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IMPROVEMENT OF MEMBRANE SURFACE ANTIMICROBIAL PROPERTIES TO ENHANCE RESISTANCE TO FOULING IN THE TREATMENT OF MUNICIPAL WASTEWATER

By

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

Master of Engineering: Chemical Engineering

in the

Faculty of Engineering and the Built Environment

at the

Cape Peninsula University of Technology

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February 2024

DECLARATION

I, Aude Mailys Minang Nkombe, declare that the contents of this dissertation/thesis represent my own unaided work and that the dissertation/thesis has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

Aude Minang Nkombe February 2024

Signed **Date**

ABSTRACT

The increase in water scarcity has become a worldwide issue due to population growth and growing pollution. Therefore, implementing wastewater management strategies and wastewater treatment techniques has been on the rise to create environmental sustainability and reduce freshwater consumption.

Municipal wastewater effluent is used for tertiary treatment to produce water quality suitable for various reuse applications. Effective tertiary treatments such as reverse osmosis (RO) membranes are additional to secondary treatments for further reduction of bacteria, organics, and inorganics in municipal wastewater. However, fouling significantly hinders reverse osmosis membrane applications as it lowers membrane performance by causing the permeate flux decline, reducing the permeate quality and shortening the membrane life span. Microbial fouling is a significant contributor, accounting for more than 45% of membrane fouling.

In this study, the surface modification of a thin film RO membrane was investigated by graft polymerization of 3-allyl-5, 5-dimethylhydantoin (ADMH) to improve the membrane's antimicrobial properties.

The modifying agent ADMH was synthesized at four different concentrations and grafted onto a low-pressure RO membrane, producing modified RO membranes with varying concentrations of ADMH. The synthesis of ADMH was confirmed by Fourier Transform Infrared Spectroscopy (FTIR), Scanning Electron Microscopy (SEM) and NMR (Nuclear Magnetic Resonance) were used to characterize the surface of modified membranes. The anti-microbial tests used two types of bacteria, E. coli (Gram-negative) and S. aureus (Gram-positive) contaminants. The membranes were further tested with humic acid and sodium bicarbonate, depicting municipal wastewater organic and inorganic foulant models, respectively.

The FTIR and NMR peaks characteristics confirmed the presence of ADMH bonds, such as the C=O bond at 3107 cm^{-1} and (=$CHCH_2$) bond at 42.17 ppm, respectively, on the surface of the membrane. The appearance of a new layer on the membrane surface shown in the cross-sectional view of the membrane.

The antimicrobial tests with E. coli and S. aureus bacteria revealed 45.23%, 58.93%, 48.48% and 33.76% enhanced mortality ratio compared to the unmodified membrane for the $M_{0.2mol/L}$, $M_{0.4mol/L}$, $M_{0.6mol/L}$ and $M_{0.8mol/L}$ respectively. In contrast, the antimicrobial tests with S. aureus bacteria revealed an improved mortality ratio of 6.71%, 37.42%, 22.89%, and 2.44% for the aforementioned membranes, respectively.

Additionally, it was found that membranes $M_{0.4mol/L}$ and $M_{0.6mol/L}$ exhibited a flux decline ratio (FDR) of 12.68% and 8.91% against E. coli, respectively, while the unmodified membrane FDR was and FRR values of 94.27% and 96.88%, respectively. Also, the same membranes had FDR values of 30.21% and 23.79% and FRR values of 59.70% and 70.15% against S. aureus.

Overall, this study demonstrated the significant impact of ADMH concentration against biofouling on reverse osmosis membranes. The ADMH exhibited qualities that contributed to improving the antimicrobial properties of reverse osmosis membranes while enhancing the membrane permeability and salt rejection, and slightly maintaining its resistance to organic and inorganic fouling. This study is an excellent step towards future studies in developing fouling mitigation methods to treat municipal wastewater.

ACKNOWLEDGEMENT

I want to thank my parents, Paul and Paulette Nkombe, for supporting me throughout my studies. For believing in me and always encouraging me. You are my example of excellence, and this achievement would not have been possible without you. In addition, I would like to express my gratitude to the following people:

- My Supervisor, Prof Mujahid Aziz, for his incomparable supervision, persistent guidance, motivation, encouragement, and technical expertise in this research field. I am thankful for his sustained academic, moral, and benevolent assistance throughout my educational journey. It has been a privilege to have him as my lecturer and supervisor.

- My co-supervisor, Mr. Godwill Kassongo, for his assistance and guidance.

- The Environmental Engineering Research Group (EnERG) for their support

- The technical and administrative staff of the Chemical Engineering Department, especially Ms Hannelene Small, Ms Elizma Alberts and Mr Alwyn Bester, were always more than willing to assist.

- Prof Vincent Okudoh and Ms Mmabatho Mobo from the Biotechnology Department (District Six Campus) for allowing access to lab equipment and providing the bacteria, strain techniques, and frozen stock storage.

- Ms Rose Gwanpu and Sanele Pokiyana from the Food Technology Department assisted with the microbiology facility and equipment.

- My sisters, Lidina, Hansy, and Paola; my brothers, Rod, Stefan, Alain and Yannick; and my niece and best friend Olivia, thank you for their moral support, prayers, and encouragements.

- To my extended family members Ariane, Dominique, Fabiola, and Jean Etienne, thank you for your support, prayers, and encouragements. My friends Guylene, Joelle, Emilie, Joviale, Winelle, Pamela, Deossa, Christian, Pradino and his wife Melany, thank you for your constant support, prayers, and motivation. I acknowledge and thank everyone who supported me throughout my studies.

DEDICATION

I dedicate this thesis to God Almighty. Thank you, Lord, for providing for me in many ways and giving me the strength to succeed and not give up. As I write this, I understand better your word that says the end of a thing is better than the beginning. You are the one above all things in my life, and as this new chapter starts, I pray not to let anything, or anyone stand above you.

RESEARCH OUTPUTS

Minang Nkombe AM , Kasongo G & Aziz M; 2024, Biofouling Resistance Improvement in Membrane-Based Municipal Wastewater Treatment: A Focus on Membrane Surface Modification by Graft Polymerization with 3-allyl-5, 5-dimethyl hydantoin. Environmental Protection Engineering (EPE). Submitted February 2024 [Paper ID.: EPE-01566-2024-01]

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ABBREVIATIONS

ADMH	3-allyl-5, 5-dimethylhydantoin (modifying agent)
AFM	Atomic Force Microscopy
Ag	Silver
AGNPs	Silver Nanoparticles
AIBA	2, 2-azobis (isobutyramidine) hydrochloride (initiator)
Ar	Denotes an aromatic ring.
BO	Biological Oxygen Demand
COD	Chemical Oxygen Demand
DOC:	Dissolved Organic Carbon
E. COLI	Escherichia Coli
FI	Fouling Index
MBR	Membrane Bioreactor
NMR	Nuclear Magnetic Resonance spectroscopy
NOM	Natural Organic Matter
NPs	Nanoparticles
RO	Reverse Osmosis
UF	Ultrafiltration
MBA	N, N-Methylenebis acrylamide
MF	Microfiltration
MI	Membrane Fouling Index
OD	Optical Density
S. AUREUS	Staphylococcus Aureus
SEM	Scanning Electron Microscopy
SDI	Silt Density Index
TDS	Total Dissolved Solids
TOC	Total Organic Carbon
TSS	Total Suspended Solids
XPS	X-rays Photoelectron Spectroscopy

CHAPTER 1

INTRODUCTION

1. Introduction

1.1 Background

Nowadays, and up to the next decade, increasing water scarcity is a worldwide issue because of population growth and growing pollution. Therefore, the main focus has been implementing wastewater management solutions and treatment techniques to create global sustainability (Mayyahi, 2018).

Wastewater is one of the most reliable water sources for treatment and wastewater reuse. Municipal wastewater effluent is suitable for tertiary treatment to produce better water quality. Tertiary treatment is an additional treatment after secondary treatment to reduce further organics, turbidity, bacteria, and other contaminants. It is meant to remove nutrients not removed in the secondary treatment, such as heavy metals and remaining inorganic dissolved and suspended solids (Shigeki et al., 2015). Several tertiary treatment processes can be used depending on the purpose of the treated water. One of the most used are membrane separation processes. Membrane technologies are one of the most used methods for reusing water from various wastewater sources (Ezugbe and Rathilal, 2020).

Membrane separation techniques in water purification systems such as reverse osmosis (RO), nanofiltration (NF), ultrafiltration (UF), microfiltration (MF) or membrane bioreactor (MBR) are primarily used in wastewater treatment plants.

MBRs are compact technologies comprising of an activated sludge process combined with membrane filtration for wastewater treatment and recycling. However, the application of the MBR process for municipal wastewater is sometimes limited and requires downstream pre-treatment, such as coagulation, or post-treatment, such as nanofiltration or reverse osmosis (Deowan et al., 2016).

Indeed, to meet the increasing water demand, RO processes are used worldwide for wastewater reclamation. RO membranes have been one of the best methods for the last two decades due to their excellent performance and low cost. Although membrane technologies present many advantages, reverse osmosis faces challenges like fouling. Fouling is the accumulation of unwanted material over the surface of the membrane. It causes a decline in permeate flux and lower permeate quality. Indeed, this creates a significant economic impact on the overall process due to the cost of maintenance or replacement and the higher pressure applied to overcome the flux decline (Maddah & Chogle, 2016).

There are various types of fouling, namely inorganic fouling (or scaling), colloidal fouling, organic fouling and microbial fouling (Jiang et al., 2017). Microbial fouling is also called biofouling; it is a severe form of membrane fouling that affects the performance of the membrane. Indeed, as Nguyen et al.,

(2012) reported, that microorganisms can multiply over time, making removal difficult. Moreover, if they are removed to 99.9%, there are still present cells that can grow back. Different methods have been studied to control membrane microbial fouling over the past years, such as membrane surface modification techniques. They consist of physically or chemically modifying the membrane surface morphology and characteristics to improve its performance (Ankoliya et al., 2018a).

Chemical graft modification improves the hydrophilicity, chlorine resistance, water permeability, salt rejection rate and fouling resistance of the polyamide composite reverse osmosis membrane (Belfer et al., 1998).

1.2 Research Problem

Municipal wastewater effluent is suitable for tertiary treatment, using reverse osmosis to produce high water quality for reuse. However, fouling, particularly microbial fouling, is a significant challenge during treatment and reduces permeate flux and quality. Membrane active layer surface modification can address this challenge by providing the surface of the membrane with the physio-chemical features necessary to enhance its antifouling properties.

1.3 Research Questions

1. Can the modifying agent improve the membrane's antimicrobial properties through chemical modification?
2. Is membrane surface modification an effective method against both gram-positive and gram-negative microorganisms?
3. What model is suitable to represent the prediction performance of the treated membrane against biofouling?

1.4 Aim & Objectives of the research.

This study aimed to improve reverse osmosis membrane surface antimicrobial properties through chemical surface modification using 3-allyl-5, 5-dimethylhydantoin (ADMH) to enhance its resistance to biofouling.

Objectives:

1. The synthesis of 3-allyl-5, 5-dimethylhydantoin (ADMH) and the modification of RO membrane surface through grafting with ADMH.
2. The analysis and characterization of the RO membrane surface properties before and after modification

3. The assessment of the antimicrobial properties of the RO membranes against Gram-negative and Gram-positive bacteria, as well as the resistance to organic and inorganic foulants before and after modification.

1.5 Delineation

This study focused on improving the antimicrobial properties of polyamide RO membrane for the treatment of municipal effluents through surface grafting using ADMH. The study was be based on a comparison between modified and unmodified membranes. The antimicrobial abilities of the modified RO membranes were assessed against two types of bacteria, one gram-negative bacteria (E. coli) and one gram-negative (S. aureus). Moreover, the study focused on modifying agent concentrations to obtain improved polyamide RO membrane performance conditions. However, parameters such as the effect of temperature and modification time were delineated.

1.6 Thesis Outline

Chapter 1: Introduction

Background of the study, with significant points on the research topic.

Chapter 2: Literature Review

Theory related to the research and the critical points of the study.

Chapter 3: Experimental Methodology

Details and specifications of the procedures, equipment, apparatus and sampling method used for the experiments.

Chapter 4: Membrane Modification – Results and Discussion

Presentation of the results and discussion related to the membrane modification and characterization..

Chapter 5: Membrane Performance Evaluation – Results and Discussion

Presentation of the results and discussion related to the membrane performance in terms of antimicrobial and application in reverse osmosis for fouling resistance assessment. Presentation of a model of the treated membrane against biofouling.

Chapter 6: Conclusion and Recommendation

Conclusion of the study and recommendations

CHAPTER 2

LITERATURE REVIEW

2. Literature Review

2.1 Wastewater Management: Purpose and Challenges

Indeed, humans widely use water for drinking, washing, food processing, and agriculture or industrial applications. Therefore, wastewater recycling is a worldwide concern to preserve fresh water and maintain the resources (Mayyahi, 2018). Indeed, wastewater is treated to improve its physical, chemical, and microbiological quality for reuse.

There are different water categories, including white water, grey water, and black water. The selection of the water for recycling purposes depends on its characteristics and the proposed standards for reuse. Greywater is adequate for recycling compared to black water because of the exposition of black to faecal matter. Moreover, blackwater waste does not have a fast breakdown and decomposition time, while all types of greywater have an excellent biodegradability. There are many types of greywater, which include municipal wastewater, carwash wastewater, industrial wastewater, and laundry wastewater. Indeed, it is critical to recycle water for reuse purposes (Zipf et al., 2016).

Xiao et al. (2014) reported that almost 300 to 400 million grams of heavy metals, harmful sludge, solvents, and other organic waste are discharged into the surrounding environment by industrial plants every year worldwide. Also, municipal wastewater must be treated to minimize its adverse environmental effects (Ezugbe and Rathilal, 2020). Indeed, treatment or other management techniques must be implemented to favour water recycling. Like many other countries, South Africa is a water-scarce country; therefore, over the last few years, it has been the focus to develop optimal wastewater management methods.

Moreover, the challenges faced by wastewater management are environmental and operational. Indeed, the most used method for municipal wastewater treatment is membrane technology due to its high efficiency and cost-efficiency. They are applied in wastewater treatment plants (WWTP) to produce higher-quality water for reuse. However, the challenges faced with membrane technology revolve around energy efficiency, water quality, sludge production and process operational challenges such as fouling (Melin et al., 2006).

2.2 Municipal Wastewater

Worldwide population growth affects water resources, creating a water shortage crisis. Indeed, wastewater management solutions have been necessary to create a sustainable environment. Municipal, industrial and hospital wastewater harms the water, soil, and atmosphere. Therefore, wastewater treatment and adequate disposal of the sludge produced are vital for protecting the environment (Mayyahi, 2018).

