CHINHOYI UNIVERSITY OF TECHNOLOGY

DEVELOPMENT OF MICROBIAL FUEL CELL PROTOTYPES FOR DOMESTIC WASTEWATER TREATMENT AND ELECTRICITY GENERATION

A thesis submitted in fulfilment of the requirements for the degree of

Master of Philosophy

In the

DEPARTMENT OF ENVIRONMENTAL CONSERVATION AND GEOINFORMATICS

SCHOOL OF WILDLIFE AND ENVIRONMENTAL SCIENCES

CHINHOYI UNIVERSITY OF TECHNOLOGY

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30 August 2024

APPROVAL FORM

The undersigned certify to have read and recommend to the Department of Environmental Conservation and Geoinformatics, School of Wildlife and Environmental Sciences, Chinhoyi University of Technology, for acceptance, a Dissertation titled: **Development of Microbial Fuel Cell Prototypes for Domestic Wastewater Treatment And Electricity Generation,** submitted by Tafadzwa Portia Mahurede, Registration Number C16127842I in fulfilment of the requirements for the Master of Philosophy Degree in Wildlife and Environmental Sciences.

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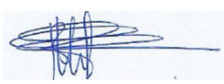

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DECLARATION FORM

I, Tafadzwa Portia Mahurede, hereby testify that this thesis is my original work, except for the content cited in the document, references, and comments within the thesis. It has not been submitted, in whole or in part, for any other degree at any other university.

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ABSTRACT

Efficient domestic wastewater treatment systems are necessary to meet good effluent standards. Adhering to effluent standards is vital for protecting public health by preventing the spread of waterborne diseases and ensuring safe drinking water. It also helps safeguard ecosystems by limiting pollutants that can harm aquatic life and degrade biodiversity. While effluent standards set limits on pollutants, they may not fully account for the complexities of environmental impact, as some harmful substances can still persist at allowable levels. Therefore, beyond simply meeting these standards, removing physical and chemical pollutants is critical for minimising long-term environmental damage, protecting ecosystems, and ensuring water safety. However, this is not the case in most domestic wastewater treatment plants in Zimbabwe. It therefore crucial to introduce sustainable, innovative and environmentally friendly wastewater treatment systems that ensure efficient wastewater treatment. The aim of this study was to design and fabricate microbial fuel cell prototypes for domestic wastewater treatment with the goal of achieving simultaneous wastewater treatment and energy generation in Zimbabwe. The study focused on four MFC prototypes: Single Chamber Activated Carbon Cathode (SCAC), Single Chamber Biochar Cathode (SCBC), Double Chamber Activated Carbon Cathode (DCAC), and Double Chamber Biochar Cathode (DCBC). The research aimed to assess the effectiveness of these prototypes in reducing wastewater parameters; Chemical Oxygen Demand (COD), Total Dissolved Solids (TDS), Electrical Conductivity, Grease and oils, phosphorous, potassium, and nitrogen, while evaluating their electricity generation capabilities. Experimental results indicated that all MFC prototypes achieved significant COD removal ($p = 0.03$) with removal efficiencies of 75% (SCAC), 82%, (SCBC), 83% (DCAC) and 95% (DCBC) demonstrating their efficacy in wastewater treatment. Among the prototypes, SCBC and DCBC exhibited superior performance in reducing COD, phosphorous, and potassium, attributed to their mesoporous structures that enhance microbial activity. However, all prototypes struggled with reducing grease, oils, electrical conductivity, and total dissolved solids (TDS) ($p > 0.05$), largely due to biofouling and suboptimal electrode materials. In terms of electricity generation, SCAC prototypes consistently outperformed SCBC prototypes and showed better voltage (maximum voltage 163 mV and 46 mV respectively) and current production (maximum current 240 µA and 51 µA respectively). DCAC prototypes consistently outperformed DCBC prototypes though DCBC had a maximum recorded voltage and current greater than DCAC prototypes (maximum voltage 504 mV and 528 mV respectively) and current production (maximum current 669 μA and 776 μA respectively). Single Chamber MFCs generally produced higher and more stable electrical outputs compared to Double Chamber MFCs, which faced higher internal resistance and instability. Energy conversion efficiency was notably low across all prototypes (less than 6%), with Double Chamber MFCs demonstrating marginally higher efficiency than Single Chamber MFCs. The study demonstrated that MFC prototypes, particularly SCBC and DCBC, are effective in wastewater treatment, achieving significant reductions in COD, phosphorous, and potassium. However, all prototypes exhibited limitations in removing grease, oils, TDS, and electrical conductivity, as well as low energy conversion efficiency. While these results show potential for MFCs in wastewater treatment, their practical application at a large scale remains limited due to inefficiencies in energy generation and operational challenges such as biofouling. Further research is necessary to optimise MFCs for large-scale use, focusing on improving energy efficiency, stability, and long-term viability.

ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to my academic supervisors for their invaluable guidance, constructive criticism, and unwavering support throughout my research. I am also profoundly grateful to the Vice Chancellor for awarding me this scholarship, and to the Directorate of Research and Graduate Studies for providing the necessary resources, direction, and encouragement. My sincere thanks go to the School of Wildlife and Environmental Sciences and the Department of Fuels and Energy for their assistance with resources and equipment essential to my studies. I am also thankful to my postgraduate friends and colleagues for their moral support and academic advice. To my family, thank you for your unwavering love, support, and sacrifices. Lastly, I wish to thank Almighty God, for without His grace, I would not have come this far.

DEDICATION

I dedicate this thesis to my future children. May it stand as a testament that with hard work and faith in the Lord, you can achieve anything you set your mind to.

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List of Abbreviations

MFC	Microbial Fuel Cell
SCAC	Single Chamber Activated Carbon Cathode
SCBC	Single Chamber Biochar Cathode
DCAC	Double Chamber Activated Carbon Cathode
DCBC	Double Chamber Biochar Cathode
ORR	Oxidation Reduction Reactions
COD	Chemical Oxygen Demand
pH	potential Hydrogen
EC	Electrical Conductivity
DC	Double Chamber
SC	Single Chamber
TDS	Total Dissolved Solids
P	Phosphorous
N	Nitrogen
K	Potassium
GaO	Grease and Oils
WWTS	Wastewater treatment systems
CWWTS	Conventional Wastewater Treatment Systems
SDGs	Sustainable Development Goals
GAC	Granular Activated Carbon

PVDF polyvinylidene fluoride

CHAPTER 1

INTRODUCTION

This chapter examines the critical issue of water pollution, exacerbated by industrialisation, population growth, and climate change, with a particular focus on Sub-Saharan Africa and Zimbabwe. The Sub-Saharan African region faces severe challenges in wastewater treatment due to outdated infrastructure and financial constraints, resulting in significant environmental and public health risks. To address these challenges, this study proposes microbial fuel cells (MFCs) as a sustainable and innovative solution for treating domestic wastewater while generating electricity. This chapter outlines the main aim of this study which is to design and fabricate MFC prototypes for domestic wastewater treatment and electricity generation. The statement of the problem addresses the inadequacies of current wastewater treatment plants, while the justification emphasizes the need for green technologies to safeguard water quality and promote sustainable development. Additionally, the chapter presents the specific objectives and hypotheses to be tested, setting the stage for the detailed research that follows.

1.1 Background of the study

Water pollution is a significant global issue exacerbated by rapid industrialisation, population growth, agricultural activities, and climate change (Bruce & Limin, 2021; Ijoma et al., 2022). Around the world, discharge of untreated or partially treated wastewater/sewage presents a number of contaminants in water bodies. These include chemicals, pathogens, heavy metals, nutrients, pharmaceuticals, and microplastics, all resulting in poor water quality causing severe risks to humans and aquatic ecosystems (Akpor et al., 2014; Manasa & Mehta, 2020; Mishra et al., 2023; Talukdar et al., 2024). The increasing effects of climate change also add to the challenges by altering rainfall patterns increasing the frequency and occurrence of droughts and floods worsening the spreading and concentration of pollutants.

In several Sub-Saharan Africa municipalities, wastewater is discharged with partial or no treatment at all, causing public and environmental health risks (Alawode et al., 2019; Bateganya et al., 2015; Janeiro et al., 2020; Kookana et al., 2020; Ripanda et al., 2022). Significant investment is required to treat wastewater before it is discharged into the environment. These challenges are especially prevalent in developing countries due to outdated treatment systems, inadequate equipment, power shortages and financial constraints. The discharge of effluent in water bodies results in water pollution and the spread of water borne diseases, which are major public health concerns (Phungela et al., 2022). Additionally, pollutants cause eutrophication, causing algal blooms which deplete oxygen in the water and harm aquatic life (Akinnawo, 2023; Brush et al., 2020).

In Zimbabwe, the situation mirrors these broader regional challenges. Overpopulation and overcrowding in Harare's suburbs areas such as Budiriro in Harare has led to overloading in wastewater treatment plants. This has resulted in epidemiological consequences, such as the 2008 and 2018 cholera outbreaks (Ayling et al., 2023; Chirisa & Chigudu, 2021; Munyenyiwa et al., 2022; Musemwa, 2021). These plants face frequent breakdowns, maintenance issues and outdated treatment systems increasing pressure on existing wastewater management systems (Muserere et al., 2014; Thebe & Mangore, 2012). This results in discharge of untreated or partially treated effluent in water bodies. This discharge contains high levels of nutrients which pose a great risk of eutrophication-related problems to the receiving waterbodies (Tendaupenyu & Magadza, 2017; Toriro, 2020).

Across Zimbabwe, conventional wastewater treatment systems (CWWTS) are primarily used. However, these systems are highly energy-intensive, costly, and generate excess sludge (Chirisa et al., 2017; Thebe & Mangore, 2012). The dual challenge of electricity scarcity for powering wastewater treatment plants and persistent water pollution poses severe risks to human health and the environment. As an alternative, some less energy-intensive or non-energy-intensive biological treatment methods, such as wastewater stabilization ponds (Gopolang & Letshwenyo, 2018; Taru et al., 2014), have been implemented. However, these methods require a large amount of land, have long hydraulic retention times, and are affected by temperature and produce odour (Begede, 2023). Therefore, there is a need for innovative, sustainable, and energy-efficient wastewater treatment solutions.

In response to these challenges, there has been growing interest in alternative technologies that can offer both wastewater treatment and energy generation. Microbial fuel cells (MFCs) represent a promising solution that addresses Zimbabwe's pressing energy and environmental concerns.

Microbial fuel cells (MFCs) represent a more suitable solution compared to other methods because they require less energy for treatment can actually provide energy which is highly in demand in Zimbabwe and they have shorter treatment times. Additionally, unlike biological methods that are temperature-dependent, MFCs can function across a range of environmental conditions, including the mesic climate of Zimbabwe. This mesic environment, characterized by moderate temperatures and seasonal rainfall, offers stable conditions that can support microbial activity, making MFCs effective in both dry and wet seasons. Microbial fuel cells (MFCs) are an advanced and eco-friendly technology that effectively treats wastewater before it is discharged into the environment (Ahmed et al., 2022; Khandaker et al., 2021; Mohyudin et al., 2022). MFCs are electrochemical devices that harness the capabilities of microorganisms to convert chemical energy into electrical energy (Aghababaie et al., 2015b; Gude, 2016a; Kouam Ida & Mandal, 2023; Malik et al., 2023). The fundamental operation of MFCs involves the anode oxidation of organic matter by bacteria, releasing electrons that then flow through the external circuit to the cathode via oxidation reduction reactions (ORR). Electrochemically active bacteria break down organic matter to produce electricity while treating the wastewater at the same time (Goswami & Mishra, 2018; Rahimnejad et al., 2011).

The use of MFCs presents several benefits, including the fact that it is an environmentally friendly way of treating wastewater while generating electricity (Priya et al., 2022). Additionally, there is a reduction in energy consumption and energy recovery from the energy inherent in the wastewater (Xu et al., 2016). In contrast to traditional methods that are energy-intensive, MFCs offer a more sustainable and energy-efficient alternative, addressing both the electricity shortages and the need for effective wastewater treatment. Despite the widespread adoption of the system in the USA, Asia, and Europe, there is limited research on the applicability of microbial fuel cells in Southern Africa, particularly in Zimbabwe. Therefore, it would be important to explore the potential of applying this wastewater treatment system in Zimbabwe. Closing this knowledge gap will not only add to the body of knowledge on MFCs but also provide insight into the applicability of MFCs in the region, which is to a large extent mesic zone.

This study focuses on the innovative design and fabrication of microbial fuel cells (MFCs) aimed at improving domestic wastewater treatment processes while simultaneously generating electricity. By addressing the dual challenges of wastewater management and renewable energy production, this research seeks to contribute to sustainable environmental solutions and the principles of the circular economy, which include, enhancing resource efficiency, and adopting a systemic approach. The study also aligns with several United Nations Sustainable Development Goals (SDGs), including SDG 3: Good Health and Well-being, SDG 6: Clean Water and Sanitation, SDG 7: Affordable and Clean Energy, SDG 9: Industry, Innovation and Infrastructure, SDG 11: Sustainable Cities and Communities, and SDG 13: Climate Action.

Given the demanding need for sustainable and energy-efficient wastewater treatment solutions in Zimbabwe, MFCs present a feasible alternative to other wastewater treatment systems. They not only address the energy demand issues associated with conventional wastewater treatment systems but also offer the added benefit of electricity generation. By integrating MFCs into the existing wastewater treatment systems, Zimbabwe can move towards a more sustainable and eco-friendly approach to managing water pollution and energy scarcity.

1.2 Statement of the problem

Efficient domestic wastewater treatment systems are necessary to meet good effluent standards, as per EMA regulations. However, this is not the case in most domestic wastewater treatment plants in Zimbabwe. Most wastewater treatment plants in the country are either obsolete or overwhelmed by effluents, mostly due to overpopulation in urban and peri-urban areas. The aging of infrastructure and the difficulty in finding replacement parts (since they are old models) are also proving to be another challenge. Electricity shortages in the country have resulted in load shedding, thus affecting the treatment processes of conventional wastewater treatment plants that require energy to function. This has resulted in the discharge of raw or partially treated wastewater from water sources, posing environmental and human health risks to the country. Thus, this study aims to explore the innovative design and fabrication of microbial fuel cells (MFCs) to improve domestic wastewater treatment processes while simultaneously generating electricity

1.3 Main objective

The main objective of the study is to design and fabricate microbial fuel cell (MFC) prototypes for domestic wastewater treatment in Zimbabwe and evaluate their efficiency in both wastewater treatment and electricity generation

1.4 Specific Objectives

i. To evaluate the changes in domestic wastewater quality before and after treatment using MFC prototypes, focusing on Chemical Oxygen Demand (COD), pH, Electrical Conductivity, Total Dissolved Solids, Phosphorous, Nitrogen, Potassium, and Grease and Oils.

ii. To compare the electricity generation performance of single-chamber and double-chamber MFC prototypes.

1.5 Hypotheses

i. The use of MFC prototypes for the treatment of domestic wastewater will lead to a significant reduction in the levels of contaminants: Chemical Oxygen Demand (COD), pH, Electrical Conductivity, Total Dissolved Solids, Phosphorous, Nitrogen, Potassium, and Grease and Oils, when compared to the untreated wastewater.

ii. Both MFC configurations will generate electricity, with one expected to perform better.

1.6 Justification

One of the biggest challenges in wastewater treatment in Zimbabwe is that the same bodies of water used for effluent discharge, such as Lake Chivero in Harare, also serve as the primary water supply for many towns. This makes it critical to develop effective and innovative technologies to treat wastewater before it enters these water sources. Microbial fuel cells (MFCs) offer a promising green technology that not only treats wastewater but also generates electricity. This electricity can power existing wastewater treatment systems, enhancing their efficiency while reducing reliance on external energy sources.

This study contributes to the field of wastewater treatment by exploring the potential of MFCs to address Zimbabwe's unique challenges, such as outdated infrastructure and energy shortages. By integrating wastewater treatment and electricity generation, the research aims to provide a sustainable solution that promotes environmental protection, meets regulatory effluent standards, and supports affordable, eco-friendly energy sources. This will ultimately safeguard water quality and support sustainable development.

1.7 Structure of the research

Chapter One introduces the background of wastewater treatment technologies and microbial fuel cells (MFCs), emphasising their importance in both wastewater treatment and energy generation. It also outlines the research problem, objectives of the study, and the justification for the research.

Chapter Two reviews related literature on the concept, design, and operational efficacy of MFCs. It covers the evolutionary history of MFC technology, different operational systems, various MFC prototypes, and explores the drivers and barriers to MFC adoption, particularly in Africa and Zimbabwe.

Chapter Three describes the materials and methods used in the research. This includes the design and fabrication of MFC prototypes, the methods for pre- and post-treatment assessment of wastewater, the procedures for assessing electricity generation, and the data analysis techniques employed.

Chapter Four presents the results obtained from the experiments, including data on wastewater treatment and electricity generation for different MFC prototypes.

Chapter Five provides a discussion of the results, focusing on the pre- and post-treatment assessment of domestic wastewater using MFC prototypes and the assessment of electricity generation. This chapter interprets the findings in the context of the research objectives and existing literature.

Chapter Six concludes the thesis with a summary of the main findings and discusses the implications of the results. It also offers recommendations for future research and suggests potential improvements for MFC technology.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter provides a comprehensive review of the literature on microbial fuel cells (MFCs) forming part of the review paper titled " A review of microbial fuel cell prototypes, their efficacy in wastewater treatment and the contextual situation for Zimbabwe" by Mahurede et al. (2023). The chapter delves into the concept design and operational efficacy of MFCs, tracing their evolutionary history and examining the various components that constitute MFC systems. It also explores the modifications in MFC systems aimed at enhancing power generation. Furthermore, this review discusses the different prototypes of MFCs and analyses the drivers and barriers for the uptake of MFC technology globally, with a particular focus on Africa. A special section is dedicated to the state of MFC research and application in Zimbabwe.

2.2 The concept design and operational efficacy of microbial fuel cells (MFCs)

A microbial fuel cell is a bioelectrical system that converts chemical energy to electrical energy through the catalytic reaction of microorganisms mostly bacteria (Slate et al., 2019a). The MFC consists of electrodes (anode and cathode), a separator or membrane, substrate (wastewater), microbes and an external circuit (Pant et al., 2016). The major function of the MFC system is electricity generation and pollutant removal. The device can be single chambered, double chambered or stacked MFC (Figure 2.1), with the most often used system being the double chambered MFCs (Yaqoob, Khatoon, et al., 2020). According to Yaqoob, Khatoon, et al. (2020) the dual chamber MFCs produce high power generation than single chamber MFC and thus, are more frequently used than the single chamber MFCs. However, Rasep et al. (2016)argues that single chamber MFCs have better performance than double chamber MFC. These confounding statements make it difficult to conclude on which MFC type outperforms the other since these experiments are done under different conditions, using different materials and the protocols used may be difficult to reproduce. This becomes a huge challenge when it comes to replicating these studies.

