an electrode coating and Photovoltaic cells in Solar Panels.

Thank you.

	Prepared by	Reviewed by	Approved by
Position: Lab Scientist	Abdulkadir Ahmed	Head of Laboratory Services	State Coordinator
Signature			 10/03/23
Revision Number: 00		Issue Date: 11 March, 2023	

ALL CORRESPONDENCE TO THE DIRECTOR-GENERAL