2.2.1 Wastewater Characteristics

According to the Western Cape Provincial Gazette Nº 7227 (2014), the wastewater and industrial effluent minimum quality limits give insight into wastewater quality and characteristics. A summary of the main parameters and elements of wastewater and their respective admitted discharge values are presented in Table 2-1 below.

Table 2- 1: South Africa municipal wastewater discharge characteristics

Section A: General		**Not less than**	**Not to exceed**
1.	Temperature at point of entry	0°C	40°C
2.	Electrical conductivity at 25 °C		500 mS/m
3.	pH Value at 25 °C	5.5	12.0
4.	Chemical oxygen demand		5 000 mg/l

Section B: Chemical substances other than heavy metals – maximum concentrations		
1.	Settle solids (60 minutes)	50 ml/l
2.	Suspended solids	1 000 mg/l
3.	Total dissolved solids at 105 °C	4 000 mg/l
4.	Chloride as Cl^-	1 500 mg/l
5.	Total sulphates as $SO4^{2-}$	1 500 mg/l
6.	Total phosphates as PO_4^{2-}	25 mg/l
7.	Total cyanides as CN^-	20 mg/l
8.	Total sulphides as S^{2-}	50 mg/l
9.	Phenol index	50 mg/l
10.	Total sugars and starches as glucose	1 500 mg/l
11.	Oils, greases, waxes, and fat	400 mg/l
12.	Sodium as Na	1 000 mg/l

Section C: Metals and inorganic content – maximum concentrations Group 2		
5.	Total arsenic as As	5 mg/l
6.	Total boron as B	5 mg/l
7.	Total lead as Pb	5 mg/l
8.	Total selenium as Se	5 mg/l
9.	Total mercury as Hg	5 mg/l
10.	Total titanium as Ti	5 mg/l
11.	Total cadmium as Cd	5 mg/l
12.	Total nickel as Ni	5 mg/l

Total collective concentration of all metals and inorganic constituents in Group 2 shall not exceed 20 mg/l

After thorough research, it was found that more studies on municipal wastewater characteristics in South Africa are needed. Two case studies in water treatment plants from South Africa are presented below to give insight into the organic and inorganic characteristics of municipal wastewater in South Africa.

The physicochemical qualities of the final effluents in a wastewater plant in the Buffalo City municipality of the Eastern Cape Province of South Africa were assessed by Odjadjare & Okoh (2010) between August 2007 and July 2008. The municipal wastewater in this region underwent treatment by chlorination using a gas chlorinator, and the investigation revolved around a monitoring program to assess the quality of the effluent.

The treatment plant is in East London and receives domestic and industrial sewage. It was found that parameters such as electrical conductivity (EC) of the samples were in the range of 29–1,015 µS/cm, and turbidity varied between 2.7 and 35 NTU. Salinity and total dissolved solids (TDS) varied from 0.36 to 35 PSU and 16 to 470 mg/L, respectively. The concentrations of the other physicochemical parameters were as follows: chemical oxygen demand (COD) 48–1,180 mg/L; dissolved oxygen (DO) 3.9–6.6 mg/L; nitrate (NO^{-3}) 0.32–6.5 mg as N/L; nitrite (NO^{-2}) (0.06–2.4 mg as N/L; and phosphate (PO_4^{-3}) 0.29–0.54 mg as P/L. The study showed that the pH, temperature, EC, turbidity, TDS, DO, and nitrate significantly varied with the changing season and sampling point.

Moreover, the study revealed that the treated effluent fell within the recommended water quality standard for pH temperature, TDS, nitrate, and nitrite; it fell short of stipulated standards for other parameters. Overall, the heavy metal levels reported in this study were lower compared to those reported in polluted rivers linked to industrial and WWTP effluents.

In another study, Osu & Okoh (2017) evaluated the occurrence of faecal coliforms, Escherichia coli (E. coli) and viruses in the final effluents of five wastewater treatment plants (WWTPs) in the Eastern Cape of South Africa. This investigation highlights on the presence of viral contamination in the water sources used for domestic water.

Section C: Metals and inorganic content – maximum concentrations Group 1		
1.	Total iron as Fe	50 mg/l
2.	Total chromium as Cr	10 mg/l
3.	Total copper as Cu	20 mg/l
4.	Total zinc as Zn	30 mg/l
Total collective concentration of all metals in Group 1 shall not exceed 50 mg/		

The samples were collected monthly from five WWTPs in the Buffalo City Local Municipality for 1 year, from September 2012 to August 2013, and the sampling period covered the four seasonal times of the year. The study revealed the presence of cultural faecal coliforms in the effluent samples from all the WWTPs. According to Department of Water Affairs and Forestry (1996), the limits are set by the South African regulatory guidelines for effluent quality discharge: a general limit of 1000 CFU/100 mL and a particular limit of 0 CFU/100 mL.

Seventeen (24.3%) of the effluent samples analysed met the special limit guideline for effluent discharge (0 CFU/100 mL), 33 (47.1%) were within the general limit (1000 CFU/100 mL), and the remaining 20 (28.6%) were above the general limit. E. coli was detected in 66.7% of the samples analysed from WWTP-A, but in 83.3% of those samples, the E. coli counts were less than 1000 CFU/100 ml. Therefore, based on the coliform counts at this treatment plant, we infer that the treatment regime is efficient. At WWTP-B, bacteria were detected in 83.3% of the samples, and 50% had very high counts. E. coli was detected in all the samples from WWPT-C, WWPT-D, and WWPT-E, and 25% of these exceeded the concentration limit at WWPT-C and 16.7% at WWPT-D.

Overall, the study revealed that the characterization of effluent from WWTPs has shown that poorly treated wastewater can be a source of E. coli in municipal wastewater effluents.

These previous case studies show that the need for improvement in wastewater treatment methods is essential to improve the quality of municipal wastewater effluents.

2.3 Membrane Technology

Membranes are reported in the literature to be helpful in the treatment of various kinds of wastewater (Lau et al., 2013). Membranes and other nano-porous materials have been considered essential technologies to address global water demand. Indeed, membrane technology applies to water treatment. It is a mechanical separation process using semipermeable membranes for separating liquid streams. It is a group of technologies that includes water and wastewater filtration systems (Goh and Ismail, 2018). They can be classified and categorized according to their configurations and removal abilities.

2.3.1 Membrane Configurations

According to Ezugbe & Rathilal (2020), there are different types of membranes, namely:

- Plate and frame
- Tubular
- Hollow fibre
- Spiral wound

a) Plate and Frame membrane

Plate and frame membranes are one of the oldest types of configurations. The membrane, feed, and product spacers, attached to a metallic frame. These spacers prevent the membrane from sticking and allow the flow of the feed and product. According to Ezugbe & Rathilal (2020), this membrane type is only commonly used for specific treatment purposes, such as wastewater containing high levels of suspended solids such as landfill leachate. Figure 1 shows a typical plate and frame design.

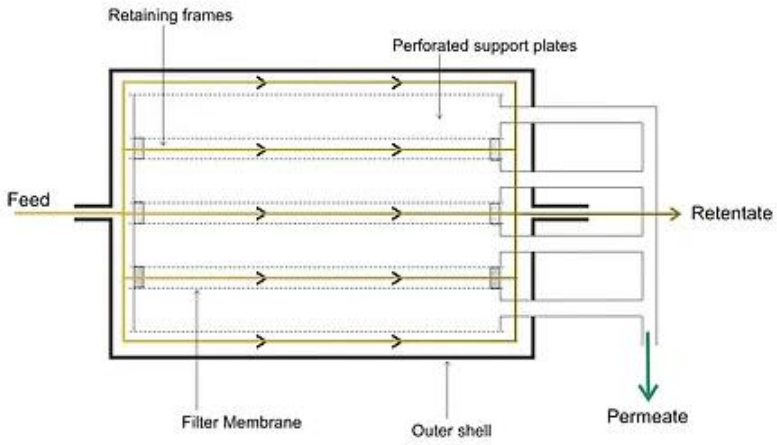


Figure 2- 1: Plate and frame membrane configuration (Stevia Technology)

b) Tubular membrane

This configuration consists of an outer shell. A perforated, porous stainless steel or fibreglass is inside the tubular shell, within which a semipermeable membrane is embedded (Ezugbe & Rathilal, 2020) . The feed water is fed into the tube under pressure. The permeate water from the membrane flows through the perforated pipe into the inside of the shell and is then collected through the permeate outlet. Tubular membranes are generally adapted to treat feed water with high solid contents.

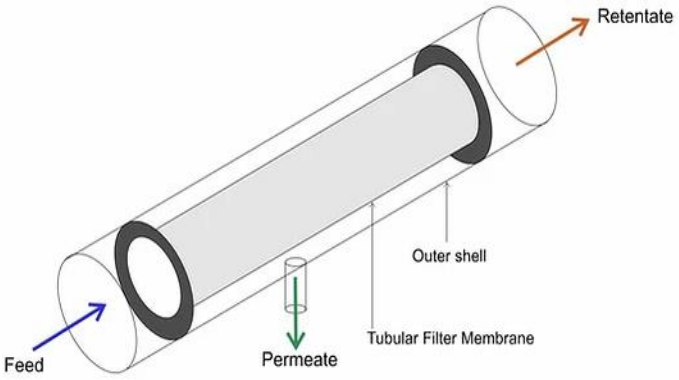


Figure 2- 2: Tubular membrane configuration (Stevia Technology)

c) Hollow fibre membrane

This configuration comprises a bundle of hollow fibres inside a pressure vessel. These fibres consist of a porous non-selective support layer of about 200 µm and an active layer of thickness of 40 nm. This active layer is the membrane but needs support to undertake the hydrostatic pressure (Elorm & Sudesh, 2020).

Moreover, depending on their use, hollow fibre modules are either shell-side (outside) feed types or bore-side (inside) feed types. The shell-side feed type is preferred for high-pressure applications (up to 70 bar), whereas the bore-side feed type is preferred for low- to medium-pressure applications. Figure 3 shows a diagram of the hollow fibre membrane. A notable advantage of this module type is its ability to accommodate large membrane areas in a single module. However, it is costly to produce due to the sophistication of the production process and the high capital requirements (Elorm & Sudesh, 2020).

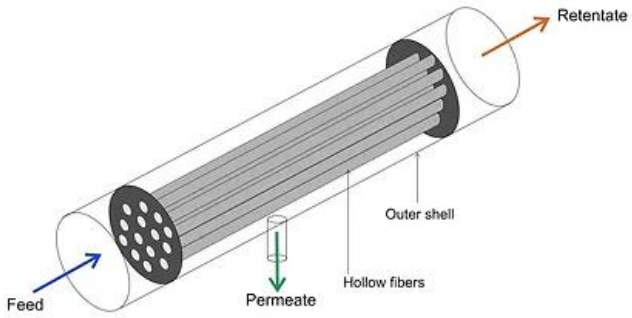


Figure 2- 3: Hollow fibre membrane (Stevia Technology)

d) Spiral wound membrane

The spiral-wound membrane module is one of the most common membrane filters in wastewater treatments (Li & Tung, 2008). It was initially developed for reverse osmosis processes but is also used for ultrafiltration and gas permeation. Indeed, they are used for processes where pressure drop must be accounted for and when counter-current flow is not needed. Moreover, the spiral wound membrane consists of perforated hollow pipe and multiple envelope membranes around the outer surface of the membrane (Koros & Fleming, 1993). Indeed, it is like a plate-and-frame system wrapped around a central collection pipe. A feed and permeate-side spacer material forms a membrane envelope along three edges. Also, a feed-side spacer separates the top layer of two flat membranes, simultaneously acting as a turbulence enhancer (Mulder, 1997). Figure 4 below shows a diagram of the spiral wound membrane configuration.

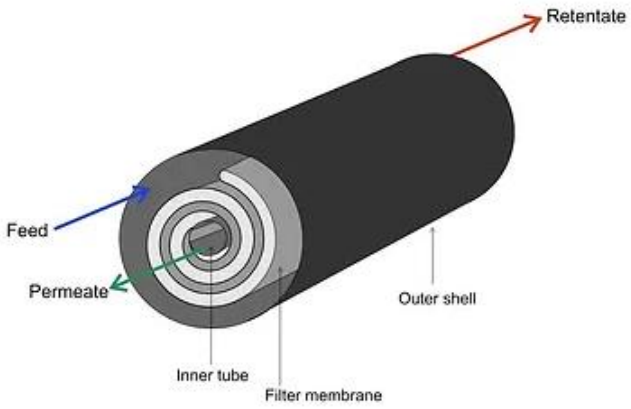


Figure 2- 4: Spiral wound membrane configuration (Stevia Technology)

2.3.2 Membrane Classification Overview

There are 4 main categories in which the different types of membrane processes can be classified according to their pore size and species being retained, namely:

- Microfiltration (MF)
- Ultrafiltration (UF)
- Nanofiltration (NF)
- Reverse Osmosis (RO)

Indeed, reverse osmosis in wastewater treatment can achieve high efficiency combined with pre-treatment processes. The differences in these filtration techniques lie mainly in the price, the characteristics of the membrane used, the purpose of the water treatment and the feed quality. Membranes are known to have varying pore size distributions relative to measured nominal pore size as a function of the membrane material used and the manufacturing method employed (García-Pacheco et al., 2015).