The Stacked MFC are MFCs connected in series or parallel (T. Kim et al., 2017). Stacking increases power production/output (B. Kim et al., 2020; Watanabe, 2008). The first attempt for MFC stacking was by Cohen in 1931 as he stacked 35 units of MFCs in series with an open circuit voltage of 35V (Cohen, 1931). MFCs connected in series have increased voltage without increasing current, whilst MFCs connected in parallel improve power by increasing the current without increasing the voltage (B. Kim et al., 2020). Due to the improved stability of redox potential across all cells, a series-parallel stack design system exhibits considerable COD removal and maximum power density (Yuvraj & V, 2017).

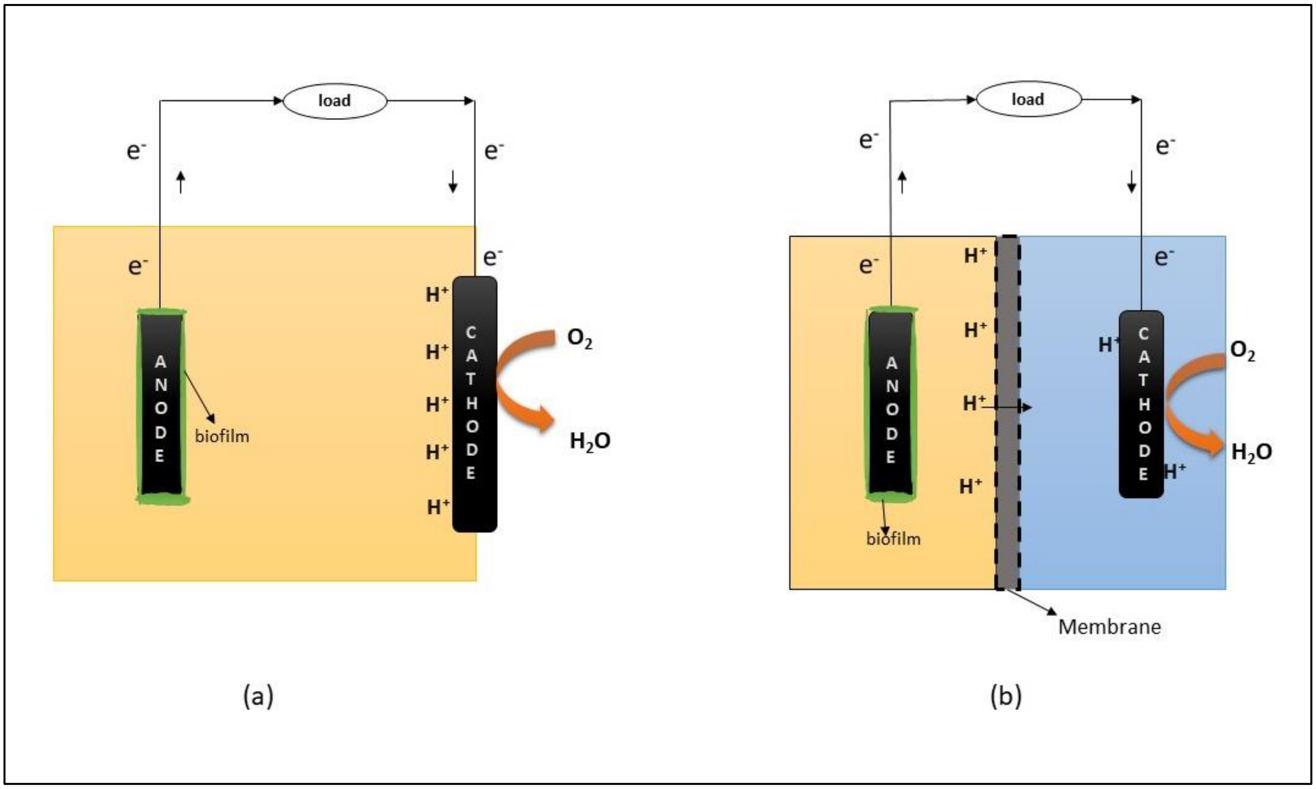

Figure 2.1: A Schematic representation of (a) Single chamber MFC and (b) Double Chamber MFC

The two primary configurations of MFCs single chamber and double chamber each offer unique advantages and drawbacks, significantly influencing their performance in wastewater treatment and electricity generation. SC MFCs have a simpler design, with anodic and cathodic reactions occurring in one compartment, often without a membrane or separator. This configuration reduces material costs, making them easier and cheaper to construct (López-Hincapié et al., 2020). Additionally, some studies report that SC MFCs can achieve higher power density due to shorter electron transfer pathways and reduced internal resistance (Jung et al., 2023; Lu et al., 2023). However, the close proximity of anodic and cathodic reactions can lead to substrate competition, reducing efficiency, and the lack of separation between the two processes may cause pH fluctuations that negatively impact microbial activity (Mersinkova et al., 2022).

In contrast, Double Chamber (DC MFCs) have two separate chambers separated by a proton exchange membrane (PEM), allowing for more controlled conditions in the anodic and cathodic compartments. This design supports more efficient electron transfer, enhances substrate utilisation, and often leads to better overall performance (Tamboli & Eswari, 2019). The separation of reactions in DC MFCs can also stabilise operational conditions, reducing pH fluctuations and supporting diverse microbial communities, which may enhance electricity generation. However, the added complexity and cost of materials, particularly the membrane such as Nafion, make DC MFCs more expensive to construct and maintain.

Despite these distinctions, findings on the performance of SC and DC MFCs are often conflicting. Some research suggests that SC MFCs generate higher power densities, while others report that DC MFCs outperform them in long-term power generation due to more effective substrate oxidation and electron transfer (Lazar et al., 2024; Xie & Eljamal, 2023). Discrepancies in power output and efficiency between the two types of MFCs may result from differences in experimental conditions, such as variations in temperature, pH, substrate concentration, and microbial communities. Furthermore, differences in electrode material, reactor scale, and operational design contribute to the conflicting results. Thus, there is need to operate these configurations under the same conditions to see which one outperforms the other in terms of wastewater treatment and electricity generation.

2.3 Evolutionary History of MFCs

MFC technology has evolved over many years (Figure 2.2) with the first experimental realisation of electricity generation by bacteria in 1911 (Potter, 1911). Subsequent research focused on the practical use of MFCs, however, these required the use of mediators (Bennetto, 1990; Cohen, 1931). These MFC mediators were toxic (causing fouling) which then resulted in the construction of the first mediator less MFCs in 1999 (B. H. Kim et al., 1999). To further improve the performance of the MFCs, there was the introduction of new designs/prototypes and the use of MFCs in treating real wastewater (Liu & Logan, 2004; B. E. Logan, 2010). From 2010 to date, a considerable amount of literature has been published on MFC operation, design and performance. However, the application of MFC in real-world systems and scaling up remains a challenge with most studies being laboratory based. It would be interesting to assess the functioning of MFCs in real systems.

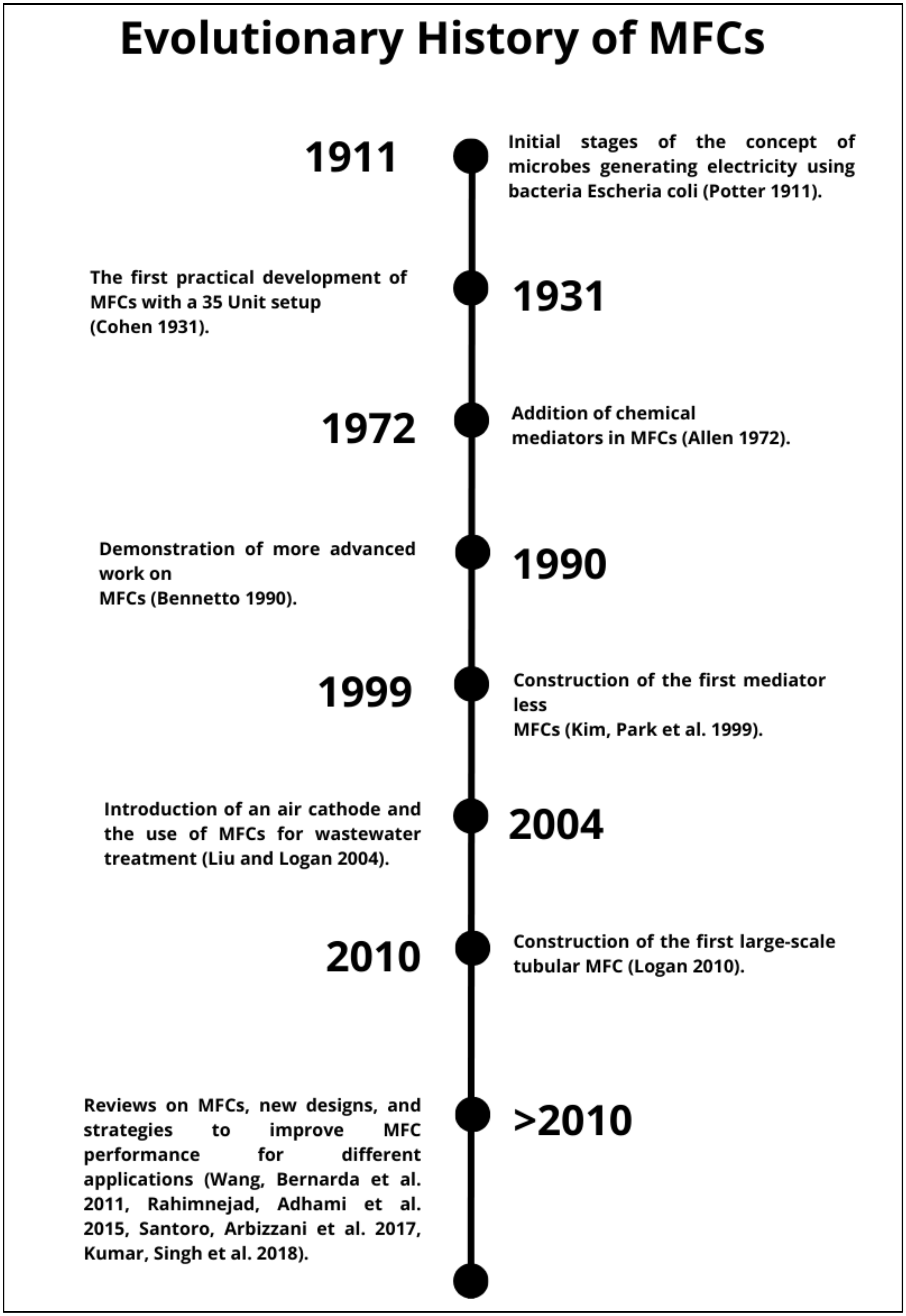

Figure 2.2: Evolutionary history of Microbial fuel cells

2.4 MFC operational system

In principle MFCs consist of two electrodes an anode (fuel electrode) and cathode (oxidant) which are two halves of a spontaneous oxidation-reduction reaction (ORR). The anode is made up of a substance that is readily oxidised (releases electrons) while the cathode being made of a substance that is readily reduced (accepts electrons) (Xu et al., 2016). An electrically negative terminal releases electrons into an electrically positive terminal. All the reaction's energy is released as heat when the anode and cathode are in close proximity. Therefore, the electrodes must be separated in such a way that electrons can flow from the anode to the cathode through an external load while still being in some sort of contact to enable the reaction to happen in order to take advantage of the available electrical energy(Larminie et al., 2003). To accomplish this, an electrolyte is used to separate the anode and cathode (substance that contains ions) (F. Li et al., 2009). The electrolyte contains ions but does not conduct electricity; as a result, preventing short circuiting between the anode and cathode.

Wastewater microorganisms oxidize biodegradable substrates to produce protons and electrons in the anode chamber, which are used to break down organic materials (Das & Kungwani, 2010). Cytochromes or redox-active proteins convey and collect the electrons produced by the metabolic activity of microbes on the anode's electrode surface before passing them to the cathode, where they interact with the electronic acceptor (for example, oxygen), through the electrical circuit (copper wire) (Kumar et al., 2015). Protons are transferred internally through the membrane at the cathode at the same time, forming a water molecule. An electrical potential difference is produced due to the difference in solution concentrations between the anode and cathode (Flimban et al., 2019). The difference in solution concentrations between the anode and the cathode results in a difference in electrical potential. The movement of electrons across the external electric circuit produces electrical power. In the cathode chamber, electrons combine with protons and oxygen to form an electron acceptor (such as oxygen or ferricyanide), which is subsequently reduced to produce water molecules among other possible outcomes (Hamelers et al., 2009).

Operation of MFC depends on factors such as pH, electrical resistance; the electrolyte used and dissolved Oxygen (DO) concentrations in the cathode (Oji et al., 2012; Palanisamy et al., 2019). Operation of MFCs in the absence of a separator results in decreased coulombic efficiency due to increased oxygen diffusion and substrate crossover (Palanisamy et al., 2019). At the anode, bacteria oxidise organic matter resulting in a loss of electrons and H^+ ions move through the PEM/separator into the cathode (Xu et al., 2016). The protons passing through PEM/separator and electrons passing through the circuit then combine at the cathode in the presence of oxygen, thus, completing the circuit (Flimban et al., 2019b; B. E. Logan, 2008).

2.4.1 Microbial Fuel Cell components

2.4.1.1 The Anode

The anode must have high compatibility, electronic conductivity, volumetric surface area and should be chemically stable to prevent corrosion and biofouling (Colombo et al., 2017). Biofouling results in reduced performance resulting in ineffective treatment of wastewater. A variety of materials can be used as anodes in MFCs but they each have their pros and cons. Metal anodes have been previously used because of chemical stability against bio corrosion and cost-effectiveness (Yamashita & Yokoyama, 2018); however, metals have low porosity levels and do not favour biofilm attachment. Thus, carbon-based materials such as carbon cloths, fibers, papers and graphite fibers and brushes are used because of their high conductivity and stability and relatively low cost (Rusli et al., 2018). Anode materials play a pivotal role in influencing power generation by determining the actual accessible area for bacteria to adhere, electron transfer efficiencies and diffusion rates of metabolic byproducts (S. Choi, 2015). The anode is responsible for bacterial growth, removal rate, electron generation, and the transformation to a cathode. Accordingly, the anode surface area should be rough to offer more bacterial adhesion at the anode to efficiently treat wastewater and electricity generation (Yaqoob, Khatoon, et al., 2020).

According to Yaqoob, Khatoon, et al. (2020), carbon cloth is the mostly used carbon material. Carbon cloth has a large surface area but is chemically unstable causing fouling thereby reducing long-term stability of the anode electrode. Carbon mesh has reasonable cost, and its open structure reduces biofouling (X. Wang et al., 2009); however, it has low electrical conductivity and poor chemical stability which results in reduced MFC performance. Granular activated carbon is biocompatible and cost effective, but it has a low electrical conductivity due to high porosity. This limits electron flow due to empty spaces present in the anode material and reduce electrochemical performance by reducing current output to enhance the biofiltration process. Graphite based anodes have good biocompatibility, mechanical strength and a reasonable surface area which results in improved performance due to increased organic matter breakdown by bacteria at the anode. Rough graphite offers reasonable results in energy generation and pollutant removal efficiency (Dekker et al., 2009). However, they are costly and offer low conductivity and hence they have limited use in both single and double chamber MFCs.

Metal or metal oxide-based anodes offer high electrical conductivity than carbon-based materials because they can facilitate effective electron flow (Dekker et al., 2009). For example, Yamashita & Yokoyama (2018)discovered that, a Molybdenum anode achieved a power density of 1296 mW/m^2. However, metal-based anodes are prone to corrosion in the long-term run, they do not have effective bacterial adhesion and are costly. Natural waste derived anodes are economically affordable, stable, they use recyclable materials (biomass waste), and they also offer good electrical conductivity (Yaqoob, Ibrahim, & Rodríguez-Couto, 2020). Examples of natural waste derived anodes include fruit peels, shells and coffee wastes (Yaqoob, Ibrahim, & Rodríguez-Couto, 2020), biochar from sewage sludge (Mian et al., 2019) and wood (Chang et al., 2020). Hung et al. (2019), studied renewable coffee water-based porous carbonized materials for anode and the MFC achieved power density of 3927 mW/m^2. Although this process is effective, much time is required to change waste materials into valuable materials to develop electrodes (Yaqoob, Ibrahim, Rafatullah, et al., 2020). On a global scale, carbon-based materials are mostly used as anode materials.

2.4.1.2 The Cathode

The cathode is costly and challenging to design and maintain and has proven limiting in most MFC designs (B. E. Logan, 2010). The cathode is regarded as a major performance limiting component for MFCs because it is the site for oxygen reduction reactions (Chen et al., 2018). Thus, if the reaction does not take place power will not be produced. Efficient cathodes have a large active surface area and great catalytic capabilities for reduction reactions (H.Y. Wang et al., 2011). An MFC cathode can be made of biocatalysts (enzymes or microbes) for the oxygen reduction reaction, abiotic catalysts (carbonaceous materials such as activated carbon, carbon nanotubes and graphene) (Yuan, Hou et al. 2016). The air cathode is the most feasible cathode configuration because it increases oxygen acceptor surface area that greatly reduces energy consumption for wastewater treatment (Pasupuleti et al., 2015). Platinum-based cathodes were previously used for their favourable reduction potential and outstanding electro catalytic activity but are being slowly dismissed due to high costs that proves to be a challenge when scaling up the MFCs for high end industrial purposes (Bose et al., 2018; Qiu et al., 2021; Zhu et al., 2022).

Carbon based materials are cost efficient, durable, stable and have a high surface area (Bose et al., 2018; Zhu et al., 2022). For example, carbon black and activated carbon have high surface area, excellent electron conductivity and they are cost effective. However, they have low catalytic ability. Graphene also has a large surface area, high conductivity and mechanical strength, but it is expensive to manufacture (Qiu et al., 2021). Metals and metal-based ORR catalysts can also be used as MFC cathodes. Metal oxides have high-cost effectiveness, environmentally friendly, simple preparation process and superior ORR electrocatalytic efficiency and excellent physiochemical properties. However, they offer poor electrical conductivity and high over potentials (Martin et al., 2011). Biocatalysts for example, microorganisms and enzymes are cheap, sustainable and resistant to biofouling. However, they are affected by an increase in pH, long term operation suffers from stability of the microbial community and biocatalysts may exhibit significantly lower ORR activity (Martin et al., 2011; Qiu et al., 2021). Overall, the cathode materials mostly used on a global are platinum and carbon-based materials. As previously mentioned, platinum is expensive hence the need to come up with cost effective materials to use as MFC cathodes.

2.4.1.3 The Membrane/Separator

MFC membranes/separators allow the transport of protons and other cations to the cathode whilst avoiding the transfer of bacteria into the cathode and the transfer of oxygen from the cathode chamber into the anode chamber (Hernández-Flores & Solorza-Feria, 2016; kondaveeti et al., 2018; Palanisamy et al., 2019). Membranes are essential to ensure an efficient and stable operation of MFCs (Ghadge, 2015). A good MFC membrane should be inexpensive, have low ionic resistance to make proton migration from the anode to the cathode easier, a non-porous microstructure to prevent oxygen transport and substrate crossover, and excellent biofouling resistance to preserve the membrane (Angioni et al., 2017). Drawbacks of separators include high internal resistance, biofouling, pH splitting, oxygen diffusion and substrate loss across the membrane (Angioni et al., 2017). These challenges result in high maintenance costs due to the need for frequent cleaning.

