MEMBRANE BIOREACTOR- DESALINATION MICROBIAL FUEL CELL HYBRID SYSTEM

by

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A Thesis presented to the Faculty of the American University of Sharjah College of Engineering In Partial Fulfillment of the Requirements for the Degree of Master of Science in Chemical Engineering

Sharjah, United Arab Emirates

April 2018
Approval Signatures

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Acknowledgement

Deepest appreciation goes to my supervisor Dr. Sameer Al-Asheh for his academic support and constructive advice.

Deserving special recognition is Dr. Ahmed A. Aidan for his crucial contribution and suggestions.

I would also like to express my gratitude to the American University of Sharjah (AUS) for offering me a graduate teaching assistantship, which provided me with the financial support as well as a great learning and teaching experience.

I acknowledge with thanks Eng. Wasil El Tahir for his guidance through LabVIEW software, and Eng. Sarmad for his help with all IT issues faced during my work.

Thanks are also extended to the faculty and staff of Chemical Engineering Department at the American University of Sharjah for their warmth encouragement and thoughtful guidance. Thank you to the manufacturing lab as well for their aid in the structuring of my unit.

I sincerely thank everyone who helped me in any way to accomplish this work. Thank you to my colleagues and fellow graduate students for making the laboratory a much more interesting place.

Last, much appreciation and gratitude to my family for their enormous and continuous support.
Dedication

To my family, husband and daughter...
Abstract

The microbial desalination fuel cell (MDFC) is an emerging desalination technology offering great promise of high salinity removal with zero energy input. Moreover, the membrane bioreactor (MBR) is of great reliability in treating domestic and industrial wastewater. The objective of this work is to introduce a hybrid system of a membrane bioreactor and a microbial desalination fuel cell for simultaneous wastewater treatment, seawater desalination and production of electricity. This hybrid system allows low cost resources, energy conservation and low sludge and carbon footprints. Synthetic wastewater, exoelectrogenic microorganisms (yeast) and substrate (glucose) were employed as the anode feed in the MDFC. Two system configurations with an immersed MBR and side-stream MBR have been proposed and compared. In addition, the hybrid system was studied under open circuit (no external load) and closed circuit modes (three different resistive loads). This research presents the success of the hybridization in comparison with a MDFC employing only yeast solution as the anolyte. In addition, it investigates the effect of some modifications namely, the cell size, solutions volume ratio and type of ion exchange membrane. Experimental tests revealed that a bench scale system of 350-ml chamber capacity can achieve higher salinity removal (+6%) and voltage production (+0.035 V) than its alternative 4500-ml chamber. Also, reducing the volume of seawater to anolyte and catholyte volumes by 29% accomplished higher desalination by 6% for the hybrid system removing almost 20% of the salts in 8 days. A total desalination rate (TDR) of 6.25 mg/hr, and a power density of 4.34×10^{-3} W/m^3 are obtained using a 300-KΩ external resistance. On the other hand, a power density of 0.222 W/m^3 and 4.69 mg/hr TDR are achieved using a 4-KΩ external load. Thus, the choice of external resistance involves a trade-off between desalination efficiency and power generation. With regards to wastewater treatment by the MBR, the system was evaluated in terms of total dissolved solids (TDS), total suspended solids (TSS), Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD) and turbidity for the permeate water. The effluent quality enhanced by more than 50% except for the COD and BOD analyses. MDFCs are good alternatives to the energy intensive desalination methods.

Keywords: Microbial Fuel cell (MFC); Membrane Bioreactor (MBR); desalination; wastewater treatment; bioelectricity production.
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<td>Anion Exchange Membrane</td>
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<td>AGMD</td>
<td>Air Gap Membrane Distillation</td>
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<td>BOD</td>
<td>Biological Oxygen Demand</td>
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<td>CEM</td>
<td>Cation Exchange Membrane</td>
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<td>COD</td>
<td>Chemical Oxygen Demand</td>
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<td>DCMD</td>
<td>Direct Contact Membrane Distillation</td>
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<td>DO</td>
<td>Dissolved Oxygen</td>
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<td>ED</td>
<td>Electro-dialysis</td>
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<td>MBR</td>
<td>Membrane Bioreactor</td>
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<td>MCM</td>
<td>Million Cubic Meter</td>
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<td>MD</td>
<td>Membrane Distillation</td>
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<td>MDC</td>
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<td>MDFC</td>
<td>Microbial Desalination Fuel Cell</td>
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<td>MED</td>
<td>Multi-effect Distillation</td>
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<td>MF</td>
<td>Microfiltration</td>
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<td>MFC</td>
<td>Microbial Fuel Cell</td>
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<td>MSF</td>
<td>Multi-stage Flash</td>
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<td>NF</td>
<td>Nanofiltration</td>
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<tr>
<td>NTU</td>
<td>Nephelometric Turbidity Units</td>
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<tr>
<td>OCV</td>
<td>Open Circuit Voltage</td>
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<td>OSHA</td>
<td>Occupational Safety and Health Administration</td>
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<td>RO</td>
<td>Reverse Osmosis</td>
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<tr>
<td>SGMD</td>
<td>Sweeping Gas Membrane Distillation</td>
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<tr>
<td>Acronym</td>
<td>Description</td>
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<td>TDR</td>
<td>Total Desalination Rate</td>
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<td>TSGMD</td>
<td>Thermostatic Sweeping Gas Membrane Distillation</td>
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<td>TSS</td>
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Chapter 1. Introduction

1.1. Overview

Water is the driving force of all nature and people should not take it for granted. It circulates around two thirds of the earth’s surface carrying the aquatic life, nutrients, organic matter and waste materials. It is also utilized domestically, commercially, in agriculture for irrigation and in industrial plants for such purposes as washing, diluting, cooling, etc. Climate change, population growth and increasing living standards lead to several environmental issues including water scarcity, where greater consumption of water resources and more pollution occur.

In order to avoid pollution and provide a clean healthy environment, factories and industrial facilities must follow regulations for the quality of wastewater discharge. Many conventional and developed treatment methods are implemented and studied. Municipal and industrial wastewater treatment plants involve pretreatment by bar screen and grit removal to remove large suspended particles, then primary sedimentation stage and secondary clarifiers to separate biological flocs. After that, the tertiary treatment takes part to enhance the effluent quality by filtration, disinfection and odor control. Finally, sludge treatment plant and disposal takes place.

Water available in nature is not suitable for direct consumption. The main water resource in the Gulf region is from the sea where the salinity levels are so high and not suitable for human use. Moreover, high salinity affects crop production and causes corrosion in water distribution system. Therefore, desalination of seawater is essential in order to provide potable water and avoid its environmental impacts. However, desalination plants are very energy intensive consuming significant capital and operation costs. Desalination systems are classified into two main categories: phase change processes (thermal methods) and single phase processes (membrane processes). Multi-effect distillation (MED), multi-stage flash (MSF) and vapor compression (VC) are the most common thermal methods, while reverse osmosis (RO) is the most known membrane technology for desalination [1]. In addition, hybrid systems can be used whether concerning the energy input or the desalination method such as membrane distillation (MD) [1].
The use of renewable energy is a good alternative to solve water shortage issues, lower costs (lower energy consumption) and protect the environment (lower gas emissions) [1, 2]. Microbial desalination fuel cell (MDFC) is an emerging technology that performs electro-dialysis for desalination of seawater with high salt removal efficiency. It is a promising energy generation process from biomass resulting in a new form of renewable energy, which is significantly needed in our society. For example, a 60 ml MDFC achieved 60% desalination in 20 hours with a maximum mean voltage of 105 mV using 3.2 kΩ and cellulose acetate membrane [3]. Another study achieved 62.2% and 57.6% using dye house effluent as organic substrate for two bacterial strains with maximum voltage of 0.585 V [4]. However, a larger scale MDFC (105 L total liquid volume) exhibited highly nonuniform performance and required applying external voltage to improve desalination rate [5]. A conventional microbial fuel cell (MFC) is a bio-fuel reactor that converts substrates to electricity at high rate and efficiency [6]. MFC technology was applied for wastewater treatment, environmental sensors, bioremediation, renewable energy production and hydrogen production [7]. For instance, a 2.6 L total volume cell made of plastic containers was used for 528 hours removing 75.9% COD from a hostel sewage water using agarose, and producing 0.95 V with a 10 Ω external resistance [8]. Also, a mixed bacterial culture consuming glucose as the carbon source produced power up to 3.6 W/m² in a 40 ml liquid phase volume [6].

Membrane bioreactor (MBR) is a process combining activated sludge treatment and membrane filtration. The reactor is similar to a conventional activated sludge process but without the need for secondary clarification and tertiary steps [9]. Membrane Bioreactors represent a great method for treating wastewater as they reduce plant footprint and cost. MBR is used for treating domestic wastewater and different industrial wastewater from textile, dairy, pharmaceutical, etc. [10]. MBR was used for the removal of selected pharmaceuticals, fragrances and endocrine disrupting compounds from wastewater with high removal rate [11, 12].

From the appealing features of both techniques (MDFC and MBR) mentioned above, a hybrid system comprised of MBR and MDFC for treating wastewater and desalination of seawater simultaneously is considered in this work. Moreover, the attractive prospective from this study is the possibility of recycling some of the sludge
from the MBR as the biomass source in MDFC instead of incineration or landfilling. In addition, the electricity generated from MDFC can be theoretically used as an energy input for the MBR; thus, reducing energy costs and achieving sustainability.

1.2. Thesis Objectives

The main objective of this work is to introduce a hybrid system of MBR and MDFC for treating synthetic wastewater and desalination of seawater simultaneously. In addition, harvesting electricity from the MBR-MDFC hybrid system is the outcome of this technology. Physical and chemical analyses of the product water quality are conducted as well. Moreover, this research focuses on implementing a practical, economical and efficient system. Specific objectives include:

- To perform and assess two different sizes (pilot and bench scales) semi batch hybrid processes.
- To monitor and compare open circuit voltage and TDS for both hybrid and MDFC only systems.
- To observe and evaluate closed circuit voltage and TDS for different external resistances. Also, calculate the maximum power output.
- To measure and compare wastewater and permeate water COD, BOD, TDS, TSS and turbidity.

1.3. Research Contribution

The main contributions of this research work can be summarized as follows:

- Propose for the first time a MBR-MDFC hybrid system, after performing several comparisons between two different schemes and sizes.
- Outline the effectiveness of the hybrid system compared with a MDFC only system in terms of salinity removal and voltage production.
- Implement a closed circuit system with different external resistances and calculating the power output of the system.

