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Evaluation of Electricity Generation using Microbial Fuel Cell Technology for Abattoir Wastewater Treatment

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DECLARATION

I, Sesie Esther Mkhwebane declare that this research report is my own unaided work. It is being submitted to the degree of Master of Science in Engineering to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any other degree or examination in any other University.

Sesie Esther Mkhwebane

Signature:

25th day of April 2021

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ABSTRACT

The main attraction to the Microbial Fuel Cell (MFC) system, is its ability to generate electricity whilst treating the wastewater. This technology continues to gain a lot of interest from researchers, with some applications proven to be successful on a small scale. Many industries in South Africa continues to struggle with the burden of disposal of wastewater, with the abattoir industry included that uses approximately 2900L of water per 1000kg live weight of animal killed, for smaller operations. The wastewater from such operations are deemed not suitable for disposal in municipal drainage system because of the contaminants in the water which poses risks associated with waterborne pathogens that can be hazardous for the general public. Therefore, the study was focused on testing the viability of generation of electricity from such wastewater and testing the ability to improve the quality of wastewater using this technology.

A double-chamber system, with carbon paper electrodes (without catalyst) was used. A Nafion 117 membrane was applied between the two chambers. The working volume for each chamber was 1L (0.001m^3) and the surface areas of both electrodes was 25cm^2 (0.0025m^2). The experiment was conducted under ambient conditions and the pH was monitored and it remained approximately at 7.

The voltage readings were taken using a multimeter device and readings from the potentiostat.

The abattoir wastewater produced power density that ranged between 0.05294 and 0.30494W/m^3, whist the use of different sized resistors indicated that the least resistor produced the maximum power density of 0.04W/m^3. Also, with the polarization curves developed, the power density of 0.0003mW/cm^2. Also, an improvement in the quality of wastewater was evident in some of the parameters with an achievement of COD removal efficiency of 38%, volatile fatty acid at 3% and nitrogen at 56%. Therefore, the MFC has demonstrated the ability to generate electricity from abattoir wastewater and has shown the ability to improve the quality of water.

Keywords

MFC, electricity, wastewater, abattoir, voltage, resistance, current, power density, COD

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LIST OF ABBREVIATIONS

MFC	Microbial Fuel Cell
OCV	Open Circuit Voltage
BOD	Biological Oxygen Demand
COD	Chemical Oxygen Demand
PEM	Proton Exchange Membrane
GHG	Green House Gas
DMRE	Department of Minerals and Energy
UNFCCC	United Nations Framework Convention on Climate Change
MW	Mega Watt
REIPPPP	Renewable Energy Independent Power Producer Procurement Programme
IPPO	Independent Power Producer Office

CHAPTER 1

INTRODUCTION

1.1 Background

The global development of renewable energy has improved and increased over the past decade and this was due to the large number of countries that implemented academic programmes on renewable energy technologies (Kandpal and Broman, 2014). One of the biggest challenges facing the global energy sector is security of supply for the existing demand, while preventing climate change due to old or poor technology of energy generation (Winkler, 2007) . It was thus critical that countries invest in efficient and cleaner technologies, for energy generation in ensuring the reduction of emission as far as reasonable as possible (REN21, 2015). This was because of many countries that embarked on efforts to curb the emissions of greenhouse gases (Barnes, 2011). The activities related to crude oil and natural gas are the main causes of greenhouse gas (GHG) emissions, which started in the industrial revolution (Wahab *et al.,* 2015). The GHG's were also determined as a major contributor to the life cycle of Agricultural processes such as growing of crops and others (Kramer*et al*, 1999). Burning of fossil fuel for energy generation has been identified as a cause of global warming from the early industrialization phenomenon (Rahman and Khondaker, 2012).

As a measure to combat the climate change, the United Nations Framework Convention on Climate Change (UNFCCC) developed and convened the Kyoto Protocol and

Copenhagen Accord in 1995 (Lau *et al*, 2012a). The Kyoto Protocol endorsed that member States embark on diligent efforts to mitigate the Green House Gas (GHG) emissions through Clean Development Mechanism technologies using renewable energy (Lau *et al* 2012b). This was further supported by the 13th Conference of the parties (COP13) that was held in Bali, Indonesia for similar reasons (Boston, 2008). It was for this reason that South Africa and other willing countries supported the Kyoto Protocol and signed the pledge for efforts on the reduction of GHG emissions (Luiz, 2008). In light of the pledge, changes were evident in the energy sector that influenced certain planning of South African industries (Howells *et al.* 2007).

The energy requirements for South Africans were set out by the Department of Mineral Resources and Energy (DMRE), as per Electricity Regulation Act 4 of 2006 (Winkler, 2007). This provided the DMRE with a tool to use, where the Integrated Resource Plan (IRP) which stipulated that the energy requirements for South Africa as well as the means to meet the energy needs through various renewable energy technologies (Lawrence, 2019). This was to balance the supply and demand cost effectively (Gross, 2015). As in the past decade or so, South Africa has had relatively high energy demand from a fossil fuel dominated generation (Winkler, 2005). This will encourage the willing inclusion of renewable energy technologies to be incorporated in the energy generation mix (M. Schloesser *et al.*).

The recent Integrated Resource Plan (IRP) was promulgated by the DMRE in October 2019, thus referred to as the IRP 2019 (Wright and Calitz, 2020). The energy capacity as estimated by the IRP was just over 52 000MW (Department of Mineral Resources and Energy, 2019). About 35000 MW of that was expected to be decommissioned from Eskom (South African electricity producer from coal) by the year 2050 due to the end of life of the coal facilities (Ireland and Burton, 2018). It was generally expected that more inclusions of cleaner sources of energy generation will replace the coal, as the coal mine reserves threatened the supply and the commitment to do away with energy generated from burning fossil fuel (Mathu, 2010).

In the past decade, investments in renewable energy has been on the rise for most countries as they go through the energy transition to cleaner energy sources that will not have detrimental effects on the environment (Oppong *et al.,* 2020). The reduction of dependence on fossil fuel as a result climate changes, energy security, natural gas reserves has caused a need for investigation of alternative fuels (Rahimnejad *et al.* 2011). This transition was also encouraged by better understanding of the detrimental effects of climate change by many countries and the innovation of newer and cost-effective technologies of energy generation (Yu *et al.,* 2020). This was also regarded as the possible solution for energy supply in regions such as sub-Saharan Africa, where traditionally the modern energy generation technologies did not exist (Sokona *et al.* 2012). This was supported by a study done by Campbell and colleagues (2003) that in Zimbabwe even the wealthiest families were using mix energy generation sources, between wood and electricity.

Energy shortages in the South African electricity grid resulted in independent electricity generation by some households, commercial and industrial facilities, referred to as small scale energy generation (SSEG) (Kessides *et al.* 2007). This was estimated that it will provide a maximum capacity of 1 MW in generation (Filipova and Morris, 2018). Furthermore, the procurement of renewable energy for the national grid, was supplemented by the Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) that was initiated in 2011 by the government and implemented by the Independent Power Producer Office (IPPO) (Department of Energy, 2015). Such a framework (auction/bidding process of renewable energy) has created and enabled an attraction of expertise and investment on renewable energy projects in South Africa (Kruger and Eberhard, 2018).

Microbial Fuel Cells (MFC) has the potential to simultaneously treat wastewater for reuse and to generate electricity; thereby producing two increasingly scarce resources. While the MFC has generated interest in the wastewater treatment field, knowledge is still limited, and many fundamental and technical problems remain to be solved. MFC technology represents a new form of renewable energy by generating electricity from what would otherwise be considered waste, such as industrial wastes or wastewater etc. A MFC is a biological reactor that turns chemical energy present in the bonds of organic compounds into electric energy, through the reactions of microorganism in aerobic conditions (Shukla *et al.,* 2004).

Electricity generation from biodegradable compounds (such as wastewater) using MFC technology has been proven to yield positive results and MFC technology has been extensively reviewed focusing on recent improvement, practical implementation, anode performance, cathodic limitations, different substrates etc. (Pandey *et al.,* 2016). MFCs have been explored as a new source of electricity generation during operational wastewater treatment (Rahimnejad *et al.,2015)*. In addition, some of the recent developments and achievements, that have seen increased power density, includes electrode material, device architecture (Zou *et al.,* 2018) and exoelectrogen (Logan, Bruce E., 2009). Some additional progress made in electricity production from MFC technology, includes MFCs powered by solar and Phototropic MFCs (Pant *et al.,* 2010).

MFC is a way of generating electricity since it not only as a renewable source but also it can be used to treat waste (Du *et al.*, 2007). It can also be used for production of secondary fuel as well as in bioremediation of toxic compounds (Pant *et al.,* 2010). However, more research is still required before domestic MFCs can be made available for commercialization.

The wastewater from various facilities, is not suitable to be disposed-off in municipal drainage system after pre-treatment due to a number of contaminants that are not suitable. Discharge costs are relatively high. Wastewater from abattoirs for example, have high levels of nutrients, suspended solids, high salt content, bacterial contamination and it is generally high in Biological Oxygen Demand (BOD) (Department of Agriculture and Rural Development, 2009). It is a costly exercise to treat the wastewater to comfort to the water quality standards (Department of Agriculture and Rural Development, 2009). Therefore, this research seeks to determine the viability of using such wastewater from industry, to generate electricity using MFC technology, whilst cleaning the wastewater for possible re-use.

1.2 Problem Statement

The two essential areas that countries are contending with, includes access to clean electricity as well as access to clean water. Two of which South Africa is battling with, considering the load shedding and that the country which is a water-scarce country. Therefore, the study is motivated by these two points.

The abattoir wastewater is made up of heavy organic material as a result of the rumen contents, the cow blood and the water used for washing (Akaluka *et al.,* 2016). Such water causes challenges for the abattoirs to deal with in a legal and responsible manner, in addition to the power requirements to run the facility. As such, this creates a demand for alternatives to dealing with the wastewater challenge.

The factors that impact the quality of the wastewater from the processing plant, depends on type of animal slaughtered, the amount of water used and the amount of water used for rendering and processing on site (Mittal, 2004). Some of the factors that affects the concentration of the wastewater from the abattoirs is the efficiency of the blood recovery from the blood pit. The measure of the concentration of the microorganisms in the wastewater can be measured by the COD. Mittal (2004) further indicated that the COD of fresh blood is as high as 375 000mg/l whilst that of the liquid manure is in the range of

15 000 to 30 000mg/l. This indicates that the wastewater sourced that contains blood, has high COD.

Due to a number of contaminants in the wastewater from various operations, it is not suitable to discard off the wastewater in the municipal drainage system, post pretreatment. According to (Department of Agriculture and Rural Development, 2009) an example is the abattoir wastewater that has high levels of suspended solids, with the content of salt high, bacterial contamination, and nutrients. The wastewater from abattoirs has potential health risk as a result of waterborne pathogens which could create an environmental and health hazard for the public (Nafarnda *et al.,* 2012).

It generally has high Biological Oxygen Demand (BOD), and this creates high costs for facilities in discarding the wastewater, due to discharge costs.

The poultry and meat industry are sub-divided into three categories based on the various stages that the animal go through, where a lot of water is used. This includes: 1) the slaughter 2) processing 3) rendering. The wastewater is generated in each stage. A lot of it is generated when the carcass is washed after the removal of the hides from the cattle, when cleaning the facilities and equipment and scalding of beef (Mittal, 2004). According to (Mittal, 2004) the wastewater also includes the blood that is not collected during the processing, bones, urine, viscera, feces, soft tissue that is removed when trimming and cutting. The quantities of water requirements for such facilities (meat and poultry industry), has been quoted to be 2900L of water per 1000kg live weight killed, for the smaller operations. However, for larger facilities, water requirements are 2693L per

1000kg live weight killed (Mittal, 2004). Further processing of the meat requires water for smaller facilities in an estimate of 5602L per 1000kg finished product and 4627L per 1000kg finished product for larger facilities. This suggests that the smaller facilities are less efficient as they use a lot more water per 1000kg meat, in comparison to the larger facilities.

1.3 Motivation/rationale

The rising cost of electricity has a direct impact on many businesses, which are unable to keep up with. Some do not survive the pressure and end up shutting down. Furthermore, the burden of the cost on businesses for disposal of wastewater are hefty and can also lead to businesses closing down or might lead to irresponsible disposal thereof, which could pose a serious health risk for communities and the environment.

In South Africa, the regulation stipulates the expectation on the abattoirs with regards to responsible handling of the wastewater to prevent water pollution or contamination if disposed in normal drainage system. Responsible disposal comes at a cost that is hefty particularly for the small operators; therefore, a need exists.

There are approximately 430 red meat abattoirs in South Africa (Department of Agriculture, Forestry and Fisheries, 2017), where most of these abattoirs slaughter on a daily basis, with water consumption that is variable (RMAA, 2008). According to Adams (2016), the abattoir utilizes about 900liters per carcass. These abattoirs with regards to the wastewater, are under the jurisdiction of Water and Sanitation requirements of which are enforced by the municipalities where the abattoirs are located (Department of

Agriculture and Rural Development, 2009). According to the AgriBook (2020), the use of water in an abattoir facility is of utmost importance and it is therefore indispensable that it was provided uninterrupted. Some of the important uses of water in the abattoir include, water that is used routinely to wash hands, rinse and sterilize the instruments and the use of boiled water and keeping the protective wear clean at all times (RMAA, 2008).

Furthermore, for pre and post slaughter sanitation to ensure cleanliness of meat contact surfaces is maintained on a routine basis, as the deep muscle tissue of a slaughtered livestock contains micro-organisms (Department of Agriculture, 2007). Surfaces are sanitized to eliminate the potential contamination of the meat and render it safe for human consumption (Gibbons *et al.,* 2006). The effluent from abattoirs require treatment prior to being discharged into the environment due to the presence of the multidrug bacteria that could be present in the abattoir wastewater (Iroha *et al.,* 2016).

Therefore, this study seeks to determine the ability of the MFC technology to generate electricity whilst improving the quality of wastewater. This could serve as a solution in future, for such businesses described.

1.4 Aims

This study aims to investigate the possibility of using MFC technology to generate electricity from the abattoir industry wastewater in South Africa, as an attempt to find alternatives that can help address issues associated with climate change and the burden of disposal of wastewater.