According to this comparison and the highlighted differences, these membrane processes can be classified in increasing order of performance: firstly, MF, UF, NF and finally RO. The following diagram gives a clear illustration of the previous statement:

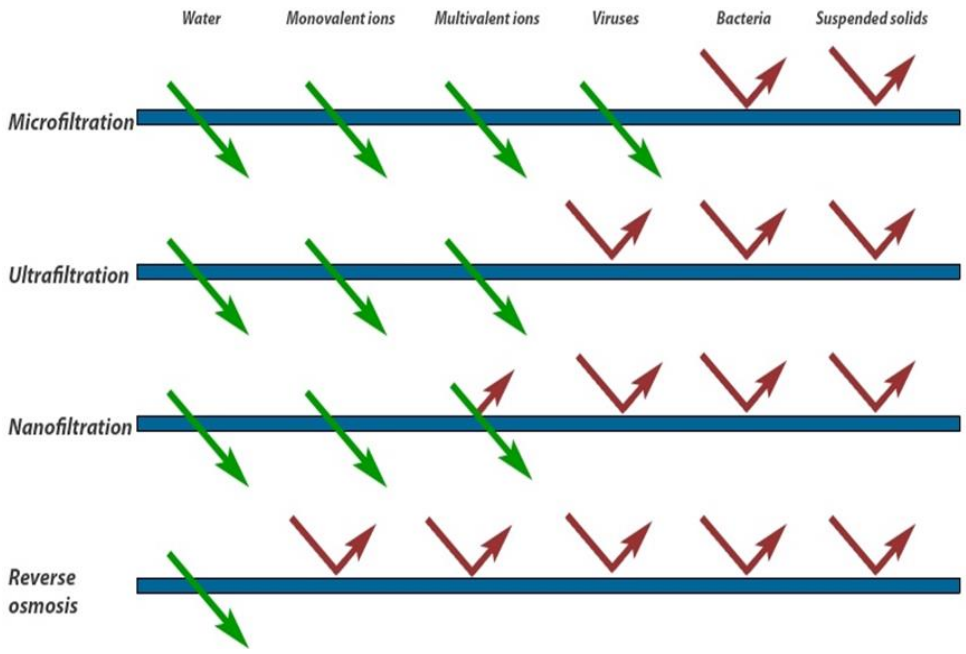


Figure 2- 5: Membrane classification by increasing order of performance (Yang et al., 2019)

a) Microfiltration (MF)

Microfiltration is a pressure-driven membrane operation. A typical application of this process is in water treatment with good turbidity removal (Manouchehri & Kargari, 2017). The pore size on MF membranes ranges from 0.1µm – 5µm and has the largest pore size among the four main membrane types. Its pores are large enough to filter out bacteria, large colloids, blood cells, high molecular weight organic matter, suspended particles, flour, talc, and many other kinds of fine dust in the solution. Because its pores are relatively large compared to other membranes, it can be operated under low pressures (0.1 – 5 bar) and therefore, low energy. Indeed, low energy allows for the lowering the cost involved in the process. MF membranes are often used in membrane bioreactors as a pre-treatment for NF and RO (Manouchehri & Kargari, 2017).

b) Ultrafiltration (UF)

UF membranes have a pore size range of 0.1µm – 0.01µm. UF membranes reject particles such as silica, viruses, endotoxins, proteins, plastics, and smoke or fumes such as zinc oxide (ZnO). It is a good option for pre-treatment as it can remove TOC turbidity and reduce the fouling potential for NF and RO membranes. Although the osmotic pressure required is higher than that of MF (1 – 10 bar), due to the decrease in pore size, the UF and the MF are both considered low-pressure membrane filtrations. They are used worldwide to reduce particle concentration and natural organic materials (NOM) (Fiksdal & Leiknes, 2006).

c) Nanofiltration (NF)

NF membranes have a pore size range of 0.001µm – 0.01µm. NF membranes can filter particles up to and including some salts, sugars, and synthetic dyes. However, it is unable to remove most aqueous salts and metallic ions. NF membranes exhibit separation characteristics in the intermediate range between RO and UF and have low-operation pressure (3 – 10 bar), high-permeation flux and high retention of multivalent ion salt advantages. Furthermore, NF is generally confined to specialist industrial uses. It has greatly succeeded regarding removing COD, as stated in literature reviews (Yorgun et al., 2008).

d) Reverse Osmosis (RO)

Reverse osmosis (RO) membranes have a pore size range of 0.0001 µm – 0.001µm. It is by far the finest separation material available to industry. It is used on a large scale for the desalination and purification of water as it filters out everything but water molecules, with pore sizes approaching the radius of some atoms in many cases. Indeed, it is the only membrane that can reliably filter out salt

and metallic ions from water. The small pore size of RO membranes requires a significant amount of osmotic pressure to force filtration (10 – 100 bar). RO is a pressure-driven membrane process with a wide range of applications and currently accounts for over 95% of existing desalination plants (García-Pacheco et al., 2015).

2.4 Membrane Bioreactor (MBR) from Municipal Wastewater Plant: Description and Applications

This section presents an overview of membrane technology and describes the process. The Membrane Bioreactor (MBR) process is one application of membrane technology that has been increasingly applied worldwide. The term MBR defines a biological process and membrane separation combined. It involves a suspended growth-activated sludge system that uses microporous membranes for solid or liquid separation. This type of system produces a microfiltration (MF) or ultrafiltration (UF) quality effluent suitable for reuse applications or provides a high-quality feed water source for Reverse Osmosis (RO) treatment (Chapman *et al., 2004*). Moreover, two configurations are used in the MBR process: side stream and submerged membrane (Naghizadeh et al., 2011). Figure 6 shows a typical MBR arrangement.

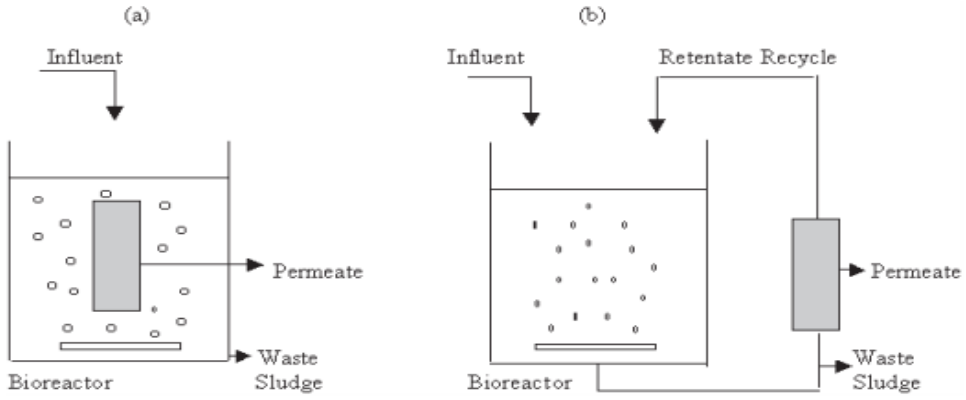


Figure 2- 6: Configuration of MBR systems: (a) Submerged; (b) side-stream MBR configuration (Melin et al., 2006)

Some of the advantages of this process are the following:

- Production of good quality effluents
- Space efficiency
- Robustness of the operation
- Reduction of downstream disinfection requirements
- Modularity
- Low sludge production

With the focus on water reuse in South Africa MBR, systems play an essential role in the wastewater treatment sector nationwide. Some of the largest wastewater treatment plants are found in South Africa namely, Stellenbosch WWTP, Zandvliet WWTW, Malmersbury WWTP and BELLVILLE WWTP. SUEZ-Water Technologies & Solutions and Koch Membrane Systems Inc. supply their membrane technologies, respectively. Indeed, implementing of wastewater treatment plants is essential for water reclamation and environmental consideration to meet wastewater standard regulations. The council

of the municipality of Cape Town has set standards applicable to industrial effluents, which include any liquid, whether containing matter in solution or suspension, released during or because of any industrial trade, manufacturing, mining or chemical process, and any laboratory, research, service, or agricultural activity (Western Cape Government, Provincial Gazette, 2014). Therefore, it is essential to put in place treatment methods such as MBR for reuse applications or discharge according to the regulations.

2.4.1 Municipal Wastewater's MBR Effluents Characteristics

The potential for water quality effluent from MBR technology was presented through two case studies comparing water quality and efficiency of the MBR process at different scales.

Naghizadeh, Mahvi and Alimohammadi study present the treatment of municipal wastewater using a pilot-scale MBR system (2011). It was found that the system removed more than 95% of the COD present inside the influent water. Moreover, turbidity and TSS removal of 99% were achieved at all operating conditions. Indeed, the paper investigated the efficiency of MBR treatment and water reuse.

According to (Melin et al., 2006), MBR contains various contaminants such as BOD, DOC, $NH_3 - N$, total coliforms, faecal coliforms and bacteriophages. In this paper, the municipality wastewater was treated using a full-scale MBR system. Indeed, the report highlighted that complete disinfection could not be performed (Melin et al., 2006). Therefore, because of microbiological parameters from the effluent, further treatment, such as reverse osmosis, could be performed to achieve higher-quality water for reuse.

Although MBR is an effective process for treating municipal wastewater, the following treatment can be applied to achieve high effluent water quality. Indeed, MBR effluents are good water feed for reverse osmosis processes (Chapman et al., 2004).

2.5 Membrane Fouling

2.5.1 Definition

Membranes are very effective in water treatment, but they lose their performance with time. One of the major causes for the loss of performance is due to substances that deposit on the membrane's surface referred to as fouling. The term fouling is used to describe the accumulation of unwanted material on a surface (Field, 2010).

Membrane fouling can be classified as hydraulically reversible and irreversible. The reversible fouling is slightly attached to the membrane. It can, therefore, be easily removed through permeate backwashing, for the irreversible fouling, which is tightly bound to the membrane, can only be removed by chemical cleaning. Indeed, irreversible fouling can result in permanent permeability loss (Tian et al., 2012).

2.5.2 Fouling Mechanisms

Reverse Osmosis is a widely used technology. However, fouling is a significant obstacle to membrane performance. Therefore, several strategies to control fouling are developed, such as pre-treatment processes, chemical membrane cleaning, and improving operating parameters such as membrane modification to improve properties. In implementing these methods, the fouling index is relevant for reverse osmosis applications.

a) Fouling Index

The Fouling Index was suggested to measure the cake formation rate on the membrane's surface. Contrary to other membrane analyses, such as the silt density index (SDI), the fouling index technique simulates reverse osmosis operations. It thus offers further information on the foulant mechanisms (Tian et al., 2012). It consists of assuming that fouling mechanisms occur according to the following:

- Pore blocking
- Cake filtration
- Cake composition
- Determination of the index using filtration

The fouling index should meet two essential conditions to predict the fouling potential in reverse osmosis applications: short-time measurements and high sensitivity responding to varying feed water quality. However, reverse osmosis membranes are not sensitive enough to detect the effect of varying feed water quality. Therefore, MF and UF membranes are usually employed for fouling index measurements.

Fouling index (FI) measurements were carried out using a humic acid solution and modified fouling index (MFI) membranes to simulate reverse osmosis. The membrane cells were allocated in series to separate the target foulant. The permeate water was entered into filtration processes consecutively (see Figure 7). Flux declination was noted due to pore-blocking mechanisms from the second membrane cell.

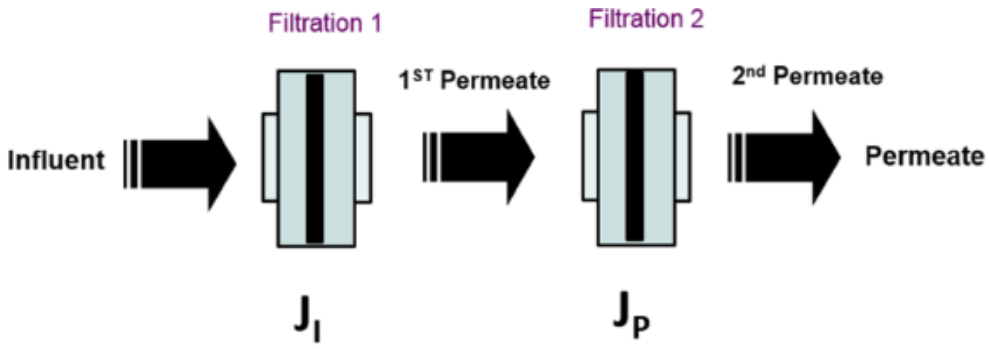


Figure 2- 7: Figure 2-7: Consecutive filtration illustration

Equation: 2- 1: Initial flux equation

$$J_I = \frac{\triangle_p}{\mu(R_m + R_b + R_c)}$$

Equation: 2- 2: Permeate flux equation

$$J_P = \frac{\triangle_p}{\mu(R_m + R_c)}$$

J_I: Initial flux

J_P: Permeate flux.

R_m: Membrane resistance

R_b: Pore blocking

R_c: Cake layer resistance

The rate of cake resistance was evaluated using Darcy's law and Hermia's classical filtration model. The FI is expected to provide an accurate prediction of the fouling potential of the cake layer through secondary filtration. The experimental results of FI were compared to the flux decline rate observed by the reverse osmosis processes (Turner et al., 2017).

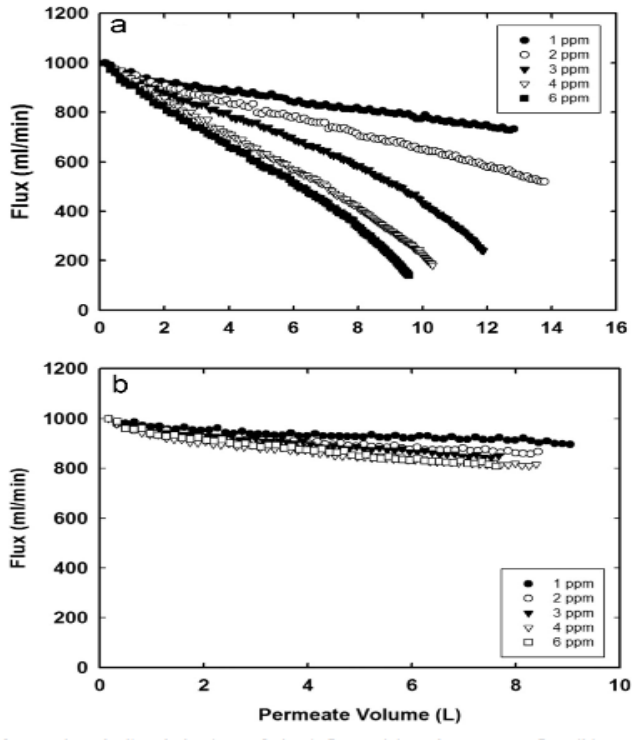


Figure 2- 8: Flux decline behaviours of (a) Influent flux (b) Permeate flux (Turner et al., 2017)

The decline was derived by pore blocking and cake filtration mechanisms in Figure (a), while only pore blocking was used in Figure (b). A significant deviation in the filtration stage 2 was observed with increased humic acid concentration. Also, it was noted that a higher pore blockage was due to the presence of particles smaller than the pore size. Comparing (a) and (b), it was concluded that pore blocking is directly proportional to the number of pollutants present. Moreover, according to (Zhao et al., 2013) it is reported that the flux decline ratio (FDR) and the flux recovery ratio (FRR) of reverse osmosis membranes are determined by the following equations:

Equation: 2- 3: Flux decline ratio

$$FDR\% = \frac{J_{W0} - J_{Wt}}{J_{W0}} \times 100$$

Equation: 2- 4: Flux recovery ratio

$$FRR\% = \frac{J_{WC}}{J_{W0}} \times 100$$

J_{W0}: Initial flux

J_{Wt}: Time dependants permeate flux.

J_{WC}: Revaluated water Flux

b) Fouling Impact

Membrane fouling can be defined as the accumulation of solute on a membrane surface or inside the pores of the membranes. The effect of fouling is a pores block and formation of a cake layer on the membrane surface which reduces its permeability. Indeed, this phenomenon impacts on the membrane performance, it weakens the membrane rejection properties and creates additional hydraulic resistance. Indeed, membrane fouling is a major operational issue in wastewater treatment processes (Ibrar et al., 2019).