1.4. Thesis Organization

The rest of the thesis is organized as follows: Chapter 2 provides background about the water shortage problem worldwide and in UAE specifically. In addition, conventional desalination methods, MDFC and MBR technologies are discussed. The materials of construction and operation of the proposed hybrid systems as both open
circuit and closed circuit system are discussed in Chapter 3 along with the types of water quality analyses performed. Chapter 4 presents the performance evaluation for the employed hybrid systems and experimental result summary. Finally, Chapter 5 concludes the thesis and outlines the future work.
Chapter 2. Background and Literature Review

2.1. Water Shortage

Water shortage and the lack of access to clean drinking water are very serious problems that governments are trying to overcome using many regulations and developed techniques. The world resources institute projected the water stress in many countries by the year 2040 as shown in Figure 1 [13]. Therefore, many possible solutions are studied and implemented to obtain adequate and satisfying water supply.

![Figure 1: Water stress in the world by 2040 [13]](image)

2.2. Statistics of Water in UAE

The Middle East region in general is known for its limited freshwater resources, little rainfall and no many rivers, but available seawater resources. The UAE in particular is one of the top 10 countries in the world suffering from water scarcity and consumes water more than the global average [14]. It is the world’s second largest water desalination producer occupying 14% of the world’s desalinated water [14]. Thus, significant investment is spent to build and operate desalination plants, as they are energy intensive.

The installed capacity of desalination water plants by the UAE authorities has increased by 2.24 MCM/day through the years 2007 to 2014 [15]. This fact offers a clear indication of the higher demand and need for desalination with time due to population growth and higher living standards. Figure 2 shows the general trend in the total amount of water produced from desalination by the different authorities in the
country during the years 2007 to 2014 (data details is in Appendix A, Table 12). Worth mentioning that in 2014 the number of desalination plants reached 46 stations [15].

![Water produced in UAE](image)

Figure 2: Quantity of produced desalinated water in the UAE - data obtained from Federal Competitiveness and Statistics Authority [9].

### 2.3. Thermal Based Desalination

Desalination processes are classified according to the separation process adopted into two categories, thermal processes involving phase change by applying heat; and membrane processes involving pressure energy [16]. Thermal technologies require tremendous amounts of energy in their operation, hence it is conveniently constructed with power station to provide the required steam [17]. The main and the most commonly used worldwide thermal based desalination methods are briefly described below.

**2.3.1. Multi-stage flash distillation (MSF).** It is the first commercial desalination technique that have been used, with considerable market share in the Middle East for long time ago [17]. It is reported that in the year 2000, MSF represented over 70% of the total production of fresh water in the gulf area [18]. It is mainly favored due to its large-scale operations and good potable water quality with 5 to 50 TDS range [16]. Nevertheless, the pumping power needed for the operation of the MSF systems is 2 to 3.5 KWh/m³ of produced water [19].

The basic principle of MSF plant is that the steam generated from the seawater evaporation condenses on the surfaces of the cooling tubes placed in the upper section of the evaporators. The MSF process consists of three main parts, brine heating,
followed by multiple effect flash distillation (heat rejection) and then a subsequent heat recovery part [16]. There are also three different design configurations for the MSF namely, once through, mixer and brine recirculation which are referred to as MSF-OT, MSF-M and MSF-BR, respectively [17]. The typical operation of the MSF process is shown in Figure 3 [18].

![Schematic diagram of the MSF process](image)

**Figure 3:** Schematic diagram of the MSF process [18].

### 2.3.2. Multiple effect distillation (MED)

Multi-effect distillation (MED) can be sometimes known as multi-effect evaporation (MEE). The process is shown in Figure 4 in which multiple evaporators are involved.

The vapor from the first evaporator condenses in the second, and the heat from its condensation serves to boil the salt water in the subsequent evaporator. Consequently, the second evaporator acts as a condenser for the vapor from the first, and the vapor in the second evaporator is like of that of the heating steam in the first. The vapor that is produced in each effect is clear fresh water [20], unlike the MSF type, where there is sequential evaporation of seawater brine through the multi-stages. Therefore, the MED type is more economic than the MSF type in terms of the operating cost and the energy consumption. In the MED type, the vapor recompression is performed through a TVC (thermal vapor compressor) or an MVC (mechanical vapor compressor) [17]. The pumping power required for the MED process operation is less than MSF ranging from 0.8 to 1.4 KWh/m³ of produced water [19].
2.3.3. Vapor compression desalination. Vapor compression (VC) system is characterized by the ability to run without the need for an outside source of steam. The energy source for VC systems is a compressed vapor produced by a mechanical compressor or a steam jet ejector rather than exchanging heat with steam. The feed water is evaporated and the vapor is conveyed to a compressor. The vapor is then compressed to increase its temperature in order to evaporate the source water sprayed from the top. The compressed vapor exchanges its heat with the feed water being sprayed on the evaporation tubes, and condenses into pure water. The basic operation principle of VC is illustrated in Figure 5. The total amount of power required for the operation of mechanical VC systems is typically 8 to 12 KWh/m³ of product water [19].
2.3.4. Membrane distillation (MD). Membrane distillation (MD) is considered as an alternative for the conventional desalination approaches and a hybrid between membranes and evaporation (non-isothermal) processes. The feed water to the MD unit is heated and the vapor passes through the pores of a membrane made of materials repellent from water molecules (hydrophobic). The membranes act as physical barriers and must be selected carefully according to certain criteria [23]. Then, the produced vapor moves to a condensation surface, e.g. foil due to the temperature difference, where it condenses to distilled water. The process is repeated several times on decreasing temperature level and the remaining brine can be removed from the last stage. MD technology has no limitation on the feed water salinity, requires no pressure, operates at relatively low temperatures and has the ability to benefit from different renewable energy sources. Despite these advantages, it is still bench-scale technology with lack of membranes and modules designed [24]. Figure 6 shows several different MD configurations with different application areas to improve the efficiency and performance of the unit.

Figure 6: Different operation modes of the membrane distillation desalination scheme [25]
The Direct Contact Membrane Distillation [DCMD] is a simple construction unit configuration, in which the membrane is in direct contact with both liquid phases; in the hot feed and cooled permeate as they circulate tangentially. The condensation takes place at the semi-permeable membrane interface on the product side. Some alterations in the design have been examined by M. Teoh et al. [26]. A comprehensive analysis of the effects of different parameters on the module performance is investigated by J. Deshpande et al. [27].

In the air gap membrane distillation (AGMD), an air gap exists between the membrane and the condensation plate. In the case of DCMD, an issue of lower efficiency due to the heat loss by conduction across the membrane exists. Hence, an air gap between the membrane and the cold frame solves this problem. On the other hand, its presence results in a decrease in the permeate flux depending on the width of the gap which forms a mass transfer resistance. Mass transfer in AGMD occurs in main four steps: i) transport of molecules from the hot liquid bulk to the membrane surface, ii) evaporation of volatile molecules at the liquid/vapor interface at the membrane pores, iii) diffusive transport of vapor through membrane pores and then through the stagnant air gap, and iii) condensation over the cold surface [28].

A vacuum pump distillation (VMD) is operated by applying vacuum pressure in the permeate side of the module. Vapor condensation happens outside the membrane module as seen in Figure 6. VMD is characterized by smaller pore size membranes since the risk of pore wetting is higher, lesser operating temperature and hydrostatic pressure, higher salt removal and permeate flux can be accomplished [23]. J. Zhang et al. developed a new approach for measuring the properties of hollow fiber membranes for VMD modeling, allowing prediction of flux for various velocities [29].

The schematic diagram of Sweeping Gas Membrane Distillation (SGMD) in Figure 6 demonstrates the principle behind its operation. A cold gas is fed in the permeate side counter currently with the feed, sweeping the vapor molecules along where it condenses outside the membrane module as in the case of VMD. The temperature of the sweeping gas increases rapidly along the column because it gains heat from the feed side. Another mode called Thermostatic Sweeping Gas Membrane Distillation (TSGMD) is introduced using a cold wall in the permeate side of the membrane to reduce the gas temperature. Sweeping gas velocity and water feed
temperature are found to be the most important operating parameters according to M. Khayet et al. [30].

2.3.5. Pervaporation desalination. Desalination via pervaporation has the same configuration of MD, but with one primary difference which is related to the membrane role as a separating media. In pervaporation, the permeate vapor is continuously removed causing a concentration gradient between the membrane sides resulting in water diffusion (Figure 7). MD hydrophobic membranes do not help in the separation performance. On the other hand, pervaporation desalination membranes are dense selective barriers for separation between the feed solution and the vapor phase [31]. Desalination by pervaporation has many merits such as the absence of applied pressure, lower operating temperatures and high salt rejection. Its disadvantages comprises in the low water flux, lack of data and separation performance dependency on the membrane material [24].

Figure 7: Desalination by pervaporation [31]

2.4. Membrane Based Desalination Technologies

2.4.1. Reverse osmosis desalination (RO). Until 1980, distillation was favored over mass transfer driven desalination methods such as electro-dialysis and reverse osmosis despite their lower costs [20]. However, relatively recently, RO desalination gained more share undertaking high daily capacity for seawater desalination. Economically, the RO process depends on the raw water quality [17]. Basically, osmosis process is a molecular filtration or ultrafiltration process, in which a semi-permeable membranes are placed between seawater or salt solution and pure water, and
naturally fresh water diffuses into the saline water due to chemical potential equilibration. In RO process, the opposite happens by applying pressure on the salt water higher than its osmotic pressure. The required pressure depends on the salt concentration of the saline water which is normally around 70 bars [32]. As a result, salt water transfers across the membrane and potable fresh water leaving the spiral wound membrane layers from the low pressure side (Figure 8).

The high water salinity may shorten the lifetime of the RO membrane module and would require a higher pressure for the RO processing [17]. “In the membrane processes, the specific energy consumption for freshwater production is about 4 to 6 kWh/m$^3$ for seawater desalination and about 1.5 to 2.5 kWh/m$^3$ for brackish water desalination [17]. Worth mentioning that RO requires feed water pretreatment, otherwise membrane fouling may occur.

2.4.2. Ultrafiltration (UF). Ultrafiltration is a membrane filtration technology where suspended solids and solutes of high molecular weight are retained in the retentate, while water and low molecular weight solutes pass through the membrane in the permeate. It is not fundamentally different from RO, microfiltration (MF) or nanofiltration (NF), except in terms of the size of the molecules it retains. Ultrafiltration retain materials of sizes larger than that in RO and requires pressure difference much
less than RO as the driving force. Hence, less energy is consumed in ultrafiltration technology. Ultrafiltration membrane is basically used for pretreatment and as a support for RO membranes to reduce the process cost. Most UF membranes use polymer materials, however, ceramic membranes are used for high temperature applications.