The objectives of this study are therefore to:

- Evaluate the viability of electrical power generation from selected wastewaters found in various industries in South Africa
- Assess amongst others the overall energy efficiency, coulombic efficiency and the current as well as power density.
- Determine the Open Circuit Voltage (OCV) of the cell
- Determine the stability and performance of the MFC
- Evaluate the extent of wastewater treatment
- Monitor selected parameters such as the organic content in terms of Biological Oxygen Demand (BOD) and Chemical Oxygen Demand (COD), the volatile fatty acids, nitrate and nitrogen.

1.5 Key Research Questions

The study is based on the evaluation of the wastewater from industry in South Africa that generates a lot of wastewater. The wastewater is used to test electricity generation and to further determine the possibility of improving the quality of water. The industry selected is the abattoir industry as a result of the wastewater generated in these facilities on a daily basis, which leads to a challenge of disposal of such water.

Below is a list of key questions that will be considered during the research work:

- Can electricity be generated from the abattoir wastewater in South Africa, using an MFC technology?

- Does the use of MFC technology improve the quality of abattoir wastewater?
- How does the electricity generation compare of the MFC cell that has external resistance applied to the open circuit voltage (OCV)?

1.6 Hypothesis

If the abattoir wastewater has sufficient microorganisms, then when it comes into contact with the anode, the electricity will be generated through the release of electrons that will travel through external circuit. This will be evident through testing using a device such as a multimeter that is connected to the cell, where voltage is generated. Furthermore, through the electrochemical reaction the improvement of the quality of water will be facilitated.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

MFC is still at pilot stages, despite promising results, due to limitations being discovered (Wang *et al.,* 2012). Factors on which the power generation depends on includes exoelectrogenic microorganism, circuit resistance, type of substrate, electrode material, electron acceptors, the configuration of the reactor (Ucar *et al*., 2017). However, (Santoro *et al.,* 2017) argues that a lot of progress has been made in this field, though further development of low cost, novel and durable electrode materials is still to be reached. Furthermore, even though several wastes have been researched, what still remains to be understood is the kinetics electroactive bacteria and the interaction between electrode and bacteria (Santoro *et al.,* 2017). Thus, the co-existence in electron transfer mechanism between bacteria and solid electrodes (Santoro *et al.,* 2017).

The use of the MFC technology has been found in a number of applications, including in seawater desalination, in biosensors, hydrogen production and in microbial electro-synthesis (Ucar *et al*., 2017). Other applications, according to (Logan *et al.,* 2015) are for remote power sources, production of biofuels and treatment of wastewater. It has also been found that the elimination of oxygen in an MFC system in the cathode and an increase in voltage (large than 0.2 – 0.3 V) in the circuit, produces hydrogen gas in the microbial electrolysis cells (Logan *et al.,* 2015).

However, some of the limitations to the application of the MFC technology, that have been identified, includes the cost of membrane (Logan *et al.,* 2015). The study further indicated that the success factors to power generation with the microbial fuel cell technology, remains the configuration of the cell and the fuel. Furthermore, (. Logan *et al*., 2012) indicated that more research is needed with regards to scalability, efficiency, reliability and the lifetime of the system.

2.2 Comparison between conventional anaerobic digestion technology and microbial fuel cell-based technology for wastewater treatment

There are certain similarities between the microbial fuel cell and the anaerobic digestion technology, where they are both intended to generate renewable energy from wastewater. The technologies are seen as complementary to one another as opposed to be in competition, with the capability of the MFC to treat low concentration substrates at lower temperatures where anaerobic digestion fails to (Pham *et al.,* 2006). This was proven by the study conducted by Vu and Min (2019) where the anaerobic digestion system was coupled with a submersible microbial fuel cell, which proved to be a success with a high COD removal and methane production and electricity generation.

Some differences however, of the two technologies are evident with the MFC that has the prospective of converting chemical energy of the microorganisms into electrical energy, with bacteria acting as a catalyst, whilst purifying the wastewater (Zhou *et al.,* 2011). This emerging technology has received a lot of interest in the research field due to the ability to generate electricity whilst treating the wastewater; however, some limitations that have been identified includes the use of expensive components and low power densities (Katuri *et al.,* 2011). This has been confirmed that even though the operational costs are lower, the capital costs due to materials used, could be as high as 8 euros per kgCOD, as opposed to the capital cost for conventional technologies that costs 0.01 - 0.1 euros per kgCOD (Zhou *et al.,* 2011).

Whilst the Anaerobic Digestion the technology for wastewater treatment, from livestock manure (Nasir*et al*., 2012). It is considered a bioconversion process that is conventional, that produces renewable energy (Pham *et al.,* 2006). This technology is viewed as an attractive treatment method due to the ability to treat organic effluents of high concentration and the process that is anaerobic (Rajeshwari *et al.,* 2000). However, some of the limitations or challenges about the anaerobic digestion include its sensitivity to some parameters of wastewater composition concerning the presence of different ions (leading to pH variations) as well as poisonous compounds that can inhibit the process (Chen *et al.,* 2014).

2.3 Basic components of microbial fuel cells.

An MFC cell consists of two compartments that separates the anode and the cathode compartments, where the two are separated by the membrane that allows only protons to diffuse through to the cathode compartment (Rahimnejad *et al.,* 2012).

Electricity generation takes place from oxidizing biodegradable organic matter through bacteria is possible with the use of MFC, which is a biochemical system (Rahimnejad *et al.,* 2011). A case where Logan and Rabaey (2012) showed that there was a lot of energy in the organic matter that was lost during the process of treatment. The production of electricity from wastewater treatment process, result in the reduction of electrical power consumption for treatment processes, which is high (Ren*et al*., 2014).

The production of energy in electrochemical processes needs a fuel for provision of electrons and the electron acceptor (Zou*et al*., 2018). In the case of MFC the organic matter serves as the fuel whilst in most cases, oxygen becomes the electron acceptor (Logan and Rabaey, 2012). Oxygen was discovered to be the primary oxidizer for systems that were operating on an aerobic respiration for bacteria even though there exit other oxidizers for anaerobic bacteria systems, which includes carbon dioxide, nitrate and sulfate (Logan and Rabaey, 2012). The bacteria in the organic matter produces electrons, which are transferred to the anode, which will subsequently flow through material that is a conductor to the cathode, and thus generating electricity (Rahimnejad *et al.,* 2015). The generation process illustrated by Schaetzle*et al.* (2009) on Figure 2-1.

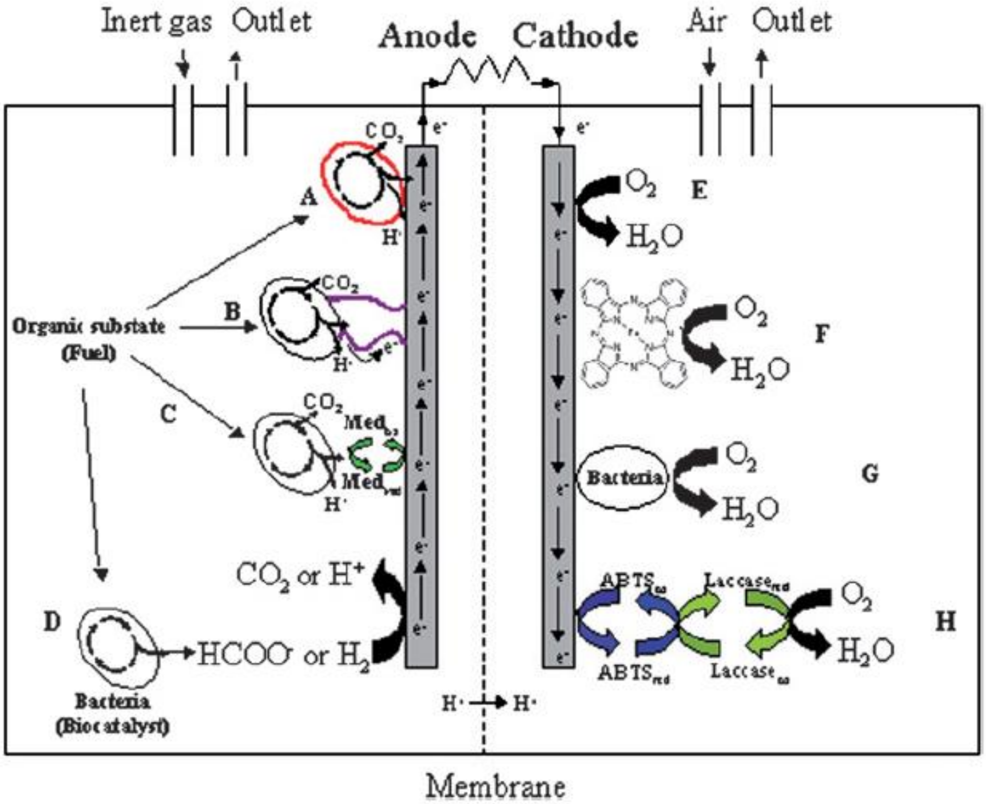

Figure 2-1 Electricity generation using microbial fuel cell principle (Schaetzle *et al.*, 2009)

There are various anode materials that are used for the generation of electricity using MFC, which have different electricity yields (Zhou *et al.,* 2011). Below is the list of materials used for anode and cathode, with their respective power output on Table 2-1.

Table 2-1 Type of anode and cathode materials used in MFC system using various wastewater (Zhou *et al.,* 2011)

Anode material	**Cathode material**	**Wastewater**	**Power output, maximum (mW/m^2)**	**COD removal**
Carbon paper	Carbon cloth (0.5mg/cm^2, Pt)	Domestic sewage	43	79
Carbon paper	Carbon cloth (0.5mg/cm^2, Pt)	Food processing wastewater	81	95
Carbon paper	Carbon paper (0.35mg/cm^2, Pt)	Swine wastewater	261	92
Carbon paper	Carbon paper (1.12mg/cm^2, Pt)	Starch wastewater	239.4	98
Carbon cloth	Carbon cloth (0.5mg/cm^2, Pt)	Primary clarifier effluent	464	40
Graphite rod	Carbon cloth (0.35mg/cm^2, Pt)	Primary clarifier effluent	26	80
Graphite cylinder	Porous graphite bar	Domestic wastewater	25	~50
Graphite plates	Graphite plates	Distillery wastewater	124.35	72.8
Plan graphite electrode	Plain graphite electrode	Chemical wastewater	~125	35.4
Graphite granules + rod	Woven graphite mat	Hospital wastewater	48	-
Activated carbon + carbon cloth	Carbon cloth (0.5mg/cm^2, Pt)	Fermented wastewater	2981	93

Carbon fiber	Stainless steel net (0.8mg/cm^2, Pt)	Brewery wastewater	264	40
Carbon felt	Graphite paper	Electroplating wastewater	1600	99.5
Carbon fiber brush	Carbon fiber brush	Coking wastewater	51.2	~100
Graphite fiber brush	Graphite fiber brush	Paper recycling wastewater	672	29

2.4 Microbes used in MFC and electron transport mechanism

Power generation from the exoelectrogenic microorganism can take place from any source that is either organic biodegradable material or inorganic matter in the water where for the degradation process oxygen is not required (Logan *et al.*, 2009). The material that can be utilized includes the acetate, hydrogen gas, glucose, ethanol, the polymers, proteins, cellulose, plus the different kinds of wastewater sourced from various places (Logan and Rabaey, 2012). Furthermore, the authors found that many microorganisms have been discovered to have the exoelectrogenic abilities; however, numerous Geobacter and Shewanella spp have shown to be popular in studies (Strycharz-Glaven *et al.,* 2011). Oxygen is the primary oxidizer for systems that are operating on an aerobic respiration for bacteria (Schaetzle *et al.*, 2009). Even though, there exits other oxidizers for anaerobic bacteria systems, which includes carbon dioxide, nitrate and sulfate (Logan and Rabaey, 2012). The exoelectrogen bacteria, in a bio-electrochemical system, have the capability of transferring the electrons outside the cell to an electron acceptor that is insoluble or electrode (Logan and Rabaey, 2012). The electrons are transferred by the bacteria using shuttles, in the form of flavins or phenazines (Watanabe *et al.,* 2009).

Alternatively, the electrons are transferred directly from the outer proteins of the membranes (Logan and Rabaey, 2012).

2.5 Design and operation

Researchers regard the wastewater as the feed for the MFC system for electricity production due to the bacteria, which subsequently moves through the circuit to combine with protons in the cathode chamber (Akaluka *et al.,* 2016). A biofilm is formed during an enrichment process, where the electrons are transferred, through the circuit to the electron acceptor in the cathode compartment (Kim *et al.*, 2007).

The electron acceptor (which has an influence on the power output as a result of its strength) became reduced (Shanthi Sravan *et al.,* 2017). The electron acceptors commonly used includes Potassium Permanganate and Manganese, oxygen, Potassium Ferricyanide and others (Jadhav *et al.,* 2014). However, recent research by Akaluka *et al* (2016) showed that Potassium Ferricyanide ($K3[Fe(CN6)]$) was most commonly used, due to its high performance.

2.5.1 MFC Membrane

Membranes are used in MFC to encourage the proton transfer from anode to cathode (Leong *et al.,* 2013). The membrane particularly, was found to be creating a low performance such as low current and power densities as a result of low ion exchange capacity that can reduce the diffusion of protons from the anode side to the cathode side, and also causing internal resistance within the cell (Sun *et al.,* 2009). Microfiltration membranes with low resistance still lead to low power densities as a result of oxygen and substrate crossover through the membrane pores, therefore, it was discovered that the ideal membrane was the new type that was non-porous with low membrane internal resistance (Kim, Y. *et al.,* 2014). The membrane type that was also used, was the Nafion that is non-porous, as it demonstrated permeability to oxygen, where some studies showed the highest oxygen mass transfer coefficient in comparison to other types (Leong *et al.,* 2013). However, Kim and colleagues (2014) discovered that the even though the Nafion membrane may be seen as the best membrane for MFC technology, it is expensive, costing approximately \$200/m^2.