Fouling can occur on the active layer, on the surface of the support layer or inside the support layer. Fouling in pressure-driven membrane processes can be classified into external and internal fouling. The fouling mechanism suggests that smaller size foulants particles enter the support layer and attach to the foulants that are already deposited on the active layer, leading to pore clogging of the membrane or internal fouling. Indeed, pore-clogging is the most severe type of fouling. and is very hard to clean up. Foulants in the support layer reduces porosity and enhance the effects of internal concentration polarization (Ibrar et al., 2019).,

2.5.3 Type of Fouling

There are four types of membrane fouling namely (Jiang et al., 2017):

- Inorganic fouling or Scaling
- Particle/colloids fouling.
- Organic fouling
- Microbial fouling

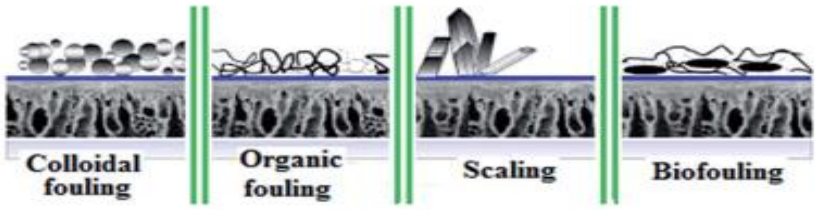


Figure 2- 9: Types of membrane fouling (Choudhury et al., 2018)

a) Inorganic fouling or scaling

Inorganic fouling or scaling is caused by the accumulation of inorganic precipitates, such as metal hydroxides and scales, on the membrane surface or within its pore structure. Precipitates are formed when the concentration of chemical species reaches their saturation point, called concentration polarisation. Scaling is a significant concern for reverse osmosis (RO) and nanofiltration (NF) because RO and NF membranes reject inorganic species. The most common inorganic scalants are calcium, barium, bicarbonate, and sulphate ions. These species form a concentrated layer on the membrane-liquid interface (Jiang et al., 2017).

b) Particles / colloidal fouling

Colloidal fouling refers to membrane fouling caused by the deposition of particles or colloids on the surface of the membrane. A colloid is a fine suspended particle ranging from a few nanometres to a few micrometres. Colloidal fouling can be influenced by various factors, such as the colloid's size, shape and charge, as well as the interactions of the membrane with the colloid's ions. The attachment coefficient of the colloids to the membrane is related to the accumulation of the van der Walls force and electrostatic force resulting from the collision of the particles. Therefore, the formation of a colloidal cake layer decreases the membrane performance (Jiang et al., 2017).

c) Organic fouling

As its name mentions, organic fouling is membrane fouling caused by organic matter. In wastewater treatment, organic fouling significantly impacts reverse osmosis treatment because of the presence of natural organic matter (NOM) concentration. They usually consist of humic substances, proteins, lipids, organic acid and more. Organic membrane fouling depends on the feed water's properties, the organic matter's molecular weight, and the foulant-surface and foulant-to-foulant interactions. This type of fouling results in a significant flux decline of the RO membrane and is difficult to eliminate due to the complex structure formed by organic matter combined with other substances (Jiang et al., 2017).

d) Microbial fouling

Microbial fouling or biofouling is the adhesion of microorganisms and proliferation on the surface of the membrane. Indeed, it is a more complex type of fouling as it involves polymeric substances and bacteria. In literature, biofouling is described in two main steps: the adhesion of the microbial cells to the membrane surface and the formation of a biofilm containing bacteria. It is reported that bacteria reproduction is noted on the surface of the membrane, where the microorganisms consume nutrients from the water and then undergo proliferation (Jiang et al., 2017).

The adhesion of microorganisms on the membrane surface is the first step before biofilm formation. Indeed, the attachment of microbial cells to the membrane is led by hydrophobic interactions, usually followed by the growth of microorganisms, which will then induce biofilm formation (Nguyen et al., 2012). The process is affected by various factors, which are summarized in the table below:

Table 2- 2: Factors affecting microorganism adhesion (Nguyen et al., 2012)

Microorganism	**Surface**	**Feed water**
Species	Chemical composition	Temperature
Composition of mixed population	Surface charge	pH
Population density	Surface tension	Dissolved organic matter

Growth phase	Hydrophobicity	Dissolved inorganics
Nutrient status	Conditioning film	Suspended matter
Hydrophobicity	Roughness	Viscosity
Charges	Porosity	Shear forces
Physiological	-	Boundary

The formation of biofilm on the surface membrane consists of the following steps (Nguyen et al., 2012):

- Firstly, the organic species and suspended particles are adsorbed on the membrane surface to form a conditioning film.
- Secondly, the microbial cells are transported to the conditioning film.
- Thirdly, the microbial cells attach themselves to the membrane surface.
- Fourthly, there is growth and metabolism of the attached microorganisms, and biofilm development.
- Finally, fluid shear forces (detachment process) limit biofilm growth to achieve a steady-state fouling resistance.

2.5.4 Effects of Fouling

According to Maddah & Chogle (2016), membrane fouling has various effects, such as:

- Membrane flux decline: because of the formation of a low permeability film on the membrane surface.
- Membrane biodegradation: Microorganisms produce acidic by-products that damage the RO membrane.
- Increased salt passage: Accumulated ions of dissolved salts on the membrane surface enhance concentration polarisation and inhibit convectional transport.
- The Increase in the differential and feed pressure is due to biofilm resistance.
- Increased energy requirements due to high-pressure requirements are due to higher feed pressure, frictional energy losses, and drag resistance to tangential flow over the membrane.
- Frequent chemical cleaning imposes a significant economic burden on RO membrane plant operation, up to 50% of the total costs, and shortens membrane life.
- Sever decline in permeate quality: This is because of all the factors previously listed.
- Higher treatment costs result from high energy requirements, cleaning demand, and membrane replacement.

However, various techniques, such as membrane surface modification, have been developed to control and prevent fouling(Maddah & Chogle, 2016).

The control of membrane microbial fouling, also called biofouling, is critical during continuous plant operation and extended periods of plant inactivity due to system repair or modifications. Moreover, biofouling must also be controlled when newly manufactured membrane modules are packaged and stored for long periods before shipping or installation because of the proliferation of bacteria (Matin et al., 2011). Therefore, some strategies are used to reduce and prevent the effect of fouling, such as pre-treatment, biocide applications, and membrane cleaning and modification. Indeed, microbial fouling translates into biofilm formation, starting with bacterial adhesion, then microcolony formation, and finally, biofilm maturation. It is in this aspect that membrane surface modification is applied to prevent or retard one or more of these steps (Matin et al., 2011).

According to Ankoliya, Mehta and Raval, surface membrane modification methods can be classified into two groups: physical surface modification and chemical surface modification (2018).

2.6 Membrane Modification Methods: Physical Surface Modification

Physical surface modification of RO membranes can be done by surface adsorption of the surface coating. Figure 9 below shows the schematic of the two processes.

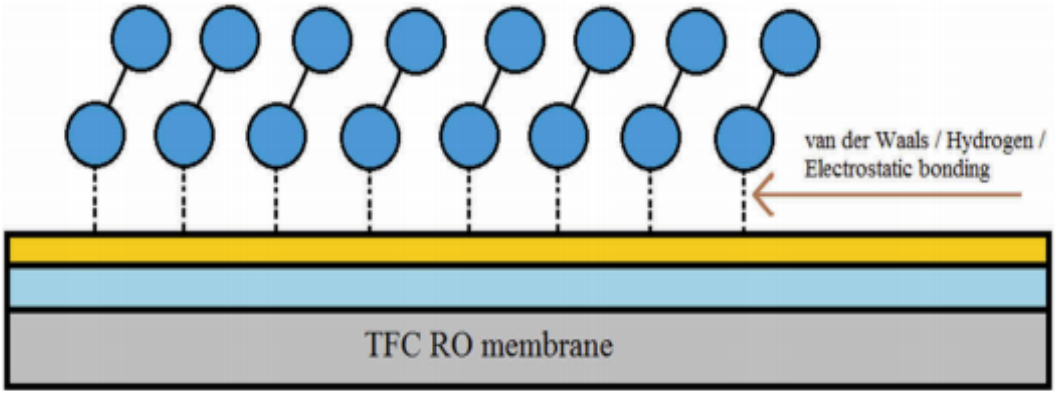


Figure 2- 10: Physical surface modification by surface adsorption or surface coating

(Ankoliya et al., 2018a)

2.6.1 Surface Adsorption

In the surface adsorption process, there is an interaction between membrane and chemicals due to the Van der Waals forces, hydrogen bonding or electrostatic bonding. Indeed, the adsorption ability of the polyamide membrane depends on the chemical adsorbed (Zhou et al., 2009). The surface adsorption method was used with charged polyelectrolytes. The technique was applied by electrostatic self-deposition to improve the antifouling properties of the membrane. The technique was reported to be efficient but not lasting over time.

2.6.2 Surface Coating

The surface coating method spreads the coating solution on the membrane and evaporates the remaining solvent to solidify the substance's coating onto the surface membrane to create a thin film (Zhou et al., 2009). Also, Su *et al.* describe the actual method applied with a solution of Titanium Oxide (TiO_2) on a polyamide membrane (2012).

2.7 Membranes Modification Methods: Chemical Surface Modification

Membrane surface modification by chemical method involves allowing contact between the polyamide layer of the membrane and the modifying agent solution. It is usually followed by evaporation or drying to create a strong bond between the modifying agent and the active layer of the membrane. Different chemical surface modification methods include hydrophilization, chemical coupling, free radial grafting, sol-gel coating, supramolecular assembly, nanoparticle enhancement and grafting polymerisation (Ankoliya et al., 2018a). Other methods include enzymatic-initiated and plasma-initiated grafting. Figure 10 below shows some of the mechanisms of chemical surface modification methods.

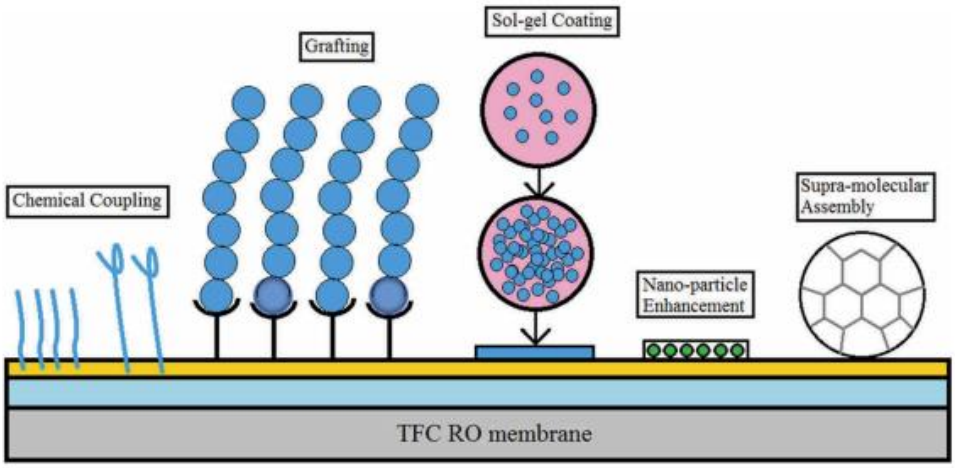


Figure 2- 11: Chemical surface modification by chemical coupling, grafting sol-gel coating, nanoparticle enhancement supramolecular assembly (Ankoliya et al., 2018a).

2.7.1 Nanoparticles Enhancement Method

Nanoparticle enhancement involves incorporating antimicrobial nanoparticles to prevent microorganisms from growing and creating a biofilm on the surface membrane (Misdan et al., 2015). Choudhury et al. (2018) reported that silver (Ag) nanoparticles (NPs) have excellent biocidal properties. They are commonly used on membrane surfaces to improve their antimicrobial properties. It was observed that silver nanoparticles (AgNPs) are toxic to Escherichia Coli (E. coli), preventing bacterial growth on the membrane surface.

Moreover, membrane modification could also be prepared using TiO_2 nanoparticles. SEM micrographs of the surface topography of the virgin membrane and the TiO_2 composite membranes strongly suggest that the higher filtration resistance of the three-coated membrane was due to blocking the membrane pores. The virgin CA membrane shows a characteristic sponge-like structure. Moreover, the loss of pores on the three-coated composite membranes increased filtration resistance, as reflected in the pure water flux and the permeability of the virgin and composite membranes and

the TiO_2 composite membranes. Therefore, it was concluded that the amount of TiO_2 on the membrane surface must be accurately controlled to obtain maximal antifouling effect (Su *et al.*, 2012).

2.8 Grafting by Enzymatic Initiation

The enzymatic grafting method has been recently developed. The principle involves an enzyme initiating the chemical or electrochemical grafting reaction. This method employs enzymes to convert the monomer or polymer chains into a reactive free radical, which undergoes a non-enzymatic reaction with the membrane. There are many advantages to the use of enzymes in membrane surface modification. Indeed, in the aspect of health and safety, enzymes reduce risks, as they do not require the use of reactive reagents and solvents. Also, this provides a potential environmental benefit (Nady et al., 2011).

A recent study on an enzyme-based method for grafting PES membranes revealed that modified membranes exhibit high fluxes and good anti-protein properties. Indeed, in the aspect of health and safety, enzymes reduce risks, as they do not require the use of reactive reagents and solvents. Also, this provides a potential environmental benefit (Nady et al., 2011).

2.8.1 Plasma Initiated Grafting.

Plasma surface treatment usually refers to a plasma reaction that results in modification of the molecular structure of the surface of atomic substitution. Plasma treatment improves the modification of surface properties. More attention is being directed toward its applications in the membrane separation field. The accelerated electrons from the plasma have enough energy to induce cleavage of the chemical bonds in the membrane structure and form macromolecule radicals, which initiate graft copolymerisation (Nady et al., 2011). The membranes gained permanent hydrophilicity. Although plasma treatment (without grafting) is often reported to increase hydrophilicity and protein repellence, this effect tends to be temporary, which could imply that the treatment has to be repeated (Nady et al., 2011).

2.8.2 Chemical Graft Polymerization

Grafting refers to fixing macromolecules and surface-modifying polymers to membrane surfaces. Grafting has various mechanisms such as cationic, anionic free radical, ultraviolet (UV), plasma or atom transfer radical polymerisation. The main benefit of the method is that it allows fine and uniform surface modification by controlling the chain length and density (Choudhury et al., 2018). Moreover, the graft modification method improves the hydrophilicity, chlorine resistance, water permeability, salt

rejection rate and antibacterial power of the polyamide composite reverse osmosis membrane (Belfer et al., 1998).