2.4.3. Electro-dialysis (ED). Electro-dialysis has been used for brackish water desalination since 1950’s [20]. It is used to transport such salt ions as Na\(^+\) and Cl\(^-\) from solution through ion-exchange membranes to another solution known as electrolyte under an applied electric potential difference. In an ED cell, the dissolved species are transferred away from the feed stream rather than the reverse. The electrically charged particles of the salt are separated from the saline water and concentrated in different compartments [20]. ED device cell is made from different constructions and materials for diverse functions; Figure 9 displays a three-chamber scheme for water desalination.

![Figure 9: Three-compartment electro-dialysis cell scheme](image)

2.5. Microbial Fuel Cell Technology (MFCs)

Microbial fuel cell (MFC) is a flourishing technology for generating consistent electricity from renewable biomass. MFCs are bioreactors that convert the chemical energy in the bonds of organic compounds into electrical energy through catalytic activity of micro-organisms under anaerobic conditions [33]. Fuel cells are similar to battery devices that store energy and can be used as portable power suppliers for small
devices and in remote locations with no power lines. MFC can serve as an alternative for wastewater treatment and for hydrogen production. Other applications of MFCs may include toxicity sensors and biosensors for monitoring water quality such as biological oxygen demand (BOD) [34]. Electricity recovery from wastewater treatment is very attractive because it provides the potential of reducing overall treatment costs while minimizing biomass production [35]. MFCs operate under relatively mild conditions, using a wide range of organic fuels [35].

The essential physical components of the MFC (Figure 10) are the anode, cathode, a cation-exchange membrane and an external wire [36]. In a MFC, bacteria oxidize the substrate releasing some electrons to the anode, where they transfer through the external wire to the cathode which is under aerobic conditions and a current is created. For each electron released, a proton is produced to the cathode through the electrolyte. The electrons and protons react with the oxygen at the cathode to form water. The cation exchange membrane separate the catholyte and the anolyte into different chambers, and act as a barrier that allows only protons to reach the cathode [7].

Figure 10: Microbial fuel cell schematic diagram [36]

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2.6. Microbial Desalination Fuel Cell Technology (MDFCs)

2.6.1. MDFCs description. The microbial desalination cell design consists of three chambers, the anode, the cathode and between them is the saline water of known TDS. Selectively permeable membranes called the ion-exchange membranes separate these chambers. An anion-exchange membrane (AEM) is placed next to the anode, and a cation-exchange membrane (CEM) is adjacent to the cathode. The anode compartment contains the exoelectrogenic microorganisms and the cathode compartment contains the oxidizer. The microorganisms possess electrical properties, which produce bioelectric potential via their metabolism. In other words, the bacteria generate electricity while oxidizing the organic matter in wastewater. The electrodes in the anode and cathode chambers are connected through an external electric circuit [36, 37]. The design of the MDFC is illustrated in Figure 11.

![Diagram of MDFC Design](image)

**Figure 11**: Microbial desalination fuel cell design.

There are different structures and configurations of MDFCs such as air cathode microbial desalination cell, biocathode microbial desalination cell, stack structure microbial desalination cell, recirculation microbial desalination cell, microbial
electrolysis desalination and chemical-production cell, capacitive microbial desalination cell, up flow microbial desalination cell, osmotic microbial desalination cell and bipolar membrane microbial desalination cell. The detailed description of these configurations and their key features and advantages are reviewed by H. M. Saeed et al. [36].

2.6.2. Operation principle of the MDFCs. Basically MDFC is an upgraded version of the conventional Microbial Fuel Cell (MFC) and a bioelectrochemical reactor as it involves biological, physical, chemical and electrochemical processes. It is primarily concerned with two processes that involve oxidation-reduction reactions. Redox reaction includes a transfer of electrons from the reducing agent to the oxidizing agent. It can be broken into half-reactions, one involving oxidation and one involving reduction. Oxidation involves loss of electrons, and an increase in oxidation number. Reduction involves gain of electrons, and a decrease in oxidation number [38].

The microbes in the anode consumes the available biodegradable organic substrate aerobically generating carbon dioxide (CO2) gas, hydrogen protons (H+) and electrons released into the anolyte according to the following oxidation reaction where n depends on the substrate used:

- Substrate + H2O + Biomass → CO2 + n H+ + n e−

No fermentation occurs as the system is under aerobic conditions, thus no methane gas produced. The electrons are transferred to the anode electrode and then travel externally through wires to the cathode electrode generating electricity. The cathode chamber completes the electric loop where oxygen is usually used as the electron acceptor to undergo reduction and produce water. The electrochemical reaction occurring in the cathode:

- O2 + 2 H+ + 2 e− → H2O

These electrode reactions create an electric potential gradient between the electrodes. Under such electric field and to achieve electro-neutrality, anions are attracted to the anode and cations are driven toward to the cathode, allowing the dissociated species of sodium chloride (NaCl) ions, Na+(cation) and Cl− (anion), to
move through the cathode and anode, respectively, and thus desalinating the water in the middle chamber.

If the substrate is glucose, the electrochemical reactions would be as follows:

Anode:
\[C_6H_{12}O_6 + 6 \text{ H}_2\text{O} + \text{Biomass} \rightarrow 6 \text{ CO}_2 + 24 \text{ H}^+ + 24 \text{ e}^-\]

Cathode:
\[6 \text{ O}_2 + 24 \text{ H}^+ + 24 \text{ e}^- \rightarrow 12 \text{ H}_2\text{O}\]

Overall Reaction:
\[C_6H_{12}O_6 + \text{Biomass} + 6 \text{ O}_2 \rightarrow 6 \text{ CO}_2 + 6 \text{ H}_2\text{O}\]

The MDFC technology is considered as a green renewable energy device, and is a completely emission free; however, because of the bacteria metabolism, CO\(_2\) is produced, but its amount is minimum (MDFC is considered a carbon neutral technology).

2.6.3. Applications and merits. The primary purposes of MDFCs are due to electricity generation and removal of pollutants. There are many functions and applications into which MDFCs have been integrated and played some important roles. These are described below [39, 40].

*Generation of bioelectricity*

Energy production is the main function of any fuel cell. MDFCs provide different levels of power depending on the substrate used, materials and design of the cell. The MDFC can be used as a pre-treatment unit for the existing plants to increase their efficiency, supply electricity, lowering the energy input and hence reducing the cost. It is evident that MDFC tackles the major challenge of desalination which is the high energy requirement as it does not only need energy input, but rather produce energy instead.

*Desalination*

MDFC separates the salt ions from the saline water by electro-dialysis. It is an emerging technology for seawater or brackish water desalination with no energy requirement unlike other conventional thermal and membrane based desalination methods discussed earlier. MDFC can achieve up to 99% removal of salt depending on
the hydraulic retention time [39]. Also, worth mentioning that the 99% removal has been accomplished with an added voltage of 0.8 V.

**Water softening**

Water hardness is a term designating the amount of the dissolved minerals calcium and magnesium in water. Hard water containing high minerals content requires pretreatment before handling it whether domestically or industrially. Common softening methods are either energy or materials consuming and may produce large amount of sludge. Again, MDFC performs an interesting alternative. M. A. Arugula et al. [41] studied and proposed a MDFC driven by enzymatic oxidation of glucose using actual and synthetic hard water with effective hardness removal results for different initial concentrations. However, enzymatic fuel cell is limited by short lifetime and high capital loss. Hence, K. S. Brastad et al. [37] developed a bench-scale MDFC design removing 90% of hardness of water samples gathered from different places in the USA.

**Removal of metals**

This represents a new revolution or innovation in industry. By the same working principle for desalination using MDFC, the saline water can be replaced by other solutions in order to separate its anions and cations, i.e. heavy metal aqueous solution. K. S. Brastad et al. [37] reported removal of four heavy metal ions of arsenic, copper, mercury and nickel by 89%, 97%, 99% and 95% from their corresponding synthetic solution using MDFC technology.

**Bio-hydrogen production**

Similar to MFCs, MDFCs can be altered into a Microbial Electro-dialysis Cell (MEDC) by applying an additional voltage desalinating water and producing hydrogen simultaneously [39, 40].

2.6.4. **Challenges and limitations.** One of the main difficulties of implementing the MDFC technology is the scaling up, which is still a challenging issue until today. F. Zhang and Z. He [5] provided a platform for the problems associated with scaling up by setting up a cell with 105 L of liquid volume.

Another challenge that MDFC faced is the membrane inefficiency due to fouling. On the long run, AEM can observe significant biofilming and CEM may suffer from inorganic scaling. Q. Ping et al. [42] conducted a research on AEM and CEM
fouling through eight months operation using artificial seawater. He found that both membranes experience fouling, but CEM resistance increases more significantly than AEM implying that CEM requires more maintenance during operation. Also, F. Hernández-Fernández et al. [43] proposed for the first time the possibility of using supported ionic liquids membranes as proton exchange membranes instead of the conventional and expensive membranes such as Nafion or Ultrex [44].

The type of microorganism involved might be hazardous and harmful, thus careful handling is an issue or safer microorganisms could be used. It is also important to consider the poisonous oxidizers usage in the cathode, as an alternative air-cathode is used in many configurations (safe and free). Low current density is attributed to the internal and external resistances. Internal resistance can be decreased by increasing the inter-membrane distance and higher saline solution conductivity [39]. The CO₂ produced from the biomass respiration results in an acidic medium; its accumulation in the long run lowers the pH of the anode chamber which may affect the performance of the microorganisms. On the other hand, pH in the cathodic chamber increases due to the accumulation of hydroxide by oxygen reduction affecting the reduction efficiency. Hence, pH imbalance is not desired and some solutions are proposed such as increasing the anodic chamber, using buffers, adding acid or base and recirculation from the low pH anode compartment to the high pH cathode compartment [39].

2.7. Membrane Bioreactors (MBR)

2.7.1. MBR description. Membrane bioreactor (MBR) technology imposes semi-permeable membrane to treat municipal or industrial wastewater. There are two kinds of membrane materials used in MBR, namely polymeric or ceramic. Another performance consideration to be taken into account is the geometric orientation of the MBR [45]. The different types of MBR membrane modules may include flat sheet, hollow fibre, multi-tubular, capillary tube, pleated filter cartridge or spiral wound.