2.5.2 Electron acceptors

A variety of electron acceptors possess different physical and chemical properties that can have an impact on the efficiency of electricity production (Huang *et al.*, 2011). The most widely used electron acceptor in the cathode compartment is oxygen, which has a high redox potential due to its oxidation capabilities and yielding clean water results (Ucar *et al.*, 2017). Even though other studies indicated that the drawbacks of the use of oxygen as an electron acceptor, was the high consumption of energy during the supply, the use of expensive catalysts and the low solubility of oxygen at higher temperature limits electron acceptor interface (Ucar, Zhang and Angelidaki, 2017; Jadhav *et al.,* 2014).

Other benefits of using alternate electron acceptor, was the reduction of operating cost and increased power generation, as indicated by Ucar *et al.* (2017) it was also the enlarged scope of MFC technology by controlling environmental pollutants as a result of ability to treat some recalcitrant compounds, such as nitrate. In the cathode, the electron acceptors, receive electrons, a significant function in the MFC (McLean *et al.,* 2010).

Some of the material used as electron acceptors in the cathode compartment include nitrate that is reduced to nitrogen gas through denitrification process (Ucar *et al.*, 2017). Other heavy metals such as mercury, iron and copper which when reduced have the ability to become less toxic and improve the wastewater quality.

Permanganate was seen as another alternative electron acceptor, which is suitable in both acidic and alkaline conditions (Jadhav *et al.,* 2014). During the reduction process, in both conditions (acidic and alkaline), it is reduced to manganese oxide by receiving three electrons (Ucar *et al.*, 2017). This proved the potential it possesses, as an electron acceptor. Previous studies indicated that permanganate had power density that was higher (50- 80% or higher) than other electron acceptors such as hexachnoferrate and oxygen which was 115.60 mW/m^2 at current density of 0.017 mA/cm^2 for permanganate, whilst for hexachnoferrate was 25.62 mW/m^2 and oxygen was 10.2 mW/m^2 (Ucar, Zhang and Angelidaki, 2017). Some of the drawbacks of permanganate as an electron accepter included the continuous liquid replacement during electricity generation due to the depletion of the permanganate and pH control in order to have a stable power output (Ucar *et al.*, 2017).

2.6 Different wastewater used in microbial fuel cells and the maximum current produced

Energy can be produced directly from biodegradable matter, including organic acids, biomass and sugars, using the microbial fuel cell (Deval *et al.*, 2013). Research indicates the use of various wastewater on the MFC technology, which functions on different carbohydrates as well as substrates that are found in wastewater to generate electricity and for wastewater treatment (Rabaey *et al.*, 2005). A study by Panday *et al.* (2016) gives a view of the investigations of different wastewater types by various researchers using different operational conditions and MFC designs, as per Table 2-2.

Table 2-2 Types of wastewater used in MFC with power output (Pandey *et al.,* 2016)

Wastewater	**Substrate concentrate**	**Power density (Wm^{-3})**	**COD removal (%)**
Bad wine	7.8 gCOD /l	3.82	41
Animal carcass wastewater	11.18 gCOD /l	2.19	50.66
Chocolate industry	1459 mgCOD /l	1.5	75
Ethanol stillage	37.890 mgCOD /l	93	81.5
Real dye wastewater	2200 mgCOD /l	8	71
Real field dairy wastewater	4.44 kgCOD /m^3	1.1	95.49
Rice mill wastewater	2250 mgCOD /l	2.3	95.5
Saline seafood wastewater	N/a	15.2	N/a
Steroidal drug industrial effluent	1340 mgCOD /l	22.3	82
Synthetic penicillin	1 g/l glucose; 50mg/l penicillin	101.2	90
Winery wastewater	2200 mgCOD /l	31.7	65
Wastewater		**Power density (mWm^{-2})**	**COD removal (%)**
Brewery wastewater	1501 mgCOD /l	669	20.7
Cassava mill wastewater	16000 mgCOD /l	1771	72
Cellulose	2 gCOD /l	1070	70
Coking wastewater	3150 - 3200 mgCOD /l	538	50
Corn stover hydrolysate	1000 mgCOD /l	861	70
Dairy industrial wastewater	53.22 kgCOD /m^3	621.13	90.46
Enteromorpha prolifera hydrolysate	1000 mgCOD /l	1027	76.1
Fermented corn stoves hydrolysate	5300 mg/l	1180	N/a
Molasses wastewater	127.500 mgCOD/l	1410.2	53.2

The synthetic penicillin wastewater has displayed the most power generation, followed by ethanol stillage and then the winery wastewater.

2.7 Equations to evaluate efficiency performance and treatability

Below are some of the calculations that were used by various researchers to determine the performance of the cell with regards to power generation and wastewater treatment, as per the research studies (Cheng *et al.*, 2006; Logan *et al.,* 2007; Vu *et al.*, 2019).

2.7.1 Current

Calculated according to Ohm's law

$I = \frac{V}{Rext}$ (2.1)

Where I is the current

V → is voltage (V)

R_{ext} → is the external resistance (Ω)

2.7.2 Current density

$Id = \frac{V}{A\ Rext}$ (2.2)

Where I is the current density

V → is voltage (mV)

R_{ext} → is the external resistance (Ω)

A → is the surface area of the cathode electrode (cm^2)

2.7.3 Power generation

$P = \frac{V^2}{R}$ (2.3)

Where P is power (W)

V → is voltage (V)

R_{ext} → is the external resistance (Ω)

2.7.4 Power density

$Pd = \frac{P}{v}$ (2.4)

Where P_d is the power density

P → is the power generated (W)

v → is the total volume of the MFC (m^3)

2.7.5 Coulombic efficiency

$CE = \frac{Cp}{Cth} 100\%$ (2.5)

Where CE is the coulombic efficiency

C_p → is the total coulombs by integrating the current over time,

C_{th} → is the theoretical amount of coulombs based on COD removed in the MFC

2.7.6 COD removal

The treatment efficiency of wastewater was determined by Panday *et al.* (2016) through the COD removal.

$ECOD = \frac{CODin - CODout}{CODin} 100\%$ (2.6)

Where E_{COD} is the efficiency of COD removal

COD_{in} → is the influent COD

COD_{out} → is the effluent COD

2.7.7 Power generation per gram COD removal

$PGCR = \frac{V^2}{R} \div COD\ Q$ (2.7)

Where PGCR is the power generation per COD removed ($W/gCOD_{removed}$)

V → is voltage (V)

R_{ext} → is the external resistance (Ω)

COD_R → COD removed (g/L)

Q → flow through the system (L/hr

2.8 Factors affecting MFC performance

Research shows that there are various factors that affects the performance of the MFC system, and subsequently the power generation and wastewater treatment. According to Zhao *et al*.(2009) one of the limiting factors of the system, is the slow biological reaction. Also, the use of porous proton exchange membrane, according to Zhuwei *et al*.(2008) leads to fouling of the system. Whilst, Deval *et al.* (2013) indicated that what plays a major role in the performance of the system, concerning the stability, efficiency and power output, is the MFC design. Furthermore, the study conducted on bioelectricity generation and contaminant removal using a constructed wetland microbial fuel cell, was affected by the substrate material size, where the larger filler size promoted abundance of bacteria that was electrochemically active (Wang *et al.,* 2017).

Other factors that were identified by Zhuwei *et al*. (2008) that have an impact on the operation of the MFC system, was the substrate feeding rate and the electrode distance, where the higher feeding rate and a longer electrode distance resulted on higher electricity generation. Findings further indicated that the type of feed has the big impact on the power generation, where glucose and acetate are said to generate more power density than the domestic water due to the concentration of the substrate and form (whether particulate or soluble) (Cheng *et al.*, 2006).

Therefore, gaps still exist in addressing the factors identified that includes slow biological reaction, membrane, substrate material size, the feeding rate, electrode distance just to name a few. These still require further studies to get concrete conclusions. Furthermore, another gap that still exists is upscaling of the system from lab scale to pilot and commercial scale. According to Katuri (2011), some of the limitations of the MFC technology, includes the expensive components and low power densities achieved. Therefore, the study will seek to test viability of using abattoir wastewater on this technology, at ambient temperature, also using electrodes not coated with catalyst.

CHAPTER 3

MATERIALS AND METHODS

3.1. Study area

The study was based on using wastewater sourced from the red meat abattoir (that is classified as a low-throughput abattoir), for testing the electricity generation and water treatment using the Microbial Fuel Cell technology. The study followed techniques that were used in other research work that were similar in assessing electricity generation and wastewater treatment.

3.2. Materials and apparatus

3.2.1. Apparatus: Design and fabrication of the –MFC

Microbial Fuel Cell kit (Wits University, Johannesburg, South Africa), made out of Plexiglas (Röhm & Haas, Philadelphia, United States of America {USA}). The MFC testkit consisted of two chambers, the anode and cathode chambers. The capacity of each chamber was 2,493 litres.

The additional equipment that was used included:

a) Lab scale (Scale Tronic, Johannesburg, South Africa)
b) Multimeter (Keysight, California, USA)
c) Proton Exchange Membrane (PEM)- Nafion 117 (Dupont, Tokyo, Japan)
d) Below, are the various components of the MFC testkit that was used for the experimental work.

Table 3-1 describes the components used during the experimental work.

Table 3-1 MFC components

Sl No	**COMPONENTS**		**DESCRIPTION**	**DIMENSION**
1	MFC	Anaerobic Chamber	Rectangular-shaped chamber, made out of Plexiglass.	Length = 20.0cm Width = 13.7cm Height = 9.1cm
		Aerobic Chamber	Rectangular-shaped chamber, made out of Plexiglass.	Length = 20.0cm Width = 13.7cm Height = 9.1cm
2	Capacity / Volume		The capacity of the chambers, was 2.493 liters each.	The working volume for each chamber was 1 liter
3	Membrane		The type of membrane used was the PEM Nafion 117.	Length = 7cm Width = 7cm Surface area = 49cm^2
4	Electrodes		The electrodes used as anode and cathode, were carbon papers, of the same dimensions.	Length = 5cm Width = 5cm Surface area = 25cm^2

3.2.2. Input material and chemicals

3.2.2.1. Electron acceptor preparation

The electron acceptor that was used for the experimental work, was the Potassium Ferricyanide (Akaluka *et al*., 2016). The steps that were followed are outlined below, in preparation of the solution (AUS-e-TUTE, 2018).

The 0.1 mol Potassium Ferricyanide, with molecular mass of 329g/mol.

Therefore, the mass to be used for the solution, was calculated using the equation below:

$m = nM$ (3.1)

Where:

n – moles (mol) present in Potassium Ferricyanide

m – mass (g)

M – molecular mass (g/mol)

$$m = nM$$

$$m = \frac{329g}{mol} X\ 0.1mol$$

$$m = 32.924g$$

Therefore, a measuring scale was used to weigh 32.924g of Potassium Ferricyanide, which was subsequently mixed with 1l of distilled water to make a solution. The solution was loaded in the cathode chamber.

3.2.2.2. Methods

3.2.2.2.1. Sampling

The wastewater from the abattoir has a large amount of organic matter from the cow rumen, cow blood and wash water (Akaluka *et al.,* 2016). Therefore, a 5 liter wastewater sample was sourced from the waste stream, at the abattoir. The sample was processed during the experimental work, whilst the balance was stored in a refrigerator at 4℃.

From the sample sourced, a portion was sent to a laboratory for chemical analysis.

3.2.2.2.2. Experimental set-up

Below is the experimental set-up, consisting of the two chambers, anode and cathode, that was separated by the PEM membrane (Das, 2017). A portable multimeter was connected to the cell, to determine the cell output. Figure 3-1 indicates the cell set-up, input and output material.

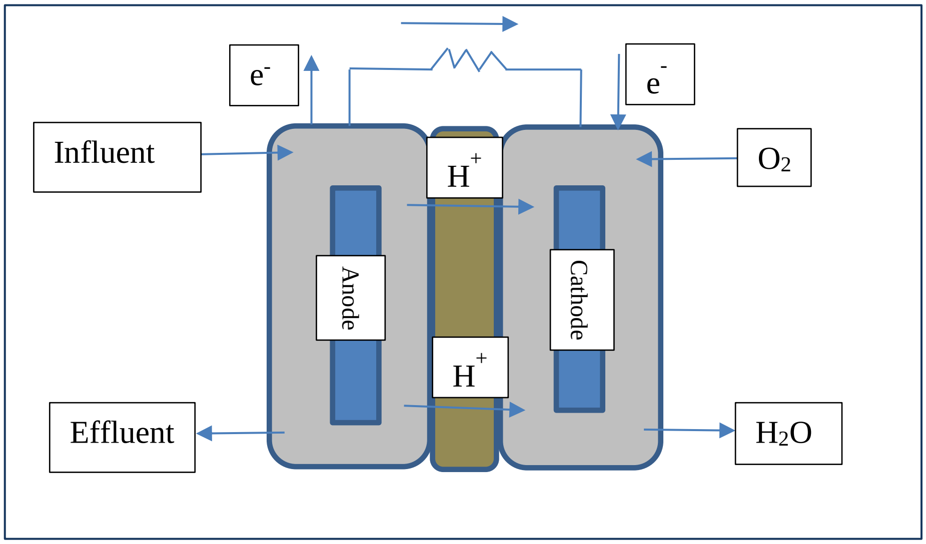

Figure 3-1 Cell set-up during operations (Das, 2017)

3.2.2.2.3. Inoculation of the wastewater

Some of the bacteria found in the animal stomach, such as the Enterococci, Escherichia coli (E.coli), Streptococcus (F.streptococcus), etc., which can be used as an inoculum (Nafarnda *et al.,* 2012). The inoculum was prepared with E.coli bacteria, with bacteria count of 2 250cfu/ml.

The inoculum of 500ml was added to the abattoir wastewater, with the initial 250ml at the beginning of the experimental work, and further 250ml after two days. The system was allowed to run where the voltage of the system was closely monitored and was considered stable for electricity production, under anaerobic conditions. The medium was changed to abattoir wastewater with COD level of 11790mg/L after four weeks of stable system, with voltage just over 50mV and further voltage readings were taken. The pH was measured using pH strips and was stable and neutral at 7.

3.2.3. Parameter readings

3.2.3.1. Evaluation of efficiency of MFC to treat wastewater

The following parameters were evaluated for the treatment of the abattoir wastewater, where samples were taken before the processing of wastewater (influent, in mg/L) and also of the processed wastewater (effluent, in mg/L). Furthermore, the removal efficiency (%) was determined.