In addition, grafting can be divided into types. One implies the binging of polymer molecules with complementary functional groups located on the surface to produce tethered chains. However, this method is rarely used in membrane surface modification because of the low density of grafted polymer chains. The other type consists of the grafting technique using the polymerization initiated from the substrate surface by attached initiating groups. The molecules of a monomer penetrate through the already grafted polymer layer easily, and significant grafted amounts can be reached. This technique is commonly used for membrane surface modification to prepare a thick grafted layer with a high grafting density (Kabir et al., 2018).
Indeed, to perform the grafting method, the membrane functional groups, hydrophobicity, and charges of the membrane must be analysed (Belfer et al., 1998).

2.8.3 Grafting Yield

The measure of the extent of polymerisation is often expressed in terms of the degree of grafting. It is defined as the percentage mass of the grafted membrane related to the unmodified membrane. The degree of grafting was evaluated with the following equation (Lee et al., 2018).

Equation 2- 5: Grafting yield equation

$$\frac{w_1 - w_0}{w_0} \times 100$$

Where w_0 is the weight of the membrane before modification and w_1 is the weight of the membrane after modification.

2.9 Membrane Modifying Agent for this Study: 3-allyl-5, 5 dimethyl hydantoin (ADMH)

2.9.1 Structure of AMDH

This study presents a novel surface modification method applied to polyamide RO membranes to improve their antimicrobial properties using a modification agent called 3-allyl-5, 5-dimethylhydantoin (ADMH). ADMH is a vinyl monomer with a hydantoin-ring chemical structure, as shown in Figure 2-12 (Sun & Sun, 2002).

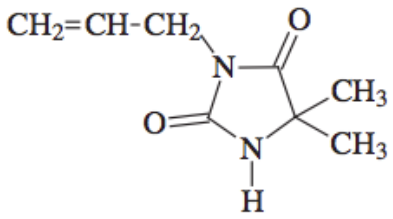


Figure 2- 12: Structure of ADMH (Zhang et al., 2013)

2.9.2 Case Studies of ADMH Use

Surface modifications, including physical and chemical treatments, can improve membrane antibiofouling properties. Indeed, it has been found that membrane antimicrobial properties can be improved by coating with polymers such as polyvinyl alcohol and ADMH (Zhang et al., 2013). Also, the other side benefit of this monomer is that it improves the chlorine resistance of the membrane. In addition, to perform the grafting method, the membrane functional groups, hydrophilicity, and membrane charges must be analysed (Belfer et al., 1998).

Zhang *et al.* (2013) published a research paper on surface membrane modification using this modifying agent. In this report, aromatic polyamide RO membrane surfaces were grafted with ADMH and N, N-Methylenebis acrylamide (MBA) to enhance its anti-bio-fouling properties and chlorine resistance. The study revealed that the membrane characterisation was effective and successful through FTIR and XPS. Moreover, the modified membrane exhibited higher hydrophobicity and salt rejection. Also, the modified presented higher antimicrobial properties than unmodified membranes (Zhang et al., 2013). In addition, 2, 2-azobis (isobutyramidine) hydrochloride (AIBA) is an initiator used with ADMH to perform grafting polymerisation. The initiator AIBA becomes positively charged in an aqueous solution and can adsorb onto the negatively charged aromatic polyamide RO membrane surfaces. Indeed, the most suitable sites in aromatic chains polyamide are at amine and carboxylic acid end groups due to their high activity in hydrogen abstraction (Wei et al., 2010).

2.10 Membrane Surface Characterization

2.10.1 Scanning Electron Microscopy (SEM-EDS)

Scanning Electron Microscopy (SEM) is mainly used for various applications such as qualification of the pore nature for the same cut-off and measuring the fouling layer. This technique provides a high-resolution surface representation (1 nm) and gives information such as roughness, pore size, pore density or pore size distribution (Tamime et al., 2011). The Energy-Dispersive X-Ray Spectroscopy (EDS) The EDS technique is used to determine the elemental composition of a membrane area qualitatively captures X-ray maps larger than the field of view provided by the SEM and can capture features which can be missed when analysing only a limited field of view. The X-rays are related to the valence electron energy of each atom, so the characteristic energy is unique for each atom. By measuring these X-rays, EDS can calculate the atomic composition of a sample.

2.10.2 Fourier Transform Infrared Spectroscopy (FTIR)

It is a Fourier Transform Infrared Spectroscopy. It is a method used to see the fouling distribution on the surface of the membrane. In the study by Benavente et al. (2016) the membrane was scanned using an infrared spectrometer. The spectrometer had a Mercuric Cadmium Telluride (MCT) detector cooled with liquid Nitrogen and a KBR beam splitter. A gold mirror was used to reference the measurements.

2.10.3 X-ray photoelectron spectroscopy (XPS)

Different characterisation methods indicate the fouling development on the surface membrane. X-ray photoelectron spectroscopy (XPS) chemically characterises the membrane surface and determines membrane modification levels. This technique is applied to the chemical characterisation of membranes and all the surface changes associated with chemical treatment. It is a highly quantitative spectroscopic technique used to characterise the chemical distribution and structure composition of the uppermost atomic surface of the samples (Ladewig & Al-Shaeli, 2017).

2.10.4 Atomic Force Microscopy (AFM)

Atomic Force Microscopy (AFM) allows a quantitative surface roughness analysis of the membrane. Indeed, it is a relatively new technique that gives topographical images of the membrane surface by scanning it with a sharp tip without any previous sample preparation (Ladewig & Al-Shaeli, 2017). Since its invention, AFM has been applied to study microfiltration, ultrafiltration, nanofiltration membranes, and other nonporous materials. This technique allows for characterising membrane surfaces, including non-conducting surfaces with a nanometre (or even atomic) resolution in wet and

dry environments. Indeed, AFM also enables the study of the adhesion of particles and the properties of the subsequent deposit during fouling (Silva *et al*, 2011).

2.10.5 Nuclear Magnetic Resonance (NMR)

NMR is one of the main techniques of characterisation used to achieve information about the chemical structure and topology of molecules. In membrane technology, a solid-state is used to identify the functional groups on the membrane. Membrane modification processes directly characterise the chemical structure of the surface-modified membranes. Moreover, it is usually used to describe the structure of the modifying agent used in the modifying process(Ladewig & Al-Shaeli, 2017).

2.11 Reverse Osmosis: Process parameters

A reverse osmosis process was performed to assess the performance of the membrane. The discussion of the study was based on a comparative analysis of the modified and unmodified membranes under the same conditions. The parameters of interest were water flux, permeability, and salt rejection. The mortality ratio of the bacteria was accounted for as a parameter (Leckie, 2007).

2.11.1 Membrane Flux

The flux of a membrane is referred to as the quantities of permeate per unit area of the membrane surface expressed per unit time. It is the rate at which the water permeates the membrane. Indeed, fouling can affect the technical efficiency of the membrane by causing build-up that reduces the permeate flux. According to Mohammadi et al. (2003), the flux of RO membranes is directly proportional to temperature and pressure. Moreover, there is also the solute flux, which is the salt flux expressing the amount of TDS through a particular area of membrane per unit time. Also, the salt flux is a function of concentration.

According to the Water Environment Federation, the formula to calculate the water flux is the following:

Equation 2- 6: pure water flux equation

$$J = \frac{Q_P}{A_{System}} = \frac{V}{A \times \Delta t}$$

Where:

$J =$ Flux $(\frac{L}{m^2}.h)$

$Q_P = permeate\ flow\ \left(\frac{L}{h}\right)$

$A_{System} = surface\ area\ of\ the\ membrane\ system\ (m^2)$

$V = volume\ of\ permeate\ (L)$

$\Delta t = interval\ time\ (hr)$

Moreover, note that the flux decline (FDR) and the flux recovery ratio (FRR) are parameters that help measure the fouling resistance of a membrane.

2.11.2 Flux Decline Ratio

The antifouling ability of the membrane is evaluated in terms of flux decline ratio (FDR), which is defined as the feed solution flux of the membrane after permeation for a specific time divided by the

feed solution flux of the initial clean membrane; the FDR value is determined by the following equation (Kolangare et al., 2018):

Equation 2- 7: Flux decline ratio

$$FDR = \left(\frac{J_0 - J_t}{J_0}\right) \times 100$$

J_0: Initial flux during filtration at t=0

J_t: Flux during filtration at a certain time t

2.11.3 Flux Recovery Ratio

The antifouling ability of the membrane is also evaluated in terms of flux recovery ratio (FRR), which is defined as the pure water flux of the fouled membrane after washing divided by the pure water flux of the initial clean membrane. The FRR value is determined by the following equation (Kolangare et al., 2018):

Equation 2- 8: Flux recovery ratio

$$FRR = \left(\frac{J_{wf}}{J_{wi}}\right) \times 100$$

J_{wi}: Pure water flux before filtration

J_{wf}: Pure water flux after filtration and rinsing

2.11.4 Permeability

RO membranes generally have higher permeability, selectivity, and average tolerance to fouling (Okamoto and Lienhard, 2019). It is reported that a low permeability membrane requires higher feed pressure to achieve reasonable permeate flux. However, high permeability membranes such as reverse osmosis allow higher permeability at lower pressure (Zhu et al., 2009). The energy cost for the RO process includes the production, the feed flow rate, and the applied feed pressure. Therefore, RO operating at lower pressure would consume less energy for a given product's water recovery. Zhu et al. (2009) reported that the required membrane would decrease with increasing membrane permeability for a given feed flow rate at a selected target recovery.

2.11.5 Salt rejection

It has been established that increasing driving pressure decreases the concentration of salts in the permeate collection due to constant salt leakage and increased water flux. The net effect of increased drive pressure is to dilute a constant amount of salt with purer water. Salt rejection is defined as the percentage of salt removed from the feed stream by the membrane (Water Environment Federation). It can be calculated by the formula shown below:

Equation 2- 9: Salt Rejection

$$R = \frac{C_f - C_P}{C_f} \times 100$$

C_f: Feed conductivity ($\mu m/cm$)

C_P: Permeate conductivity ($\mu m/cm$)

R: Salt rejection (%)

Indeed, conductivity measurement is expected to be used as an indication of TDS.

2.11.6 Mortality ratio

a) Bacteria

Wastewater is treated for various reuse purposes such as agriculture, aquaculture, or industrial. MBR effluents may be exposed to resistance and bacteria remaining in the treated water. There are different bacteria and microorganisms responsible for biofouling. Staphylococcus aureus is a Gram-positive bacteria commonly found in the skin of humans and multiple species that causes minor to severe infections (Ankoliya et al., 2018). Moreover, it was found that most studies performed biofouling control experience with Escherichia coli (E. coli) as Gram-negative bacteria. This study will be focused on the two bacteria mentioned previously because some studies showed that Gram-positive bacteria were more resistant to disinfection than Gram-negative bacteria (Silhavy et al., 2014). Therefore, the objective is to assess the performance of the membrane with both types of bacteria.

b) Counting methods

There are various ways to enumerate to perform bacteria counting in a sample. The principle implies that viable cell count allows for identifying the number of actively growing/dividing cells in a sample. The plate count or spread plate method consists of bacteria developing a colony on a nutrient medium. The colony becomes visible to the naked eye, and then the number of colonies on a plate can be counted. For the method to be efficient, the original sample must be diluted so that, on average, between 30 and 300 colonies of the bacteria are grown. Indeed, less than 30 colonies statistically compromise the interpretation, and more than 300 colonies usually result in overlapping colonies and imprecision in the count. Several dilutions are typically cultured to ensure that an appropriate number of colonies will be generated. Moreover, a colony-forming unit is CFU, which estimates the number of viable bacteria (Salvesen & Vadstein, 2000).

c) Mortality ratio

The mortality ratio is the number of viable bacteria in contact with the membrane for a given (A) contact time subtracted from the number of viable bacteria not in contact with the membrane surface as (B) (Wang et al., 2015).

Equation 2- 10: Mortality ratio

$$R = \left(\frac{B-A}{B}\right) \times 100$$

CHAPTER 3

EXPERIMENTAL METHODOLOGY

3. Methodology

This section presents all the different experimental procedures related to the study. The methodology is divided into five sections as follows:

- ADMH synthesis
- Membrane surface modification
- Membrane characterisation
- Biofouling test: Static and dynamic adhesion tests
- Inorganics and organics fouling tests using the Reverse osmosis (RO) cell system.

3.1 ADMH synthesis

ADMH is the modifying agent that was used for this experiment. It was synthesised and used for membrane surface modification according to the method described by Wei *et al.* (2010).

3.1.1 List of Chemicals for ADMH Synthesis

Potassium hydroxide (KOH), 5.5-dimethyl hydantoin (DMH), deionised water (DI), allyl bromide, methanol, and petroleum ether were used for the ADMH synthesis. The chemicals were sourced from Sigma Adrich by Merck and were used without further purification.

3.1.2 Procedure for ADMH Synthesis

The synthesis of ADMH was done according to the Gabriel reaction (Wei et al., 2010). The chemical reaction is below in Figure 3-1:

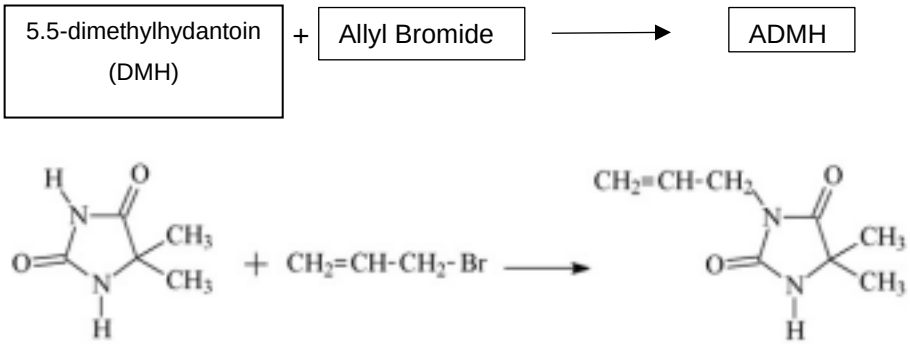


Figure 3-1: Reaction between DMH and allyl bromide to produce ADMH (Wei et al., 2010)

Experimental conditions:

- Synthesis Temperature: 60 ºC
- Duration: 2 hours

Procedure:

1. A solution A of 2.8g (0.05 mol) of KOH in 25 mL of deionized water was made.
2. 6.4g (0.05 mol) of DMH was added to solution A.
3. A Solution B of 4.4 mL (0.05 mol) allyl bromide in 10 mL of methanol was made.
4. Solution A and solution B were combined.
5. The combined solution was stirred at 60 ◦C for two h
6. The solution was cooled and dried under reduced pressure at approximately 25 ◦C.
7. The resulting solid was recrystallized from petroleum as follows:
    - 100g of solvent petroleum ether was heated up near boiling point (30◦C)
    - The solvent was progressively added to the impure solids (just enough) until complete, dissolution and the heating source was removed. Then the solvent allowed to cool to room temperature and the crystals were formed.
    - The content of the beaker was filtrated using a Buchner funnel vacuum for 6 hours.
8. Multiple batches of ADMH were made to prepare the aqueous solution to modify the membranes.