The MBR operation can be classified according to the placement of the membranes either as internal/submerged/immersed inside the biological reactor; or external/side stream where membranes are a separate process unit requiring an intermediate pumping step, as shown in Figure 12.
In the immersed type, the membrane module is installed in the main bioreactor vessel or in a separate tank. The permeate is pumped back through the membrane for backwash and the biomass is also continuously pumped back to the main vessel for higher efficiency and performance. Aeration is also required to reduce membrane fouling. Membrane modules can also be removed to an offline cleaning tank. A. Aidan et al. [46] found an optimum schedule for service-backwash time of 2 minutes backwash and 10 minutes service time.

2.7.2. Operation principle of the MBR. MBR combines biological treatment processes with membrane filtration to provide an advanced level of organic and suspended solids removal. The feed through the MBR is separated into the passed permeate, and the rejected retentate. The solid–liquid separation is achieved by Microfiltration (MF) or Ultrafiltration (UF) membranes. Hence, the degree of selectivity depends on the membrane pore size [45]. Solid material deposition (blinding) can cause membrane fouling on the long run. Hence, backwashing is essential, membrane cleaning methods can be either physical (with air), or chemical (using base, acids or oxidants). Organic fouling can be cleaned with sodium hypochlorite while inorganic fouling can be removed with oxalic acid [47]. The primary reasons of membrane fouling are adsorption of macromolecular, growth of biofilms on the membrane surface, precipitation of inorganic matter, and aging of the membrane [47]. An example of membrane backwashing process is shown in Figure 13.
2.7.3. Applications and merits. MBR proved to be an attractive and high reliability option for the treatment of wastewater. It yields a treated water stream free of suspended solids and microorganisms that qualifies it to be discharged or reclaimed for irrigation purposes. This reactor functions both as a treatment method and as clarifier. As a result, it is characterised by the compact design and the small plant footprint compared to conventional settlement separation system where the secondary clarifiers and tertiary filtration processes are eliminated and replaced by the MBR. This allows easy upgrade of old treatment plants and easy retrofit. Stable process operation, efficient removal of nutrients, low excess sludge production and high sludge age, making degradation of complex compounds possible, are all essential advantages of the MBR technology. In addition, MBR can be applied as a pretreatment unit for RO process [9].

2.7.4. Challenges and limitations. The most significant disadvantage of MBRs is the high capital and operational costs. The MBR process is expensive due to aeration (energy demand) and filtration (membranes). Nevertheless, its technology has developed significantly over the years reducing its costs drastically. Another main drawback is the membrane complexity and fouling. In order to avoid operational problems, pretreatment is essential by screening the inlet wastewater to get rid of large particles and unwanted solids to protect the membranes and increase their working life.
The fundamental health aspect which should be carefully considered is handling the sludge from the biological system as it may contain certain level of contaminants that originally present in the wastewater. Thus, the final sludge should be dewatered mechanically or in a drying bed for proper disposal to landfills or buried under earth to avoid nuisance.

2.8. MBR-MFC Hybrid System

Y.P. Wang et al. [48] developed a cost effective integrated system between MBR and MFC with great promise of stable and continuous electricity production that reached 6 W/m³ power density over a long period of 40 days. L. Malaeb et al. [49] also developed a new MBR-MFC hybrid system for simultaneous treatment of wastewater and ultrafiltration using an air-biocathode MFC with 6.8 W/m³ power density and high effluent quality. Using dewatered sludge as a fuel in the anodic chamber reduced the startup time, improved stability and avoided any big drop in the pH as demonstrated by F. Meng et al. [50].

To our best knowledge, a MBR-MDFC hybrid system for treating wastewater, desalination and electricity generation is still an ongoing research, and it is the subject of this thesis to consider this issue. In this case, the sludge produced from the MBR can be fed to the anodic chamber or simply immerse the membrane module inside the anode chamber, and the electricity from the MDFC may thus reduce the power needed to operate the MBR.
Chapter 3. Materials and Methodology

3.1. MBR-MDFC Unit Setup and Materials

Two different units of the MBR and MDFC were prepared from similar materials, but with different scales. These units/materials and their dimensions are listed in Table 1.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Material</th>
<th>Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>MDFC Chambers</td>
<td>Acrylic glass</td>
<td>15 × 22 × 19 cm; 1 cm thickness; 4.5 L effective volume</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8 × 11 × 12.5 cm; 2 cm thickness; 350 ml effective volume</td>
</tr>
<tr>
<td>MBR Membrane</td>
<td>Ceramic flat sheet membrane</td>
<td>10 × 9.5 × 0.7 cm; 0.2 µm pore size; 22 channels</td>
</tr>
<tr>
<td>Ion exchange membranes</td>
<td>Nafion</td>
<td>22 × 19 cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6 × 9 cm</td>
</tr>
</tbody>
</table>

Acrylic glass is transparent, thermoplastic, light weight and shatter resistant; therefore, it was the material of choice for the construction of the cell body.

Fuel cells most commonly incorporate fluorocarbon membranes such as perfluoronated Nafion membrane which exhibits excellent chemical durability and high ionic conductivity. Worth mentioning, the cation exchange membranes have cation exchange groups (anionic charged groups), and cations selectively permeate through the membrane. As for the anion exchange membranes, they have anion exchange groups (cationic charged groups), and anions selectively permeate through the membrane [51, 52].

Generally, the electrode materials must be conductive, biocompatible, and chemically stable in the reactor solution. Carbon is the most versatile and simplest material, which is available in various forms. Carbon fiber and cloth have been extensively used as electrode materials offering high overall internal surface area [44].
A photograph of the working compartment for the two scales hybrid systems of membrane bioreactor – microbial desalination fuel cell (MBR – MDFC) are shown in Figure 14.

The large scale unit capacity can be increased by adding extra acrylic glass chambers assembled by longer metal rods. On the other hand, the smaller unit volume can be either reduced or increased; since the single chamber is made of multiple acrylic glass plates, and thus providing more flexibility. The cells are held together by threaded rods and screwed tightly with bolts in such that the cathode and saline water chambers are separated by a CEM. In the same manner, the anode chamber and the saline water chambers are separated by an AEM. Each chamber or plates are sealed together with neoprene gaskets to prevent leakages.

Figures 14 and 16 show the block diagrams of the two proposed MBR-MFDC hybrid systems. The first diagram (Figure 15) illustrates a hybrid process where the ceramic membrane is immersed in the anode chamber, while the second one (Figure 16) represents a side stream MBR acting as a subsequent treatment step. Also, the latter system differs as it requires scrapping off the sludge to return it back to the desalination microbial fuel cell. Each system has its own advantages and disadvantages as will be discussed in chapter 4.
Figure 15: Schematic diagram for the first proposed hybrid system: 1) air feed stream, 2) compressed air to the cathode diffuser, 3) compressed air to the anode diffuser, 4) cathode chamber, 5) seawater chamber, 6) anode chamber, 7) seawater feed stream, 8) desalinated water product stream, 9) voltmeter, 10) wastewater feed line, 11) overflow stream, 12) membrane permeate, 13) vacuum suction line, 14) membrane backwash stream, 15) drain, 16) permeate and backwash tank, 17) ceramic membrane

Figure 16: Schematic diagram for the second proposed hybrid system: 1) wastewater feed tank, 2) feed valve, 3) air feed stream, 4) cathode chamber, 5) seawater chamber, 6) anode chamber, 7) carbon fibers as electrodes, 8) voltmeter, 9) MBR feed valve, 10) ceramic membrane, 11) permeate pump, 12) Permeate tank, 13) MBR sludge
3.2. System Operation

Before operation, leak tests are performed at least three times by filling the cell for about one hour until no leak is noticed and ensured. Then, the cell is washed with distilled water; this step acts also as a confirmation for the leak testing part.

A synthetic wastewater feed of known composition, as described in Table 2, is fed to the anode chamber. Two grams of yeast (Saccharomyces cerevisiae) is prepared in a 50 ml phosphate buffer solution and preheated to 40°C; this is in order to activate yeast before adding to the process unit [53]. Glucose is added as substrate source for the bacteria by the same amount as yeast. Air is provided by an air diffuser to improve ion exchange for motion inducing and provision of oxygen necessary for microbial growth. The microbial activity is monitored by the measurement of the dissolved oxygen (DO) occasionally.

<table>
<thead>
<tr>
<th>Component</th>
<th>Composition [g/L]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acetic acid</td>
<td>31.6</td>
</tr>
<tr>
<td>NH$_4$Cl</td>
<td>8.8</td>
</tr>
<tr>
<td>KH$_2$PO$_4$</td>
<td>1.3</td>
</tr>
<tr>
<td>FeCl$_3$6H$_2$O</td>
<td>0.1</td>
</tr>
<tr>
<td>CaCl$_2$</td>
<td>0.2</td>
</tr>
<tr>
<td>MgSO$_4$</td>
<td>0.2</td>
</tr>
<tr>
<td>KCl</td>
<td>0.2</td>
</tr>
<tr>
<td>NaCl</td>
<td>0.2</td>
</tr>
<tr>
<td>NaHCO$_3$</td>
<td>49.8</td>
</tr>
</tbody>
</table>

An oxidizing agent is used at the cathode chamber under aeration. The oxidizing agent is 0.02 M potassium hexacyanoferrate III which is not considered as a hazardous substance according to OSHA 29 CFR 1910.1200. Phosphate buffer solution of pH 7 (4.08 g Na$_2$HPO$_4$ and 3.29 NaH$_2$PO$_4$ in 500 ml distilled water) is used to maintain the pH at certain level [54]. The cathode chamber is also under aeration to provide more oxygen as an electron acceptor.
Saline water of total dissolved solids similar to the sea water (33 g/L in average) is fed from the top through cylindrical opening into the middle chamber where desalination occurs. All is fed under room temperature.

Carbon fiber electrodes are inserted in both the anode and cathode compartments and the voltage production is monitored. To measure the cell potential, one can use a crude voltmeter, which works by drawing current through a known resistance. Yet, some energy is wasted due to the frictional heating that occurs when current flows through the wire [38]. Therefore, to determine the cell maximum potential, digital voltmeter was used that draws only a negligible amount of current [38].

The treated water is drawn from the ceramic membrane by a dosing pump set at 100% frequency and 50% stroke. Backwashing is essential to prolong membrane life and avoid clogging, consequently, high quality effluent. Industrially, it can be done by utilizing a vacuum pump and opening the backwash stream pump and valves and closing the final permeate valve (Figure 15). In this work, backwashing was accomplished on a weekly and daily basis using distilled water in the first and second proposed systems, respectively. The experimental work performed is done under semi batch mode in the case of the immersed system.

For the second type of MBR-MFDC unit and according to Figure 16, the inlet and outlet flowrates are made the same and adjusted to approximatly 5 ml/min; this is in order to avoid possible flooding. Low flowrate is preferred for adequate contact time in the anode chamber.