- BOD
- COD
- Kjedahl nitrogen
- Nitrates
- Volatile Fatty Acids

The abattoir wastewater was analysed by standard methods as described under water quality analysis section in Table 3-1.

3.2.3.2. Electrochemical measurements

The electricity output from the cell, was monitored by determining the parameters, through the use of a portable multimeter device, and also by measurements of physical properties of the cell. The voltage (V) in a closed circuit and across an external resistor in the MFC circuit was monitored at almost on a daily interval using a multimeter connected to a personal computer. The values obtained were to be further used in the Ohms Law to determine the power generated by the cell, as well as the efficiency of the cell. The current (I) and power (P = IV) were calculated as previously described, with the power density normalized to the projected surface area of the anode.

Table 3-2 highlights the equations that were followed to determine various parameters from the cell.

Table 3-2 Power generation equations

Parameter	**Equation**
Current	$I = \frac{V}{Rext}$
Current density	$Id = \frac{V}{A\ Rext}$
Power generation	$P = \frac{V^2}{R}$
Power density	$Pd = \frac{P}{v}$
COD removal	$ECOD = \frac{CODin - CODout}{CODin}\ 100\%$

A batch mode was used for the experiment, which consisted of two chambers that contained the substrate on one chamber and an electron acceptor solution on the other, the Potassium Ferricyanide. The performance of the cell was monitored over a period of time, during which measurements were taken regularly. The system operated at room temperature and the pH was monitored using the pH testing strips (SimaAldrich, Darmstadt, Germany) and the electrical output measurements recorded using a digital multimeter (Keysight, California, USA), as per Figure 3-2.

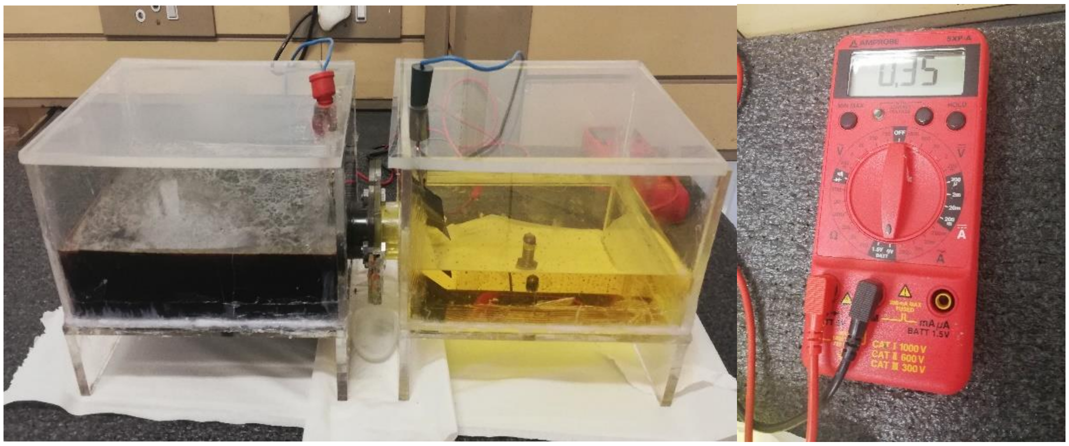

Figure 3-2 Microbial Fuel Cell connected to a multimeter

The voltage (V) readings were taken, which were used to calculate current (A), using Ohm's Law. This made possible to determine the Power (W) generated by the cell, from the equation P = IV. The Power Density (W/m^3) was calculated by dividing the Power by volume (m^3), whilst the Current Density (A/m^2) was calculated by dividing the current by the surface area of the anode (m^2).

Furthermore, MFC polarization curves were obtained using a potentiostat that is digitally controlled and connected to the computer for output readings, where the data was used to formulate the curves. These were essentially used for testing the stability of the system and determining the maximum sustainable power generated by the MFC system. This was operated as variable resistor with the range between 1700Ω and 1900Ω; whilst the voltage over resistance was recorded (with variation of less than 0.5mV/min) and calculation of the current density and power density, normalized to the surface area of the anode ($25cm^2$).

The quality of wastewater was monitored by determining certain parameters of the wastewater in the beginning and another test performed after the experiment. The tests included COD, BOD, nitrate, volatile fatty acids and nitrogen. The efficiency of COD removal was determined, as well as for the nitrogen and volatile fatty acids.

3.2.4. Wastewater treatment

The development and commissioning of accessible technologies such as MFC, can generate electricity for abattoirs and treating the wastewater at the same time (Mostafa *et al.,* 2011). Table 3-3 shows the list of water parameters and the usefulness of the tests.

Table 3-3 Water parameters and tests used to determine water quality from abattoirs

Parameters	**Relevancy of the test**	**Process of biodegradation**	**Source**
Chemical Oxygen Demand (COD)	Measure of concentration of organic matter	Biochemical degradation	(The University of Georgia, 2010)
Total nitrogen (N)	Measure of concentration for targeted nutrients that can contribute to the acceleration of the water bodies undergoing natural aging.	Eutrophication	(World Bank and Government of The Netherlands, 2000)
Biochemical Oxygen Demand (BOD)	Measure concentration of organic matter that is the relative strength.	Biological decomposition	(The University of Georgia, 2010)
Ammonia nitrogen	This is a measure of targeted nutrients on how concentrated it is, that can contribute to the acceleration of the water bodies undergoing natural aging	Eutrophication	(World Bank and Government of The Netherlands, 2000)
Volatile Fatty Acids	These are formed during the process of organic matter, found in wastewater from food industry, municipal, livestock farm.	Anaerobic biodegradation	(Zygmunt and Banel,)
Nitrate nitrogen	Measure of targeted nutrients that can contribute to the acceleration of water bodies undergoing natural aging.	Eutrophication	(Westminster College, 1993)

3.2.4.1. Water quality assessment

The wastewater sourced from the abattoir, contains various microorganisms, which are mostly pathogenic, such as the Salmonella typhi, Shigella, Neisseria lactamica and others (Rabah *et al.,* 2008). The water chemical analysis to check its quality prior the experimental analysis was done; where a sample was taken and analysed for various parameters, listed on Table 3-4. These analyses are called the physiochemical analysis. These tests were conducted before and after the experiment (Akaluka *et al.,* 2016).

Table 3-4 Method used for water analysis

Method Name	Method Number	Method Type	Original Method
Biochemical Oxygen Demand (BOD)	WLAB/020/B.O.D./Method	Titrimetric	5210 Biochemical Oxygen Demand (BOD); 5-Day BOD Test): *Standard Methods for Examination of Water and Wastewater; 20th Edition*, Biochemical Oxygen Demand; Determination of the BOD_5 with dilution of the water sample; Merck
Chemical Oxygen Demand (COD)	WLAB/018/C.O.D./Method	Titrimetric	5220 Chemical Oxygen Demand (COD);

			Closed Reflux, Titrimetric Method: *Standard Methods for Examination of Water and Wastewater; 20th Edition*
Kjedahl Nitrogen	WLAB/025/T.K.N./Method	Titrimetric	4500-N_{org} Nitrogen (Organic); Semi-micro-Kjeldahl Method): *Standard Methods for Examination of Water and Wastewater; 20th Edition*, Instrument manual
Nitrates	WLAB/046/Discrete analyser/Method	Colorimetric / Spectrophotometric	Instrument manual
Volatile Fatty Acids	WLAB/029/V.F.A./Method	Colorimetric / Spectrophotometric	5560 Organic and Volatile Acids; Distillation Method: *Standard Methods for Examination of Water and Wastewater; 20th Edition*, Instrument manual

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Bioelectricity generation

4.1.1 Cell performance: multimeter

The anodic chamber was inoculated with bacteria over three weeks. Water concentrated with bacteria, the E-coli with a total count of 2 250 CFU/ml was introduced to the substrate (which had a volume of 750ml in the anode chamber). The initial dose of 250ml was loaded during the first day of the experimental work, followed by another dose of 125ml in the second day 2 and also in the third day.

This step was with the aim of help formulating the biofilm, which has been alluded to by many researchers that the presence thereof plays an important role in electricity generation and efficiency of the anode function (Sanchez-Herrera *et al.,* 2014)

The voltage obtained from the cell was recorded using a multimeter, with the readings recorded every second day and the system monitored for a peak. The maximum Open Circuit Voltage (OCV) was observed at 0.65V after three weeks, where the voltage began to drop, and the substrate was decanted. The voltage output was plotted on Figure 4-1.

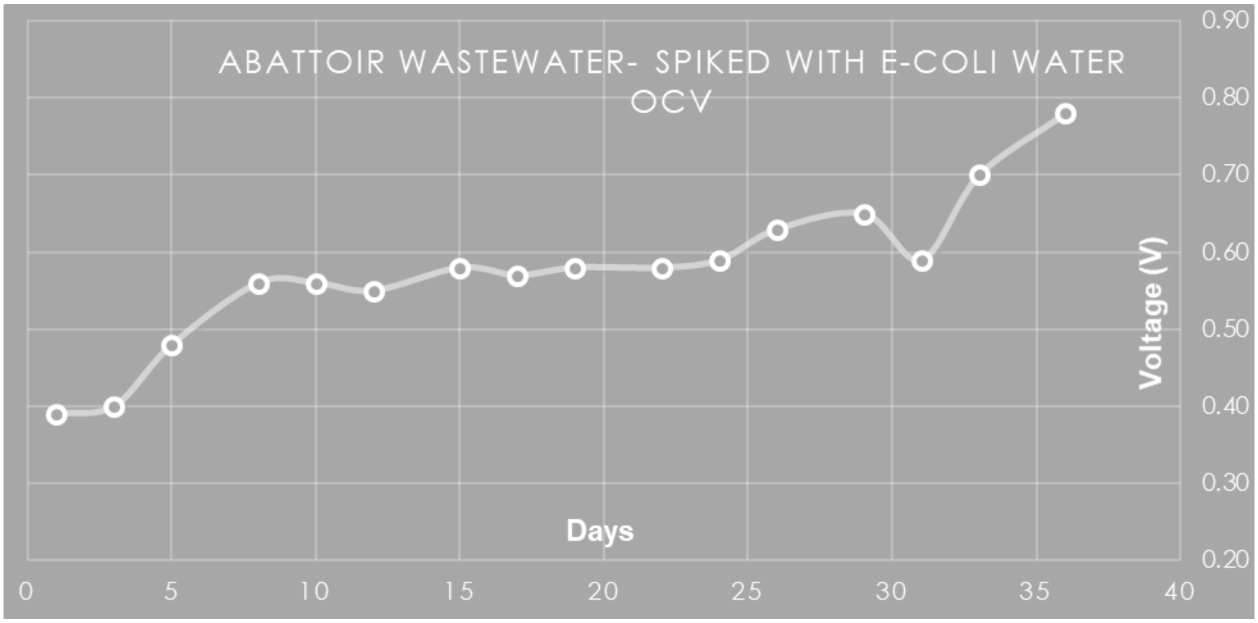

Figure 4-1 Voltage output during inoculation stage

An OCV can lead to higher voltage generation, however real conditions have resistance that must be overcome (Kamau *et al.,* 2017). Therefore, the experiment considered both OCV as well as conditions where external resistance is applied. The depiction in Figure 4-1 indicated the highest voltage output on OCV where the circuit was disconnected; the initial voltage was at 0.39V and steadily increased to reach maximum 0.65V. Similar results were displayed by the study that was undertaken for just over 16 days and resulted with OCV of 0.76V (Mostafa *et al.,* 2011). Similarly, the findings by Pandey *et al* (2016) showed that the animal carcass wastewater yielded a maximum OCV of 0.55V. The findings by Wang, Cheng and Huang (2010) discovered that the OCV using the Escherichia coli obtained the maximum voltage output of 0.88V.

4.1.2 Power generation

Figure 4-2 is the calculated current against the voltage obtained during the experiment.

Calculated current

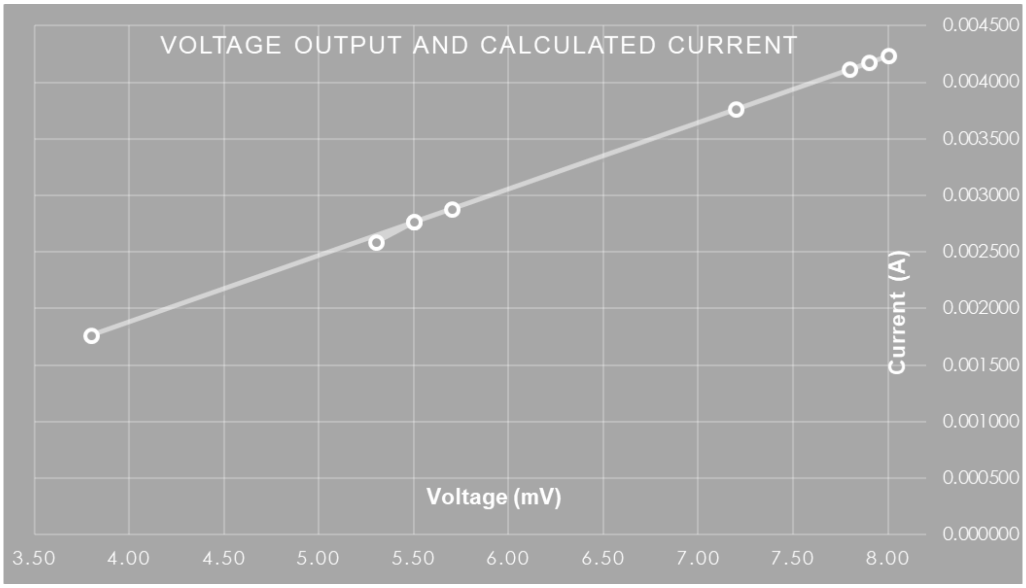

Figure 4-2 Calculated current

The current gradually increased from 0.00176A as the voltage increased and peaked at 0.000424A. The current and voltage having a linear relationship where increasing voltage resulted to the increased current. This linear relationship is as a result of Ohms law, that confirms that the current that flows in a circuit is directly proportional to the voltage.

Furthermore, the voltage output on the cell was monitored and recorded at an external resistance of 1700Ω. The highest voltage obtained was 0.8mV whilst the calculated maximum current was 0.000424A. The results indicated that the system constructed, was functional as voltage was able to be recorded within a period of 10days. Similar results were obtained in the study that was done using a double chamber design, where artificial wastewater of known laboratory bacteria was used and resulted with a 0.491V voltage and 0.491mA current (Deval *et al*. 2013).