Separators are essential in the functioning of configurations with a small electrode spacing (such as flat-plate designs), however, they are optional in the case of large electrode spacing configurations (Kazemi et al., 2016). Membranes include cation exchange membranes (CEM) for example Nafion (Hernández-Flores & Solorza-Feria, 2016), anion exchange membranes, nylon fibres, glass fibres, ceramics and natural rubber (Salar-García et al., 2018). The proton exchange membrane is at times referred to as CEM because it allows the transfer of other cations such as Na^+ and NH_4^+ apart from the protons. This competition therefore inhibits proton transfer to the cathode inhibiting performance (Oji et al., 2012). Nafion provides great performance for MFCs, however, it is expensive up to \$1400/m^2 (Roy, Marzorati et al. 2017). Sulphonated biochar PEM is affordable, and its negative surface prevents biofouling on the membrane surface making it a suitable alternative (Zhu et al., 2022).

A salt bridge is an economic alternative to highly priced proton exchange membranes in the construction of MFCs. It also acts as proton transfer channel from the anode to the cathode. However, it results in high internal resistance (Sudarsan et al., 2015). According to Mohamed et al. (2016), carbon membranes exhibit a higher performance than anion membranes due to their fast proton transfer and low resistance. Though ceramic separators have excellent applicability due to their high physical strength, rigid nature, low cost and the ability to with stand extreme conditions of alkalinity and acidity; however, they have increased internal resistance with long term operation (Niranjit Khuman et al., 2019; Pasternak et al., 2015). An anion exchange membrane has high anion conductivity, however, it has relatively high ohmic resistance and biofilm growth during long term operation (X. Li et al., 2018). Glass fibres have high level of proton and low oxygen transfer and produces low ohmic resistance, however, they are non-biodegradable which might be an environmental risk (Aghababaie et al., 2015a). Non-woven fabrics of polypropylene offer high power density, high proton diffusion, applicable for large scale and affordable material cost (Kondaveeti et al., 2014).

2.4.1.4 Microbes

In the anode chamber, microbes anaerobically oxidise organic matter in wastewater releasing protons, electrons and carbon dioxide. The protons pass through the anode chamber to the cathode chamber via the PEM, while electrons pass through the external circuit (Ucar et al., 2017). Microbes oxidise organic matter in wastewater producing electrons which are transported to the anode and protons to the solution (B. E. Logan, 2008). In the biofilm, electrons are transferred through mediators, direct contact and/or nanowires produced by bacteria (B. E. Logan, 2008). Microbes such as *Rhodoferax ferrireducens, Geobacter sulfurreducens* and *Shewanella putrefaciens* do not require mediators, unlike *Saccharomyces cerevisiae* and *Escherichia coli* require mediators for electron transfer (Aghababaie et al., 2015a; Franks & Nevin, 2010; Rabaey et al., 2008).

In direct electron transfer, metal reducing bacteria such as *Geobacter sulfurreducens, Rhodoferax ferrireducens* and *Shewanella putrefaciens* use insoluble electron acceptors such as Fe (III) Oxide to transfer electrons to the external circuit, whilst mediator electronic transfer is facilitated by redox mediators. Different substrates influence the type of bacteria which in turn affects performance (Y. Zhang et al., 2009), thus, a mixture of bio-waste can result in more electricity generation (Konovalova et al., 2018). Bacteria can survive under extreme conditions of pH, temperature and salinity (Oh & Logan, 2007). Bacteria are self-replicating, thus, can be able to sustain MFCs. Microbes can be present as single and mixed cultures. Mixed cultures produce more power as opposed to single cultures due to the diversity of the bacteria in the solution. Examples of microbes found in wastewater include Clostridium, Geobacter, and Shewanella (Palanisamy et al., 2019).

Mixed cultures have nutrient adaptability, stress resistance, they are readily available in the environment and offer the best performance, whilst pure cultures produce low power generation than that of mixed cultures (Aghababaie et al., 2015a; Rabaey et al., 2008; Uria Moltó et al., 2017).

Geobacter sulfurreducens is the predominant genus on the anode with good power generation and high coloumbic efficiency. However, it is not suitable for actual application in the environment because of its limited metabolic diversity and flexibility (Franks & Nevin, 2010; Rabaey et al., 2008; Yang et al., 2017). *Escherichia coli* is highly abundant in wastewater, but it requires mediators and produces current after long acclimation times (Aghababaie et al., 2015a; B. Logan, 2009).

2.4.1.5 Wastewater type

Wastewater is the main substrate in microbial fuel cells, and it provides both microbes and organic matter required for giving off electrons. The most dominant pollutants in municipal/domestic wastewater are organic matter, microbes, BOD, different hydrocarbons including pharmaceuticals and detergents, suspended solid, range of heavy metals and coliforms (Kataki et al., 2021). These pollutants can be used in electricity generation; however, municipal wastewater has lower BOD concentrations yielding low energy densities and it is difficult to maintain stable power production (Gude, 2016b; He et al., 2017a; Munoz-Cupa et al., 2021). Industrial wastewater constitutes wastewater from industrial processing plants such as petrochemical, coffee processing, acid mine drainage, tannery effluent, milk parlour, slaughter house, steel making, pulp and paper, oil field, floriculture, textile and agro-food wastewaters. The main characteristics of industrial effluent are its high organic load and COD, high acidity or alkalinity, colour, turbidity, nutrient load, TSS, salts, colloids and specific toxic contaminants(Kataki et al., 2021). Industrial wastewater is high strength wastewater but may lack microbes depending on the type of effluent. For example, there are challenges in finding appropriate bacterial community that can utilize the mixture of dyes in dye wastewater (Gude, 2016b; Pant et al., 2010). Agricultural wastewater from different farming operations produces effluent streams that require prior treatment before being discharged to environment. Pollutants in agricultural wastewater include organic and biodegradable load, excess concentrations of nutrients and some pesticides and herbicides (Kataki et al., 2021). Agricultural wastewater is high strength wastewater, it has better efficiency because of methanogenic inhibitors and natural presence of electron transferring mediators e.g., lignin. However, other agricultural wastewater types such as swine wastewater produce volatile acids produced during fermentation of substrates (He et al., 2017a; Min et al., 2005; Pandey et al., 2016). Synthetic wastewater is easy to control in terms of loading strength, pH and conductivity (Pant et al., 2010).

2.4.2 MFC system modifications for higher power generation

The selection of material to be used as electrode is crucial for power generation in an MFC with regards to electron transfer, electrochemical properties and microbial adhesion. Material cost must be reduced, and power densities maximized for MFCs to be applied in the field. Despite the differences in the criteria for material selection for anode and cathode, both should have high surface area, electrochemical properties, material stability and cost effectiveness and biocompatibility (Pant et al., 2010; Rani et al., 2023a). Increasing the effective surface area reduces internal resistance and enhances electrode kinetics by providing more reactions sites. High electrical conductivity and low interfacial impedance, facilitates effective flow of electrons through the circuit. The electrode material should be stable and durable in order to provide long term performance with minimum fouling or degradation. Moreover, electrode material should be cost effective, accessible and sustainable, for economic viability of the technology at large scale (Rani et al., 2023b). Anode materials should be highly biocompatible to enable efficient biofilm formation by bacterial adhesion thereby increasing overall MFC performance (Rani et al., 2023b). The anode material should also be environmentally friendly in order to minimize the carbon footprint during its production.

Anode modification carbon nanotube (CNTs) and conductive polymers (CPs) provide a large specific surface area, extremely high conductivity, mechanical flexibility, reduced cellular toxicity and improved electrocatalytic activity (Agrahari et al., 2022a, 2022b). Graphene modified electrodes also offer large specific surface area, high electronic conductivity and good biocompatibility (Ma et al., 2023). Modification using metal or metal oxides provide a high rate of redox reaction and electrical conductivity (Yaqoob, Ibrahim, & Rodríguez-Couto, 2020). However, metals are costly making them a poor alternative especially if scaling up is to be considered. Metal oxides for example, MnO_2, FeO_2 and Fe_2O_3 have structural stability, they are cost effective, nontoxic and good biocompatibility (Agrahari et al., 2022b). Electrodes can also be modified by using natural materials such as biomass wastes. This is an advantage because the electrodes are made from recyclable materials, they are readily available and stable, cost-effective and eco-friendly nature (Yaqoob, Ibrahim, & Rodríguez-Couto, 2020). Microbial bio-cathodes can act as modified cathodes. They use microorganisms as the electrocatalytic agents for oxygen reduction reactions. Bio-cathodes have many advantages such as self-regeneration; low cost; sustainability and great activity at neutral pH. However, bio-cathodes have disadvantages such as low power generation and dependency of the performance on an illumination (Nitisoravut et al., 2017). The use of waste materials to construct modified electrodes for MFCs would be more significant and interesting in terms of cost efficiency and sustainability.

2.5 Microbial fuel cells (MFCs) prototypes

Several MFC prototypes have been proposed to efficiently treat wastewater and increase their power output. The studies are also focused on developing cost effective yet high performing MFCs with potential for scalability. Some of the prototypes are shown in Table 2.1. According to Aziz et al. (2013), the two chambered H-shape with a proton exchange membrane is mostly used. Nevertheless, single chambered MFC are mostly being used because of their reduced internal resistance, cutting membrane/separator costs and direct diffusion of air to the cathode (S. Roy et al., 2016). A rotating graphite fibre brush air cathode was tested against a non-rotating static air cathode and produced a power output of 879±16 mW/m^2 and 486 ± 11 mW/m^2. Rotating cathode increased catalytic sites for oxygen reduction reaction and improved oxygen diffusion. This therefore increases performance, simplifies reactor design and allows it to be integrated into existing wastewater treatment facilities (Chen et al., 2018). Chen et al. (2018) suggested a passive rotation of the air-cathode purely by wastewater movement. However, wastewater movement might not have much power to propel the movement of the cathode efficiently enough to cause a reaction.

A cost-effective microbial fuel cell (MFC) system was developed in order to recover silver metal from silver ion containing wastewaters. Maximum power density was 4 W/m^2 (C. Choi & Yufeng, 2011). Graphene: a building block of graphite attracted a lot of attention in 2004 due to its extra ordinary properties of increased surface area, high conductivity and mechanical strength and low cost resources (ElMekawy et al., 2017). It shuttles current at high rates than carbon nanotubes. However, scalable industrial production of graphene remains a challenge since graphene materials are prepared by sophisticated laboratory scale synthesis techniques (ElMekawy et al., 2017). This negatively affects Sub Saharan African countries as some lack such sophisticated equipment to produce the material.

Tamta et al. (2020), designed a new MFC system made up of a stack of 12 vertically arranged constructed wetlands coupled with MFCs. The COD removal increased gradually with decreasing external resistance reaching 98.5% at 0.08 Ω, NH_4^+-N removal efficiency was 90.4 % at 15 kΩ and 86.9 % for NO_3-N at 0.08 kΩ. The maximum power density for the system reached was 30.85 mW/m^3 at 15 kΩ. The advantage of this setup is, through the coupling of the two methods of wastewater treatment, there was a combination of their benefits such as low cost of construction, lesser land footprint, operation, wastewater treatment and electricity generation and maintenance. Through the study, it was also discovered that a low external resistance results in the growth and metabolism of microorganisms and nutrient removal. However, even with the integration of the methods (constructed wetlands and MFCs) and stacking; electricity generation still remained quite low. Microalgae based MFCs are an efficient system for removing nitrogen, phosphorus and carbon dioxide from wastewater and bioelectricity production. However, its challenge is in oxygen cross over (Arun et al., 2020a). There is therefore need to select algal strains that are suitable for use in both the anode and cathode compartments.

Buitrón & Cervantes-Astorga (2013); tested a low-cost single chamber MFC with a graphite cathode catalyst. It generated a power density of 9.2 mW/m^2 and degraded 80% of fed organic matter (367 mgO_2L^{-1}) with an internal resistance of 8.530 Ω. This MFC produced 1.52 times more power density than the platinum catalysed cell. (Zhang et al., 2015); designed a flexible and low cost polypyrole nanotubes membrane as an anode for electricity generation in MFC. It had a high surface area improving bacteria interaction at the anode. The polypyrole MFC had a maximum power density of 612mW/m^2. Behera (2011), constructed earthen pot MFCs with the pot as the anode chamber. From synthetic wastewater, a power density of 24.32 mW/m^2 was achieved using a 3 cm wall thickness MFC. Though a low cost MFC was able to outperform the platinum catalysed cell, its power output was still quite low. Most of the MFC prototypes have different configurations, use different materials and operate under different operational parameters making it difficult to compare them. Moreso, some of the experiments do not use real wastewater as the substrate which makes it difficult to conclude whether they will be efficient in treating wastewater or not.

Table 2.1:Examples of microbial fuel cell prototypes, materials used, type of wastewater, power produced and wastewater treatment efficiency

MFC Type	Anode Material	Cathode Material	Membrane/ separator	Type of wastewater	Electricity generation	Pollutant removal	Reference
Single chamber MFC	Graphite fibre brush	Binder-free coating of N, P co-doped carbon ORR catalyst onto a graphite fibre brush current collector rotating three-dimensional air-cathode	Anion exchange membrane	50 mM phosphate buffer solution with pH 7.0 was used as an electrolyte solution	879±16 mW/m^2	_	(Chen et al., 2018)
Two chambered MFC	Carbon brush	Carbon cloth with gas diffusion layers	Anion exchange membrane	Sludge with anolyte	4.25 W/m^2	silver metal recovery efficiencies as high as 99.91 ± 0.00%	(C. Choi & Yufeng, 2011)

Dynamic membrane MFC	Tubular shape carbon felt	Activated carbon fibre felts connected to the circuit by graphite rods	Nylon mesh used as a dynamic membrane supporting layer connected to the circuit by graphite rods	Inoculated using granular anaerobic wastewater sludge, fed a synthetic medium containing glucose, $NaHCO_3$, NH_4Cl, NaH_2PO_4, and NaCl	1923 mW/m^3	-	(X. Li et al., 2018)
Stack of 12 vertically arranged constructed wetlands coupled with MFCs	Granular graphite layer with a rectangular graphite rod as current collector	Granular graphite layer with a rectangular graphite rod as discharging of electrons	_	Synthetic wastewater (grey water)	30.85 mW/m^3	NH_4^+-N 90.4 %, NO_3-N 86.9 % COD 98.5%	(Tamta et al., 2020)

Single chamber MFCs	Graphite fibre brushes	Fe–N–C catalyst on AC with stainless steel mesh current collector	Hydrophobic PVDF membrane diffusion layer	Sodium acetate dissolved in a 50 mM phosphate buffer solution amended with 12.5 mL L−1 minerals and 5 mL L−1 vitamins	2.4 ±0.1 W/m^2	_	(Yang et al., 2020)
Two chambered MFC	Platinum rod	Platinum rod	PEM made from sulphonated biochar	Synthetic wastewater with sucrose as a carbon source	0.278 Wl^{-1}	_	(Chakraborty et al., 2020)
Single chamber MFC	Graphite fibres distributed along two twisted wires of titanium	Graphite paper	Membraneless	20 % of municipal wastewater and 80 % of a synthetic	9.2 mW/m^2	80% organic matter degradation	(Buitrón & Cervantes-Astorga, 2013)

				solution containing sodium acetate as the source of carbon			
Air cathode microbial fuel cells	Carbon felt	Carbon cloth with a diffusive layer	Proton exchange membrane	sodium acetate, phosphate buffer solution, vitamins and trace minerals	458.85 mW/m^3	-	(M. Li et al., 2018a)
Earthen pot MFCs	Stainless steel mesh	Graphite plate	Earthen pot acted as PEM	Synthetic wastewater with sucrose as carbon source Inoculated with	24.32 mW/m^2	_	(Behera, 2011)

				anaerobic sludge			
Double chamber microbial fuel cells	Zinc	Copper	Proton exchange membrane (salt bridge)	Organic waste of avocado	566.80 ± 13.48 mW/cm^2	-	(Rojas-Flores et al., 2022)
H type double chamber MFC	Anode enriched with microorganisms	_	Nafion 117 membrane	Whey	1800 ±120 W/m^2	90 days (92.8% tCOD)	(Kassongo & Togo, 2011)

2.6 Drivers and barriers for the uptake of MFCs in the World and Africa

2.6.1 Drivers for the uptake of MCFs in the World and Africa

2.6.1.1 Wastewater treatment

MFCs are capable of nutrient removal of high strength wastewaters making it a great competitor against other Wastewater treatment systems (WWTS) (Gude, 2016b). Microbial fuel cells are also efficient in heavy metal removal, thus can help solve the issue of biomagnification and bioaccumulation in waters that receive treated water using other sources of wastewater treatment (Gambino et al., 2021). Microbial fuel cells are adaptable to decentralised wastewater treatment making them applicable to any area even those that lack electricity (Fan et al., 2021). The treatment process results in the production of lower sludge volumes reducing sludge handling costs. Microorganisms present in the wastewater can self-generate meaning there is no need to periodically place bacteria in the MFCs (Aquino Neto et al., 2018).

2.6.1.2 Electricity generation

Coupled with WWT, MFCs produce electricity. MFCs utilise waste as fuel and have low chemical requirements thus making them cost effective once operation commences (Mateo et al., 2018). Wastewater contains more energy than the energy used to treat it. This energy is therefore converted to electricity during the breakdown of organic matter by bacteria. The process operates at ambient temperatures and does not require energy for aeration (Yaqoob, Khatoon, et al., 2020).

2.6.1.3 Climate smart and environmentally friendly

The MFC WWT process has a low carbon footprint making it a very sustainable and environmentally friendly solution. The treated wastewater/effluent can be used for water reclamation especially in areas where water scarcity is a problem (Saravanan et al., 2021), for example irrigation, recreational activities, industrial and urban reuse. The drivers and barriers for the uptake of MFCs are highlighted in Figure 2.3.