The cell can be operated in two modes: open circuit voltage (OCV), and closed circuit with different external loads. In this work, a multi-meter is used to read the open circuit voltage and a National instruments device is used for closed circuit voltage data acquisition. National Instruments device (Austin, TX) employs LabVIEW 2013 software. LabVIEW contains a comprehensive set of tools for acquiring, analyzing, displaying, and storing data. LabVIEW programs is kind of virtual instruments (VIs) as their appearance and operation often imitate physical instruments, such as multimeters. They are block based programming. There are two windows when creating a new VI: the front panel window and the block diagram.
Figure 17 shows the software block diagram window. It includes Data acquisition assistant that enables different system configurations and converts signals from the device into numbers. The block diagram window also contains voltage and current graphical source code. The current values are obtained by dividing the voltage over the selected resistance. Voltage and current data are then merged to be exported as text or excel files. Array index and selector input are used for interchanging between the channels under different external resistances values. There are also various functions that can be seen on the block diagram window such as the stop function to end running the while loop. As for the timer function, it allows controlling the time intervals for data logging, which is set at 5 seconds. Terminals are entry and exit ports that exchange information between the front panel and block diagram. The front panel window is the user interface for the VI, which displays the data charts as seen in Figure 18. It can be witnessed that the current curve is of analogous trend as the voltage curve, where the current is obtained from ohm’s law:

\[ I = \frac{V}{R} \]

\( I \) is the current in Ampere (A), \( V \) is the voltage in volts (V) and \( R \) is the external resistance in ohms (Ω). The power \( P \), expressed in Watts (W) is calculated by the following relationship:

\[ P = V \times I = \frac{V^2}{R} \]

Power is often normalized to some characteristic of the reactor in order to make it possible to compare power output of different systems [44]. Here, the power is normalized to anode chamber volume (350 ml), and found by:

\[ P = \frac{V^2}{R \times 350 \times 10^6} \]

The previous equation gives the power density in W/m³.
Figure 17: LabVIEW block diagram window

Figure 18: LabVIEW front panel window
3.3. **Water Analysis**

The quality of water is assessed by the following parameters and measurement devices which are formerly calibrated.

3.3.1. **Turbidity.** It measures the clarity of water. It is attributed to the suspended particles scattering or absorbing the light in water such as insoluble organics and microorganisms. It is an indirect measure of the total suspended solids (TSS) in water. The instrument used for measuring the turbidity is ‘HANNA instruments LP 2000 turbidity meter’. It requires 10 ml of solution filled in a glass cuvet. Turbidity is reported in units called a Nephelometric Turbidity Unit (NTU). This technique requires the photodetector in the meter to be placed at a 90 degree angle from the illumination source. As light bounces off the suspended particles, the photodetector can measure the scattered light [55].

3.3.2. **pH.** The pH affects biological and chemical reactions, and measured for most water. pH is measured using a ‘MARTINI instruments multiparameter bench meter Mi 180’. Worth mentioning that the pH sensor must be calibrated regularly to ensure measurement accuracy.

3.3.3. **Total suspended solids (TSS).** They are particles that are larger than 2.5 microns found in the water column. The TSS is determined by filtering a known sample volume through a grade 42 filter paper manufactured by Whatman International Ltd Maidstone, England. The material remaining on the filter after drying at 103°C is the TSS, which is the weight difference before and after drying. Volatile suspended solids (VSS) are determined by heating the TSS (filtered solids) for 15 to 20 minutes at 550°C in an electric furnace, cooling it and again weighing the filter, i.e. the weight difference. Total suspended solids are reported in milligrams of solids per liter of water (mg/L).

3.3.4. **Total dissolved solids (TDS).** It represents the amount of solids dissolved in water and typically include dissolved salts and dissolved organic matter. It combines the sum of all ion particles that are smaller than 2 microns (0.0002 cm). Dissolved solids can cause corrosion to water distribution systems, undesirable taste for potable water and often indicates a high alkalinity or hardness. It can be measured by using TDS measurement device. Forty ml sample is taken each time for the measurement. For the case of data logging when the cell is operated under external resistances, ‘MARTINI
instruments multiparameter bench meter (Mi 180)’ is utilized for measuring the TDS, conductivity and NaCl percentage. Total dissolved solids is often reported as mg/L.

Conductivity is a measure of the capability of water to pass electrical flow, which is directly related to the concentration of ions in water. Hence, conductivity is directly related to the TDS available in water. The measurement unit often used for conductivity is micro-Siemens per centimeter (µS/cm).

Desalination efficiency or salinity removal percentage is found by:

\[
\text{Desalination}\% = \frac{\text{initial TDS} - \text{final TDS}}{\text{initial TDS}} \times 100
\]

Total desalination rate (TDR) is expressed in mg/hr and is calculated by:

\[
TDR = \frac{(C_0 - C_t)V_d}{t}
\]

\(C_o\) and \(C_t\) are the initial and final concentrations of NaCl respectively, \(V_d\) is the liquid volume within the desalination chamber and \(t\) is the time of desalination period.

3.3.5. Dissolved oxygen (DO). It is the amount of free, non-compound oxygen (i.e. O₂ alone) dissolved in water. It affects wastewater treatment process that utilizes microorganisms. It is an important parameter in assessing water quality because of its influence on the organisms living within a body of water. The solubility of oxygen in water is influenced by several parameters; it decreases as temperature increases, decreases as salt levels increase, and increases as pressure increases. DO levels can range from less than 1 mg/L to more than 20 mg/L depending on how all of these factors interact (Temperature, pressure and salt amount) [56]. Measuring of DO value is performed by a Milwaukee DO sensor, in which its probe is immersed in the anode chamber to provide the DO value as mg DO/L.

3.3.6. Chemical oxygen demand (COD). It is the amount of oxygen required to oxidize a waste which represents an indirect measure of organic impurities. The more carbon containing pollutants present in water, the more oxygen needed by microorganisms to oxidize waste to CO₂ and H₂O. The most common methods for estimating the oxygen demand are chemical oxygen demand (COD), biological oxygen demand (BOD) and theoretical oxygen demand (TOD).
COD is the amount of oxygen required to oxidize any organic matter by an oxidizing agent. The oxidizing agent usually used is chromic acid which is a mixture of potassium dichromate and sulfuric acid. First, the mixture is digested by heating to 150°C for 120 minutes and then the remaining oxidizing agent is measured and compared to the initial amount. The difference between the two values is the COD of the sample. The kit used for this purpose is COD kit (AquaLytic, Germany).

3.3.7. Biological oxygen demand (BOD). It is the amount of oxygen needed to oxidize any organic matter in the water biochemically. Standard conditions for BOD analysis are: darkness to prevent algae from producing oxygen, 20°C and an excess of nutrients. The BOD test usually takes 5 days to complete. It is measured by filling a BOD bottle with 428 ml of solution.
Chapter 4. Results and Discussion

In this chapter, the experimental results achieved for the implemented proposed MBR-MDFC hybrid system are presented and discussed. The different findings from multiple cases, towards achieving most satisfying performance are also compared and discussed.

4.1. Immersed System: Pilot Scale versus bench scale hybrid systems

4.1.1. Experimental results. For this case study, the first proposed system (Figure 15) was used, where an immersed ceramic membrane is in the anode chamber performing as a MBR. Table 3 below lists the experimental results of the two different scales comparison.

<table>
<thead>
<tr>
<th>System scale</th>
<th>Pilot scale</th>
<th>Bench scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation time</td>
<td>4 days</td>
<td>4 days</td>
</tr>
<tr>
<td>Initial TDS [g/L]</td>
<td>36.00</td>
<td>34.80</td>
</tr>
<tr>
<td>Final TDS [g/L]</td>
<td>34.30</td>
<td>31.20</td>
</tr>
<tr>
<td>Salt removal %</td>
<td>4.722</td>
<td>10.35</td>
</tr>
<tr>
<td>Voltage [Volts]</td>
<td>0.572</td>
<td>0.607</td>
</tr>
<tr>
<td>Wastewater turbidity [NTU]</td>
<td>345.0</td>
<td>345.0</td>
</tr>
<tr>
<td>Permeate water turbidity [NTU]</td>
<td>73.00</td>
<td>157.0</td>
</tr>
<tr>
<td>Wastewater TDS [g/L]</td>
<td>33.60</td>
<td>33.60</td>
</tr>
<tr>
<td>Permeate water TDS [g/L]</td>
<td>21.50</td>
<td>15.00</td>
</tr>
</tbody>
</table>

Saline water of 36.00 and 34.80 g/L TDS are fed into a pilot scale and bench scale hybrid systems, respectively. The large cell achieved 4.722% salinity removal where the TDS dropped from 36.00 to 34.30 g/L for 4 days operation time producing 0.5720 V. As for the smaller cell, 10.35% salinity removal is achieved with a decrease in the TDS from 34.80 to 31.20 g/L in 4 days operation time producing 0.6070 V. The results are shown in Figure 19 (with more details in Appendix A, Table 13).

In addition, the wastewater turbidity and TDS are decreased from 345.0 NTU and 33.60 g/L to 157.0 NTU and 15.00 g/L, respectively for the case of the bench scale system; while for the larger scale system they decreased to 73.00 NTU and 21.50 g/L TDS, respectively, as they appear in permeate water from the MBR.
4.1.2. Performance evaluation. The experimental work revealed the success of the system in wastewater treatment, voltage generation and seawater desalination, which requires further improvement (e.g. side stream system configuration is suggested and tested). The bench scale exhibited higher salinity removal and voltage production than that of pilot scale for the 4 days operation time. Scaling up the cell leads to many factors causing lower system efficiency. Larger system requires more vigorous mixing for uniform ion distribution and transportation. The bulk volume of salt water adjacent to the ion exchange membranes experience better ion transfer. Therefore, it takes more time for the salt ions to dissociate from the water in a large system, in oppose to a smaller scale system. However, the bench scale cell potential/voltage is larger than pilot scale potential throughout the four days operation as seen in Figure 19, which shows high electron transferal to the anode due to the high electrode surface area to volume ratio. Nevertheless, the voltage difference between the two systems is not significant after the four days of operation.

Figure 19 demonstrates how in both scale systems the TDS drops most rapidly at the beginning, then decreases in a slower manner throughout the rest of operation time. TDS curve undergoes more fluctuation for the pilot scale unit due to the ununiformed solution. As for voltage generation, it was observed that the pilot scale system started at a lower value of 0.3430 V, but increased steadily almost reaching the smaller unit voltage value of 0.6070.