3.2 Membrane Surface Modification

An RO virgin membrane was cut to a specific size of 22 x 14 cm for the surface modification experiment. The membrane piece was then placed into a graft polymerisation apparatus designed and built for the modification experiment. In addition, all experiments were duplicated for later analysis. The main parameters in this procedure are the concentrations of the modifying agent.

3.2.1 Material for Membrane Modification

- membrane graft polymerization apparatus (22x14x5cm)
- Peristaltic pump
- Temperature probes
- Magnetic stirrer
- Water bath
- Oven
- Scissors
- Beakers

3.2.2 List of Chemicals for Membrane Modification

3-allyl-5, 5-dimethylhydantoin (ADMH), initiator 2, 2-azobis (isobutyramidine) hydrochloride (AIBA), Deionised water with less than 5 µS/cm conductivity.

3.2.3 Procedure for Membrane Modification

The graft polymerization apparatus was built specifically for the modification process. The set-up was adapted from the system used by Kim (2020) see Figure 3-1 below, to enable an even coating of the membrane sheets.

Experimental Conditions:

- Solution Temperature: 60 ºC
- Initiator concentration: 0.2 wt.%
- Initiator's contact Time: 15 min
- ADMH concentration: 0.2mol/L; 0.4mol/L; 0.6mol/L and 0.8mol/L
- Grafting contact time: 20 min and
- heat treatment Temperature: 60 ºC

Membrane modification experimental set-up:

Figure 3- 2: Picture of membrane modification process experimental set-up

The modification process was done according to the procedure described below, and Table 3-1 shows the primary equipment identification and placement in the process shown in Figure 3-3.

Table 3-1: Modification equipment description

Number	Equipment
1&2	Temperature meters with probes
3	Peristaltic Pump
4	Membrane Modification Apparatus
5	Water Bath
6	A beaker containing ADMH solution

Process flow diagram:

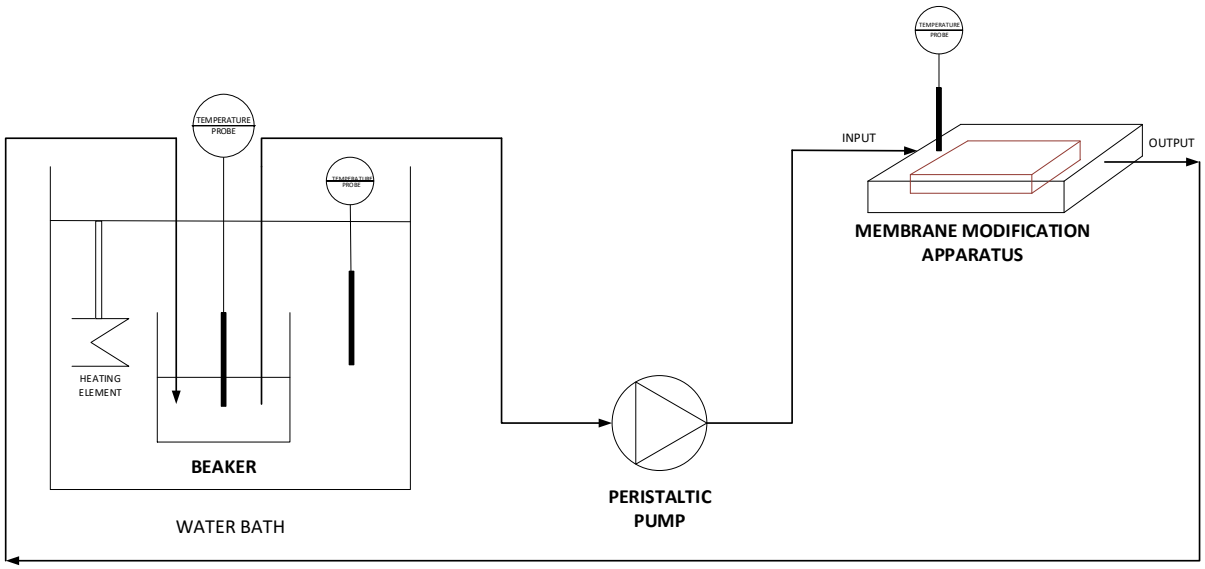


Figure 3-3: Membrane Osmosis - Process Representation Adapted from Kim (2020)

Procedure:

The modification procedure was similar to the method employed by Wei et al., adapted to the conditions specified above (2010).

1. The raw membrane was cut into pieces (22 x 14 cm)
2. The membrane pieces were immersed in DI water a day before the experiment.
3. On the day of the experiment, excess water was removed, and the membrane was taped on the inside of the inner frame of the apparatus to ensure the modifying agent solution was solely in contact with the active surface of the membrane.
4. The aqueous solutions of the initiator AIBA (0.02 wt.%) equivalent to a mass of 0.02g in 100mL and the grafting monomer ADMH solutions at different concentrations of 0.2 mol/L; 0.4 mol/L; 0.6 mol/L and 0.8 mol/L equivalent to 2.5g, 5g, 7.5g and 10g dissolved in 100mL of water respectively, were previously prepared.
5. The initiator solution was circulated in the membrane apparatus, and excess solutions were removed from the membrane piece by drying with nitrogen.
6. The apparatus was then flushed for 15 min using deionised water with output to waste.
7. The ADMH solution was then pumped through the system for 20 min before removing the excess solution from the membrane by drying it with nitrogen.
8. The membrane was then treated for 15 min with heat treatment at 70 °C for 15min.
9. The resulting membranes were then removed from the frames, thoroughly rinsed, and stored in deionised water for analysis. Let $M_{0.2mol/L}$, $M_{0.4mol/L}$, $M_{0.6mol/L}$ and $M_{0.8mol/L}$ be the modified membrane and M_0 the unmodified membrane.

10. The process was repeated for the other concentrations and was triplicated to produce enough membrane for the antibacterial test, RO membrane performance against the biofouling test and membrane characterization.

In the above grafting process, after every coating of an aqueous solution containing an initiator or monomer onto the membrane surface, the excess solvent was removed before initiating the graft polymerization to ensure a solvent-free graft reaction. Indeed, these conditions can minimize the formation of homo-polymerization of the monomers and, therefore, increase graft efficiency.

3.3 Membrane Characterization

The following techniques were used to characterize the membrane before and after the modification process:

- Scanning Electron Microscopy EDX (SEM-EDs)
- Fourier Transformed Infrared Spectroscopy (FTIR),
- Nuclear Magnetic Resonance (NMR)

3.3.1 Scanning Electron Microscopy (SEM)

The SEM–EDS analysis was done by the Electron Microscope Unit of the University of Cape Town, using an FEI Nova Nano SEM. The magnitude used was 1200 at 50-100 µm distance to assess the morphology of the membrane before and after grafting. Each membrane sample was dried overnight prior to the analysis, and the top view and cross-sectional were provided by SEM analysis.

3.3.2 Fourier Transformed Infrared Spectroscopy (FTIR)

The FTIR was performed using a “PerkinElmer Spectrum Two FTIR spectrometer” to confirm ADMH grafting onto the polyamide layer of the membrane.

3.3.3 Nuclear Magnetic Resonance (NMR)

A 13C CPMAS solid-state NMR was done by the Electron Microscope Unit from the University of Western Cape to characterise the membrane surface and determine the membrane modification level. The Solid state NMR experiments were carried out using a 2.5 mm outer diameter zirconia rotors (Bruker, Karlsruhe, Germany); ^{13}C NMR spectra were obtained with a Bruker AVANCE III HD 500 MHz (11.1 Tesla) standard bore spectrometer and a triple channel broad band probe (Trigamma™ MAS probe), at a magic angle spinning rate of 10 kHz, frequencies of 500 MHz (^{1}H) and 125.8 MHz (^{13}C) and standard cross polarization (CP) MAS techniques (^{1}H π/2 pulse length 3.4 µs and ^{13}C π/2 pulse length 4.0 µs, ^{1}H cross polarization field 120 kHz, ^{1}H–^{13}C cross polarization contact time 2.0 ms, broadband SPINAL64 decoupling during signal acquisition at a ^{1}H field strength of 120 kHz, recycle time 3 s, typical number of scans accumulated per spectrum *ca.* 10000). Chemical shifts were referenced to the downfield methylene signal from solid Glycine at 43.7 ppm.

3.4 Biofouling Tests Methodology

The following chemicals were used for the biofouling tests:

Nutrient broth powder, nutrient agar, E. coli strain, S. aureus strain, deionised water, glycerol.

3.4.1 Static Adhesion Test

The gram-negative E. coli bacteria and gram-positive S. aureus bacteria solutions were used as model microorganisms to assess the antimicrobial ability of the modified membranes.

a) Material for Static Adhesion Tests

- Sterilized Erlenmeyer flasks and beakers
- Petri dishes
- Incubator
- UV light
- Micropipette
- Bunsen burner
- Spectrometer
- Autoclave machine
- Petri dishes
- Beakers
- Magnetic stirrer

b) Procedure for bacteria culturing prior to test

The procedure for bacteria culturing described below has been adapted from (Wang et al., 2015) and (Tuttle et al., 2021).

1. 28g of nutrient agar powder was dissolved in 1L de-ionised water.
2. 25g of nutrient broth powder was dissolved in 1L de-ionised water.
3. The solutions of nutrient broth and nutrient agar were autoclaved at 121 °C and allowed to cool down.
4. The nutrient agar was allowed to cool down enough to be manipulated without solidification.
5. The agar solution was poured into petri dishes for cooling and let to solidify.
6. 5 µL of E. coli solution was preserved in a glycerol stock at -80℃ and poured onto Petri dishes.
7. The later petri dishes were then incubated at 37℃ overnight.
8. The next day, a pure colony was streaked from the petri dishes and inoculated in 10 mL of nutrient broth overnight.

9. The next day, the 10mL nutrient broth with E. coli was inoculated in a volumetric flask containing 240mL nutrient broth, taking the total volume to 250mL.
10. The diluted bacteria suspension in fresh liquid medium was further grown to exponential phase (determined by a growth curve see optical density study in Appendix 4B of this report)
11. The broth's optical density (OD) was monitored to obtain an optical density of approximately ± 0.47Abs (at a wavelength of 590 nm) to monitor the growth of the bacteria until ready for adhesion tests.
12. The same procedure was applied for the gram-positive bacteria (S. Aureus).

c) Static adhesion experimental tests on membranes

Short-term bacterial adhesion tests for the fouling propensity evaluation of modified and unmodified membranes according to the procedure used by Wang et al. (2015) and Tuttle et al. (2021).

1. The membrane was cut into small circles of 88 mm in diameter and placed under UV for half an hour.
2. The pieces of modified and unmodified membranes were placed for 3 hours in contact in the incubator at 37℃ with Nutrient broth (NB) of approximately ± 0.47Abs (at 590 nm) containing E. coli suspension previously prepared.
3. A blank control contaminated broth solution that was not in contact with the membranes was also incubated for the same contact time for control.
4. The membrane pieces were then removed and rinsed with saline water, and 1 mL of the suspension solution collected was diluted in series (2-10 folds).
5. 100 µL of diluents were plated on nutrient agar (NA) in Petri dishes, labelled into a distinguishing pattern and incubated at 37℃ for 20 hours.
6. The same dilution process was for the blank control and plated on petri dishes.
7. The petri dishes were removed, and the number of E. coli bacteria in contact with each membrane was determined by the plate count method.
8. The same procedure was applied with S. Aureus bacteria for both the unmodified and modified membrane

3.4.2 Fouling Tests Using the Reverse Osmosis (RO) Cell System

The membranes underwent filtration experiments to evaluate their permeability, selectivity, and resistance to fouling. The unmodified and ADMH-modified membranes were tested by crossflow filtration of bacterial suspensions to evaluate their antibacterial potential. The optimum membrane was further tested for inorganic, organic fouling.

a) System Set-up for Reverse Osmosis

The experiments were performed in a laboratory using a GE OSMONICS RO cell. It is a laboratory-scale crossflow membrane test unit. The feed solution was a different synthetic feed solution to assess the membrane performance against fouling. The water was pumped through the cell using a hydra-cell pump. The permeate water was discharged into a collecting beaker, and the retentate was recycled back to the feed tank. LabVIEW software was used to help visualize every aspect of the set-up, and measurement data such as conductivity, flow rate, velocity and the pressure around the cell was monitored using a hydraulic pump. The feed pressure was regulated to achieve a constant flux to avoid membrane breaking.

b) Material and Equipment for RO Set-up

- Feed tank
- Hydra-Cell pump
- Pipes
- GE OSMONICS RO cell
- Computer with software LabVIEW
- Portable EC meter
- Portable pH meter
- Stopwatch
- Measuring cylinder