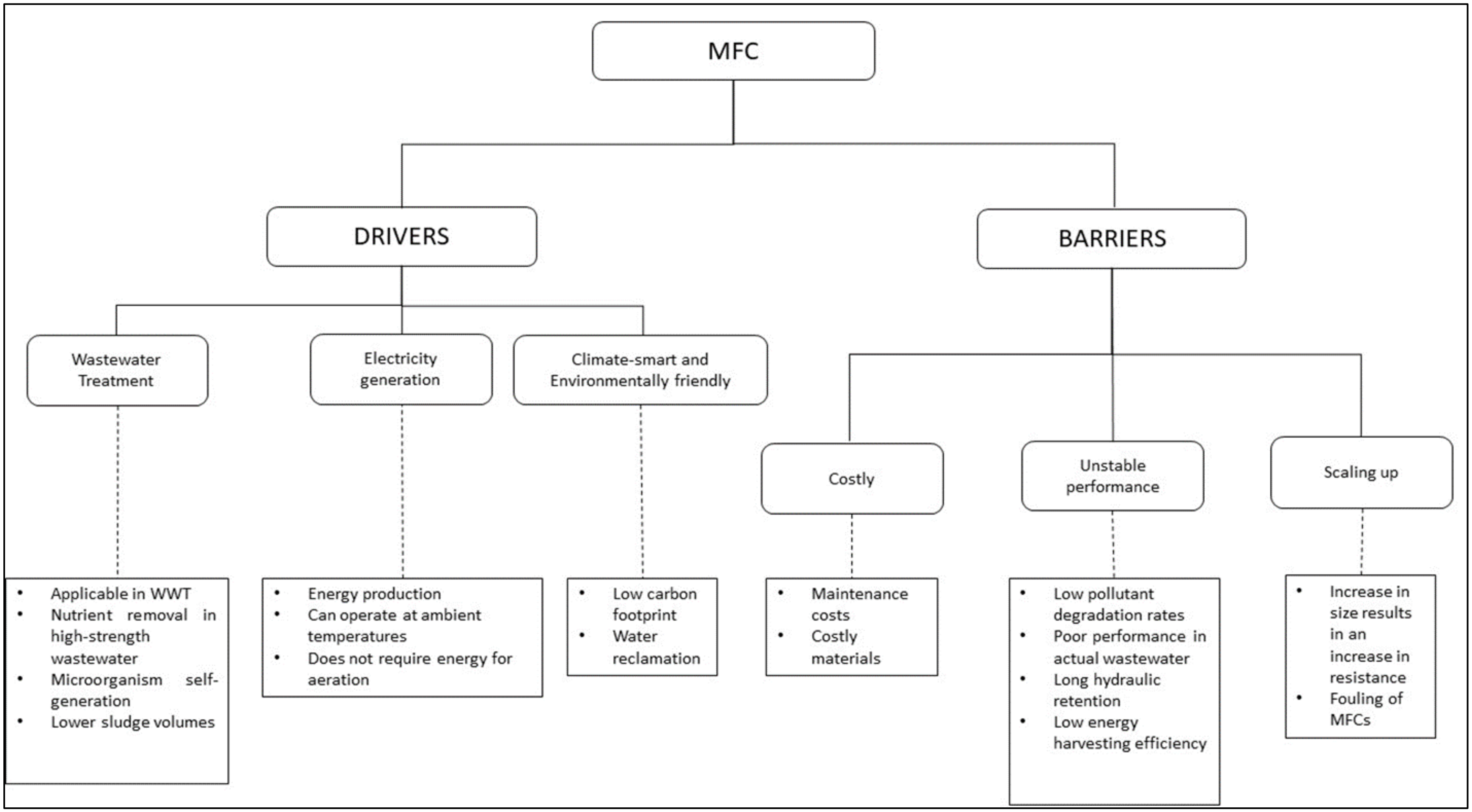

Figure 2.3: Drivers and barriers for MFC uptake of MFCs

2.6.2 Barriers and contextual issues in the uptake and use of MFCs in Africa

2.6.2.1 High cost

Like any technology, microbial fuel cells come with their share of challenges. Reducing material costs remains a challenge in microbial fuel cell construction (Yaqoob, Ibrahim, & Rodríguez-Couto, 2020). Most materials used in MFC construction such as Nafion membranes and platinum electrodes are expensive (Banerjee et al., 2022; He et al., 2017a; Hernández-Flores et al., 2016; Slate et al., 2019b; Trapero et al., 2017). Additionally, the electrodes and PEM need be replaced every five years of MFC operation, adding a total extended maintenance cost to the already expensive reducing materials (Palanisamy et al., 2019). If the capital costs of MFCs outweigh those of conventional activated sludge, conventional activated sludge might as well remain in use more so for impoverished developing countries in Africa.

2.6.2.2 Unstable performance

Another disadvantage of MFC is that it has a low energy harvesting efficiency whilst treating real wastewater and has unstable performance long-term (anode and membrane biofouling) (Ghadge, 2015). Microbial fuel cells have low pollutant degradation rates and poor performance with actual wastewater in real systems (Gude, 2016b), thus making them an inefficient wastewater treatment system. They have long hydraulic retention times meaning that larger reactor volumes are required which add to the capital and maintenance costs (Gude, 2016b). It is also unclear if the MFC WWT process can remove impurities such as grease and microplastics in wastewater. This therefore becomes a limiting factor in implementing MFCs in impoverished countries such as Zimbabwe. Most MFC studies focus on power generation rather than the actual treatment of wastewater making it difficult to conclude on whether MFCs are efficient at pollution reduction at a broader scale.

2.6.2.3 Scaling up

Scaling up of MFC technology remains a challenge especially in the selection of materials, such as separators and electrodes. During MFC operation electrode poisoning during wastewater treatment, pH alleviation in the anode and cathode chambers, aeration for catholyte reduction, and nitrogen purging for maintaining a large anaerobic system still remain a challenge (Jayapriya & Gummadi, 2022). Increasing MFC size directly causes increased electrode distance resulting in high internal resistance ultimately leading to decreased power output (Oji et al., 2012). Miniaturisation of MFC when scaling up is therefore advantageous as it allows high surface area to volume ratio, short electrode distance and fast response time thus producing better performance than macro sized MFCs (S. Choi, 2015b). However, miniaturisation may not really make sense when treating large volumes of wastewater as it might prove to be costly, it can take up space and the time for wastewater treatment becomes prolonged. Consequently, if MFCs are to be applied in real settings, future studies should emphasize on increasing MFC size without affecting its performance.

2.7 Microbial fuel cells in Africa

According to Striebig (2017), many developing countries in Africa, Latin America and parts of Asia have unreliable electrical sources and little access to clean water. Thus, MFCs can be an effective technology in providing even low power electricity to charge phones and power light emitting diode (LED) lights. Microbial fuel cells are still in their infant stages in developing countries due to complexities of simplifying the design and cost of materials (Justin, 2010). According to Ash et al. (2017), MFCs can be used to generate electricity for low power devices such as LED bulbs to be used in emergency cases particularly in Africa where the majority of the people have no access to electricity.

Though South Africa has large coal reserves, it has recognised the need to diversify its energy mix (Ndlovu & Inglesi-Lotz, 2019). This need for diversification is also now being realised by other countries due to the ever-increasing demand for energy in their countries. A study by Stafford et al. (2012)in South Africa evaluated the applicability of various technologies for energy recovery from wastewater. Microbial fuel cells were found to be suitable for use with low concentration organics in wastewater and its direct conversion to electricity. However, MFCs were found to be capital intensive, with a wide variability of COD removal in terms of wastewater type and the fact that it is still in its developmental stages presents a high-risk investment opportunity that can only be realised with the aid of high capital from governments and other interested parties. At present, this appears to be a far-fetched aim for highly impoverished African countries grappling with provision of basic human needs such as clean water, health, shelter and food.

In Tanzania, MFCs were used as biosensors in the monitoring of faecal pollution in groundwater. Microbial fuel sensors provided low cost and low maintenance whilst ensuring ground water quality (Velasquez et al., 2017). This study evaluated the potential of four microbial fuel cell (MFC) systems placed in different areas of a groundwater well for low-cost monitoring of faecal pollution. The MFC designs included sediment/bulk liquid (SED/BL), sediment/sediment (SED/SED), bulk liquid/air (BL/Air), and bulk liquid/bulk liquid (BL/BL). The electrode assemblies use affordable, durable materials to generate a contamination signal without the need for external energy or chemical inputs. However, the primary focus of the study was on environmental remediation, specifically detecting faecal matter in groundwater, rather than on the electricity generation capabilities of the MFCs or their use in wastewater treatment. As a result, the findings are less applicable to research aimed at MFC-based wastewater treatment and energy production. Another study by Kunik (2015), focused on the feasibility of MFCs in Tanzania through technical analysis and interviews with Tanzanian locals for cultural feasibility. The MFC operated with diluted manure and achieved a power density of 16.1 mW/m^2 and a 93 % reduction in faecal coliforms. Although this study showed evidence of electricity generation in MFCs, it did not use wastewater as a substrate for MFCs hence limiting its applicability in wastewater treatment. From the interviews, the locals seemed interested in the new technology provided it was safe and clean.

2.7.1 Microbial fuel cells in Zimbabwe

In Zimbabwe, there is little and/or anecdotal information on the use of Microbial fuel cells for wastewater treatment and electricity generation. This is a huge gap warranting studies on microbial fuel cells in the country. From the few available literature, it appears MFCs adoption in Zimbabwe and Africa is moving at a very slow pace requiring the need for more research that focuses on low-cost fabrication of MFCs such that they can be implemented by low-income communities in Zimbabwe. Major challenges remain in meeting SDG 6 Clean Water and Sanitation and SDG 7 Affordable and Clean Energy (Dziva & Kabonga, 2021). Therefore, the use of MFCs in Zimbabwe is timely and necessary in order to meet the country's Vision 2030 and Sustainable Development Goals (SDGs). The MFCs will result in improved sanitation through the treatment of wastewater and affordable and clean energy through the generation of electricity. Though the power generated from MFCs is quite low, it can be used for lighting and charging phones since the country is facing huge power cuts due to load shedding.

The economic state of Zimbabwe is a big setback in the development of MFCs in the country. Using the international poverty line at USD $1.90 per person per day, Zimbabwe ranks as 150 over 189 countries (Nwani & Osuji, 2020). Thus, if the capital costs of MFCs outweigh the operation and maintenance of conventional wastewater treatment systems; conventional wastewater treatment systems might as well remain in use. If MFCs are to be implemented in Zimbabwe, there is definitely need to use cost effective yet efficient materials which can be accessible even to low-income households. This is to ensure that there is country wide access to the technology even using the simplest designs and materials.

From the review, carbon-based materials, natural waste derived materials (biochar), biocatalysts and ceramics offer cheap alternatives to the otherwise expensive materials whilst producing favourable power and efficient wastewater treatment. Future studies should therefore focus on modifying these low-cost materials to produce higher power generation coupled with efficient wastewater treatment.

For the existent MFC prototypes the literature examination reflected that most anodes and cathodes are made from carbonaceous material, the separators used are mainly made from Nafion and SMFC and DCMFC are the mostly used designs. Scoping through the evolutionary history of the development of the MFCs from the initial prototype by Potter in 1911 and first practical development by Cohen in 1931 most studies on MFCs were reported/published from 2004 to date. Assessment of the operational efficacy of the existent MFC prototypes indicated that although MFCs can generate electricity and treat wastewater, the power generated is very low and the treatment system is not applicable in real world settings mainly due to their small sizes and materials used. From the available literature on MFCs it appears the main drivers for the uptake of this technology, mostly for affluent developed nations, comprise the ability to simultaneously treat wastewater and generate electricity, heavy metal removal, lower sludge volumes and low carbon footprint. This simply stems from their ability to afford the high-cost anodes/cathodes. This is however, a challenge for African countries including Zimbabwe as they cannot afford these materials and the MFCs require high maintenance costs.

If MFCs are to be implemented in Zimbabwe, there is definitely need to use cost effective but efficient materials which can be accessible even to low-income households. Carbon based materials, natural waste derived materials, biocatalysts and ceramics can be implemented in MFCs in Zimbabwe due to their cost effectiveness whilst producing favourable power and efficient wastewater treatment. For future studies and practical uptake of MFCs it is recommended that low-cost materials that ensure maximum power generation and efficient wastewater treatment are to be investigated before they are to be adopted in Zimbabwe. Further research should also be done to investigate the large-scale use of MFCs in real wastewater systems. MFC experiments should also compare different MFC configurations under the same conditions so as to not have biased results. From this review, it is clear that MFCs cannot be used in isolation; hence, they should be integrated with other existing sustainable wastewater treatment systems and renewable sources of electricity generation.

Summary

In summary, microbial fuel cells (MFCs) convert chemical energy into electricity with simultaneous wastewater treatment and can be mainly in single chambered and double chambered configurations. Conflicting studies make it difficult to conclude which MFC type outperforms the others as experiments are often conducted under varying conditions and using different materials. The evolutionary history of MFCs can be traced back to the first experimental generation of electricity by bacteria in 1911. Since then, there have been improvements in MFC design, prototypes, and wastewater treatment. Despite the advancements in literature and research, the application of MFCs in real-world systems and scaling up remains a challenge that needs to be addressed. From the review, it is clear that carbon-based materials, natural waste derived materials (biochar), biocatalysts and ceramics offer cheap alternatives to the otherwise expensive materials whilst producing favourable power and efficient wastewater treatment.

For the existent MFC prototypes the literature examination reflected that most anodes and cathodes are made from carbonaceous material, the separators used are mainly made from Nafion and SMFC and DCMFC are the mostly used designs. Assessment of the operational efficacy of the existent MFC prototypes indicated that although MFCs can generate electricity and treat wastewater, the power generated is very low and the treatment system is not applicable in real world settings mainly due to their small sizes and materials used. From the available literature on MFCs it appears the main drivers for the uptake of this technology, mostly for affluent developed nations, comprise the ability to simultaneously treat wastewater and generate electricity, heavy metal removal, lower sludge volumes and low carbon footprint. This simply stems from their ability to afford the high-cost anodes/cathodes. This is, however, a challenge for African countries including Zimbabwe as they cannot afford these materials and the MFCs require high maintenance costs. Therefore, this study will use cost effective but efficient materials for the fabrication of MFC prototypes.

CHAPTER 3

MATERIALS AND METHODS

3.1 Introduction

This chapter describes the design and construction process for the MFC prototypes, including the selection of materials, dimensions, and operational parameters. It then outlines the methodology used to assess pre- and post-treatment of domestic wastewater using Microbial Fuel Cell Prototypes. Electricity Generation Assessment of the MFC prototypes is also included in detail. The analysis of domestic wastewater treatment data and electricity generation data is highlighted.

3.2 Design and fabrication of MFC prototypes in double chamber and single chamber configurations

The research is grounded in a positivist epistemological framework, which emphasises objectivity, empirical evidence, and quantitative methods. Based on a thorough literature review, the experimental design focused on Single Chamber and Double Chamber MFCs, which are simple and widely studied designs. Due to conflicting performance reports in the literature, the study compared the two designs, prioritising control over variables such as electrode material, chamber size, separator type and used the same substrate (wastewater) to ensure a clear analysis of each prototype's efficiency in electricity generation and wastewater treatment.

The rationale for focusing on the cathode material stems from its significant impact on MFC performance, as highlighted in the review. The choice of biochar powder and granular activated carbon as electrode materials was informed by their cost-effectiveness, high porosity, and conductivity, making them ideal for use in Zimbabwe. Stainless steel was selected for its corrosion resistance, mechanical support, and electrical conductivity. These materials were chosen over alternatives like carbon cloth or platinum-coated electrodes due to their affordability and local availability, which are crucial for scaling MFCs in resource-limited settings.

Autodesk (2023) software was used to create designs for both double and single chamber microbial fuel cell (MFC) prototypes. The single chamber MFCs were designed with dimensions of 10 cm × 10 cm × 10 cm, with one side open to accommodate the air cathode placement. The double chamber MFCs had dimensions of 23 cm × 10 cm × 10 cm, with the middle part separated by a 3 cm gap, resulting in each chamber measuring 10 cm × 10 cm × 10 cm. The designs facilitated electrode placement and electrical connections. The inner sides of the chambers were drilled with 1 cm holes to permit proton transfer.

Acrylic sheets were cut to the specified dimensions using a grinder and were then assembled to form the chambers. The joints were sealed with marine silicon, resulting in four Single chambered MFCs and four Double chambered MFCs (see Figure 3.1). The configuration of the MFC prototypes is detailed in Table 3.1.

Table 3.1:Configuration and Materials of MFC Prototypes

Type of MFC		**Anode Material**	**Separator**	**Cathode Material**
Single Chamber MFC	1	Biochar powder	N/A	Biochar powder
	2	Biochar powder	N/A	Biochar powder
	3	Biochar powder	N/A	Granular Activated Carbon
	4	Biochar powder	N/A	Granular Activated Carbon
Double Chamber MFC	1	Biochar powder	Agar salt bridge	Biochar powder
	2	Biochar powder	Agar salt bridge	Biochar powder
	3	Biochar powder	Agar salt bridge	Granular Activated Carbon
	4	Biochar powder	Agar salt bridge	Granular Activated Carbon

Stainless steel mesh wire mesh #8; 2.38 mm aperture was cut to make all anodes (6 cm × 7 cm) and double chamber cathodes (7 cm × 7 cm). Biochar powder was produced from maize stalks following the method described by Makepa et al. (2023). Biochar powder was mixed with a binder polyvinylidene fluoride (PVDF) solution to form a paste, which was then applied to all the stainless-steel wire mesh anodes and two double chamber cathodes, and allowed to dry. Granular Activated Carbon (0.4 mm granular size) was similarly mixed with a PVDF binder solution to form a paste, which was applied to the other two double chamber cathodes and allowed to dry. This method of fast pyrolysis for biochar production was selected because it provides rapid and uniform heating, reducing processing time, direct heating which minimises energy loss, making the process more efficient, it produces higher yields with improved porosity and surface area and enables precise control over temperature and reaction conditions for consistent biochar quality.

For the single chamber cathodes, two were made following the phase inversion method described by Yang et al. (2014), using granular activated carbon. The other two single chamber cathodes were made using biochar in place of the activated carbon, following the same method. The electrodes were placed in their respective compartments, with the anode in the anaerobic chamber and the cathode in the aerobic chamber. The single chamber MFC cathodes were then affixed to the chamber using clear epoxy and sealed with marine silicon. The phase inversion method was chosen because it simplifies the production process while ensuring high efficiency and cost-effectiveness. It was also selected for its precise control over the porosity of the cathode material, which is critical for optimising oxygen diffusion and maximizing the surface area for electrochemical reactions (Yang et al., 2014; Yi et al., 2023).

To create the salt bridge, a solution of 10% agar in 1 M NaCl was prepared and heated until the agar was fully dissolved. This solution was then poured into the separator opening in the double chamber MFCs. After solidification, it served as a salt bridge, connecting the cathode and anode chambers. The electrodes were secured in their respective chambers with clear epoxy, and copper wire was used as a conductor and a 680 Ω resistor to complete the circuit.

(a) (b)

Figure 3.1: (a) Double chamber MFC configurations and (b) Single chamber MFC configurations

3.3 Pre- and Post-Treatment Assessment of Domestic Wastewater Treatment Using Microbial Fuel Cell Prototypes

Raw domestic wastewater samples were collected from the Fernlea sewage treatment plant (FTP) which is adjacent to Chinhoyi University of Technology (CUT). The wastewater was collected in the morning at around 10 am. Physical wastewater parameters, including dissolved oxygen, pH, electrical conductivity (EC), and total dissolved solids (TDS), were measured in situ. Ten 1-liter water samples were collected using acid-washed polyethylene bottles for further laboratory analysis. Approximately 500 mL of domestic wastewater was placed in the anode chamber of each MFC prototype. The anode chambers were completely sealed to create an oxygenless environment. There was a 12 days acclimatisation period to allow the microorganisms to adapt to the new environment and begin forming biofilms on the electrodes. The acclimatization period in MFCs can extend up to several weeks, but its progress is often indicated by the formation of a stable biofilm on the anode (E. Zhang et al., 2016). For this study, the period was limited to 12 days because that's when the biofilm had fully formed on the anodes.