The turbidity, which gives an indication of the total suspended solids in water, decreased more significantly in the case of pilot scale system. This can be attributed to
the fact that many precipitates settled down and stuck in the bottom of the chamber since
the reactor is batch leaving the upper liquid volume clearer and thus indicating better
wastewater treatment than the bench scale in regards of turbidity assessment, which is
not necessarily the case. For just and fair valuation between the two scales, mixing prior
to sampling should be done. However, mixing in large volume unit is of course not as
effective as in smaller volume units as it is not possible to reach all corners and may
miss few areas. Hence, the bench scale system presents more uniform solution and more
accurate readings. The water TDS in the permeate dropped more in the smaller hybrid
system as mentioned indicating higher microbial activity with more dissolved salts
consumption (nutrients content) in the wastewater fed to the anode chamber.

The set up and handling of the larger unit is much more difficult and is time
consuming. Moreover, the membrane cleaning and backwashing requires frequent cell
disassembling. Hence, backwashing cannot be done more frequently during the process;
i.e., time, efforts and resources are of concerns. The only advantage of the larger scale,
is footprint reduction, nevertheless, a hybrid system with side-stream MBR allows easy
plant retrofit and unit maintenance. In addition, side-stream MBR would be more
practical as suggested in Figure 16, because otherwise many membranes will be
employed for each unit which are considered very costly. Smaller units can be stacked
for industrial application where great production is desired. Stacking them up in series
would also increase the voltage generation.

4.2. Side Stream MBR-MDFC Hybrid System Versus MDFC only

4.2.1. Experimental results. The second proposed system (Figure 16) was used
along with a conventional microbial desalination cell (with only yeast in the anode
chamber) for the purpose of comparison. Both are of the same size (350 ml chamber
capacity) and fed with saline water of 32.2 g/L TDS. The main experimental results are
tabulated in Table 4 below.

<table>
<thead>
<tr>
<th>System</th>
<th>Hybrid</th>
<th>MDFC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation time</td>
<td>12 days</td>
<td>12 days</td>
</tr>
<tr>
<td>Initial TDS [g/L]</td>
<td>32.20</td>
<td>32.20</td>
</tr>
<tr>
<td>Final TDS [g/L]</td>
<td>25.40</td>
<td>23.20</td>
</tr>
<tr>
<td>Salt removal %</td>
<td>21.12</td>
<td>27.95</td>
</tr>
<tr>
<td>Maximum voltage [Volts]</td>
<td>0.616</td>
<td>0.588</td>
</tr>
</tbody>
</table>
In the case of hybrid system, 21.12% salinity removal was achieved with a drop in the TDS from 32.20 g/L to 25.40 g/L, and maximum voltage attaining 0.6160 V in 12 days operation time. In the case of MDFC, 27.95% salt removal was achieved with a decrease in the TDS from 32.20 g/L to 23.20 g/L, and maximum voltage production of 0.5880 V in 12 days operation. The results are shown in Figure 20 (with more details in Appendix A, Table 14).

![Figure 20: TDS and voltage results for side stream MBR-MFDC system](image)

**4.2.2. Performance evaluation.** This experiment was conducted for a long period (12 days) showing the long durability of the ion exchange membranes. The hybrid system exhibited higher voltage production than the MDFC, but inferior salt deduction percentage. The drop in voltage, in day 4, 7 and 11 as shown in Figure 20, was mainly due to leaving the unit overnight with no air (due to lab safety regulations). When air and glucose were added to the system, to enhance bacterial activity, the microbial cell shortly stimulate voltage production. Overall, the hybrid system voltage generation is less fluctuate than the MDFC as observed in Figure 20, which may be attributed to the bacterial nutrients available in the wastewater elements sustaining the microbial growth.

These results encourages the success and effectiveness of the hybrid system proposed with further modifications to enhance salt removal percentage such as reducing saline water volume and trying a different ion exchange membrane.
4.3. MBR-MDFC Hybrid System with Smaller Middle Chamber

4.3.1. Experimental results. Again, the second proposed system (Figure 16) was used along with a conventional microbial desalination cell, but with smaller middle chamber for water desalination of size 250 ml which is fed with saline water of 35.1 g/L TDS. The sizes of both anode and cathode chambers were not changed (350 ml). Table 5 briefly lists the results from this experiment.

<table>
<thead>
<tr>
<th>System</th>
<th>Hybrid</th>
<th>MDFC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation time</td>
<td>8 days</td>
<td>8 days</td>
</tr>
<tr>
<td>Initial TDS [g/L]</td>
<td>35.10</td>
<td>35.10</td>
</tr>
<tr>
<td>Final TDS [g/L]</td>
<td>28.10</td>
<td>26.10</td>
</tr>
<tr>
<td>Salt removal %</td>
<td>19.94</td>
<td>25.64</td>
</tr>
<tr>
<td>Maximum voltage [Volts]</td>
<td>0.586</td>
<td>0.550</td>
</tr>
</tbody>
</table>

The hybrid system accomplished 19.94% salt removal with a drop in the TDS from 35.10 g/L to 28.10 g/L, and maximum voltage reaching 0.5860 V in 8 days operation time. On the other hand, implementation of MDFC resulted in 25.64% saline removal with a decrease in the TDS from 35.10 g/L to 26.10 g/L, and maximum voltage production of 0.5500 V in 8 days operation. The results are shown in Figure 21 (with more details in Appendix A, Table 15).

Figure 21: TDS and voltage results for hybrid system with smaller middle chamber
4.3.2. Performance evaluation. Reducing the seawater volume to anolyte and catholyte volumes did enhance the salt removal efficiency as illustrated in Table 6. It also narrowed the gap between the hybrid system and MDFC TDS curves as observed in Figure 21, where the TDS difference is null throughout the first seven days. The voltage is steadily increasing in the hybrid system in a higher fashion than MDFC. The drop in voltage in the hybrid system curve, as seen in Figure 21 in day 5, was caused by a sudden increase in the overflow flow rate causing the anolyte volume to decrease drastically.

Now for scheme evaluation, in the larger middle chamber volume systems (350 ml), the desalination reached 13.96% in the hybrid system and 21.12% in MDFC by the eighth day (Figure 20). As for the decreased middle compartment (250 ml) in both hybrid and MDFC systems, salt removal percentage reached 19.94% and 25.64 % respectively in 8 days as recorded in Table 5. Accordingly, decreasing the middle chamber reduced the internal resistance and enhanced the desalination rate especially in the hybrid system as illuminated in Table 6.

Table 6: Effect of reducing middle chamber volume on desalination

<table>
<thead>
<tr>
<th>System</th>
<th>Hybrid</th>
<th>MDFC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation time</td>
<td>8 days</td>
<td>8 days</td>
</tr>
<tr>
<td>350 ml middle chamber</td>
<td>13.96%</td>
<td>21.12%</td>
</tr>
<tr>
<td>desalination%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>250 ml middle chamber</td>
<td>19.94%</td>
<td>25.64%</td>
</tr>
<tr>
<td>desalination%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.4. Closed Circuit System

Previous tests were performed under open circuit voltage (OCV) cells operation with no external resistance (infinite resistance). Alternatively, tests with different resistances are employed, namely 10.2, 3833 and 302200 ohm. The system is integrated with Martini instruments multiparameter bench meter (Mi 180) and National instruments device. Both instruments were connected with a computer for data logging.

In one scenario, a channel with external resistance of 10.20 Ω value was selected from the front panel in LabVIEW software. Seawater characteristic was initially at 29.60 g/L (TDS), 59.30 mS/cm (conductivity) and 116.0% (NaCl percentage; it was then dropped to 27.55 g/L, 55.10 mS/cm and 107.9%, respectively. Thus, salinity removal of 6.930% was achieved in four days.
Figure 22, which is exported from the MI 180 software, reveals the conductivity curve decreasing slowly. The conductivity as stated before is directly related to the TDS by a 0.5 TDS factor. Consequently, the TDS curve would be of similar trend. The sudden drops in the conductivity curve (blue line) are due to taking samples from the middle chamber for testing.

![Conductivity chart for system under 10.2 ohm external resistance](image1)

Figure 22: Conductivity chart for system under 10.2 ohm external resistance

Figure 23 displays the voltage data acquisition, where data points are five seconds apart. Throughout the process there are tremendous fluctuations, yet slightly increasing until keeping steady around the same average point. The maximum voltage reached is 0.03303 V, however, since it is a single unrepeated point, it may be considered as an error point due to system debugging. Consequently, the maximum voltage obtained is considered to be 0.01839 V with 1.803 mA current value and 0.09476 W/m$^3$ power density.

![Closed circuit cell voltage with 10.2 ohm external resistance](image2)

Figure 23: Closed circuit cell voltage with 10.2 ohm external resistance
In another scenario, the port with external resistance of 3833 Ω value was chosen as well from the front panel in LabVIEW software. Seawater characteristics was originally 29.70 g/L (TDS), 59.40 mS/cm (conductivity) and 116.1% (NaCl percentage); they were then decreased to 27.90 g/L, 55.80 mS/cm and 109.1%, respectively. Thus, a salinity removal of 6.060% is achieved in four days. Figure 24 indicated that the TDS curve declining gently.

Figure 24: TDS curve for system under 3833 ohm

Figure 25 illustrates the voltage values for this system, which are also taken every five seconds. It is quite observable that there are much less fluctuations and a smoother curve is established than that in Figure 23. The voltage propagates rapidly at the beginning and continues to raise up to the maximum voltage of 0.5461 V with 0.1425 mA current value and 0.2223 W/m³ power density.

Figure 25: Closed circuit cell voltage with 3833 ohm external resistance
An external load of 302200 Ω value is also designated from the front panel in LabVIEW software. In this case, TDS, conductivity and salinity of seawater decreased from 30.20 g/L, 60.40 mS/cm and 118.1% (NaCL percentage) to 27.80 g/L, 55.60 mS/cm and 108.7%, respectively. Thus, 7.950% desalination was achieved in four days. Figure 26 indicates that the TDS curve falling gradually.

Figure 26: TDS curve for system under 302200 ohm

Figure 27 shows the voltage results under 302200 ohm external load. The curve is definitely more leveled than what is shown in Figure 23, but a bit more fluctuated than that in Figure 25. The voltage keeps increasing with some few setbacks attaining a maximum value of 0.6779 V with 0.002243 mA current value and 4.344 mW/m³ power density.

Figure 27: Closed circuit cell voltage with 302200 ohm external resistance.
4.5. Wastewater Results

The growth of bacteria is determined not only by the composition of their surroundings but by sudden changes in the living environment. Dissolved oxygen was monitored regularly because a decrease in DO indicates higher oxygen consumption and thus progress in microbial growth. The MDFC activity enhanced when glucose or a new bacterial batch was added. Table 7 exhibits the DO measurements over 3 days. Sample number 8 and 15 represent the beginning of the second and third day’s readings respectively. The increase on these DO readings, thus lower microbial activity is due to leaving the system unattended overnight, with no substrate addition or aeration.