Current density and power density

In Table 4-1 and

Figure 4-3 the calculated current density and power density were plotted, where the current density peaked at 0.0106 A/m^2 after 8 days whilst the power density peaked at 0.3049 W/m^2 also during the 8th day of the experiment.

Table 4-1 Current density and power density

Current density	Power density
0.004411765	0.052941176
0.009411765	0.240941176
0.009852941	0.264058824
0.010588235	0.304941176
0.010294118	0.288235294
0.010441176	0.296529412
0.007205882	0.141235294
0.006911765	0.129941176
0.006470588	0.113882353
0.006911765	0.129941176

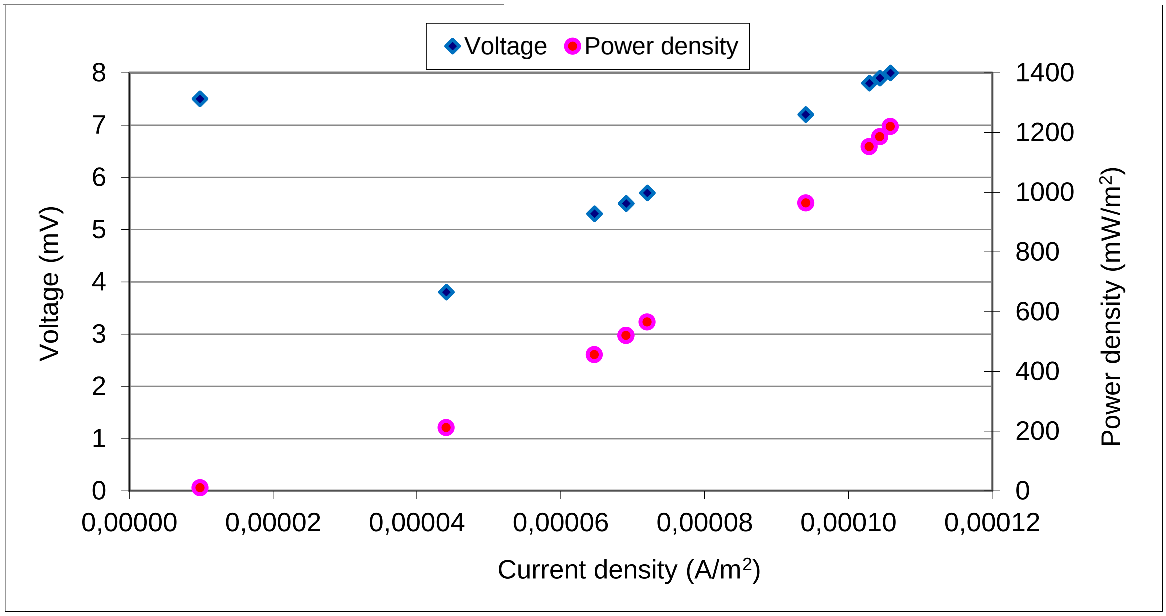

Figure 4-3 Calculated current and power densities

The current density obtained ranged between 0.00441 to 0.01059A/m^2. Whilst the power density obtained ranged between 10.562mW/m^2 and 12.197mW/m^2. The obtained power density was more than what was achieved on a study that utilized the E coli substrate where a maximum power density was 97.7mW/m^2 with 470Ω external/working resistance (Wang*et al*., 2010). The emphasis being that with longer period given (culture time), better power performance will be result, as depicted in Figure 4-3 with increasing output. The MFC performance linked to good bacterial growth and metabolism. The observed power density is in line with what other studies obtained, with a range between 4.66mW/m^2 and 10.13mW/m^2 (Ghangrekar and Shinde, 2007).

4.2 Effect of external resistance on power generation

As alluded to by Rahimnejad *et al* (2011), the Open Circuit Voltage (OCV) conditions can yield the highest voltage output, however for real applications, resistance exists in the circuit. Therefore, an experiment was conducted to determine the effect of applying the external resistance, against the OCV.

Table 4-2 Voltage (V) output at different resistor sizes

Days	No resistor	1000Ω resistor	1500Ω resistor	2200Ω resistor
1	0.35	0.05	0.04	0.06
2	0.39	0.01	0.01	0.02
4	0.59	0.02	0.02	0.03
7	0.75	0.2	0.16	0.23
9	0.64	0.04	0.09	0.07

Resistors with different resistance sizes were used in the study, which ranged between 47Ω and 2 200Ω were used on a five-day period. Voltage readings were taken for all resistors in the circuit, however the readings of the two lowest resistors 47Ω and 474Ω, were neglected due to the lowest output obtained. The low voltage output from the lowest resistor is in-line with the findings by Kamau *et al* (2017) that a low external resistance produces weak power, as the resistance is lower than the internal resistance. Therefore, voltage obtained from the resistors 1000Ω, 1500Ω and 2200Ω were recorded.

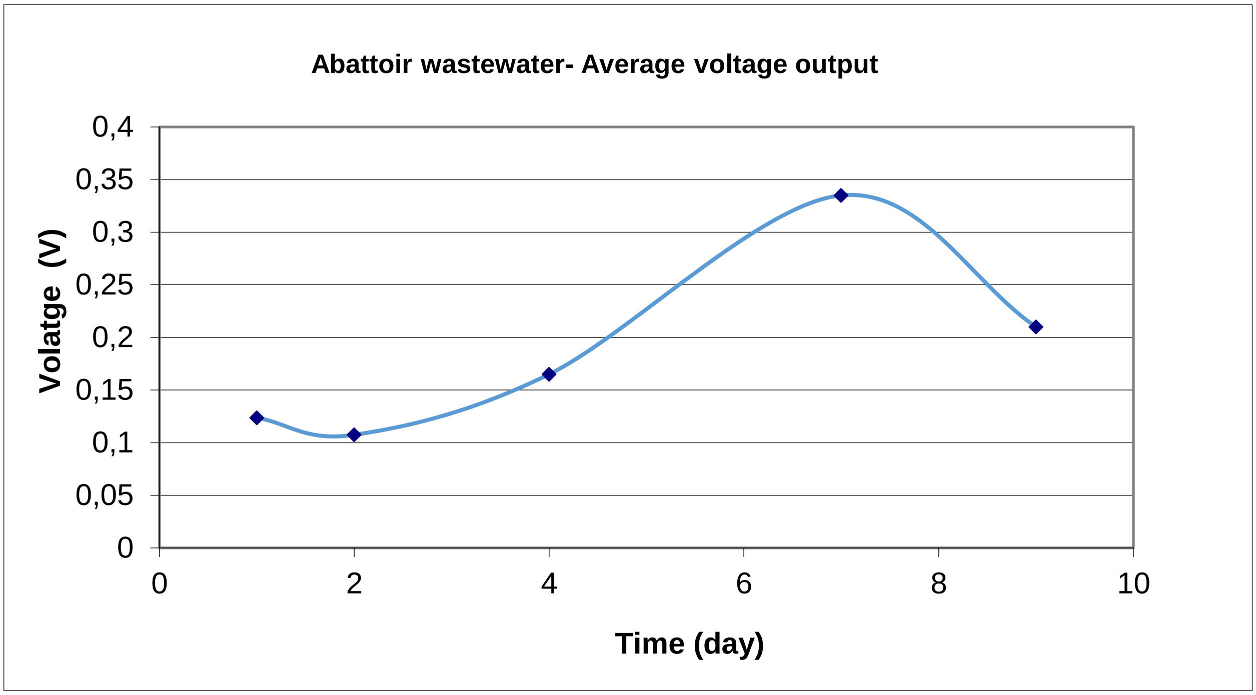

Figure 4-4 Average voltage output, from the different resistors applied when testing the abattoir wastewater.

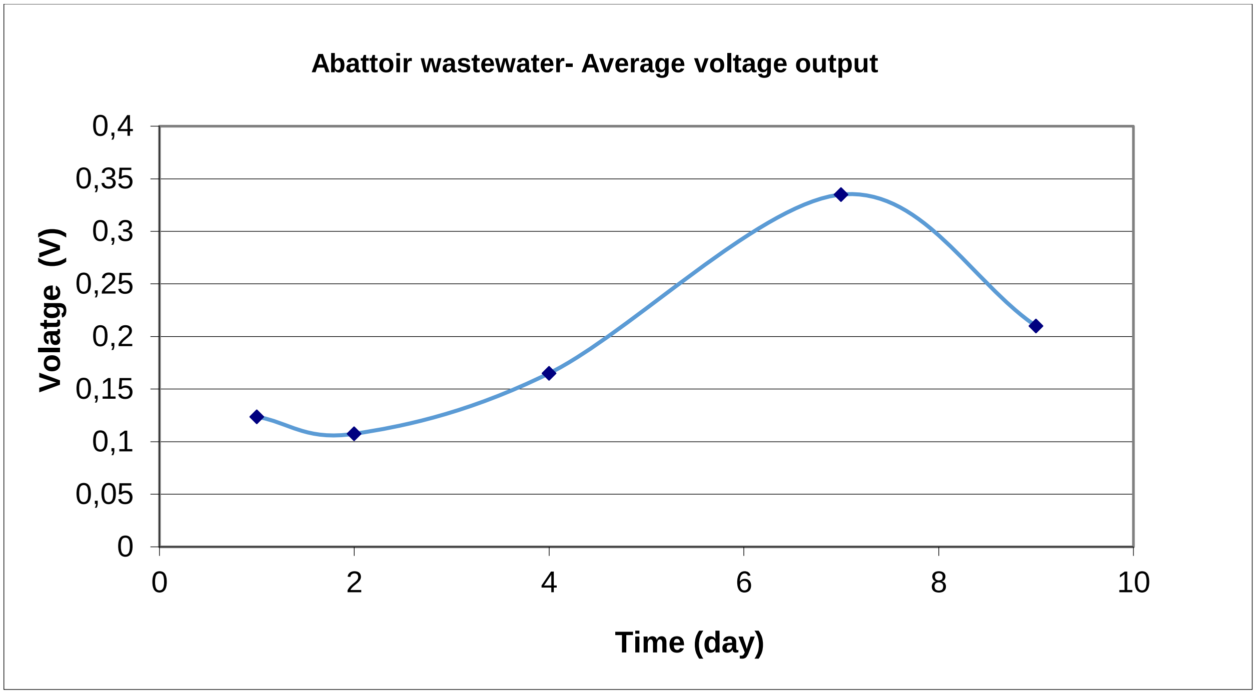

Figure 4-4 Voltage output across different resistor sizes

The voltage obtained at OCV was far greater than the voltage obtained with resistance applied as per the depiction in Table 4-2. The OCV peaked at 0.75V after 7 days. The voltage obtained when a 2200Ω was applied, peaked at 0.23V after 7 days; which correlates with the observations by Kamau *et al* (2017) as well as Ghangrekar and Shinde (2007) that the voltage increased with the increasing external resistance.

However, the average voltage at day 7 was 0.335V as indicated in Figure 4-4. The peak in voltage was followed by a drop in output for the different scenarios, which indicates the depletion of the bacteria.

Current and power density

The voltage obtained when the resistors were incorporated, was used to calculate the current, current density and the power density. Figure 4-5, is the depiction of the current density when the different sized resistors were connected (1000Ω, 1500Ω and 2200Ω), where the averages were taken. Table 4-3 shows the current density obtained with different resistance.

Table 4-3 Current density at different resistors

	Days				
Resistance (Ω)	1	2	4	7	9
1	0.001125	0.00025	0.0005	0.005	0.001
1.5	0.000666667	0.000167	0.000333	0.002667	0.0015
2.2	0.000681818	0.000227	0.000341	0.002614	0.000795

The current density (normalized by the surface area of the anode) obtained in the three scenarios shows a similar pattern where on the second day of experiment, the density dropped and started picking in day four, and fell thereafter. The highest current density as reflected in Table 4-3 was obtained when the 1000Ω was attached to the cell at 0.005A/m^2, followed by the current density of the1500Ω resistor and the least current density was obtained with the 2200Ω resistor at 0.0026A/m^2.

The current density was in a range of 0.000227A/m^2 and 0.005 A/m^2 when various resistor sizes were incorporated. The highest current density of 0.005A/m^2 was obtained with the lowest resistor of 1000Ω, whilst the least current density was obtained with the highest resistor at 2000Ω. This was in aligned with the observation on the restriction of the current that is able to flow from anode to cathode, as a result of high external resistance (Kamau *et al.,* 2017). A similar observation was noted by Mohan, Mohanaksishna and Sarma (2010) that at higher external resistance applied, the system discharges electrons.

The average current density was taken during the run it was plotted below

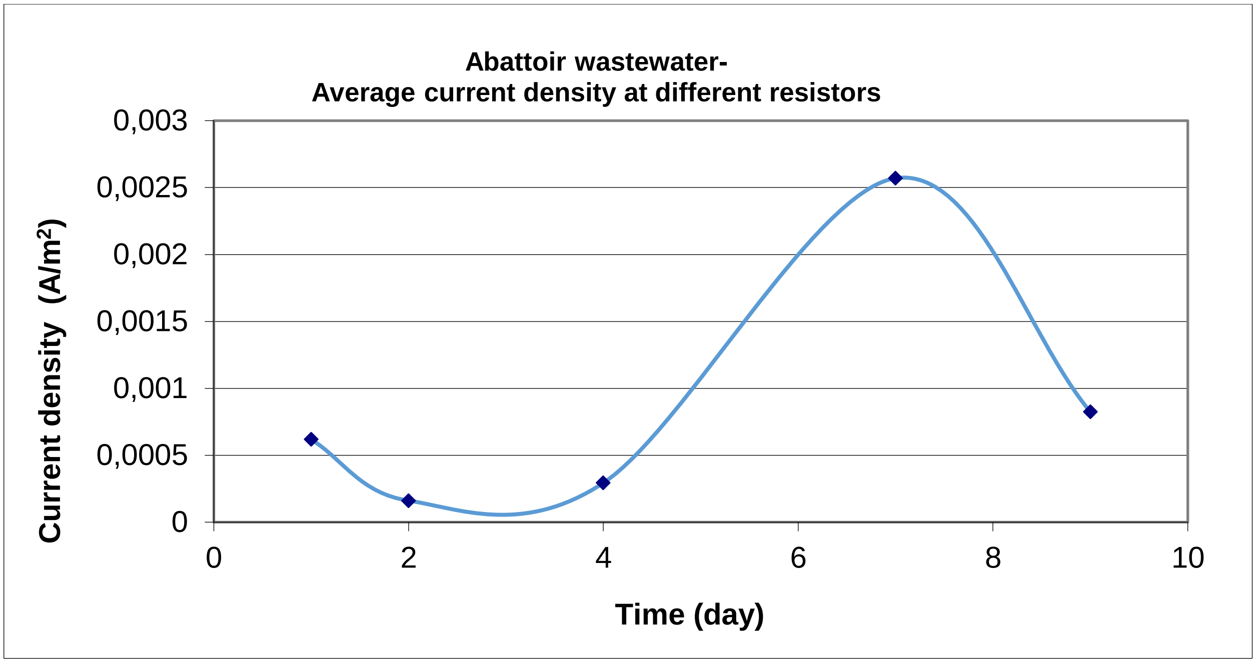

Figure 4-5 Average current density

The peak obtained from the average current density as reflected in Figure 4-5, was 0.00257A/m^2, which is somewhat in the middle of some of the results from research work where the current ranged between 0A/m^2 and 4A/m^2 (Yao *et al.,* 2014).