Five 1-liter bottles were filled and preserved onsite for specific analyses: Chemical Oxygen Demand (COD) by adding 2 mL of sulphuric acid, Total Nitrogen by adding 0.8 mL of sulphuric acid, Potassium by adding 5 mL of nitric acid, Total Phosphorus by adding 2 mL of sulphuric acid, and Grease and Oils. The collected water samples were cooled and refrigerated at 4°C, and ice blocks were used during transportation in a cooler box to the laboratory. In the laboratory, wastewater samples were analysed according to standard procedures as outlined by Rice et al. (2012). Total Phosphorus (TP) was determined using the colorimetric method, Total Nitrogen (TN) using the persulphate method, and Chemical Oxygen Demand (COD) using the colorimetric method. Grease and oils were extracted using hexane and measured using gravimetric methods. Wastewater was also tested for the same parameters after treatment (after 32 days) in each respective MFC prototype. The wastewater was tested for each parameter in triplicate (from each prototype testing for homogeneity) to ensure the reliability and accuracy of the results.

3.4 Electricity Generation Assessment

A digital multimeter (Siltron Model: MA5830L) was used to measure voltage and current. Measurements were recorded twice daily, in the morning and afternoon. The microbial fuel cell (MFC) prototypes were left in an open circuit condition for 12 days to allow for the acclimatisation of bacteria to the anode electrodes. During this acclimatisation period, only voltage was measured under open circuit conditions. On the thirteenth day, each circuit was closed using a 680 Ω resistor as a load. Voltage and current were then measured in both the morning and afternoon, and power output was subsequently calculated.

3.5 Data Analysis

3.5.1 Pre- and Post-Treatment Assessment of Domestic Wastewater Using Microbial Fuel Cell Prototypes

The effect of different MFC prototypes on the treatment of domestic wastewater was tested by testing the reduction in the levels of Chemical Oxygen Demand (COD), pH, electrical conductivity, total dissolved solids, phosphorous, nitrogen, potassium, and grease and oils, before and after treating the wastewater. The data was entered into Microsoft Excel. The initial data was collected before the wastewater was treated in the MFC prototypes, and then tested again for the wastewater parameters after 32 days (when the prototypes were showing constant current and voltage). The treatment efficiency for each prototype was measured for each wastewater parameter (except pH) using the following formula:

$$Treatment\ Efficiency(\%) = \left(\frac{Initial\ value\ - Final\ value}{Initial\ value}\right) \times 100$$

Since pH is a logarithmic measure of hydrogen ion concentration, the formula for calculating the relative change in hydrogen ion concentration was used to accurately assess the treatment efficiency in terms of pH change, as it provides a precise quantitative measure of neutralisation. It is calculated using the formula:

$$Relative\ Change\ (\%) = \left(\frac{[H^+]_{initial} - [H^+]_{final}}{[H^+]_{initial}}\right) \times 100$$

Where, $[H^+]_{initial}$ is the initial hydrogen ion concentration.

$[H^+]_{final}$ is the final hydrogen ion concentration.

The wastewater data for all parameters were tested for normality using the Shapiro-Wilk test, which failed to meet normality assumptions. Therefore, the Wilcoxon signed-rank test for comparing two related samples was used to compare wastewater parameters before and after treatment in the MFC prototypes. Subsequently, the Wilcoxon rank sum test with continuity correction was used to compare the distributions of these differences between the prototypes. The MFC prototypes were compared as (Single Chamber Activated Carbon Cathode) SCAC vs (Single Chamber Biochar Cathode) SCBC MFCs, (Double Chamber Activated Carbon Cathode) DCAC vs (Double Chamber Biochar Cathode) DCBC MFCs, and double chamber vs single chamber MFCs. All statistical analyses were performed using R Studio.

3.5.2 Electricity Generation Assessment

Current, voltage, power, and volume of substrate (wastewater) data were entered for each MFC prototype over 32 days into MS Excel. The current and voltage data were tested for normality using the Shapiro-Wilk normality test and failed to meet normality assumptions. Consequently, the Mann-Whitney U Test was used to compare voltage and current across SCAC vs. SCBC MFCs, and DCAC vs. DCBC MFCs and double chamber vs. single chamber MFCs. To determine which configuration (e.g., DCAC or DCBC) had higher voltage and current, their mean values were compared, with the prototype exhibiting a higher mean value being considered to have higher voltage and/or current. All statistical analyses were performed using R Studio.

The energy conversion efficiency, which is the ratio of electrical energy produced to the energy stored in the substrate (wastewater), was calculated for the MFC prototypes using the following formula:

$$Energy\ Conversion\ Efficiency(\%) = \left(\frac{Electrical\ energy\ output}{Chemical\ energy\ input}\right) \times 100$$

Where, ***Electrical energy output*** is the energy produced by the MFC and is calculated using the formula:

Electrical energy output (J)=Voltage (V)×Current (I)×Time (t)

Voltage (V): The potential difference across the MFC.

Current (I): The flow of electric charge, in amperes (A).

Time (t): The duration for which the current is produced, in seconds (s).

Chemical energy input is the energy available in the substrate (organic matter in the wastewater) and can be determined from the chemical COD (Chemical Oxygen Demand). It is calculated using the formula:

$$Chemical\ energy\ input\ (J) = COD\ (g) \times Energy\ per\ gram\ of\ COD\ (J/g$$

Where, *COD (g)* is the mass of the COD removed indicating the amount of organic matter available for conversion.

CHAPTER 4

RESULTS

4.0 Introduction

This chapter presents the results of the study on the design and fabrication of microbial fuel cell (MFC) prototypes for domestic wastewater treatment and electricity generation. The findings are divided into two main parts: the pre- and post-treatment assessment of domestic wastewater using different MFC prototypes and the evaluation of their electricity generation efficiency. The first part examines the wastewater treatment efficiency of double chamber vs single chamber MFCs, as well as the specific performance of DCAC vs DCBC, and SCAC versus SCBC MFC prototypes in removing pollutants such as COD, pH, electrical conductivity, total dissolved solids, total nitrogen, potassium, phosphorous, and grease and oils. The second part evaluates the electricity generation of these MFC prototypes, comparing the voltage and current output between double chamber and single chamber configurations, as well as between the different cathode types (DCAC vs. DCBC and SCAC vs. SCBC). Additionally, it assesses the energy conversion efficiency across all prototypes, considering the relationship between energy production and wastewater treatment effectiveness.

4.1 Design and fabrication of MFC prototypes in double chamber and single chamber configurations

The prototypes developed in this study were designed with key considerations of material availability, affordability, and performance efficiency, particularly in the context of low-income communities. Both single chamber and double chamber microbial fuel cells (MFCs) were fabricated using locally sourced and cost-effective materials, as outlined in the previous chapter. The design of the single and double chamber MFCs prioritised simplicity, affordability, and functionality. The single chamber MFCs were constructed with dimensions of 10 cm × 10 cm × 10 cm, with one open side to allow for air cathode placement, while the double chamber MFCs had dimensions of 23 cm × 10 cm × 10 cm, separated by a 3 cm gap for the agar salt bridge. Both configurations utilised locally available materials, making the prototypes highly suitable for scaling in resource-constrained environments.

The electrode materials biochar powder and granular activated carbon powder were selected due to their high conductivity, porosity, and affordability, which are critical for maximising the efficiency of the MFCs while keeping production costs low. Biochar was produced from maize stalks (which are regarded as “waste”) using the fast pyrolysis process, ensuring a sustainable and locally viable source of electrode material. The use of stainless steel as the structural support for the electrodes provided additional benefits in terms of corrosion resistance and durability. This design is particularly advantageous for communities in Zimbabwe, where resources are limited and solutions must be both affordable and effective.

For the single chamber MFC cathodes, the phase inversion method was employed to create cathodes from both granular activated carbon and biochar because of its ability to precisely control the porosity of the cathode material, oxygen diffusion optimisation and enhancing electrochemical reactions, which are critical for electricity generation in MFCs. Additionally, the fast pyrolysis process used to produce biochar electrodes ensured high yields of biochar with improved porosity and surface area. This process, which offers precise control over temperature and reaction conditions, was selected for its efficiency and low cost, making it particularly suited to the economic constraints of low-income communities. The double chamber MFCs also included a salt bridge made from 10% agar in 1 M NaCl, further improving the separation between the cathode and anode chambers and contributing to overall system performance. Overall performance evaluation of the protypes is highlighted in the following sections for wastewater treatment and electricity generation.

4.2 Pre- and Post-Treatment Assessment of Domestic Wastewater Using Microbial Fuel Cell Prototypes

4.2.1 Pre- and Post-Treatment Assessment of Domestic Wastewater in SCAC and SCBC MFCs

Both SCAC and SCBC significantly reduced COD from 558.67 mg/L to 137.83 mg/L (SCAC) and 101.5 mg/L (SCBC) (Table 4.1), with reductions well beyond the 60 mg/L standard for the "Blue" category according to Zimbabwe Effluent Standards for discharge according to the Environmental Management (Appendix 1). This suggests that both prototypes substantially improve water quality, though not to a level that meets the strictest environmental safety standards. The p-value (0.03) confirms that the reductions are statistically significant for both systems. Phosphorous was reduced to 5.77 mg/L (SCAC) and 4.48 mg/L (SCBC), both exceeding the blue and green effluent standards (≤0.5 mg/L and ≤1.5 mg/L, respectively). Despite this, the reduction is significant for both prototypes ($p = 0.03$), indicating notable improvement in wastewater treatment even though the effluent remains classified in the red category.

SCBC achieved a significantly higher reduction in potassium compared to SCAC, with 7.72 mg/L vs 5.71 mg/L, respectively ($p = 0.01$). These reductions are below the threshold for potassium listed in the red category (above 500 mg/L), meaning that both systems effectively reduce potassium to safe levels in this context. Both prototypes achieved significant reductions in nitrogen, with final values of 0.23 mg/L (SCAC) and 0.16 mg/L (SCBC), well below the ≤3 mg/L allowed in the blue category. This positions both prototypes as highly effective in nitrogen removal. The post-treatment pH for SCAC (6.86) and SCBC (8.44) falls within the blue category range of 6-9, aligning well with environmental safety standards.

The post-treatment EC values for both prototypes were around 1130-1144 µS/cm, which is slightly above the blue standard (≤1000 µS/cm), but still within safe ranges as per the green category (≤2000 µS/cm). This indicates moderate improvement in water quality. SCBC achieved better removal of grease and oils (14 mg/L) compared to SCAC (30.82 mg/L), but both values exceed the green effluent standard (≤5 mg/L). While significant improvements were noted, neither prototype reaches environmentally safe levels for grease and oils. The TDS increased slightly in both SCAC and SCBC after treatment, with values of 800 mg/L and 840 mg/L, respectively. These values remain within the blue and green standards (≤500 mg/L and ≤1500 mg/L), indicating that both systems produce effluent that meets acceptable environmental criteria.

Overall, both SCAC and SCBC were effective in reducing COD, phosphorous, potassium, nitrogen, and pH. SCBC was significantly more effective in potassium removal and pH adjustment, but for other parameters, including COD, phosphorous, nitrogen, electrical conductivity, grease and oils, and TDS, there were no significant differences between the two prototypes.

Table 4.1:Wilcoxon Signed-Rank Test Results for Before and After Wastewater Treatment Measurements, and Wilcoxon Rank-Sum Test for Comparing Treatment Efficiency Between SCAC and SCBC MFC Prototypes

Wastewater Parameter	**SCAC Before Treatment**	**SCAC After Treatment**	**SCAC (mean difference)**	**SCAC (p-value)**	**SCBC Before Treatment**	**SCBC After Treatment**	**SCBC (mean difference)**	**SCBC (p-value)**	**SCAC VS SCBC (p-value)**
COD (mg/L)	558.67	137.83	420.83 ± 56.17	0.03	558.67	101.5	457.17 ± 87.99	0.03	0.30
Phosphorous (mg/L)	19.83	5.77	14.07 ± 1.44	0.03	19.83	4.48	15.35 ± 1.44	0.03	0.13
Potassium (mg/L)	8.90	3.19	5.71 ± 0.21	0.03	8.90	1.18	7.72 ± 0.10	0.03	0.01
Nitrogen (mg/L)	2.62	0.23	2.39 ± 1.4	0.03	2.62	0.16	2.46 ± 1.40	0.03	0.38
pH	5.67	6.86	1.19 ± 0.22	0.04	5.67	8.44	2.77 ± 0.21	0.04	0.004
EC (µs/cm)	1291	1130	161.83 ± 62.38	0.03	1291	1144	147.33 ± 147.56	0.06	0.81
Grease and Oils (mg/L)	59.00	30.82	28.19 ± 30.97	0.09	59.00	14.00	45 ± 13.90	0.03	0.38
TDS (mg/L)	794.00	800.00	-5.83 ± 117.84	1	794.00	840.00	-45.83 ± 127.58	0.60	0.58

Figure 4.1 shows the treatment efficiency as a percentage of various wastewater parameters for both SCAC and SCBC MFC prototypes. Both prototypes exhibited the highest treatment efficiency in pH (94% and 99% respectively), followed by total nitrogen (91% and 94% respectively), COD (75% and 82% respectively). Both prototypes demonstrated low treatment efficiency in removing Grease and Oils (39% for SCAC and 31% for SCBC), Total Dissolved Solids (0% for both prototypes), and Electrical Conductivity (12% for SCAC and 11% for SCBC). Overall, SCBC MFC prototypes showed better treatment efficiency across all wastewater parameters except grease and oils. However, SCAC MFC prototypes exhibited higher treatment efficiency for COD compared to SCAC MFC prototypes.

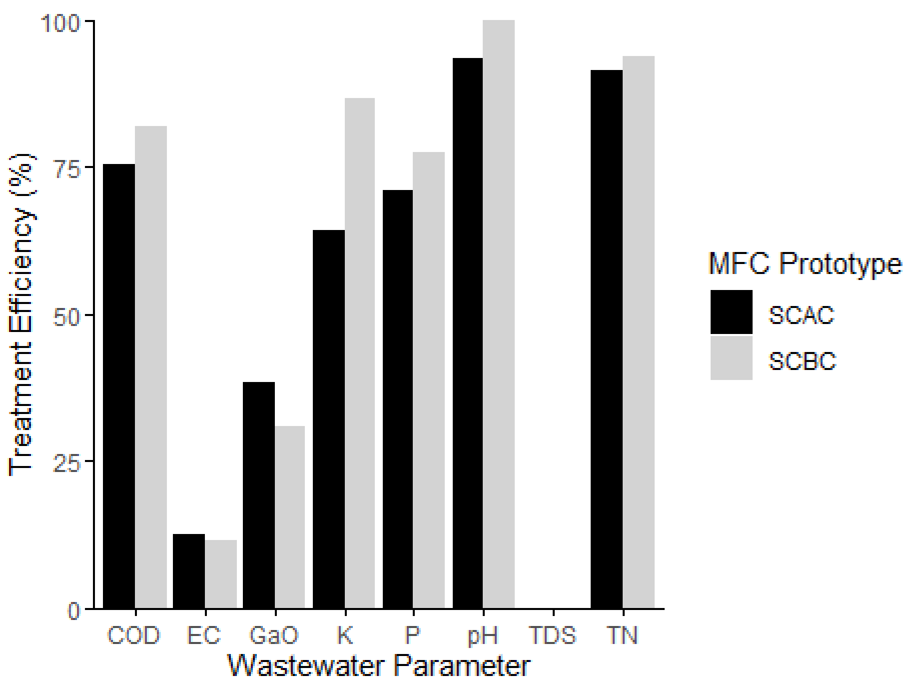

Figure 4.1:Wastewater treatment efficiency (%) of wastewater parameters for SCAC and SCBC MFC prototypes

4.2.2 Pre- and Post-Treatment Assessment of Domestic Wastewater of DCAC and DCBC MFCs

The Wilcoxon Signed-Rank and Rank-Sum Test results indicate that both DCAC and DCBC MFC prototypes significantly reduced several key wastewater parameters, with some notable differences in efficiency. The most significant reductions were observed in COD, phosphorous, and potassium concentrations, all of which showed p-values of 0.03 for the within-prototype comparisons. Between the two prototypes, DCBC was consistently more effective than DCAC, particularly for COD ($p = 0.01$), phosphorous ($p = 0.01$), and potassium ($p = 0.01$), but there were no significant differences for parameters like nitrogen, pH, electrical conductivity (EC), grease and oils, and total dissolved solids (TDS).

The reduction in COD from 558.67 mg/L to 95 mg/L for DCAC and to 23 mg/L for DCBC represents a significant improvement in organic pollutant removal, bringing the effluent within the "Yellow" category (60 mg/L - 150 mg/L) for DCAC and the "Blue" category (≤60 mg/L) for DCBC. This means that DCBC meets Zimbabwe's Environmental Management (Effluent and Solid Waste Disposal Regulations), which is essential for achieving environmentally safe discharge into water bodies. For practical domestic wastewater treatment, this result demonstrates the high potential of DCBC MFCs for reducing COD levels to meet local environmental standards, while DCAC may require further optimization to meet the blue category. Both prototypes reduced phosphorous levels significantly, with DCBC outperforming DCAC (mean reductions of 16.06 mg/L vs. 12.01 mg/L). However, even after treatment, the concentrations remained above the red category threshold (≤5 mg/L) with final levels of 7.83 mg/L for DCAC and 3.77 mg/L for DCBC. These results indicate that while DCBC is more effective, neither prototype can fully meet the blue category standard for phosphorous (≤0.5 mg/L). In practical terms, this suggests that MFC technology, while improving phosphorous removal, may need to be coupled with additional treatment processes to meet the strictest effluent standards for phosphorous.

For potassium, DCBC again showed a greater reduction (from 8.9 mg/L to 0.93 mg/L) compared to DCAC (from 8.9 mg/L to 3.56 mg/L). Both systems met the "Blue" category standard since there are no specific effluent limits for potassium in Zimbabwe's regulations. This reduction is beneficial for minimising nutrient loads in receiving water bodies, which could help mitigate issues like eutrophication. Nitrogen concentrations were reduced by both prototypes to near-zero levels (below 0.32 mg/L), well within the "Blue" category (≤3 mg/L). This substantial reduction is critical for preventing the nitrogen-driven eutrophication of aquatic ecosystems. Both prototypes also brought the pH levels into the safe 6-9 range required by the "Blue" category, reflecting their effectiveness in maintaining environmentally friendly effluent pH levels. For electrical conductivity (EC), neither prototype performed optimally, as final EC levels far exceeded the blue category limit of ≤1000 µS/cm, with 16410 µS/cm for DCAC and 15355 µS/cm for DCBC. Despite the statistically significant changes within each prototype, the treatment process did not significantly reduce EC between the two systems ($p = 0.17$). This indicates that the prototypes were not effective in addressing salinity-related issues in the wastewater, suggesting the need for further optimisation to meet effluent standards for EC.