Table 7: Dissolved oxygen readings over 3 days

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Dissolved oxygen (DO) [mg/L]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10.0</td>
</tr>
<tr>
<td>2</td>
<td>9.5</td>
</tr>
<tr>
<td>3</td>
<td>1.8</td>
</tr>
<tr>
<td>4</td>
<td>0.7</td>
</tr>
<tr>
<td>5</td>
<td>0.5</td>
</tr>
<tr>
<td>6</td>
<td>0.7</td>
</tr>
<tr>
<td>7</td>
<td>0.8</td>
</tr>
<tr>
<td>8</td>
<td>3.0</td>
</tr>
<tr>
<td>9</td>
<td>8.3</td>
</tr>
<tr>
<td>10</td>
<td>8.1</td>
</tr>
<tr>
<td>11</td>
<td>7.7</td>
</tr>
<tr>
<td>12</td>
<td>1.4</td>
</tr>
<tr>
<td>13</td>
<td>1.0</td>
</tr>
<tr>
<td>14</td>
<td>0.8</td>
</tr>
<tr>
<td>15</td>
<td>7.5</td>
</tr>
<tr>
<td>16</td>
<td>7.0</td>
</tr>
<tr>
<td>17</td>
<td>2.1</td>
</tr>
<tr>
<td>18</td>
<td>0.9</td>
</tr>
<tr>
<td>19</td>
<td>1.0</td>
</tr>
<tr>
<td>20</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Multiple samples have been taken to test the permeate water quality in terms of TDS, TSS, COD, BOD and turbidity; they have been decreased by 55.53%, 90.21%, 29.43%, 32.94% and 94.08% respectively. The aim is to reach the environmental general standards for effluent discharge. Table 8 presents the average values of wastewater and permeate water qualities. Turbidity, COD and TDS detailed quantities are recorded in Appendix A, Tables 16, 17 and 18 respectively where each value was
taken for a one week system run. According to the environmental protection act 2002 regulations [57], the maximum permissible limit for COD is 120 mg/L and for BOD is 40 mg/L. In reference to Table 8, there is still a need for a second MBR treatment unit in order to meet the quality standards. The most important factor for ensuring the best water quality possible is the membrane backwashing, which is necessary to avoid clogging and inefficient treatment.

Table 8: Wastewater and permeate water quality

<table>
<thead>
<tr>
<th>Quality parameter</th>
<th>Turbidity [NTU]</th>
<th>TDS [g/L]</th>
<th>TSS</th>
<th>COD [g/L]</th>
<th>BOD [ppm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wastewater</td>
<td>679</td>
<td>28.2</td>
<td>2.731</td>
<td>11.86</td>
<td>61.14</td>
</tr>
<tr>
<td>Product water</td>
<td>40.178</td>
<td>12.54</td>
<td>0.2674</td>
<td>8.37</td>
<td>41</td>
</tr>
</tbody>
</table>

4.6. Results Summary

The main results of the experimental work can be divided mainly to two parts: open circuit mode and closed circuit mode. Table 9 summarizes results for the case of open circuit mode. A smaller scale MDFC with small capacity middle chamber and a side stream MBR system demonstrates better results. In general, hybrid system proved to accomplish higher voltage production but lower salinity removal. On day eight using equal sized compartments (350 ml), the salt removal reached 13.975% and 21.118% for the hybrid and MDFC systems respectively. Hence, desalination percentage increased with smaller middle chamber, due to lowering the internal resistance of the cell.

Table 9: Open circuit system results summary

<table>
<thead>
<tr>
<th>System</th>
<th>Operation days</th>
<th>Desalination percentage</th>
<th>Maximum voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Immersed system</td>
<td>Pilot scale</td>
<td>Four days</td>
<td>4.720%</td>
</tr>
<tr>
<td></td>
<td>Bench scale</td>
<td></td>
<td>10.35%</td>
</tr>
<tr>
<td>Side stream system</td>
<td>Hybrid</td>
<td>Twelve days</td>
<td>21.12%</td>
</tr>
<tr>
<td></td>
<td>MDFC</td>
<td></td>
<td>27.95%</td>
</tr>
<tr>
<td>System with smaller middle chamber</td>
<td>Hybrid</td>
<td>Eight days</td>
<td>19.94%</td>
</tr>
<tr>
<td></td>
<td>MDFC</td>
<td></td>
<td>25.64%</td>
</tr>
</tbody>
</table>
Table 10 summarizes the results for the case of closed circuit mode at different resistances. When the external resistance increases, the current decreases and the voltage increases. The maximum power is obtained when the internal and external resistances are equal. Table 10 shows that the power yield increases when varying the load from $10.2 \, \Omega$ to $3833 \, \Omega$. Nevertheless, external load value of $302200 \, \Omega$ allows high voltage production, but low power output; thus, lower resistance is preferred. According to these results, the best external resistance value lies between either $3833 \, \Omega$ and $10.2 \, \Omega$ or $3833 \, \Omega$ and $302200 \, \Omega$ for the maximum power. This confirms that if the external resistance is higher or lower than internal resistance, generated power will decrease [58].

From Table 10, it is witnessed that the maximum TDR of $6.25 \, \text{mg/hr}$ corresponds to the lowest power density of $4.344\times10^{-3} \, \text{W/m}^3$ and minimum TDR of $4.69 \, \text{mg/hr}$ is parallel to the maximum power density of $0.2223 \, \text{W/m}^3$. Thus, the selection of the best external resistance requires a trade-off between desalination efficiency and power generation.

Table 10: Closed circuit system results summary

<table>
<thead>
<tr>
<th>Resistance</th>
<th>10.2 Ω</th>
<th>3833 Ω</th>
<th>302200 Ω</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day 1 TDS$_{avg}$ [g/L]</td>
<td>29.30</td>
<td>29.34</td>
<td>29.70</td>
</tr>
<tr>
<td>Day 2 TDS$_{avg}$ [g/L]</td>
<td>29.12</td>
<td>29.05</td>
<td>29.40</td>
</tr>
<tr>
<td>Day 3 TDS$_{avg}$ [g/L]</td>
<td>28.70</td>
<td>28.59</td>
<td>28.10</td>
</tr>
<tr>
<td>Day 4 TDS$_{avg}$ [g/L]</td>
<td>27.74</td>
<td>28.19</td>
<td>27.90</td>
</tr>
<tr>
<td>Total desalination rate</td>
<td>5.34 mg/hr</td>
<td>4.69 mg/hr</td>
<td>6.25 mg/hr</td>
</tr>
<tr>
<td>Desalination percentage</td>
<td>6.93%</td>
<td>6.06%</td>
<td>7.95%</td>
</tr>
<tr>
<td>Maximum voltage</td>
<td>0.01839 V</td>
<td>0.5461 V</td>
<td>0.6779 V</td>
</tr>
<tr>
<td>Maximum current</td>
<td>1.803 mA</td>
<td>0.1425 mA</td>
<td>0.002243 mA</td>
</tr>
<tr>
<td>Maximum power density</td>
<td>$0.09476 \text{ W/m}^3$</td>
<td>$0.2223 \text{ W/m}^3$</td>
<td>$4.344\times10^{-3} \text{ W/m}^3$</td>
</tr>
</tbody>
</table>

Another approach was tested in order to enhance desalination efficiency using cellulose acetate membrane as it resulted from literature in 60% desalination within
20 hours [3]. Using this membrane in this research, the desalination percentage boosted to 39.07\% decreasing the TDS from 30.2 g/L to 18.4 g/L in 24 hours. However, disorder was noticed in the system. The middle chamber volume increased and flooded outside the cell. Significant decrease in the other chambers liquid volume was observed as well. As an explanation, the cellulose acetate membrane worked as a forward osmosis membrane rather than an ion exchange membrane causing the water molecules to escape towards the middle compartment causing dilution and greatly reducing the TDS. Hence, the MDFC loses its definition, as the salt ions do not dissociate from the saline water.

pH measurements were recorded for confirmation of no pH imbalances. The pH in the middle chamber fluctuates between 8.26 and 8.46 as seen in Figure 28, and stays quite stable at an average of 6.71 in the cathode chamber (Figure 29) due to the buffer solution inhabitation. The anode chamber pH decreases slowly from 6.25 to 5.65 (Figure 30) because of the continuous wastewater feed and the bacteria metabolism. The pH readings for the solutions in all the chambers were taken every 5 seconds.

![Figure 28: pH chart for the solution in the middle chamber](image-url)
Table 11 demonstrates some contrasts between this work and what have been cited in literature. For example, higher desalination percentage of 62.2% was recorded using 14 ml chamber volume and dye house effluent as the organic substrate for two bacterial strains [4], and of 60% using 60 ml total capacity and cellulose acetate membrane [3] which was experimented in our work as mentioned earlier. However, we aim to treat wastewater using unharmful microorganisms and have achieved 21% in 12 days desalination and increased power density (from 0.15 to 0.22 W/m³) despite implementing a scaled up cell size of almost 25 times bigger than that listed in literature. Also, a bigger anode volume by 1050 ml is cited and accomplished about 41% salt removal using dewatered sludge as a fuel and higher power density of 3.2 W/m³ [50], however, this was attained over a long period of 130 days. Usage of potassium
ferricyanide as the oxidizing agent in the cathode chamber is neither sustainable nor cost effective [36, 41], and hence used for laboratory practice only. Industrially air cathodic chamber offers a better alternative, as oxygen is available, sustainable and ecofriendly. Moreover, it may increase power output since 6.0 W/m$^3$ [48] and 6.8 W/m$^3$ [49] power densities were resulted using air-cathode as seen in Table 11.

<table>
<thead>
<tr>
<th>Table 11: Comparison with literature summary</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electrodes</strong></td>
</tr>
<tr>
<td><strong>Chamber volume</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Ion exchange membrane</strong></td>
</tr>
<tr>
<td><strong>Anolyte</strong></td>
</tr>
<tr>
<td><strong>Catholyte</strong></td>
</tr>
<tr>
<td><strong>Micro-organisms</strong></td>
</tr>
<tr>
<td><strong>Maximum voltage</strong></td>
</tr>
<tr>
<td><strong>Desalination %</strong></td>
</tr>
<tr>
<td><strong>Maximum power density</strong></td>
</tr>
</tbody>
</table>
Chapter 5. Conclusion and Recommendations

In this thesis, we addressed the issue of water shortage and the need for developing new methods for water treatment with minimum energy input. A hybrid system using MBR and MDFC was studied and implemented, for both desalination and wastewater treatment. Moreover, the proposed hybrid system offers the potential of power production achieving energy conservation and ultimately sustainability.