Power density

Figure 4-6 shows the power density obtained when different sized resistors (1000Ω, 1500Ω and 2200Ω) were applied to the cell. The average of the power density was obtained. This power density was normalized by the area of the anode.

Table 4-4 Power density obtained at different resistor sizes

			Days		
Resistance (Ω)	1	2	4	7	9
1000	0.000081	0.000004	0.000016	0.0016	0.000064
1500	4.26667E-05	2.67E-06	1.07E-05	0.000683	0.000216
2200	6.54545E-05	7.27E-06	0.013636	0.000962	8.91E-05

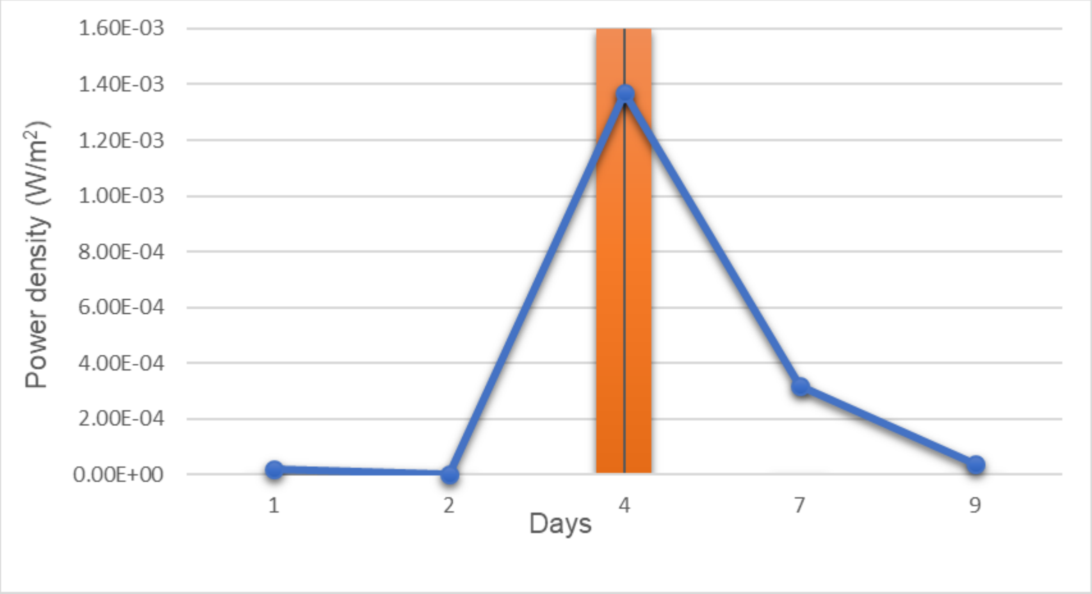

Figure 4-6 Average power density

Below is a depiction of the output for voltage, current density and power density.

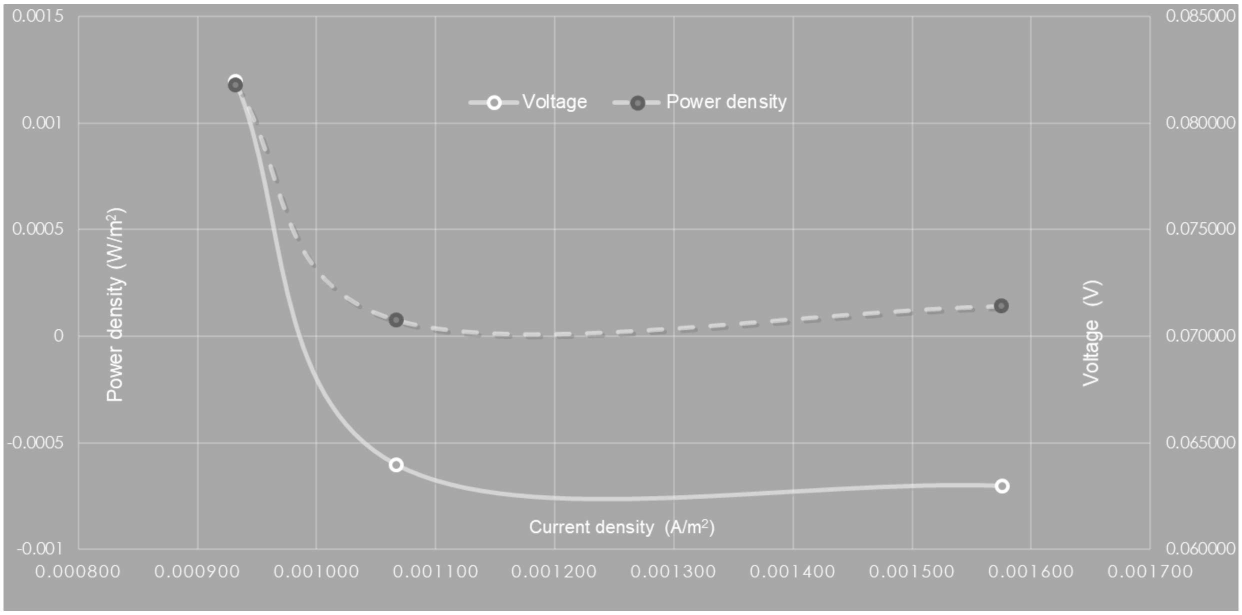

Figure 4-7 Power density, current density and voltage

The power density obtained with different external resistance applied, was very low in the beginning and peaked from day 3, where the maximum power density was achieved in day four. The power density obtained with the least resistance of 1000Ω was the highest, with a peak at 0.000016W/m^2 on 4th day. Whilst the power density peaked for all output from the resistance in day 7 with 0.0016W/m^2 obtained with 1000Ω, 0.000683W/m^2 for 1500Ω and 0.000962W/m^2 2200Ω resistance. However, the power density achieved with the highest external resistance of 2200Ω, was 0.000962W/m^2 slightly higher than the one obtained with 1500Ω resistance, this correlating with the study by Kamau *et al* (2017) that increasing external resistance lead to power increase.

4.3 Polarization curves

To further understand how stable the system was as well as the evaluation of the performance of the anode, using the potentiostat- glavanostat system (Autolab, PGSTAT12, Ecochemie) the polarization curves were created.

The polarization curve was achieved with the external resistance of 1700Ω. Below in Figure 4-8 Figure 4-9 and Figure 4-10 are the curves obtained during the experiment, which were aimed at analysing the characteristics of the MFC. The display of a fuel cell voltage output and for a given current loading.

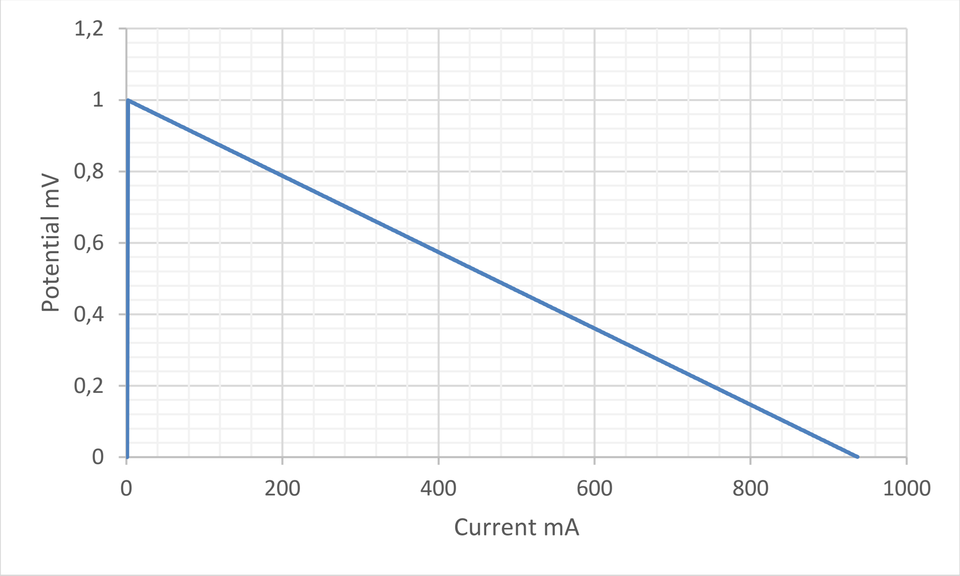

Figure 4-8 Polarization curve: voltage for current loading

The polarization curves obtained serving as a representation of the voltage being the function of the current that is calculated through the use of Ohm's Law (Logan, *et al.,* 2006).

The polarization curves are broken down into three zones that comprises of:

- Starting with the zero current from the Open Circuit Voltage (OCV) where the sharp decrease of voltage

- The slow falling of the voltage, with the voltage dip that corresponds with the current in a linear manner
- At higher currents, there will be fast fall of voltage, which is an indication of concentration losses.

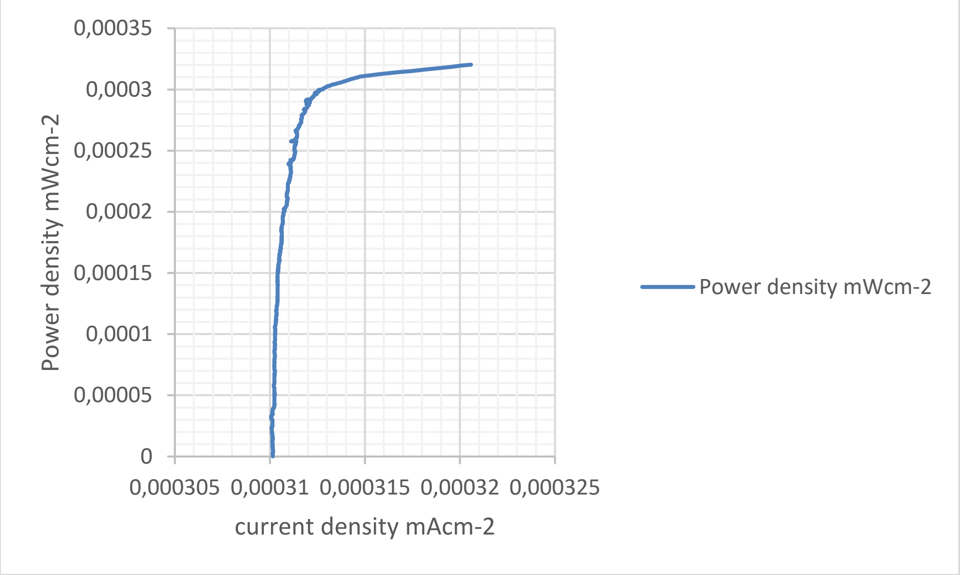

Figure 4-9 Power curve: power density and current density

Figure 4-9 is a depiction of what is called a power curve which can be described as the power density as a function for the current density. The power density increases with the increasing current density and peak at 0.0003mW/cm^2. This is similar to the findings on the study by Simeon et al (2020)

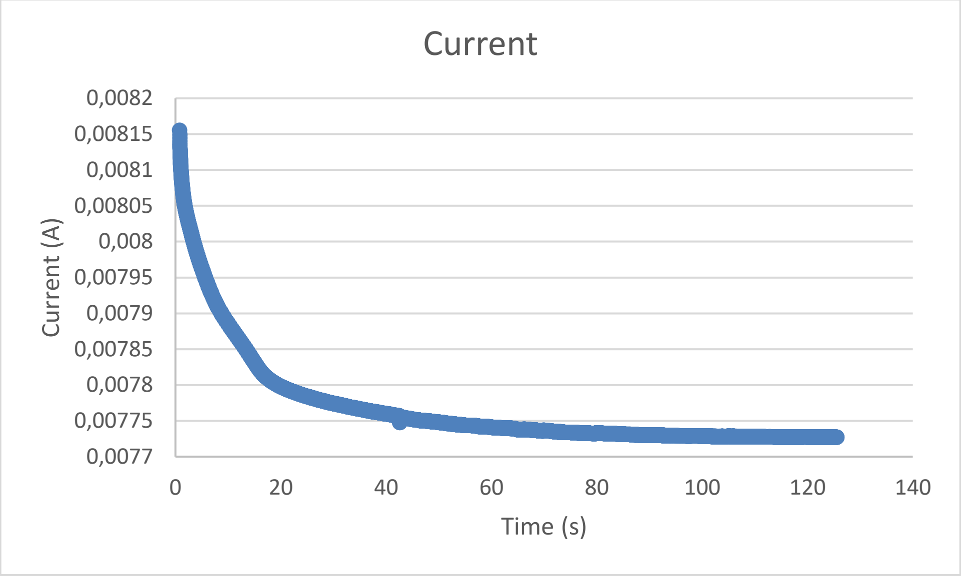

Figure 4-10 Polarization curve: chronoamperometry

Figure 4-10 depicts the behaviour of the current generated over time, which in this case, 130seconds. This is done to test the performance of the electrode. The current had a significant drop from 0.00815A to 0.0078A within the first 20 seconds.

4.4 Wastewater treatment

4.4.1 COD removal

As per the method used by Liu *et al* (2012), for analysis of COD, a quick digestion spectrophotometry (Beckman Coulter DU800, CA, USA) was used.