Both DCAC and DCBC MFCs struggled to significantly reduce grease and oil concentrations ($p = 0.44$ for DCAC and $p = 0.31$ for DCBC), and neither prototype achieved the blue category standard (≤2.5 mg/L). Similarly, for TDS, both systems showed increased concentrations post-treatment, which exceeded the acceptable limits of ≤1500 mg/L for the blue category and fell within the yellow category (≤2000 mg/L). These results imply that while MFC technology is effective for some pollutants, additional treatment stages may be required to meet standards for parameters like TDS and grease and oils.

Overall, both prototypes achieved significant improvements in reducing COD, phosphorous, potassium, and nitrogen levels, with DCBC consistently outperforming DCAC. However, in terms of meeting Zimbabwe's environmental standards, only DCBC fully complied with the standards for COD, while neither prototype met the strictest requirements for phosphorous, EC, grease and oils, or TDS. For real-world applications, the ability of MFCs to bring wastewater parameters into compliance with regulatory standards holds great potential, but some pollutants may require additional treatment to ensure environmentally safe effluent discharge.

Table 4.2:Wilcoxon Signed-Rank Test Results for Before and After Wastewater Treatment Measurements, and Wilcoxon Rank-Sum Test for Comparing Treatment Efficiency Between DCAC and DCBC MFC Prototypes

Wastewater Parameter	**DCAC Before Treatment**	**DCAC After Treatment**	**DCAC (mean difference)**	**DCAC (p-value)**	**DCBC Before Treatment**	**DCBC After Treatment**	**DCBC (mean difference)**	**DCBC (p-value)**	**DCAC VS DCBC (p-value)**
COD (mg/L)	558.67	95.00	463.67 ± 29.69	0.03	558.67	23.00	535.67 ± 13.63	0.03	0.01
Phosphorous (mg/L)	19.83	7.83	12.01 ± 1.42	0.03	19.83	3.77	16.06 ± 1.44	0.03	0.01
Potassium (mg/L)	8.90	3.56	5.34 ± 0.10	0.03	8.90	0.93	7.97 ± 0.09	0.03	0.01
Nitrogen (mg/L)	2.62	0.32	2.30 ± 1.40	0.03	2.62	0.14	2.48 ± 1.41	0.03	0.38
pH	5.67	7.77	2.10 ± 0.22	0.04	5.67	7.79	2.12 ± 0.33	0.04	1
EC (µs/cm)	1291	16410	-15118.7 ± 1348.18	0.03	1291	15355	-14063.7 ± 2306.37	0.03	0.17
Grease and Oils (mg/L)	59.00	57.83	1.18 ± 47.25	0.44	59.00	68.17	-9.17 ± 19.97	0.31	0.94
TDS (mg/L)	794.00	10000.00	-9206.33 ± 113.32	0.03	794.00	9750.00	-8956.33 ± 296.38	0.03	0.16

Figure 4.2 shows the treatment efficiency as a percentage of various wastewater parameters for both DCAC and DCBC MFC prototypes. Both prototypes exhibited the highest treatment efficiency in pH (99%), followed by total nitrogen (88% for DCAC and 95% for DCBC) and COD (83% for DCAC and 95% for DCBC). Both prototypes demonstrated low treatment efficiency in removing Grease and Oils (23% for DCAC and 15% for DCBC), as well as for Total Dissolved Solids and Electrical Conductivity (0% for both prototypes). Overall, DCBC MFC prototypes showed better treatment efficiency across most wastewater parameters, including pH, total nitrogen, phosphorus (81%), potassium (90%), grease and oils, and electrical conductivity, except for grease and oils. However, DCAC MFC prototypes exhibited better treatment efficiency for grease and oils compared to DCBC MFC prototypes.

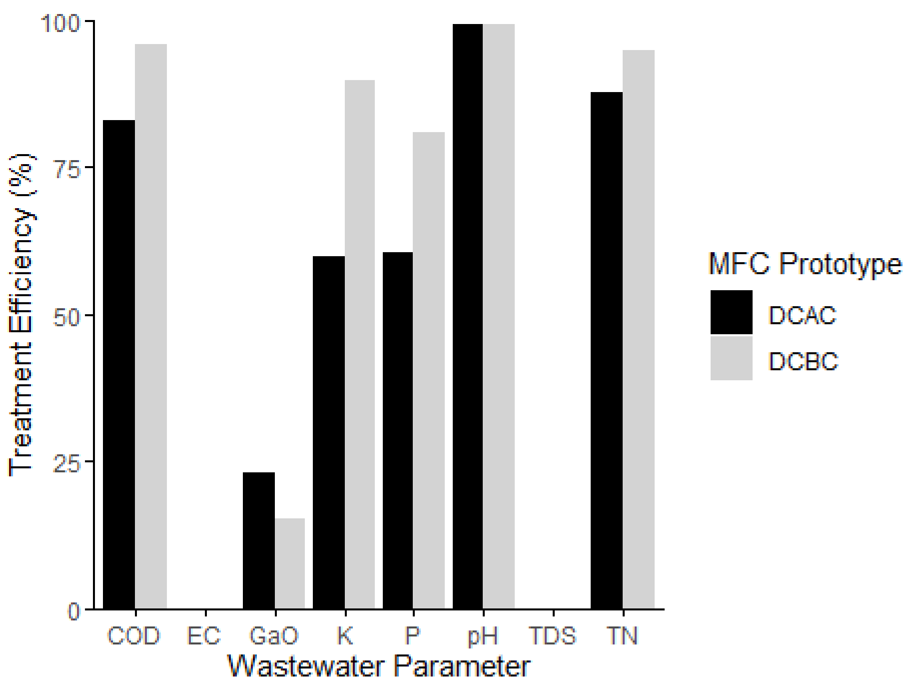

Figure 4.2: Wastewater treatment efficiency (%) of wastewater parameters for DCAC and DCBC MFC prototypes

4.2.3 Pre- and Post-Treatment Assessment of Domestic Wastewater of Double Chamber and Single Chamber MFCs

The study evaluated the effectiveness of Double Chamber (DC) and Single Chamber (SC) Microbial Fuel Cells (MFCs) in treating domestic wastewater, focusing on key parameters such as Chemical Oxygen Demand (COD), pH, Electrical Conductivity (EC), Total Dissolved Solids (TDS), phosphorous, nitrogen, potassium, and grease and oils. Both MFC types demonstrated significant reductions in several parameters, though their performance varied. In terms of COD, both DC and SC MFCs showed a significant reduction after treatment, with the Double Chamber MFC achieving an average reduction of 499.67 mg/L and the Single Chamber MFC reducing COD by 439 mg/L. This level of reduction aligns with regulatory standards set by Zimbabwe's Environmental Management Agency (EMA), where the safe discharge limit for COD is ≤60 mg/L. While both systems performed well, the difference between them was not statistically significant ($p = 0.057$), indicating that both are comparably effective in reducing COD levels to meet effluent standards.

For phosphorous, both DC and SC MFCs achieved substantial reductions (14.03 mg/L and 14.71 mg/L, respectively), with no significant difference between them ($p = 0.665$). However, these levels are above the EMA's blue category threshold of ≤0.5 mg/L, indicating that neither system sufficiently reduces phosphorous to meet the effluent standards. Despite this, the reductions are noteworthy and could contribute to improvements in overall wastewater quality. The study also found that both MFC types were equally effective in reducing potassium (DC: 6.66 mg/L, SC: 6.72 mg/L), nitrogen (DC: 2.39 mg/L, SC: 2.42 mg/L), and pH changes (DC: 2.11, SC: 1.98), with no significant differences observed. The pH adjustments are particularly relevant, as both MFCs shifted wastewater pH towards neutral levels, fitting within the EMA's safe discharge range of 6–9 for domestic wastewater.

Electrical conductivity (EC) was a parameter where significant differences were noted between the MFC types. The Single Chamber MFC showed a substantial improvement, with a reduction of 154.58 µS/cm, while the Double Chamber MFC actually increased EC levels by -14591 μS/cm, indicating decreased treatment efficiency for this parameter. The Single Chamber MFC's EC reduction aligns more closely with EMA's green category standard for effluent discharge (≤2000 μS/cm), while the Double Chamber MFC's post-treatment EC far exceeds this limit, marking a clear disadvantage in treating EC. For grease and oils, the Single Chamber MFC outperformed the Double Chamber, achieving a significant reduction (36.60 mg/L, $p = 0.001$), while the Double Chamber MFC did not show a significant improvement ($p = 0.203$). According to the EMA standards, grease and oil concentrations should not exceed 2.5 mg/L for safe discharge, highlighting the importance of this reduction. Though the Single Chamber MFC made progress, the post-treatment levels remain above acceptable limits, suggesting room for further improvement in treatment efficacy. Total Dissolved Solids (TDS) presented challenges for both MFC types. The Double Chamber MFC significantly increased TDS after treatment (-9081.33 mg/L), while the Single Chamber MFC showed a minimal and non-significant increase (-25.83 mg/L). Both systems failed to reduce TDS to acceptable EMA standards (≤500 mg/L for blue category), indicating that neither was effective in managing this parameter.

Overall, both MFC prototypes demonstrated significant treatment effects across several parameters. The Single Chamber MFC was more effective in reducing electrical conductivity and grease and oils, while both systems were similarly effective in reducing COD, phosphorous, potassium, nitrogen, and pH. However, neither system successfully managed Total Dissolved Solids, and additional interventions may be required to meet the EMA effluent standards for this parameter. Overall, these findings highlight the potential of MFCs in domestic wastewater treatment, while also pointing to areas for further optimisation to ensure compliance with environmental regulations.

Table 4.3: Wilcoxon Signed-Rank Test Results for Before and After Wastewater Treatment Measurements, and Wilcoxon Rank-Sum Test for Comparing Treatment Efficiency Between Single Chamber and Double Chamber MFC Prototypes

Wastewater Parameter	**Double Chamber Before Treatment**	**Double Chamber After Treatment**	**Double chamber (mean difference)**	**Double chamber (p-value)**	**Single Chamber Before Treatment**	**Single Chamber After Treatment**	**Single chamber (mean difference)**	**Single chamber (p-value)**	**Double chamber VS Single chamber (p-value)**
COD (mg/L)	558.67	59.00	499.67 ± 43.58	0.0005	558.67	119.67	439 ± 72.89	0.0005	0.057
Phosphorous (mg/L)	19.83	5.80	14.03 ± 2.52	0.0005	19.83	5.12	14.71 ± 1.49	0.0005	0.665
Potassium (mg/L)	8.90	2.24	6.66 ± 1.38	0.0005	8.9	2.18	6.72 ± 1.06	0.0005	0.977
Nitrogen (mg/L)	2.62	0.23	2.39 ± 1.34	0.0005	2.62	0.19	2.42 ± 1.33	0.0005	0.977
pH	5.67	7.78	2.11 ± 0.27	0.002	5.67	7.65	1.98 ± 0.85	0.002	1
EC (µs/cm)	1291	15883	-14591 ± 1883.51	0.0005	1291	1137	154.58 ± 108.28	0.0001	0.00004
Grease and Oils (mg/L)	59.00	63.00	-4 ± 35	0.203	59.00	22.41	36.60 ± 24.52	0.001	0.002
TDS (mg/L)	794.00	9875.00	-9081.33 ± 250.62	0.002	794.00	820.00	-25.83 ± 118.94	0.58	0.00003

Figure 4.3 shows the treatment efficiency as a percentage of various wastewater parameters for both double chamber and single chamber MFC prototypes. Both prototypes exhibited the highest treatment efficiency in pH (99%), followed by total nitrogen (92%), COD, and potassium (75%). The treatment efficiency for total phosphorus was similar between the prototypes, with double chamber MFCs at 71% and single chamber MFCs at 74%.Both prototypes demonstrated low treatment efficiency in removing Grease and Oils (19% for double chamber and 34% for single chamber), Total Dissolved Solids (0% for both prototypes), and Electrical Conductivity (0% for double chamber and 11% for single chamber).Overall, single chamber MFC prototypes showed better treatment efficiency across most wastewater parameters, including pH, total nitrogen, phosphorus, potassium, grease and oils, and electrical conductivity. However, double chamber MFC prototypes exhibited higher treatment efficiency for COD compared to single chamber MFC prototypes.

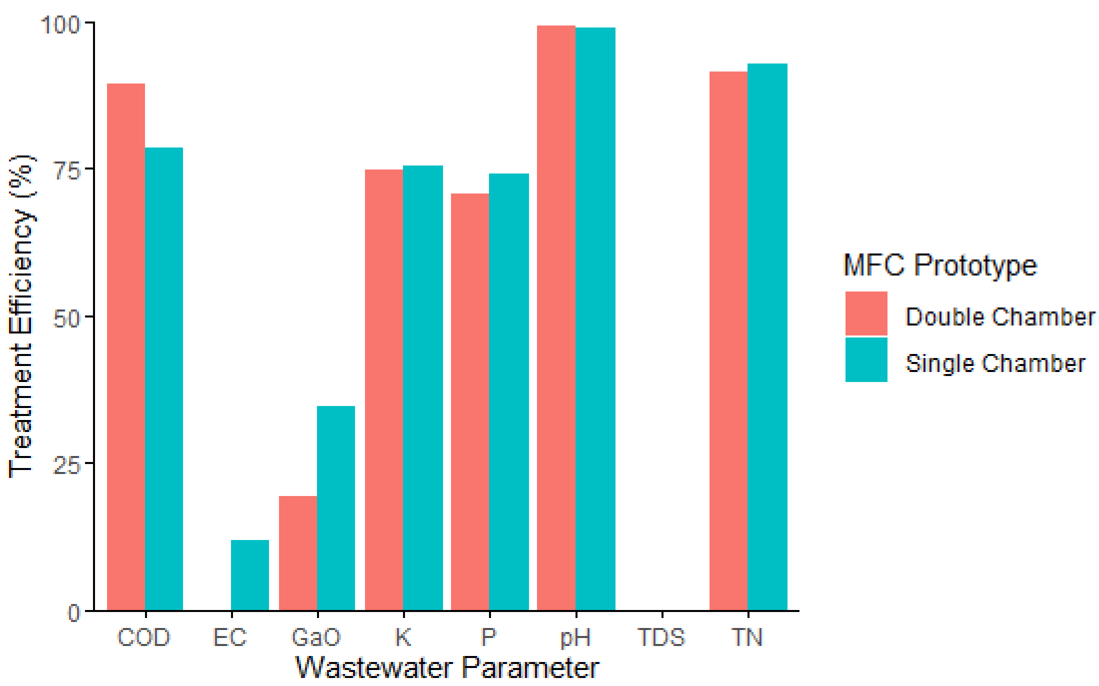

Figure 4.3: Wastewater treatment efficiency of wastewater parameters for Double Chamber and Single Chamber MFC prototypes

4.4 Electricity Generation Assessment

4.4.1 To compare and assess the electricity generated between SCAC and SCBC MFC prototypes

Figure 4.4 shows the voltage and current produced by SCAC and SCBC MFC prototypes over a 32-day period. To determine which prototypes produced higher voltage and current, measures of central tendency were calculated. SCAC MFC prototypes produced more voltage and current compared to SCBC MFC prototypes. The voltage for SCAC MFC prototypes had a median of 6.3 mV, a mean of 23 mV, and ranged from -141 mV to 163 mV. The current had a median of 3.15 µA, a mean of 22.68 µA, and ranged from -207 µA to 240 µA. For SCBC MFC prototypes, the voltage had a median of 7 mV, a mean of 7.46 mV, and ranged from -28 mV to 46 mV. The current had a median of 2.3 µA, a mean of 5.26 µA, and ranged from -41 µA to 51 µA. Overall, SCAC MFC prototypes produced more voltage and current values compared to SCBC MFC prototypes. Both prototypes performed better during the first ten days, after which the voltage and current reduced and stabilized at lower levels over the remainder of the 32-day period. There was a significant difference in the voltage and current between the two MFC prototypes (Mann-Whitney U test, $p < 0.05$).

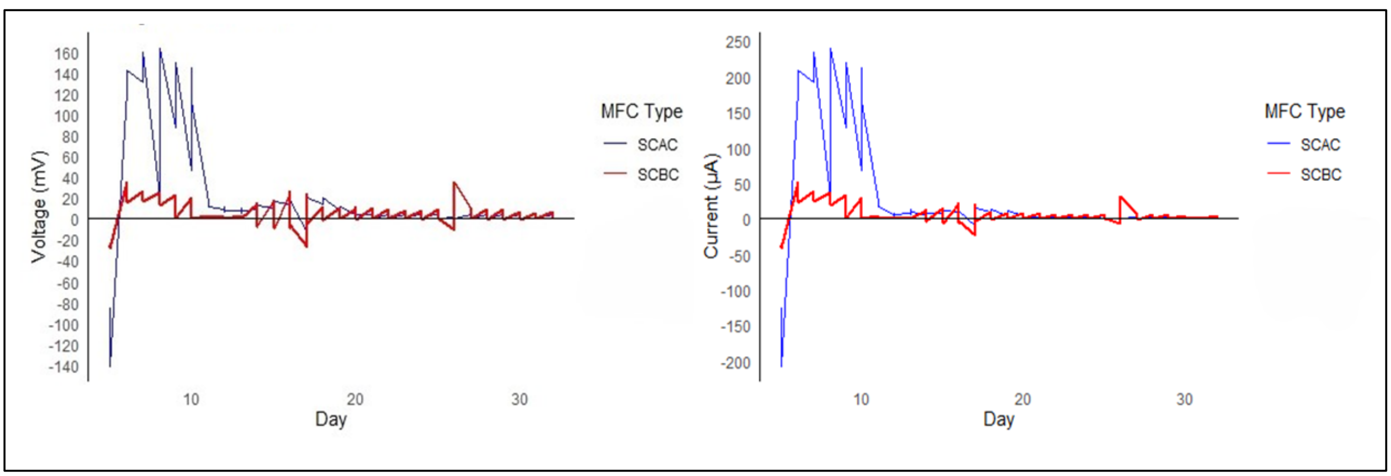

Figure 4.4: Voltage and current produced by DCAC and DCBC MFC prototypes over a 32-day period

4.4.2 To compare and assess the electricity generated between DCAC and DCBC MFC prototypes

Figure 4.5 shows the voltage and current produced by DCAC and DCBC MFC prototypes over a 32-day period. To determine which prototypes produced higher voltage and current, measures of central tendency were calculated. DCAC MFC prototypes produced more voltage and current compared to DCBC MFC prototypes. The voltage for DCAC MFC prototypes had a median of 2.05 mV, a mean of 22.63 mV, and ranged from -501 mV to 504 mV. The current had a median of 0.9 µA, a mean of 6.83 µA, and ranged from -736 µA to 669 µA. For DCBC MFC prototypes, the voltage had a median of -1 mV, a mean of 5.47 mV, and ranged from -493 mV to 528 mV. The current had a median of -2.65 µA, a mean of -8.08 µA, and ranged from -725µA to 776 µA. DCBC MFC prototypes produced more negative voltage and current values compared to DCAC MFC prototypes. Both prototypes performed better during the first ten days, after which the voltage and current reduced and stabilized at lower levels over the remainder of the 32-day period. There was a significant difference in the voltage and current between the two MFC prototypes (Mann-Whitney U test, $p < 0.05$).