It can be concluded that the combination of MBR-MDFC is a promising technology as it results in high quality effluent and energy recovery. It serves great benefits of utilizing the sludge from the MBR as the biomass source and generating electricity from it. The proposed continuous hybrid system was endorsed when compared with a conventional batch MDFC regarding salt deduction and voltage generation. The hybrid system exhibited slightly lower desalination removal percentage (about 6% difference), but better voltage production (around 35 mV difference) than MDFC only unit.

There are many variables affecting the system performance. It was found that the volume ratio of desalination chamber to anode and cathode chambers affects the salt removal percentage; a smaller value by 29% approximately improved the desalination efficiency by nearly 6%. In addition, the initial seawater, yeast and glucose concentration are contributing factors as well. Consequently, these factors were fixed for the sake of performing justified comparisons between the hybrid and MDFC systems. Utilizing yeast, as the exoelectrogenic microorganisms is fruitful and a much safer choice. It is suggested that other microorganisms and bacterial cultures may be studied in order to improve power output and cell effectiveness if dealing with more hazardous substances is tolerable and safely handled. Anode and cathode electrode distance influences the internal resistance of the cell and thus the power generation output and choice of external resistance. Choosing the external load value is very important for optimum power generation and desalination. Thus, in order to find the optimum external resistance value, a variable resistor may be used to manipulate the desired results requirement whether better power generation or faster desalination. The main issues that may be encountered are scaling up the cell and membrane inefficiency. The reactor size does not only affect the internal resistance, but also the hydraulic retention
time \((\text{reactor volume/volumetric flowrate})\). Therefore, stacking smaller cells is a better alternative to scaling up the cell, which will provide higher electricity generation. Nafion ion exchange membranes proves to provide long stability, but require higher ion conductivity because the total desalination rate is rather slow. As for the cellulose acetate membrane, they proved to be unsuitable in the proposed system because they worked as forward osmosis membranes causing TDS reduction by dilution rather than ion separation. Future system development may consider supported ionic liquids membranes as ion exchange membranes for improving the membrane characteristics and consequently MDFC efficiency. Furthermore, an additional MBR unit is needed for better permeate quality and meeting the effluent discharge quality regulations in regards of COD and BOD. Establishing proper backwashing method and schedule is crucial for the MBR good conduct operation. Most prominent influences on discharge water quality is namely backwashing and well secured piping system offering zero leakage to prevent any undesired impurities intrusion.

The results obtained represents the footprint for the development of a more efficient, economic and continuous operating hybrid system that can be stacked as a stand alone unit for simultaneous wastewater treatment and seawater desalination. This scheme has the potential to be used to integrate a wastewater treatment plant with a desalination facility. Remaining sludge can be further used as fertilizers. Moreover, by the same concept of removing salt ions from seawater, the system can be used and tested for removing heavy metals from a solution or treating produced water as well.
References


[12] J. Radjenović, M. Petrović, and D. Barceló, "Fate and distribution of pharmaceuticals in wastewater and sewage sludge of the conventional activated..."


### Appendix A

Table 12: UAE water statistics data from 2007 to 2014

<table>
<thead>
<tr>
<th>Year</th>
<th>Total water produced in the UAE [MCM]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>1514.6</td>
</tr>
<tr>
<td>2008</td>
<td>1594.1</td>
</tr>
<tr>
<td>2009</td>
<td>1652.7</td>
</tr>
<tr>
<td>2010</td>
<td>1679.6</td>
</tr>
<tr>
<td>2011</td>
<td>1713.3</td>
</tr>
<tr>
<td>2012</td>
<td>1818.6</td>
</tr>
<tr>
<td>2013</td>
<td>1874.6</td>
</tr>
<tr>
<td>2014</td>
<td>1949.2</td>
</tr>
</tbody>
</table>

Table 13: Immersed system TDS and voltage results (pilot vs bench)

<table>
<thead>
<tr>
<th>Reading number</th>
<th>TDS [g/L]</th>
<th>Voltage [V]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pilot System</td>
<td>Bench System</td>
</tr>
<tr>
<td>0</td>
<td>36.0</td>
<td>34.8</td>
</tr>
<tr>
<td>1</td>
<td>35.1</td>
<td>33.0</td>
</tr>
<tr>
<td>2</td>
<td>35.0</td>
<td>32.9</td>
</tr>
<tr>
<td>3</td>
<td>34.8</td>
<td>32.9</td>
</tr>
<tr>
<td>4</td>
<td>35.0</td>
<td>32.8</td>
</tr>
<tr>
<td>5</td>
<td>34.7</td>
<td>32.7</td>
</tr>
<tr>
<td>6</td>
<td>35.0</td>
<td>32.6</td>
</tr>
<tr>
<td>7</td>
<td>35.2</td>
<td>32.7</td>
</tr>
<tr>
<td>8</td>
<td>35.1</td>
<td>32.2</td>
</tr>
<tr>
<td>9</td>
<td>35.0</td>
<td>32.3</td>
</tr>
<tr>
<td>10</td>
<td>34.6</td>
<td>31.7</td>
</tr>
</tbody>
</table>

Table 14: Side stream system TDS and voltage results (hybrid vs MDFC)

<table>
<thead>
<tr>
<th>Reading number</th>
<th>TDS [g/L]</th>
<th>Voltage [V]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hybrid System</td>
<td>MDFC System</td>
</tr>
<tr>
<td>0</td>
<td>32.2</td>
<td>32.2</td>
</tr>
<tr>
<td>1</td>
<td>32.0</td>
<td>31.3</td>
</tr>
<tr>
<td>2</td>
<td>31.8</td>
<td>31.1</td>
</tr>
<tr>
<td>3</td>
<td>31.8</td>
<td>31.3</td>
</tr>
<tr>
<td>4</td>
<td>31.5</td>
<td>30.9</td>
</tr>
<tr>
<td>5</td>
<td>31.3</td>
<td>30.6</td>
</tr>
<tr>
<td>6</td>
<td>28.8</td>
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<td>7</td>
<td>27.7</td>
<td>25.4</td>
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<td>8</td>
<td>27.7</td>
<td>25.4</td>
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<td>9</td>
<td>27.4</td>
<td>25.1</td>
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<td>10</td>
<td>27.2</td>
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<td>11</td>
<td>26.8</td>
<td>24.4</td>
</tr>
<tr>
<td>12</td>
<td>25.4</td>
<td>23.2</td>
</tr>
</tbody>
</table>
Table 15: System with smaller middle chamber TDS and voltage results (hybrid vs MDFC)

<table>
<thead>
<tr>
<th>Reading number</th>
<th>TDS [g/L]</th>
<th>Voltage [V]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hybrid System</td>
<td>MDFC System</td>
</tr>
<tr>
<td>0</td>
<td>35.1</td>
<td>35.1</td>
</tr>
<tr>
<td>1</td>
<td>34.7</td>
<td>34.9</td>
</tr>
<tr>
<td>2</td>
<td>34.6</td>
<td>34.8</td>
</tr>
<tr>
<td>3</td>
<td>33.7</td>
<td>33.5</td>
</tr>
<tr>
<td>4</td>
<td>33.4</td>
<td>33.4</td>
</tr>
<tr>
<td>5</td>
<td>32.7</td>
<td>32.5</td>
</tr>
<tr>
<td>6</td>
<td>32.4</td>
<td>32.2</td>
</tr>
<tr>
<td>7</td>
<td>28.1</td>
<td>26.1</td>
</tr>
</tbody>
</table>

Table 16: Wastewater and permeate water turbidity readings

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Wastewater turbidity [NTU]</th>
<th>Permeate water turbidity [NTU]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>345</td>
<td>38.40</td>
</tr>
<tr>
<td>2</td>
<td>648</td>
<td>75.00</td>
</tr>
<tr>
<td>3</td>
<td>797</td>
<td>53.00</td>
</tr>
<tr>
<td>4</td>
<td>757</td>
<td>10.08</td>
</tr>
<tr>
<td>5</td>
<td>854</td>
<td>24.41</td>
</tr>
</tbody>
</table>

Table 17: COD readings for wastewater and permeate water

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Wastewater COD [g/L]</th>
<th>Permeate water COD [g/L]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12.65</td>
<td>10.03</td>
</tr>
<tr>
<td>2</td>
<td>12.3</td>
<td>7.81</td>
</tr>
<tr>
<td>3</td>
<td>10.76</td>
<td>8.09</td>
</tr>
<tr>
<td>4</td>
<td>11.92</td>
<td>9.14</td>
</tr>
<tr>
<td>5</td>
<td>11.68</td>
<td>7.04</td>
</tr>
<tr>
<td>6</td>
<td>-</td>
<td>7.75</td>
</tr>
<tr>
<td>7</td>
<td>-</td>
<td>8.76</td>
</tr>
</tbody>
</table>

Table 18: Wastewater and permeate water TDS

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Wastewater TDS [g/L]</th>
<th>Permeate water TDS [g/L]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30.8</td>
<td>14.5</td>
</tr>
<tr>
<td>2</td>
<td>25.0</td>
<td>13.0</td>
</tr>
<tr>
<td>3</td>
<td>27.4</td>
<td>9.4</td>
</tr>
<tr>
<td>4</td>
<td>29.9</td>
<td>15.8</td>
</tr>
<tr>
<td>5</td>
<td>28.0</td>
<td>10.0</td>
</tr>
</tbody>
</table>
Vita

Noora Hussein Adam Mukhtar was born in 1990, in Abu Dhabi, United Arab Emirates. She received her primary education in Abu Dhabi, UAE and her secondary education in Khartoum, Sudan. She received her B.Sc. degree in Chemical Engineering from Khartoum University in 2013.

In 2014, she joined training programs at the Supply Chain Department (Pasgianos Food and Beverage Company, Sudan), and at the Quality Assurance and Production Departments (DAL Food Industries, Sudan). From 2014 to 2015, she worked as part of the engineering team at the Ministry of Petroleum, General Directorate of Energy Affairs (Khartoum Refinery energy audit project).

In September 2015, she joined the Chemical Engineering master's program in the American University of Sharjah as a graduate teaching assistant. During her master's study, she participated in both of the Graduate Students Research Conferences for the years 2017 and 2018 and was awarded the best paper award in 2018. Also, she participated in the Future Generation Competition-Smart Energy 2018 and won the judges choice runner up award. Her research interests are in water treatment and renewable energy.