Figure 3-4: Picture of GE Osmonics reverse osmosis membrane cell

c) Reverse Osmosis Process Representation

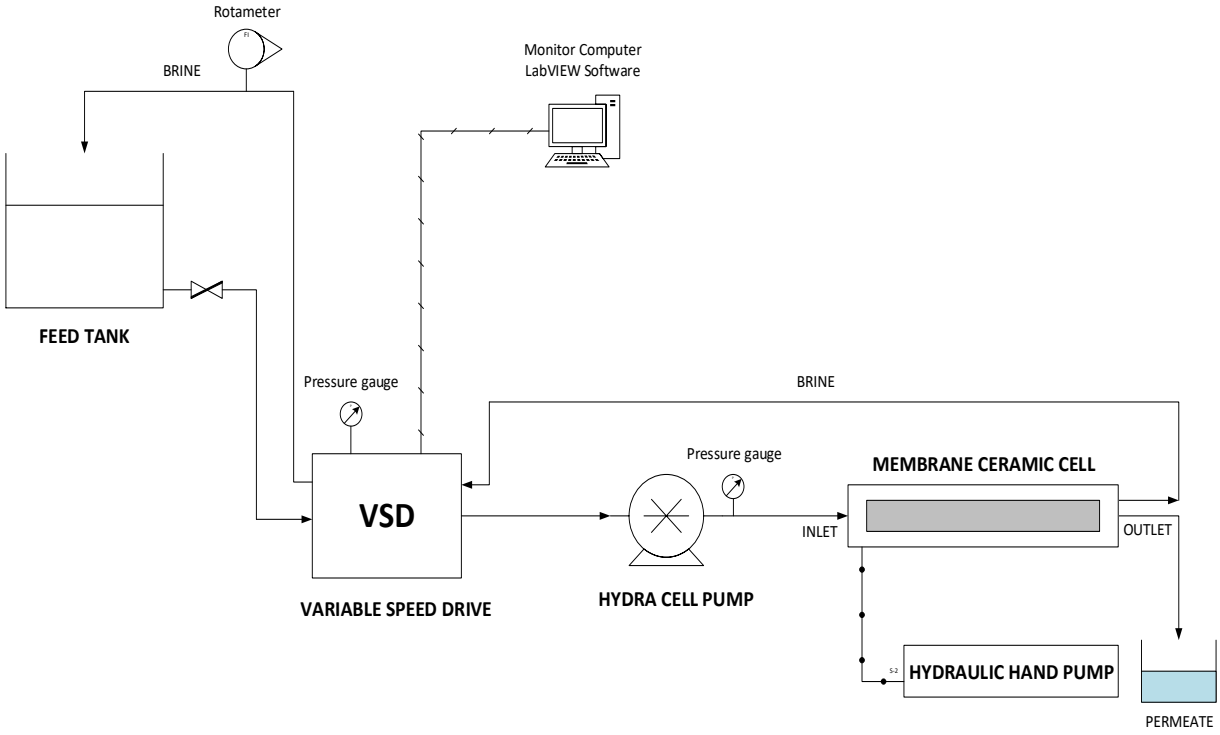


Figure 3- 5: RO Reverse Osmosis Ms Visio representation

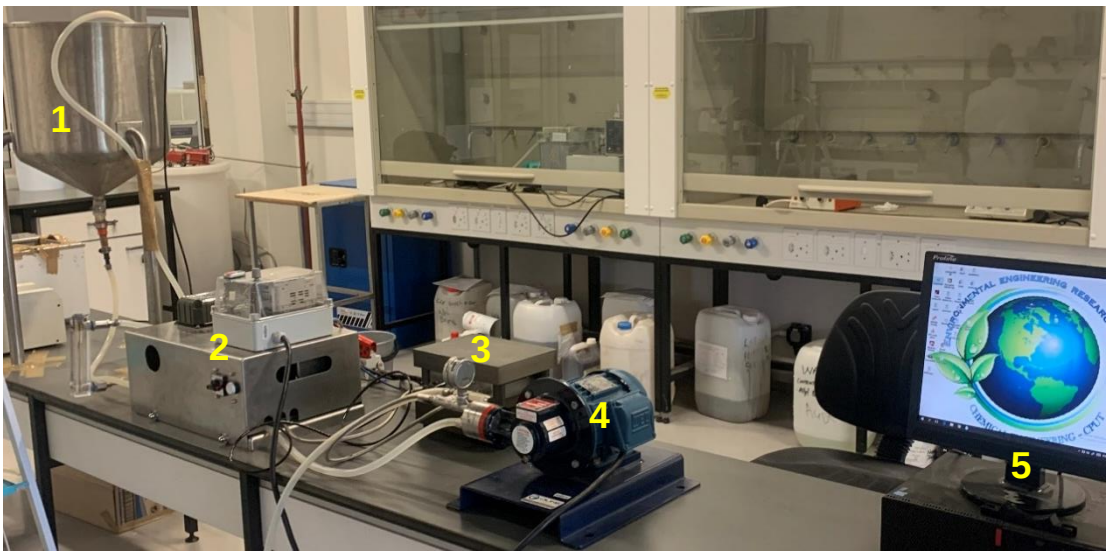


Figure 3-6: Picture of Reverse Osmosis process laboratory set-up

Table 3- 2: Modification equipment description

N°	Equipment
1	Feed Tank
2	VSD (Velocity Speed Drive)
3	Membrane Cell
4	Hydra cell pump
5	Monitoring computer

d) Procedure for Reverse Osmosis Cell Prepping and Preliminary Tests.

Proper start-up of reverse osmosis systems is essential to prepare the membranes for operation and prevent any membrane damage due to overfeeding or hydraulic shock. Following the proper start-up sequence also helps ensure the system operating parameters conform to design specifications to achieve system water quality and productivity.

Procedure:

1. The system piping was replaced entirely before starting the process.
2. The reverse osmosis equipment was switched on and set to a pressure of 15 bar (±3 bar), with a constant flow rate of 2L/min. The
3. The reverse osmosis process was flushed for 4 hours for cleaning with deionised water; then, the equipment was switched off.
4. The pressure hydraulic pressure was released, and the membrane cell module was opened.
5. Two spacers were cut out in the same shape as the membrane cell's active area surface. The spacer with bigger holes is placed on the higher-pressure side (feed side); the spacer with smaller holes is placed on the low-pressure side (permeate side).
6. The spacers were then wetted and rinsed with deionised water.
7. The membrane was previously cut from an opened spiral wound DOW FILMTEC XLE-4040 membranes into smaller chunks and kept in deionised water.
8. The optimum feed pressure was assessed within the FilmTech recommended range (100psi to 600psi) for the XLE membrane and an aqueous solution of NaCl 0.2wt% for salt rejection assessment.

e) Feed Solutions preparation

Municipal wastewater is characterized according to the following major components presented in Table 3-3 below (Sangita et al., 2022)

Table 3-3: Municipal wastewater characteristics

Mineral constituents						
Sodium salt	Chlorine compound	Nitrate	Sulfate	Bicarbonate	Chlorine	Phosphorus
Heavy metals						
Arsenic (As)	Lead (Pb)	Mercury (Hg)	Fluorine (F)	Cadmium (Cd)	Chromium (Cr)	Copper (Cu)
Organic constituents						
Animal waste	Vegetable waste	Oils	Garden waste	Food ingredients	Solid organic waste	Excretory waste
Microbiological forms						
Protozoa	Algae	Bacteria	Fungi	Archaea	Viruses	Plankton
Harmful gases						
Methane (CH_4)	Ammonia (NH_3)	Carbon dioxide (CO_2)	Carbon monoxide (CO)	Hydrogen sulfide (H_2S)	Chlorine (Cl)	Sulfur dioxide (SO_2)

Fouling experiments were conducted using contaminants identified as the main fouling elements of municipal wastewater. Hence the feed solutions during the fouling experiments were prepared to simulate municipal wastewater secondary effluent (Kasongo, et al. 2019).

The membranes were tested with foulants individually to distinctly assess the resistance to fouling of membranes to each type of fouling. Gram-negative E. coli and Gram-positive S. aureus were used as biofoulants; sodium bicarbonate and humic acid were used as inorganic and organic foulants model, respectively. Tables 3-4 shows the different feed solutions used for this experiment.

Table 3-4: Feed solutions and experimental conditions

	Feed	**Feed Composition**	**Operating Conditions**
1	Pure Water Feed	Deionized water (5µS/m)	Time: 120 min Pressure: 15 bar Temperature: Room Temp
2	Salted Water Feed	Deionized water + NaCl (500ppm)	Time: 240 min Pressure: 15 bar Temperature: Room Temp
3	Organic Foulant Feed	Deionized water + Humic Acid (100mg/L)	Time: 240 min Pressure: 15 bar Temperature: Room Temp

4	Inorganic Foulant Feed	Deionized water + Sodium Bicarbonate (100mg/L)	Time: 240 min Pressure: 15 bar Temperature: Room Temp
5	Microbial Wastewater Feed gram positive	Autoclaved Nutrient Broth + E. coli suspension ($1.24 \times 10^7 CFU/mL$)	Time: 240 min Pressure: 15 bar Temperature: 37°C (maintained for bacteria viability)
6	Microbial wastewater Feed gram positive	Autoclaved Nutrient Broth + S. aureus suspension ($8.10 \times 10^6 CFU/mL$)	Time: 4 hours Pressure: 15 bar Temperature: 37°C (bacteria viability)

Organic and Inorganic Feed

1. Synthetic feeds were prepared for each run (Table 3-3). The required chemical mass (Humic acid and Sodium Bicarbonate) was weighed on an analytically.
2. After that, the required mass was put into a beaker to be diluted with 4.5L of deionised water using a magnetic stirrer.
3. This step was done individually for each foulant. As the chemicals dissolved, the solution was poured into a 20L container.
4. The tank was then filled with water to make a total feed volume of synthetic feed that was continuously stirred using a mixer during the process.

Microbial Feed

The feed preparation procedure was adapted from the method employed by Karkhanechi et al. (2014). Moreover, the feed concentration is specified in Table 3-3 according to an OD density study found in Appendix 3B.

1. A pure colony was streaked from the petri dishes and inoculated in 10 mL of nutrient broth overnight at 37°C like the procedure in section 3.3.3
2. The next day, the 10mL nutrient broth with E. coli was inoculated in a volumetric flask containing 240mL nutrient broth, taking the total volume to 250mL.
3. The broth's optical density (OD) was monitored to obtain an optical density of approximately ± 0.47Abs (at a wavelength of 590 nm) to monitor the time-dependent growth of the bacteria indication until it is ready for the biofouling tests.

4. The initial flux was recorded, and the filtration was carried out using diluted 4 bottles 250mL of E. coli in 2L autoclaved nutrient broth as feed. After filtration, the water flux of the membrane was carried out (Cihanoğlu & Altinkaya, 2020).
5. The system was clean between runs flushing using 99% Ethanol.

List of chemicals

Deionised water, 100mg/L Sodium Bicarbonate, 100 mg/ Humic acid, nutrient broth, and E. coli and S. Aureus strains.

f) Fouling experimental Runs

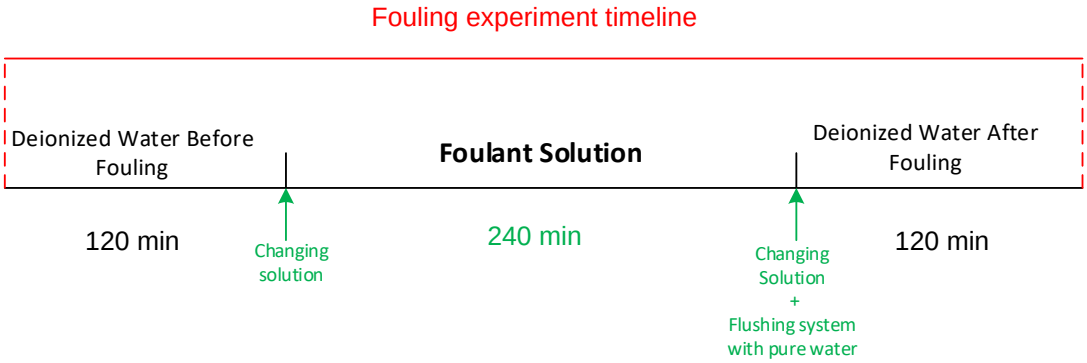


Figure 3-7: Reverse Osmosis timeline

After the RO apparatus set up, the best-performing modified and unmodified membranes in the biofouling test were further evaluated for permeability, salt rejection and fouling resistance.

The experiment conditions are specified in Table 3 and Table 4, and the procedure is described as follows:

1. The membrane pieces were then cut to smaller a size of 14.5 x 9.5 cm, giving an active surface area of 0.013775 m^2 that covers the inner sealer inside the flat RO cell.
2. The spacer layer of the membrane was placed, and then the membrane sheet was placed on its shiny side facing down on the cell. The permeate carrier layer was then placed.
3. After the first membrane cut, a cardboard template piece was cut to the exact measurement of the RO cell active area and used for further membrane pieces.
4. The cell was closed, placed back in its holder and compressed using the hydraulic pump.
5. The hydraulic pump pressure was then to be set to the optimum 15 bar and brine flow rate maintained at 2 litres per minutes. After the cell was secured, the feed solution was added, and the pump was switched on. The pressure was regulated to 15bar using a pressure regulator valve.
6. The fouling experiments were done afterwards according to the following procedure.

7. The system was switched on, and the LabVIEW program was started to control the system's operating conditions and record data using the software logger.
8. The first set of experiments was done using deionised water. The flux was recorded every 30 min. This step was done for all modified and the unmodified membrane M_0 $M_{0.2}$,$M_{0.4}$ $M_{0.6}$ and $M_{0.8}$.
9. The deionised water was drained and replaced with synthetic feeds prepared before the RO cell start-up.
10. After the system reached stability again at the required system conditions, the conductivity and TDS of the feed, brine and permeate was recorded every 30 minutes throughout the experimental run for all membranes M_0 $M_{0.2}$, $M_{0.4}$, $M_{0.6}$ and $M_{0.8}$
11. Once filtration was done was the system was cleaned with deionised water by flushing 5L of water per cleaning cycle.
12. The deionised water was drained and replaced with the next feed, including the microbial foulant solution of S. aureus prepared before RO cell start-up. Step 10 was then repeated.
13. After every experimental run, the system was flushed with deionised water to remove impurities and build-up.

CHAPTER 4

MEMBRANE MODIFICATION - RESULTS AND DISCUSSION

4. Membrane Modification and Characterization

The results of the membrane modification are presented in different sections as follows:

- Modifying agent: ADMH synthesis and characterization
- Membrane characterization
- Membrane grafting yield.

4.1 Modifying agent: ADMH Synthesis and Characterization

4.1.1 ADMH Synthesis

ADMH was synthetized according to the methodology specified in section 3.1 (Wei et al., 2010).

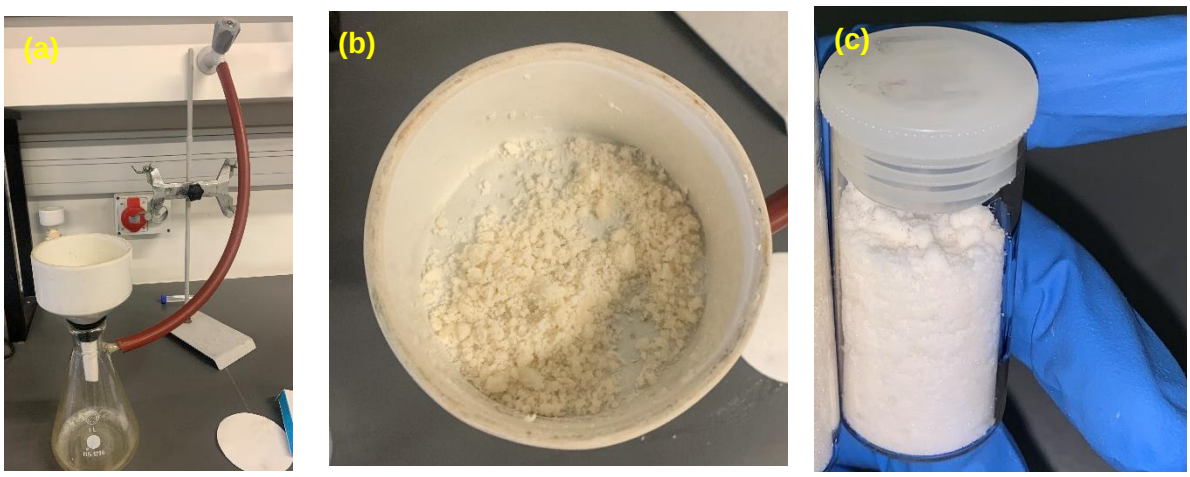


Figure 4-1: Picture of ADMH synthesized. (a) Primary drying set-up under vacuum (b) Drying ADMH sample (c) Dried ADMH sample

The resulting solid was recrystallized from petroleum ether and then dried entirely again. The yielding of the first three batches is presented in Table 4-1 below. The theoretical yield proposed in this table is according to Wei *et al.* (2010).