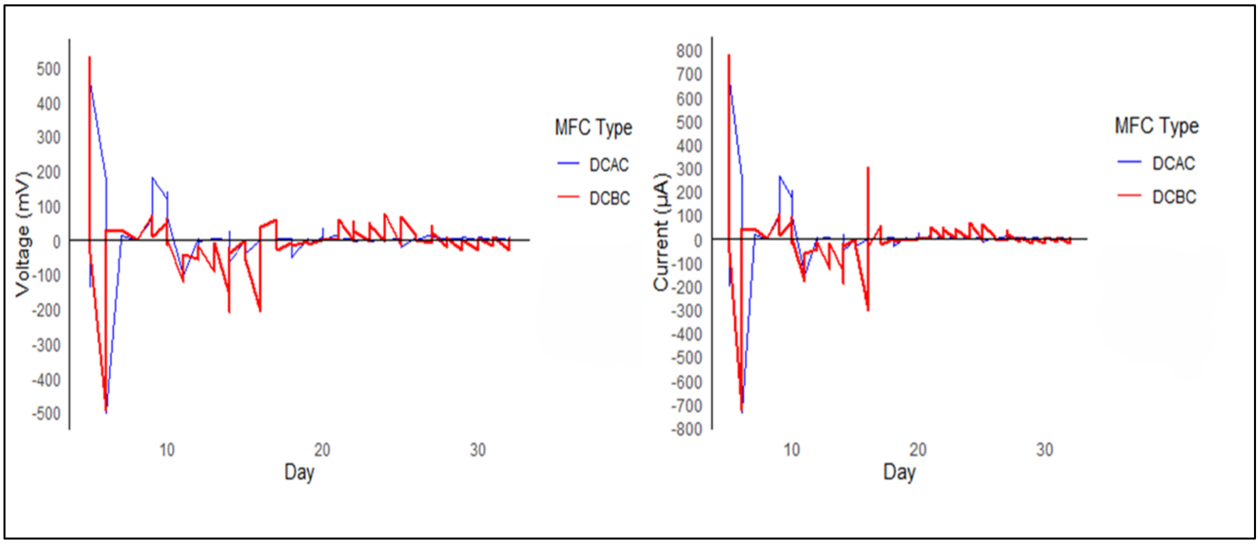

Figure 4.5: Voltage and current produced by DCAC and DCBC MFC prototypes over a 32-day period

4.4.3 To compare and assess the electricity generated between double chamber and single chamber MFC prototypes

Figure 4.6 shows the voltage and current produced by double chamber and single chamber MFC prototypes over a 32-day period. To determine which prototypes produced higher voltage and current, measures of central tendency were calculated. Single chamber MFC prototypes produced more voltage and current compared to double chamber MFC prototypes. The voltage for single chamber MFC prototypes had a median of 6.85 mV, a mean of 15.02 mV, and ranged from -141 mV to 163 mV. The current had a median of 2.9 µA, a mean of 13.97 µA, and ranged from -207 µA to 240 µA. For double chamber MFC prototypes, the voltage had a median of 1 mV, a mean of 14 mV, and ranged from -501 mV to 528 mV. The current had a median of 0.15 µA, a mean of -0.62 µA, and ranged from -737 µA to 776 µA. Although double chamber MFC prototypes produced more negative voltage and current values compared to single chamber MFC prototypes, overall, they produced the highest voltage and current. Both prototypes performed better during the first ten days, after which the voltage and current reduced and stabilized at lower levels over the remainder of the 32-day period. There was a significant difference in the voltage and current between the two MFC prototypes (Mann-Whitney U test, $p < 0.05$).

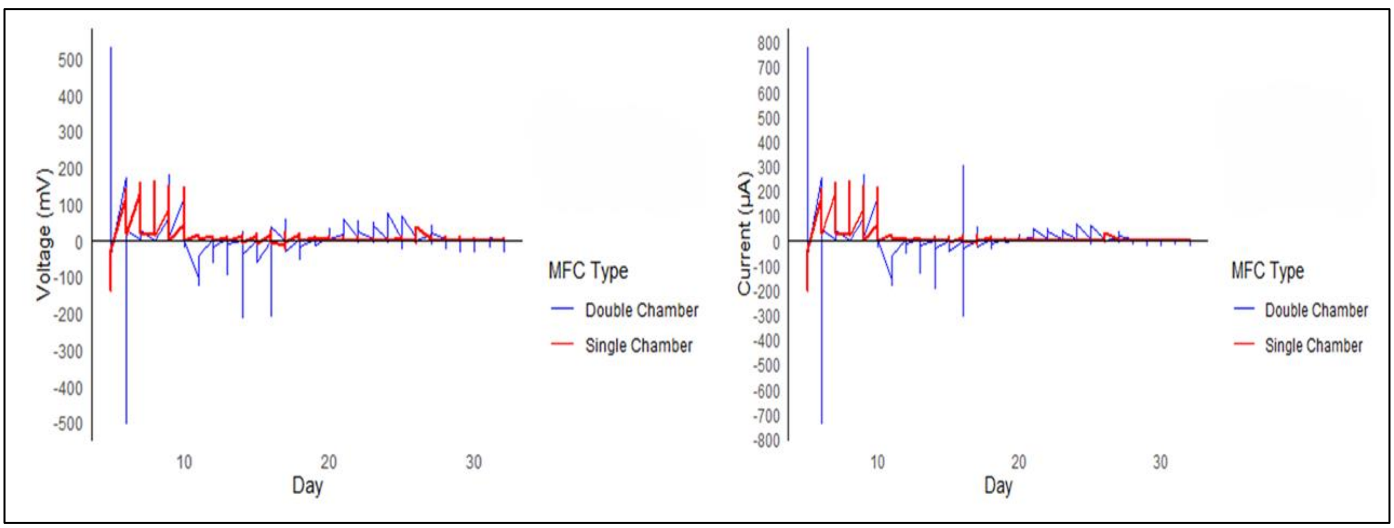

Figure 4.6: Voltage and current produced by Double chamber and Single chamber MFC prototypes over a 32-day period

4.4.4 Energy conversion efficiency across MFC prototypes

All MFC prototypes demonstrated high COD Removal Efficiency (%), indicating their effectiveness in treating wastewater. However, they all had very low energy conversion efficiency (Table 4.4). Comparing the Double Chamber and Single Chamber MFC prototypes, the Double Chamber prototypes showed better energy conversion efficiency (5.62%) compared to the Single Chamber prototypes (1.09%). Within the Double Chamber MFC prototypes, DCAC had a slightly higher energy conversion efficiency (3.14%) than DCBC (2.55%). For the Single Chamber MFC prototypes, both SCAC (1.09%) and SCBC (0.05%) exhibited very low energy conversion efficiencies. Overall, while all prototypes required high energy input, they produced very low energy output, resulting in low energy conversion efficiencies.

Table 4.4: COD Removal Efficiency (%) and Energy Conversion Efficiency of MFC prototypes

MFC TYPE	COD Removal Efficiency (%)	Energy input (J)	Energy Output (J)	Energy Conversion Efficiency (%)
DOUBLE CHAMBER	89.45	2910.60	163.61	5.62
SINGLE CHAMBER	78.53	2658.76	29.02	1.09
DCAC	83.01	2503.23	78.71	3.14
DCBC	95.89	3325.02	84.90	2.55
SCAC	75.31	2549.74	27.67	1.09
SCBC	81.75	2794.65	1.35	0.05

CHAPTER 5

DISCUSSION

5.1 Introduction

The objectives of this study were twofold: (i) to evaluate the effectiveness of different Microbial Fuel Cell (MFC) prototypes specifically, Single Chamber (SC) and Double Chamber (DC) configurations in treating domestic wastewater, and (ii) to compare and assess the electricity generation capabilities of these MFC prototypes in terms of current, voltage, and energy conversion efficiency. The assessment of wastewater treatment focused on key parameters such as Chemical Oxygen Demand (COD), pH, Electrical Conductivity, Total Dissolved Solids (TDS), Phosphorous, Nitrogen, Potassium, and Grease and Oils. Meanwhile, the electricity generation capabilities were evaluated by analysing the current and voltage output and calculating the energy conversion efficiency of each prototype. The MFC prototypes were categorised into four groups: SCAC (Single Chamber Activated Carbon Cathode), SCBC (Single Chamber Biochar Cathode), DCAC (Double Chamber Activated Carbon Cathode), and DCBC (Double Chamber Biochar Cathode).

Key findings from the first objective revealed that both Single Chamber (SCAC, SCBC) and Double Chamber (DCAC, DCBC) MFC prototypes effectively reduced COD, Phosphorous, Potassium, and Nitrogen levels in wastewater, with no significant differences between them for most parameters. However, SCBC was more effective in altering pH and reducing Potassium than SCAC, while DCBC showed greater reductions in COD, Phosphorous, and Potassium compared to DCAC. Both configurations demonstrated low efficiency in removing Grease and Oils, Electrical Conductivity, and Total Dissolved Solids (TDS).

For the second objective, results showed that Single Chamber MFCs generally produced higher voltage and current compared to Double Chamber MFCs, particularly in the initial ten days, before stabilising at lower levels. SCAC produced the highest voltage and current among Single Chamber

MFCs, while DCAC outperformed DCBC among Double Chamber MFCs. Despite these outputs, all prototypes exhibited low energy conversion efficiencies, with Double Chamber MFCs achieving slightly higher efficiency than Single Chamber MFCs.

The subsequent sections will delve deeper into these findings, comparing the performance of Single Chamber MFCs (SCAC vs. SCBC) and Double Chamber MFCs (DCAC vs. DCBC) in terms of both wastewater treatment efficiency and electricity generation. The discussion will further interpret these results in the context of existing literature, explore their implications for the practical application of MFC technology.

5.2 Pre- and Post-Treatment Assessment of Domestic Wastewater Using Microbial Fuel Cell Prototypes

5.2.1 Pre- and Post-Treatment Assessment of Domestic Wastewater of SCAC and SCBC MFCs

The similar efficiencies of SCAC and SCBC MFC prototypes in removing COD, phosphorous, potassium and nitrogen can be attributed to shared characteristics of activated carbon and biochar. According to Marzeddu et al. (2022), activated carbon and biochar possess mesoporous structures, with pore sizes ranging from 2 to 50 nm. Activated carbon exhibits exceptionally high surface areas, up to 3500 m^2/g, while biochar, although typically lower in surface area, remains effective depending on its production method (Coker et al., 2023; G. Li et al., 2023). These porous structures facilitate enhanced microbial colonisation and oxygen diffusion, crucial for efficient wastewater treatment in MFCs. They also both effectively catalyse the Oxygen Reduction Reaction (ORR), crucial for the MFC process and their similar electron transfer properties and high adsorption capacities for nutrients contribute to their equal performance in removing these wastewater parameters (Kottis et al., 2024; Marzeddu et al., 2022).

Both SCAC and SCBC prototypes resulted in an increase in pH, with SCBC MFCs demonstrating greater effectiveness in altering pH compared to SCAC MFCs. The increase in pH is noteworthy given that the optimal pH for microbial fuel cells (MFCs) and microbial electrolysis cells (MECs) in domestic wastewater treatment ranges between 6 and 7 (S. Li & Chen, 2018). According toHalim et al. (2021), the optimum operating pH for MFC containing municipal wastewater and hospital wastewater was found to be 8 which explains why SCBC prototypes were able to treat the wastewater better than SCAC.

Both prototypes demonstrated low treatment efficiency in removing grease and oils, electrical conductivity and total dissolved solids. According to Lawan et al. (2022), packing the cathode chamber with activated carbon significantly improves power density and COD removal efficiency in SCMFCs treating fats, oil and grease trap effluent. This therefore means fats, oil and grease removal is efficient in other MFC configurations. This was attributed to biofouling which was noticed on the cathodes of both prototypes. Specific bacteria might also be required to ensure efficient removal of these parameters in wastewater. In Industrial wastewater, MFC showed 17% Total Dissolved Solids removal (Prasad et al., 2015). Distillery wastewater was treated in Microbial Fuel Cell (MFC), the removal of dissolved solids in both single and double chambered MFC was found to be 48% (Hampannavar & Pradeep, 2011). This suggests that MFCs are not effective at removing TDS and other parameters. Biofilms also formed on the stainless-steel mesh side of both cathodes for the two prototypes. Biofilm formation can result in biofouling which results in a decrease in MFC performance (Bilgiç, 2023). Cleaning methods and catalyst regeneration techniques are essential for maintaining long-term stability and performance of SCMFCs. Removing biofouling from both the surface and inside the catalyst layer can significantly enhance power density and wastewater treatment (Al Lawati et al., 2019a; D. Li et al., 2016).

5.2.2 Pre- and Post-Treatment Assessment of Domestic Wastewater of DCAC and DCBC MFCs

Both DCAC and DCBC prototypes showed statistically significant decreases in COD, phosphorous and potassium, nitrogen levels after treatment with DCBC MFCs showing greater reduction in COD, phosphorous and potassium levels compared to DCAC MFCs. For pH, DCAC and DCBC MFCs showed statistically significant difference in wastewater treatment. However, there was no significant difference in treatment efficiency between DCAC and DCBC MFCs in pH. Biochar-based MFCs have shown high efficiency in reducing chemical oxygen demand (COD) and adsorbing nutrients like phosphorus and potassium due to their enhanced microbial activity and adsorption capacity making it effective in reducing these elements from wastewater

(T. M. Huggins et al., 2016). The addition of GAC to the cathode chamber promotes oxygen reduction reactions(Tursun et al., 2016; Yap et al., 2021). While both materials are effective, biochar often shows superior performance in nutrient recovery and sustainability. Activated carbon, on the other hand, may offer higher power densities but at a higher cost and environmental impact (Díaz et al., 2024; T. M. Huggins et al., 2016).

Both prototypes failed to reduce TDS concentrations and Electrical Conductivity and had low treatment efficiency in removing Grese and Oils. The choice of electrode material and its configuration can significantly impact the performance of MFCs. If the electrodes are not optimised for the specific contaminants, it can lead to poor treatment efficiency (Gurikar et al., 2021). Thus, the electrodes used for both prototypes may not be effective in removing these parameters. In addition, the microbial community in the MFCs might not be well-suited for degrading grease and oils. Certain bacteria are more effective at breaking down these compounds, and their absence or low abundance can result in poor removal efficiency (L. Zhang et al., 2011). Grease and oils are hydrophobic and can form a layer on the surface of the electrodes, hindering the contact between the microbes and the contaminants. This can reduce the efficiency of biodegradation (Sheela, 2020).

During the experiment, natural algae growth was observed in the anode chambers of both DCAC and DCBC MFC prototypes. The presence of algae could have contributed to the degradation of COD and nutrients in the wastewater, as algae are photosynthetic organisms capable of breaking down organic matter. However, the oxygen produced by the algae posed a challenge to maintaining the necessary anaerobic conditions in the anode chamber. The introduction of oxygen led to the formation of rust (Figure 5.1) around the anode electrodes and within the wastewater, which increased electrical conductivity and total dissolved solids (TDS) levels. Additionally, the rust formation caused damage to the biofilm, which is critical for the optimal performance of microbial fuel cells (Santoro et al., 2020). This therefore affected the wastewater treatment efficiency of the MFCs.

Microalgae based MFCs are an efficient system for removing nitrogen, phosphorus and carbon dioxide from wastewater and bioelectricity production. However, its challenge is in oxygen cross over (Arun et al., 2020a). There is therefore need to select algal strains that are suitable for use in both the anode and cathode compartments.

Figure 5.1: Shows rust and algae on the anode electrode of Double Chamber MFC

5.2.3 Pre- and Post-Treatment Assessment of Domestic Wastewater of Double Chamber and Single Chamber MFCs

Both the Double Chamber and Single Chamber MFCs demonstrated a significant reduction in COD, phosphorous, potassium, nitrogen after treatment. Both chambers were comparably effective in reducing COD phosphorous, potassium, nitrogen. Both MFC types caused significant changes in the pH of the wastewater, however, the comparison between the two prototypes revealed no significant difference, indicating that both MFCs alter pH to a similar extent. Though both Double Chamber and Single Chamber MFCs had low treatment efficiency in removing Grease and Oils, Single Chamber MFCs had a slightly higher treatment efficiency. Both protypes were not efficient in TDS removal. Double Chamber MFCs could not reduce Electrical Conductivity, however, Single Chamber MFCs slightly removed Electrical Conductivity. Overall, Single Chamber MFCs showed better wastewater treatment efficiency than Double Chamber MFCs. This is because Double Chamber MFCs tend to have higher internal resistance, which can reduce overall efficiency whilst, Single Chamber MFCs generally have lower internal resistance, which can improve power output (Golzarian et al., 2024). The air cathode is the most feasible cathode configuration because it increases oxygen acceptor surface area that greatly reduces energy consumption for wastewater treatment (Pasupuleti et al., 2015).

Both Single Chamber and Double Chamber MFCs failed to effectively remove grease and oils. In a study by Sharma et al. (2023), 7.3 folds of power density and 3.3 folds enhancement in current density were observed at 1% of fats, oil and grease (FOG) in wastewater but only produced. Whilst at 1.5% FOG augmentation to the anode, the power density gradually decreased to 3.25 folds whereas the current density reduced to 2.6 folds. This was attributed to the excess FOG addition that disturbs the electrogenic microbial diversity. The biodegradation and bioelectricity generation under high FOG loading was comparatively low. High concentrations of FOG can inhibit the activity of electroactive microbes in the anode chamber. In contrast, in a study by Huarachi-Olivera et al. (2018), there was 95% removal of oils and fats in the catholyte from an initial concentration of oils 2634 mg/L to 143 mg/L after 32 days. This was attribute to the use of the microalga Chlorella vulgaris and bacterial communities. This therefore means that for grease and oils to be removed in wastewater during MFC treatment specific microbial communities have to be introduced in the MFC to ensure efficient treatment of grease and oils in wastewater.