The equation utilized used for determining the efficiency of COD removal, was the following:

$$\mathrm{ECOD} = \frac{\mathrm{CODin} - \mathrm{CODout}}{\mathrm{CODin}}\ X\ 100\ (4.1)$$

$$\mathrm{ECOD} = \frac{36288 - 22579}{36288}\ X\ 100.$$

E_{COD} = 38%

The calculated COD removal for the experiment was 38%. The lower rate could be alluded to the removal rate of organic substrate that is constant substrate load as a result of the batch process operation, this slowing the biodegradation process (Capodaglio *et al.,* 2013).

4.4.2 Wastewater improvement

Furthermore, additional parameters were analysed of the wastewater, prior processing and post processing to determine quality improvements.

Table 4-5 are the wastewater results, of the influent and effluent and further determination of removal efficiency of the respective material.

As per the method used by Liu *et al* (2012), for analysis of nitrates, a quick digestion spectrophotometry (Beckman Coulter DU800, CA, USA), also for the volatile fatty acid. The Kjedahl Nitrogen, COD and BOD (Robotic Titration Soliprep, Metrohm, Australia).

Table 4-5 Wastewater analysis

Water parameters	Influent (mg/L)	Effluent (mg/L)	Removal efficiency (mg/L)	Removal efficiency (%)
COD	36288	22579	13709	38
BOD	17200	20000	_	_
Volatile Fatty Acids	5985	5835	150	3

Nitrate	<0.1	<0.1	_	_
Nitrogen	4900	2156	2744	56

The results indicated a maximum COD removal of 38%, whilst the volatile fatty acids and nitrogen removal had 3% and 56% removal, respectively. However, substrate showed small traces of nitrate which was less than 0.1mg/L before the experiment and also after.

In addition to power generation, the MFC displayed good substrate degradation, as evident with a few parameters that were observed. Few water parameters that were measured before processing and after, indicated improvement to the quality of the wastewater. The system achieved a COD removal of 38%, volatile fatty acids had a removal of 3% and nitrogen 56% was achieved. The review of the experimental findings of various studies on MFC, indicated that the use of animal carcass wastewater led to COD removal of 50.66%, which is slightly higher than what the current study obtained (Pandey *et al.,* 2016). A large amount was removed of the substrate by the bacteria through the oxygen that diffused through the cathode, which led to the overall COD removal efficiencies (Cheng*et al*., 2006).

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The voltage output was recorded at different cell conditions which was further used to calculate current density and power density (amongst others). This allowed assessing the viability of electricity generation. The experimental work successfully illustrated the feasibility of bioelectricity generation, through the use of the abattoir wastewater, using the MFC system that consisted of two chambers, with no catalyst. The feasibility of the use of abattoir wastewater as anodic substrate was illustrated by the data obtained. The energy stored in the microorganism was converted by the biocatalyst into electrical energy. The power generated depicted similar behaviour as with other research findings with gradual increase in production, reaching the peak which is followed by a gradual drop in power generated. The cell had a peak in power density at 97.7mW/m^2 with 470Ω external/working resistance that was applied; this proving that the abattoir wastewater used can generate electricity using the MFC technology.

The system further demonstrated the ability to improve the quality of water as evident on the improved water parameters. This indicating that there are certain parameters that are improved when the system is utilized, this including the reduction rate on COD of 38%, Volatile Fatty Acids reduced by 3% and the Nitrogen that reduced by 56%. This clearly indicated some improvement in the quality of water, considering the parameters that were tested. Small scale abattoir could consider such a system that will help generate electricity for their needs, whilst improving the quality of their wastewater.

5.2 Recommendations

The concept of using an MFC to generate electricity whilst treating the wastewater from abattoir facilities, is more ideal for the small-scale abattoirs that have limited resources and are less equipped in handling the wastewater. Hence, further research work that can be recommended is the use of an alternative electron acceptor that is cost effective to minimize the operational costs as much as possible. Also considering using a system that is membrane-less, in an attempt to further reduce costs associated with operating such a facility. Also further investigating upscaling of the system, in order to be able to handle large quantities of wastewater from abattoir facilities.

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APPENDICES

Annexure 1

Multimeter readings during the experiment

1) Inoculation stage

Abattoir Wastewater- Spiked with E-coli Water				
		Date	**Volume (l)**	**Voltage**
Inoculation period	Week 1	14 Sep 20	1	0.39
		16 Sep 20	1.125	0.4
		18 Sep 20	1.25	0.48
	Week 2	21 Sep 20	1.25	0.56
		23 Sep 20	1.25	0.56
		25 Sep 20	1.25	0.55
	Week 3	28 Sep 20	1.25	0.58

		30 Sep 20	1.25	0.57
		02 Oct 20	1.25	0.58
	Week 4	05 Oct 20	1.25	0.58
		07 Oct 20	1.25	0.59
		09 Oct 20	1.25	0.63
	Week 5	12 Oct 20	1.25	0.65
		14 Oct 20	1.25	0.59

2) Electricity generation test

Period	**Volume (m^3)**	**Cathode area (m^2)**	**Voltage (V) Without resistor**	**Voltage (V) With resistor**
1	0.001	0.025	0.38	0.30
2	0.001	0.025	0.72	0.64
3	0.001	0.025	0.75	0.67
4	0.001	0.025	0.8	0.72
5	0.001	0.025	0.78	0.70
6	0.001	0.025	0.79	0.71
7	0.001	0.025	0.57	0.49
8	0.001	0.025	0.55	0.47

9	0.001	0.025	0.53	0.44
10	0.001	0.025	0.55	0.47

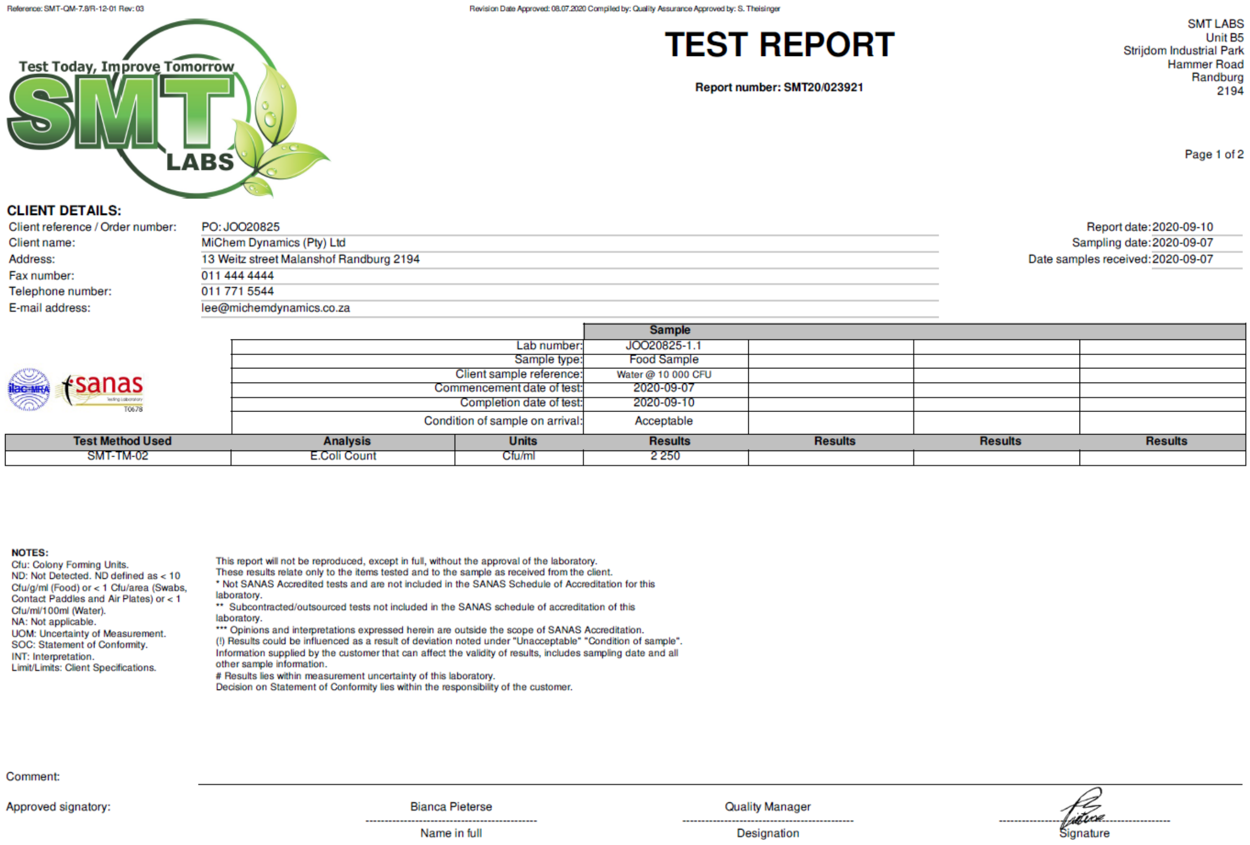
3) Voltage output with different resistors

Experimental work: voltage output with external resistance				
Day	**No resistor**	**1.0KΩ resistor**	**1.5KΩ resistor**	**2.2KΩ resistor**
1	0.35	0.05	0.04	0.06
2	0.39	0.01	0.01	0.02
3	0.59	0.02	0.02	0.03
4	0.75	0.2	0.16	0.23
5	0.64	0.04	0.09	0.07

Annexure 2

Wastewater analysis

1) SMT E-coli water certificate



Reference: SMT-QM-7.8/R-12-01 Rev: 03

Revision Date Approved: 08.07.2020 Compiled by: Quality Assurance Approved by: S. Theisinger

Test Today, Improve Tomorrow
SMT LABS

TEST REPORT

Report number: SMT20/023921

SMT LABS
Unit B5
Strijdom Industrial Park
Hammer Road
Randburg
2194

Page 1 of 2

CLIENT DETAILS:

Client reference / Order number: PO: JOO20825
Client name: MiChem Dynamics (Pty) Ltd
Address: 13 Weitz street Malanshof Randburg 2194
Fax number: 011 444 4444
Telephone number: 011 771 5544
E-mail address: lee@michemdynamics.co.za

Report date: 2020-09-10
Sampling date: 2020-09-07
Date samples received: 2020-09-07

sanas testing laboratory T0678

	Sample			
Lab number:	JOO20825-1.1			
Sample type:	Food Sample			
Client sample reference:	Water @ 10 000 CFU			
Commencement date of test:	2020-09-07			
Completion date of test:	2020-09-10			
Condition of sample on arrival:	Acceptable			

Test Method Used	Analysis	Units	Results	Results	Results	Results
SMT-TM-02	E.Coli Count	Cfu/ml	2 250			

NOTES:
Cfu: Colony Forming Units.
ND: Not Detected. ND defined as < 10 Cfu/g/ml (Food) or < 1 Cfu/area (Swabs, Contact Paddles and Air Plates) or < 1 Cfu/ml/100ml (Water).
NA: Not applicable.
UOM: Uncertainty of Measurement.
SOC: Statement of Conformity.
INT: Interpretation.
Limit/Limits: Client Specifications.

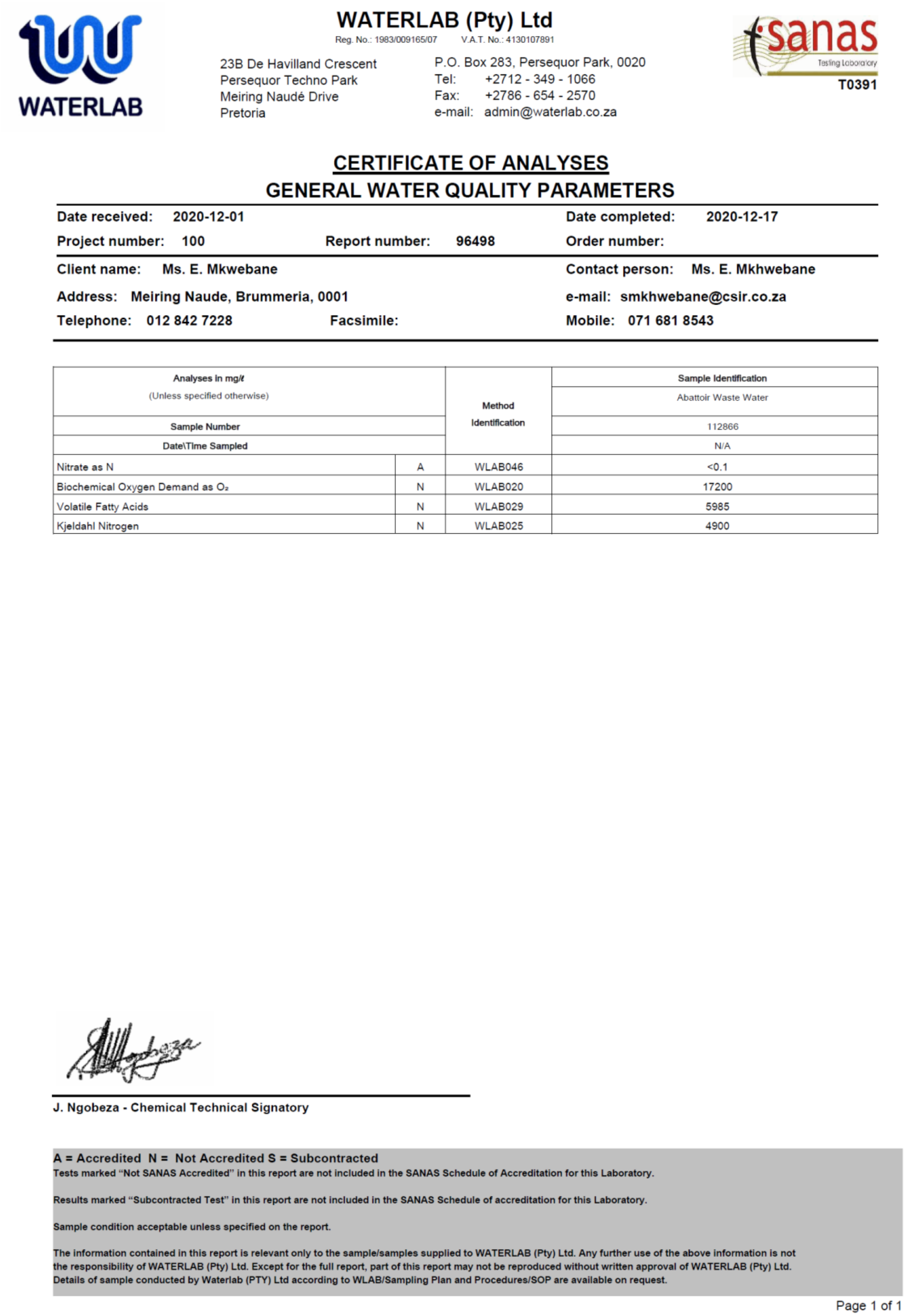
This report will not be reproduced, except in full, without the approval of the laboratory.
These results relate only to the items tested and to the sample as received from the client.
* Not SANAS Accredited tests and are not included in the SANAS Schedule of Accreditation for this laboratory.
** Subcontracted/outsourced tests not included in the SANAS schedule of accreditation of this laboratory.
*** Opinions and interpretations expressed herein are outside the scope of SANAS Accreditation.
(!) Results could be influenced as a result of deviation noted under "Unacceptable" "Condition of sample".
Information supplied by the customer that can affect the validity of results, includes sampling date and all other sample information.
Results lies within measurement uncertainty of this laboratory.
Decision on Statement of Conformity lies within the responsibility of the customer.