Algae was unintentionally introduced in the MFCs as it was present in the domestic wastewater the algae then started to grow due to light exposure. Therefore, the algae together with the active bacteria played a crucial role in removing COD, Phosphorous, Nitrogen and Potassium in the wastewater. This can be supported by other studies that the presence of algae in the anode chamber can results in COD and nutrient removal. In a study by Velasquez-Orta et al. (2009), algae present in the substrate had an effect on the final COD removal obtained and the type of microbial communities present. Algae can also donate electrons to the anode with the electrons generated by a combination of photosynthesis and respiration (He et al., 2017b; Thorne et al., 2011). Shukla & Kumar (2018), reported studies where algae were used as the only source of electron donor with a maximum voltage of 0.792 V by *Tetraselmis gracilis*. According to (Arun et al., 2020b), the use of algae for cathodic reactions reduces the cost for mechanical aeration can due to the oxygen produced by algal photosynthesis and uptake of carbon dioxide, Nitrogen and Phosphorous during the light period in the anode chamber.

The results of the Double Chamber (DC) and Single Chamber (SC) MFCs were compared to the Zimbabwe Environmental Management Agency (EMA) effluent standards (Appendix 1), which classify wastewater parameters based on environmental safety: blue indicates environmentally safe, green indicates low environmental hazard, yellow indicates medium environmental hazard, and red indicates high environmental hazard.

After treatment, the COD levels for the DC MFCs were classified as environmentally safe (blue), while the SC MFCs were categorized as a medium environmental hazard (yellow). Potassium levels for both Single and Double chamber configurations were within the safe zone (blue). Phosphorous levels, despite showing significant removal, remained in the high environmental hazard category (red) for both configurations. Nitrogen and pH levels for both MFC types were classified as environmentally safe (blue). Electrical conductivity was considered a high environmental hazard (red) for the DC MFCs but a low environmental hazard (green) for the SC MFCs. For grease and oils, both configurations were categorized as high environmental hazard (red). For total dissolved solids (TDS), DC MFCs fell into the high environmental hazard category (red), whereas SC MFCs were categorized as low environmental hazard (green).

COD for DC MFC is in safe levels most probably due to the presence of algae as previously mentioned not necessarily due to its effectiveness. Electrical Conductivity (EC) and Total Dissolved Solids (TDS) indicate differing performance between MFC types. DC MFCs pose a high environmental hazard for EC and TDS, whereas SC MFCs are considered a low hazard. This difference suggests that DC MFCs may contribute to higher levels of salts and other dissolved substances, potentially impacting water quality and ecosystem health. Grease and Oils remain a high environmental hazard for both MFC configurations, indicating that neither MFC type effectively reduces these substances to safe levels. This points to a need for additional treatment or alternative methods to address grease and oil contamination.

5.3 Electricity Generation Assessment

5.3.1 To compare and assess the electricity generated between SCAC and SCBC MFC prototypes

Both prototypes performed better during the first ten days, after which the voltage and current reduced and stabilised at lower levels over the remainder of the 32-day period. However, SCAC MFCs performed better than SCBC MFCs. This low performance is attributed to biofouling noticed at the cathode due the presence of algae in the chamber.The low voltage in SCBC MFCs is similar to the voltage obtained in a study by Hu et al. (2024), MFCs assembled using walnut shells as biochar generated a voltage of up to 75.26 mV at an external resistance of 1000 Ω. A low-cost biochar derived from corncob was prepared by a facile pyrolysis method and generated voltage of 0.221 V (M. Li et al., 2018b). However, Huggins et al. (2014) argues that biochar electrodes can achieve power outputs similar to GAC and graphite granules, while being 90% cheaper and having a reduced carbon footprint and it is a cost-effective and sustainable electrode material for electricity production in microbial fuel cells, comparable to granular activated carbon. Granular activated carbon air cathodes outperform biochar air cathodes in single-chamber MFCs for electricity generation due to enhanced cathode performance and power densities (Vargas et al., 2022). While both materials are effective, GAC often provides higher power densities due to its superior electrical conductivity. However, biochar might offer additional benefits in terms of sustainability and nutrient recovery (H. Roy et al., 2023; Yang et al., 2016). While both materials are effective, biochar often shows superior performance in nutrient recovery and sustainability. Activated carbon, on the other hand, may offer higher power densities but at a higher cost and environmental impact (Díaz et al., 2024; T. M. Huggins et al., 2016).

After wastewater treatment SCAC MFCs had a lower pH of 6.86 as compared to 8.44 of SCBC. In a study by G. S. Jadhav & Ghangrekar (2009), the highest current was generated at pH of 6.5 in the anodic chamber. Acidophilic pH in the anodic chamber showed effective performance with respect to power output, but no visible influence on wastewater treatment efficiency. Acidophilic pH microenvironments improve microbial fuel cell performance, while substrate degradation is higher in neutral conditions (Raghavulu et al., 2009). In contrast, Halim et al. (2021) found that the maximum output of current density, voltage, and power density in microbial fuel cells was obtained at pH 8; with the optimum operating pH for MFC containing municipal wastewater found to be 8.

During MFC operation, biofilms were seen forming on the cathodes for both SCAC and SCBC on the anode chamber side. In air-cathode MFCs, the diffusion of soluble metabolic products from bacteria favours the growth and development of fungi or bacteria, resulting in biofouling on the cathode or membrane which impedes the ORR and thus reduces the performance of MFCs (Noori et al., 2019). The presence of a biofilm can increase the internal resistance of the MFC. As the biofilm grows, it creates an additional barrier to ion transfer, increasing the ohmic resistance. This results in a decrease in the overall efficiency of the MFC, as more energy is lost to overcome this resistance (Al Lawati et al., 2019b).

5.3.2 To compare and assess the electricity generated between DCAC and DCBC MFC prototypes

DCAC MFC prototypes produced more voltage and current compared to DCBC MFC prototypes. DCBC MFC prototypes produced more negative voltage and current values compared to DCAC MFC prototypes. Both prototypes performed better during the first ten days, after which the voltage and current reduced and stabilized at lower levels over the remainder of the 32-day period. This suggests that the configuration of the DCAC prototypes might be more efficient in facilitating electrochemical reactions and electron transfer, likely due to factors such as better oxygen reduction at the cathode. Biochar, derived from wood-based sources, has demonstrated comparable power outputs to granular AC and graphite granules while being significantly more cost-effective and environmentally friendly(T. Huggins et al., 2014) which contrasts with results obtained in this experiment. The negative voltage and current recorded in both prototypes might have been as a result of rust and algae (Figure 5.1) present in the anode chambers resulting in decreased performance. The potential difference between the anode and cathode can sometimes result in negative voltage if the anode potential becomes more positive than the cathode potential. This can be influenced by the type of microorganisms, substrate concentration, and the materials used for electrodes and Negative current can occur if there is a reverse flow of electrons, which might be due to issues like biofilm detachment, changes in the microbial community, or disruptions in the electron transfer pathways (Hil Me et al., 2022; Santoro et al., 2022). Therefore, there is need to look into metal reducing bacteria such as *Geobacter sulfurreducens, Rhodoferax ferrireducens* and *Shewanella putrefaciens which* use insoluble electron acceptors such as Fe (III) Oxide to transfer electrons to the external circuit (Y. Zhang et al., 2009), thus reducing the amount of rust in wastewater.

5.3.3 To compare and assess the electricity generated between double chamber and single chamber MFC prototypes

Single chamber MFC prototypes produced more overall voltage and current compared to double chamber MFC prototypes. Although double chamber MFC prototypes produced more negative voltage and current values compared to single chamber MFC prototypes, overall, they produced the highest voltage and current. Both prototypes performed better during the first ten days, after which the voltage and current reduced and stabilized at lower levels over the remainder of the 32-day period. Single chambered MFC have reduced internal resistance (S. Roy et al., 2016) resulting in less negative voltage and current being recorded. A salt bridge is an economic alternative to highly priced proton exchange membranes in the construction of MFCs. It also acts as proton transfer channel from the anode to the cathode. However, it results in high internal resistance (Sudarsan et al., 2015). Which is why DC MFCs showed unstable performance. Another reason why there was low electricity generation is because municipal/domestic wastewater has lower BOD concentrations yielding low energy densities and it is difficult to maintain stable power production (Gude, 2016b; He et al., 2017a; Munoz-Cupa et al., 2021).

5.3.4 Energy conversion efficiency across MFC prototypes

All MFC prototypes demonstrated high COD removal efficiency, indicating their effectiveness in wastewater treatment, but had low energy conversion efficiency. Among the Single Chamber prototypes, both SCAC and SCBC exhibited very low energy conversion efficiencies. In comparison, within the Double Chamber prototypes, DCAC had a slightly higher energy conversion efficiency than DCBC. Overall, while all prototypes required high energy input, they produced low energy output, leading to low energy conversion efficiencies. This suggests that while the MFCs are successful in breaking down organic matter, they are not equally effective at converting the energy released during this process into usable electrical energy. Double Chamber prototypes were more efficient in energy conversion than Single Chamber prototypes. This improvement could be attributed to the separate anode and cathode chambers, which may provide more favourable conditions for microbial activity and energy conversion. The Double Chamber designs might allow for better control over environmental conditions, such as pH and oxygen levels, which can enhance microbial metabolism and electron transfer efficiency. MFCs is that it has a low energy harvesting efficiency whilst treating real wastewater and has unstable performance long-term (anode and membrane biofouling) (Ghadge, 2015). Low energy conversion efficiency in all the Microbial Fuel Cells can also be attributed to biofouling noted in the MFCs and wastewater concentration.

The MFC prototypes designed in this study demonstrated efficient wastewater treatment but relatively low electricity generation compared to similar prototypes discussed in the literature. Nevertheless, these MFC prototypes are well-suited and cost-effective for implementation in a Zimbabwean context. In terms of wastewater treatment, their performance is competitive with prototypes developed in more industrialised nations. However, significant improvements are needed in electricity generation, particularly in addressing the low energy conversion efficiency observed. If this challenge is not effectively managed, the MFC system may struggle to meet the country's energy demands.

5.4 Limitations of the study

A key limitation of this study was the constraint on resources. Initially, the aim was to evaluate the efficiency of various biochar types as cost-effective materials for MFC electrodes, assessing their performance in both wastewater treatment and electricity generation. However, budget limitations prevented testing across multiple prototypes, which would have increased costs. Additionally, the study sought to analyse the pore structure and surface area of the biochar compared to granular activated carbon powder, but due to financial constraints and the unavailability of necessary equipment at the university, sample testing could not be conducted. Another limitation was the focus on a single sampling site, the Fernlea Sewage Treatment Plant, which may not fully represent the diversity of wastewater treatment facilities in Zimbabwe. Finally, the bacteria and algae in the

MFC prototypes, which significantly influenced their performance, could not be identified due to budgetary restrictions.

CHAPTER 6

CONCLUSION AND RECOMMENDATIONS

6.1 Introduction

This chapter provides a summary of the key findings from the research on the fabrication of microbial fuel cell (MFC) prototypes, their effectiveness in wastewater treatment, and their potential for electricity generation. It also presents recommendations based on the results obtained, suggesting improvements in MFC design and operation, and identifies areas for future research to enhance the application of MFC technology in wastewater treatment and sustainable energy production.

6.2 Conclusion

The primary aim of this study was to design and fabricate microbial fuel cell (MFC) prototypes for the dual purpose of treating domestic wastewater and generating electricity. The study evaluated the efficacy of these MFCs in a Zimbabwean context, focusing on wastewater treatment efficiency and electricity generation capabilities.

6.2.1 Wastewater Treatment

The study assessed the effectiveness of Single Chamber (SC) and Double Chamber (DC) Microbial Fuel Cells (MFCs) in treating domestic wastewater, focusing on SCAC (Single Chamber Activated Carbon Cathode), SCBC (Single Chamber Biochar Cathode), DCAC (Double Chamber Activated Carbon Cathode), and DCBC (Double Chamber Biochar Cathode) prototypes. Both SC and DC MFC types significantly reduced Chemical Oxygen Demand (COD), phosphorous, potassium, and nitrogen levels. SCBC and DCBC prototypes demonstrated slightly better performance in COD, phosphorous, and potassium reduction, likely due to their enhanced adsorption capacities and mesoporous structures, which facilitate microbial activity and oxygen diffusion.

However, all prototypes were less effective in reducing grease and oils, electrical conductivity, and total dissolved solids (TDS), likely due to factors such as biofouling, suboptimal electrode materials, and the need for specific microbial communities. The presence of algae also affected performance, particularly in maintaining anaerobic conditions necessary for efficient treatment. Overall, SC MFCs showed better treatment efficiency than DC MFCs, particularly in reducing electrical conductivity and grease and oils. However, both MFC types require further optimisation to improve the removal of TDS and grease and oils, suggesting the need for enhanced design and targeted microbial communities to increase overall treatment effectiveness.

6.2.2 Electricity Generation

In summary, DCAC MFC prototypes and SCAC MFCs generally outperformed their counterparts in terms of voltage and current production. SCAC MFCs showed better performance than SCBC MFCs during the initial operation phase due to superior conductivity and a more favourable pH, though both faced issues with biofouling. Double Chamber MFCs consistently produced higher electrical outputs compared to Single Chamber MFCs, but suffered from higher internal resistance and instability likely due to salt bridges and aerobic conditions created in the anode chamber because of the algae. Overall, both MFC types need enhancements in electrode materials and biofouling management to improve long-term efficiency and stability.

6.2.3 Energy Conversion Efficiency

In conclusion, while all MFC prototypes effectively removed COD from wastewater, they exhibited low energy conversion efficiencies. Double Chamber prototypes generally outperformed Single Chamber prototypes in energy conversion, with DCAC showing slightly higher efficiency than DCBC. Despite their high COD removal, the low energy conversion efficiency across all prototypes suggests that while MFCs are effective in wastewater treatment, they are less efficient at converting this treatment into usable electrical energy. The improved performance of Double Chamber MFCs may be due to better control of environmental conditions, such as pH and oxygen levels, which enhance microbial activity and electron transfer. However, issues such as biofouling and wastewater concentration still limit overall energy efficiency, indicating a need for further optimisation of MFC designs to enhance both treatment and energy conversion.

6.3 Recommendations

The study offers significant insights into the performance characteristics of various microbial fuel cell (MFC) prototypes, highlighting their respective strengths and limitations in wastewater treatment and electricity generation. The following are the recommendations from the research:

1. The findings demonstrate that activated carbon cathodes are superior in generating electricity, regardless of whether the MFC is of the single chamber or double chamber type. In contrast, biochar cathodes exhibit greater efficacy in wastewater treatment. Consequently, the choice of MFC prototype should be guided by the primary objective—whether prioritising electricity production or enhancing wastewater treatment efficiency. Thus, investigations should be done in integrating biochar and activated carbon in cathodes so as to ensure both effective wastewater treatment and electricity generation. This balance may also result in an increase in energy conversion efficiency in MFCs.
2. Modify MFC designs to better address the challenges associated with removing grease and oils. This might involve optimising the configuration of electrodes or incorporating specialised microbial communities to enhance treatment efficacy. Supplementary treatment processes may also be necessary to achieve compliance with environmental safety standards.
3. Target improvements in the removal of total dissolved solids (TDS) and other challenging contaminants. This could include refining the design of both SC and DC MFCs or developing hybrid systems to better handle diverse wastewater characteristics.
4. Investigate the use of metal-reducing bacteria, such as *Geobacter sulfurreducens* and *Shewanella putrefaciens* and the use of algae in microbial fuel cells, to improve electron transfer efficiency and reduce internal resistance in MFCs.

5. Develop and apply strategies to mitigate biofouling on electrodes and membranes, such as using antifouling coatings or regular cleaning protocols, to maintain optimal performance and extend the lifespan of MFCs.

6. The disparity in performance between DC and SC MFCs for certain parameters (e.g., COD, EC, and TDS) suggests that specific modifications to chamber design or operational parameters could enhance treatment efficacy.

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APPENDICES

Appendix 1: Zimbabwe Effluent Standards for discharge according to the Environmental Management (Effluent and Solid Waste Disposal Regulations Statutory Instrument 6/2007)

		Zimbabwe Effluent standards			
Parameter	**Units**	**Blue**	**Green**	**Yellow**	**Red**
Colour	TCU	≤15	-	-	-
pH	-	6 – 9	5-6; 9-10	4-5; 10-12	0-4; 12-14
Turbidity	NTU	≤ 5	-	-	-
Conductivity	uS/cm	≤ 1000	≤ 2000	≤3000	≤ 3500
Sus. solids	mg/l	≤ 25	≤ 50	≤ 100	≤150
TDS	mg/l	≤ 500	≤ 1500	≤ 2000	≤ 3000
Alkalinity	mg/L(CaCO 3)	-	-	-	<500
Total hardness	mg/l(CaCO3)	-	-	-	-
Phenolic Compounds	mg/l	≤ 0.01	>0.04	>0.06	≤ 0.1
Chlorides	mg/l (Cl^-)	≤250	≤ 300	≤ 400	≤ 500
Sulphates	mg/l($SO4^{2-}$)	≤250	≤ 300	≤ 400	≤ 500
Phosphate	mg/l(P)	≤ 0.5	≤ 1.5	≤ 3	≤ 5
Grease & Oils	mg/l	≤ 2.5	≤ 5	≤ 7.5	≤ 10
Detergents	mg/l	≤ 1	≤ 2	≤ 3	≤ 5
DO	%	≥60	≥50	≥30	≥15
5-Day-B.O. D	mg/l	≤ 30	≤ 50	≤ 100	≤ 120
Nitrates	mg/l ($NO^{-}3$)	-	-	-	-
Nitrites	mg/l($NO^{-}3$)	≤ 3	≤ 5	≤ 8	≤ 10
Fluoride	mg/l F^-)	≤ 1	≤ 2	≤ 4	≤ 6
Potassium	mg/l	-	-	-	>500
Sodium	mg/l	≤ 200	≤ 300	≤500	≤ 1000
Manganese	mg/l	≤ 0.1	≤ 0.3	≤ 0.4	≤ 0.5
C.O.D.	mg/l	≤ 60	≤ 90	≤ 150	≤200
Chromium (Tot)	mg/l	≤ 1.0	≤ 1.2	≤ 1.6	≤2.0
Copper	mg/l	≤ 1.0	≤ 2.0	≤ 3.0	≤5.0
Zinc	mg/l	≤ 0.5	≤ 4.0	≤ 5.0	≤15
Arsenic	mg/l	≤ 0.05	≤ 0.1	≤ 0.15	≤ 0.3
Cyanide	mg/l	≤ 0.07	≤ 0.1	≤ 0.15	≤ 0.3
Iron	mg/l	≤ 1	≤ 2	≤ 5	≤ 8
Nickel	mg/l	≤ 0.3	≤ 0.6	≤ 0.9	≤ 1.5
Cadmium	mg/l	≤ 0.01	≤ 0.05	≤ 0.1	≤ 0.3
Mercury (Tot)	mg/l	≤ 0.01	≤ 0.02	≤ 0.03	≤ 0.05
Lead	mg/l	≤ 0.05	≤ 0.1	≤ 0.2	≤ 0.5

Ammonia	mg/l	≤ 0.5	≤ 1	≤ 1.5	≤ 2
Chromium(vi)	mg/l	≤ 0.05	≤ 0.1	≤ 0.2	≤ 0.5
Total coliforms	Counts/ 100 ml	≤1000	>1000	>1500	≤2000

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