Comment:

Approved signatory:

Bianca Pieterse	Quality Manager	
Name in full	Designation	Signature

2) WaterLab wastewater analysis certificate - prior the experimental work



WATERLAB (Pty) Ltd
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T0391

CERTIFICATE OF ANALYSES
GENERAL WATER QUALITY PARAMETERS

Date received: 2020-12-01
Date completed: 2020-12-17
Project number: 100
Report number: 96498
Order number:

Client name: Ms. E. Mkwebane
Contact person: Ms. E. Mkhwebane
Address: Meiring Naude, Brummeria, 0001
e-mail: smkhwebane@csir.co.za
Telephone: 012 842 7228
Facsimile:
Mobile: 071 681 8543

Analyses in mg/ℓ (Unless specified otherwise)		Method Identification	Sample Identification Abattoir Waste Water
Sample Number			112866
Date\Time Sampled			N/A
Nitrate as N	A	WLAB046	<0.1
Biochemical Oxygen Demand as O_2	N	WLAB020	17200
Volatile Fatty Acids	N	WLAB029	5985
Kjeldahl Nitrogen	N	WLAB025	4900

J. Ngobeza - Chemical Technical Signatory

A = Accredited N = Not Accredited S = Subcontracted

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Sample condition acceptable unless specified on the report.

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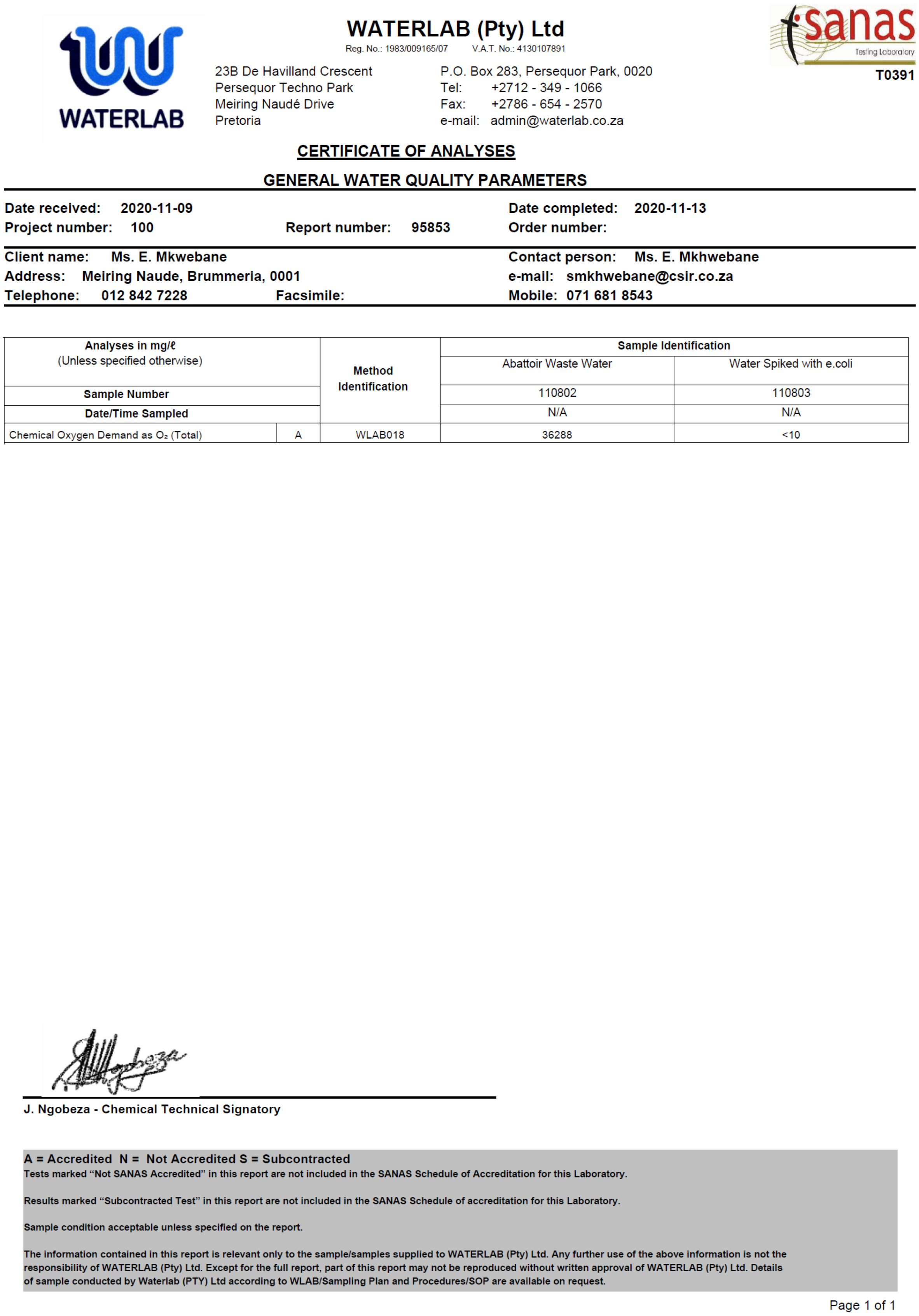

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T0391

CERTIFICATE OF ANALYSES

GENERAL WATER QUALITY PARAMETERS

Date received: 2020-11-09 **Date completed:** 2020-11-13
Project number: 100 **Report number:** 95853 **Order number:**

Client name: Ms. E. Mkwebane **Contact person:** Ms. E. Mkhwebane
Address: Meiring Naude, Brummeria, 0001 **e-mail:** smkhwebane@csir.co.za
Telephone: 012 842 7228 **Facsimile:** **Mobile:** 071 681 8543

Analyses in mg/ℓ (Unless specified otherwise)		**Method Identification**	**Sample Identification**	
			Abattoir Waste Water	Water Spiked with e.coli
Sample Number			110802	110803
Date/Time Sampled			N/A	N/A
Chemical Oxygen Demand as O_2 (Total)	A	WLAB018	36288	<10

Ngobeza

J. Ngobeza - Chemical Technical Signatory

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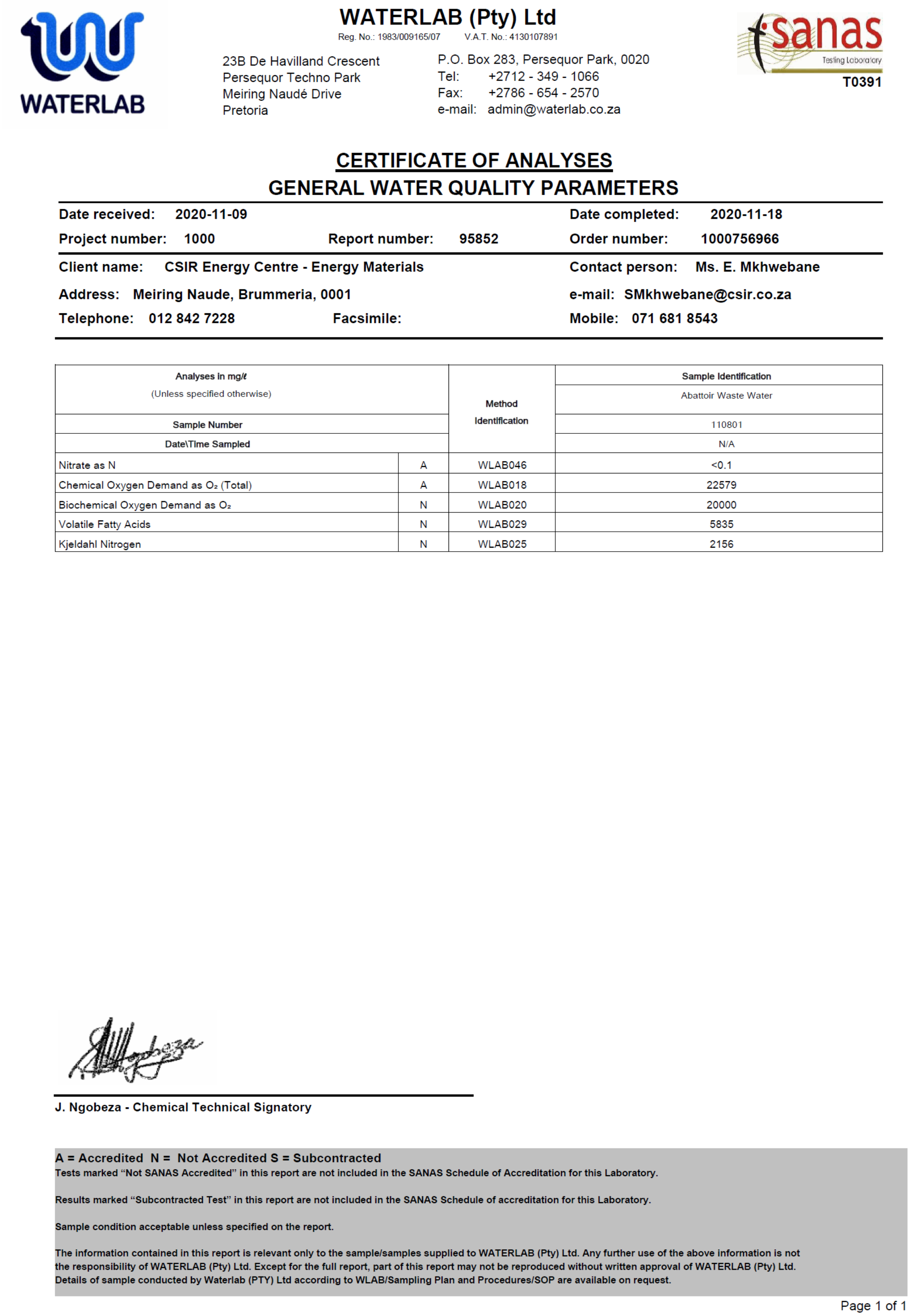
3) WaterLab wastewater analysis certificate- after the experimental work



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CERTIFICATE OF ANALYSES
GENERAL WATER QUALITY PARAMETERS

Date received: 2020-11-09 **Date completed:** 2020-11-18

Project number: 1000 **Report number:** 95852 **Order number:** 1000756966

Client name: CSIR Energy Centre - Energy Materials **Contact person:** Ms. E. Mkhwebane

Address: Meiring Naude, Brummeria, 0001 **e-mail:** SMkhwebane@csir.co.za

Telephone: 012 842 7228 **Facsimile:** **Mobile:** 071 681 8543

Analyses in mg/ℓ (Unless specified otherwise)		**Method Identification**	**Sample Identification** Abattoir Waste Water
Sample Number			110801
Date\Time Sampled			N/A
Nitrate as N	A	WLAB046	<0.1
Chemical Oxygen Demand as O_2 (Total)	A	WLAB018	22579
Biochemical Oxygen Demand as O_2	N	WLAB020	20000
Volatile Fatty Acids	N	WLAB029	5835
Kjeldahl Nitrogen	N	WLAB025	2156

J. Ngobeza - Chemical Technical Signatory

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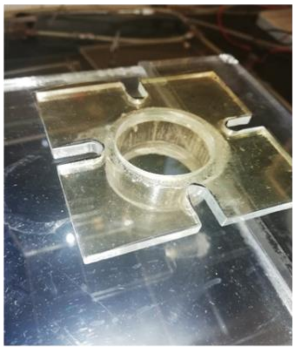
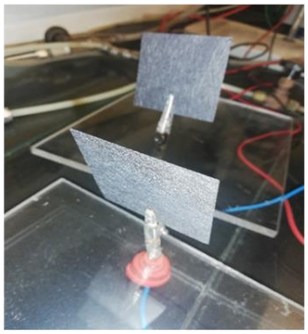
Annexure 3

1) Cell materials and components

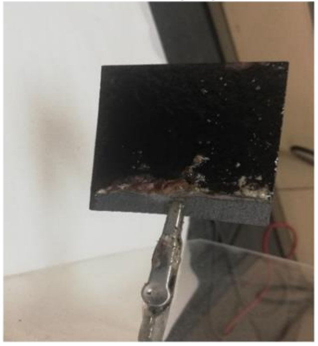
Nafion 117 membrane



Carbon paper

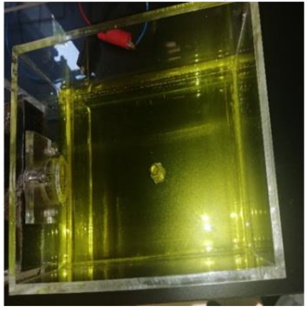


Used carbon paper



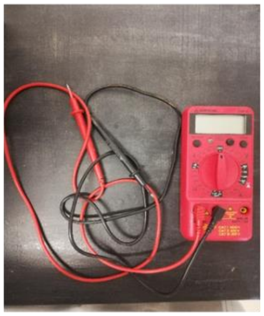
Abattoir wastewater

Potassium Ferricyanide



E-coli water

Multimeter



2) Abattoir wastewater pH readings

Random Wastewater pH readings