Table 4-1: ADMH yield Table

Batch N°	1	2	3
Theoretical mass yield (g)	5,6	5,6	5,6
Actual mass yield (g)	3,75	2,5	4,1
% Yield	**67**	**44,6**	**73,2**

4.1.2 ADMH Characterization

The ADMH was then characterized by FTIR using the PerkinElmer FTIR spectrum two spectrometer with a scan range of 400-4000 cm^{-1} to confirm the purity of the chemical. The results are presented in Figure 4-2, which shows the FTIR results for ADMH that was characterized after modification.

Figure 4-2: ADMH FTIR Results

The FTIR of ADMH presents some trend similarities to the ADMH characterisation presented by Liu et al. (2020). The absorption peaks at 3173 cm^{-1} is due to the stretching vibration of the $N-H$ bond and the strong pick at 1696cm^{-1} are due to a carbonyl group. The peak at 3090 cm^{-1} shows the strong stretching vibration of the $=CH$ bond with a weak stretching vibration peak of the $C=C$ bond at 1642 cm^{-1}. Also, the peak in 1772 cm^{-1} is due to stretching vibrations of the $C=O$ bond in ADMH. Moreover, the peak at 1335 cm^{-1} is due to the in-plane bending vibration of the $=CH$ bond, while the absorptions peaks at 942 cm^{-1} and 990 cm^{-1} are present because of to the out-plane bending of the $=CH_2$ bond (Liu et al., 2020).

4.2 Membrane Grafting Yield.

The degree of grafting was evaluated for each membrane sample before and after modification. Dried 2x2cm square pieces were used as standard size before and after modification. The results are presented in Figure 4-5 below.

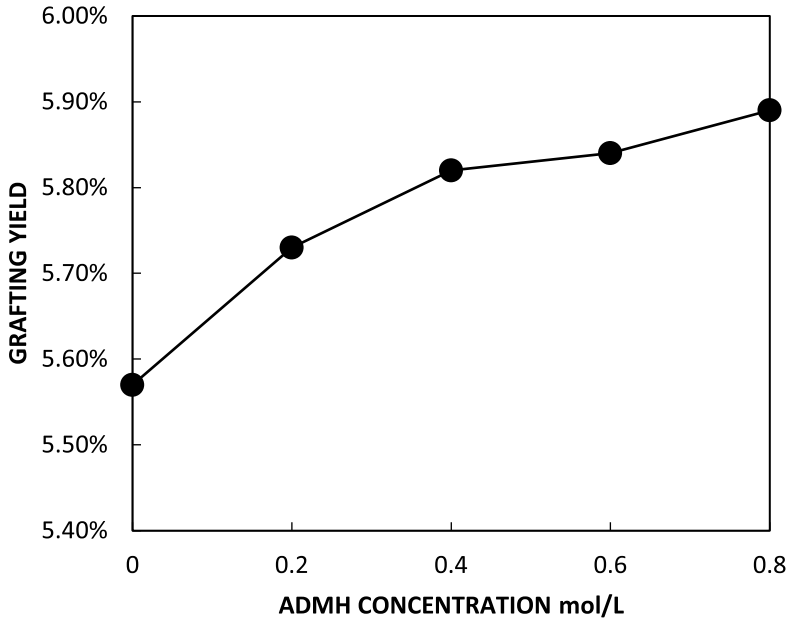


Figure 4-3: Grafting yield of ADMH

The grafting yield was found to be 5.57%, 5.82%, 5.84% and 5.89% for 0.2mo/L, 0.4 mol/L, 0.6mol/L and 0.8 mol/L of ADMH concentration, respectively. It is observed that the degree of grafting increases with the grafting concentration. As Ahmad (2021) suggested the higher availability of monomer molecules on the membrane's surface impacts the chain propagation for the graft polymerization of the RO membrane. It is similar to the trend presented by Muhamad et al. (2022) who suggest that the change in the properties of modified membranes is a function of grafting yield which is highly dependent on the reaction conditions, like the concentration of the modifying agent. Moreover, Mushtaq et al. (2021) also observed that the grafting yield follows the same trend as the concentration of the modifying agent. Indeed, the grafting yield increases with the increased monomer concentration for the modified membranes. The higher the concentration, the higher the availability of the agent molecules, which assist the chain propagation for the grafting of the membrane

4.3 Membrane Characterization

FTIR and SEM showed the effect of surface grafting of ADMH on the membrane surface.

4.3.1 FTIR Analysis

FTIR analysis was performed to detect any chemical changes on the membrane surface.

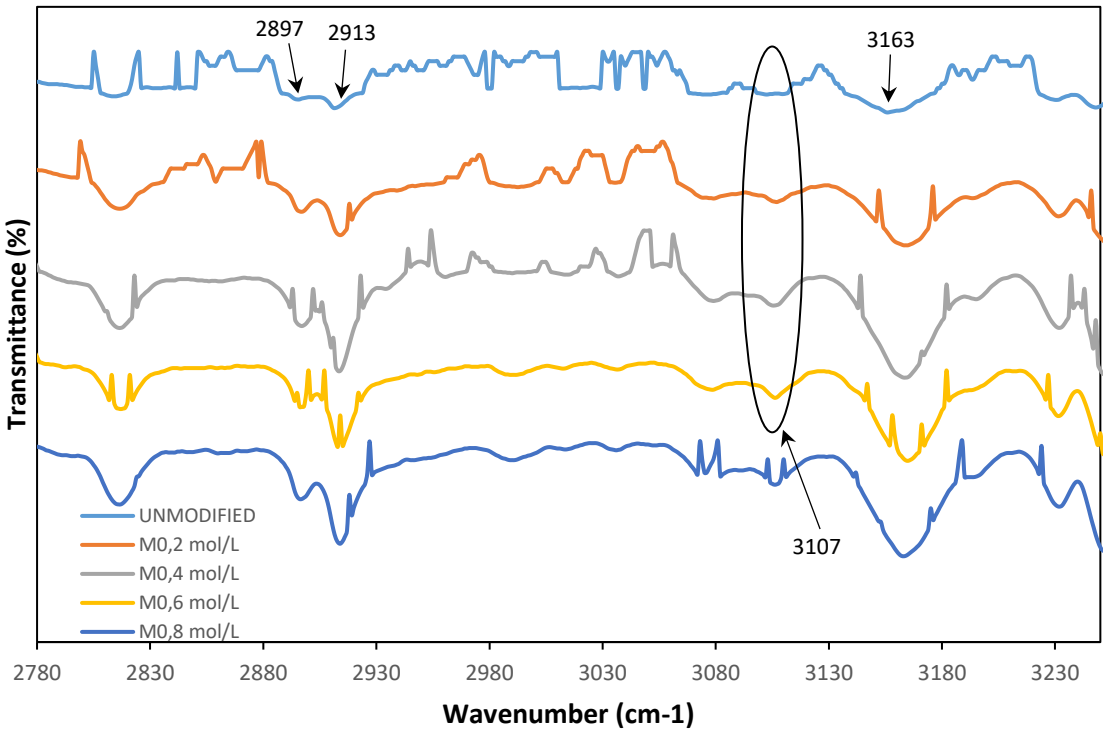


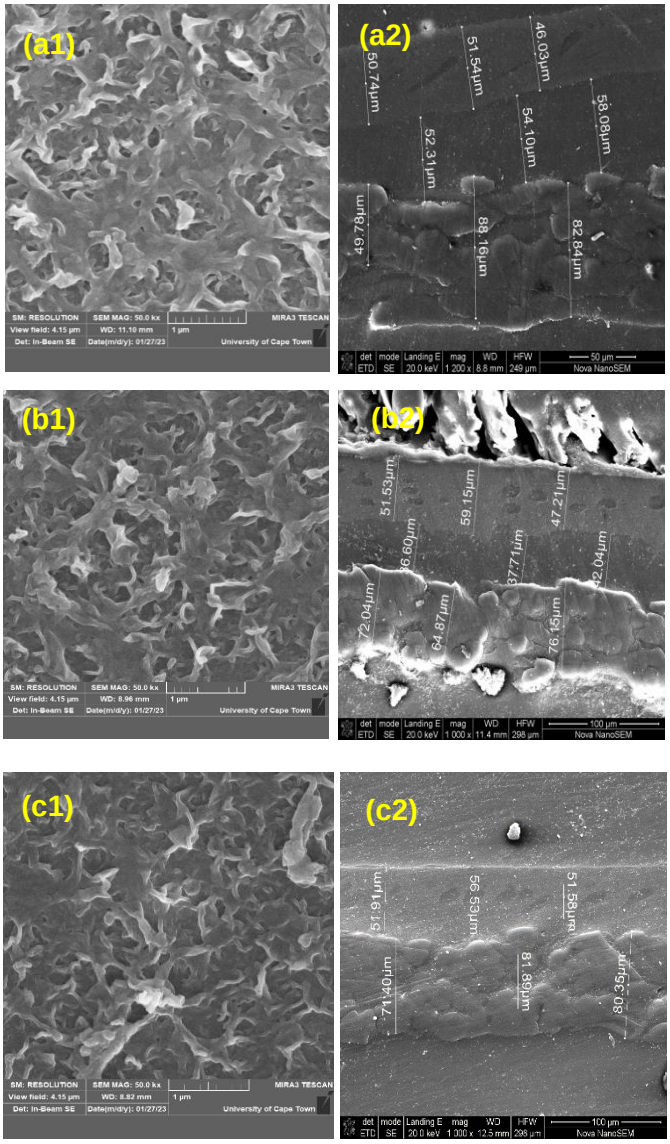
Figure 4-4: FTIR spectra for the Unmodified, M_0, $M_{0.2mol/L}$, $M_{0.4mol/L}$, $M_{0.6mol/L}$ and $M_{0.8mol/L}$ (modified membranes with 0.2 mol/L, 0.4 mol/L, 0.6 mol/L and 0.8 mol/L respectively) in the wavenumber range of 2780-3230 cm^{-1}

The FTIR analysis was used to verify the graft polymerization of ADMH on the surface of the polyamide reverse osmosis membranes. Figure 4-4 shows the FTIR spectra of the unmodified membrane and the ADMH grafted membranes. The appearance of the characteristic peaks is similar to the ones reported by Wei et al. (2010). The FTIR spectra of ADMH-grafted membranes clearly show the appearance of a new band in 3107 cm^{-1}, a C=O bond in ADMH. It is noticed that the band is more visible as the concentration of ADMH increases. Indeed, this observation suggest that ADMH has been successfully grafted onto the aromatic polyamide RO membrane surface, and the degree of grafting is more important with increasing grafting concentration (Wei et al., 2010). The peaks at 2897 cm^{-1}, 2913 cm^{-1} are like the $C-O$ (amide I) stretching, the hydrogen bonded $C-O$ (amide I) stretching, and $N-H$ (amide II) in-plane bending, respectively. These stretchings are characteristics aromatic polyamide in the barrier layer.

The strong stretching at 3163 cm^{-1} is a $Ar-O-Ar$ stretching; the Ar an is aromatic ring, which is also characteristic of the membrane support layer (Zhou et al., 2009). These findings are consistent with the findings reported by Wei et al., (2010) and therefore confirm the successful graft of ADMH on membranes surface.

4.3.2 SEM Analysis

SEM analysis was done to assess the membrane morphology before and after modification. Figure 4-5 shows the top view SEM images of the RO membranes surface at 1 µm magnification and the cross-sectional images of the membranes on the left and the right, respectively.



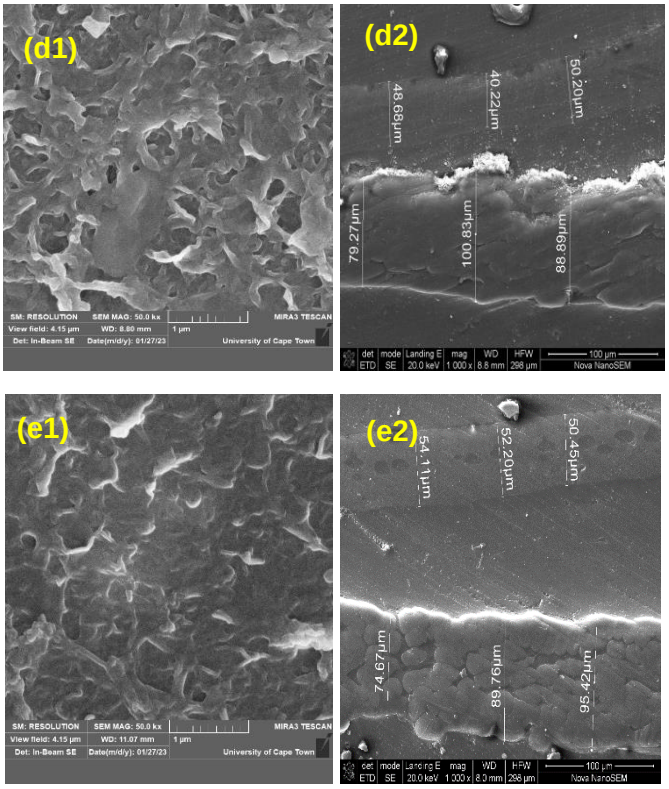


Figure 4-5: SEM images of Top View and Cross-Sectional View (a) Unmodified membrane (b) 0.2 mol/L Grafted membrane (c) 0.4 mol/L Grafted membrane (d) 0.6 mol/L Grafted membrane (e) 0.8 mol/L Grafted membrane

The typical multi-layered ridge-and-valley structure was observed in the unmodified membranes in Figure (a1). Indeed, the top view SEM images of the modified membranes indicate partial or complete filling of the pores of the XLE-4040 membrane by grafting chains. For the modified membranes, a less uniform appearance is observed, with the presence of matter in the form of irregularities. This observation is evident for the 0.6 mol/L grafted membrane shown in Figure (d1). The irregularities of the ridges identified on the surface of the membrane confirm the adhesion of the ADMH on the surface, as suggested by Vatanpour & Zoqi (2017). Also, the irregularities are more prominent with increasing concentration. The membrane surface modification caused the valleys of the commercial membranes to be filled with the grafting polymer ADMH. This trend causes a smoother less roughness, which leads to fouling reduction.

Figure 4-5 also presents the cross-sectional view of the membrane samples of the unmodified and the grafted membranes M_0, $M_{0.2mol/L}$, $M_{0.4mol/L}$, $M_{0.6mol/L}$ and $M_{0.8mol/L}$ shown on the (a2), (b2), (c2), (d2) and (e2) images respectively. Figure (a2) shows the cross-sectional view of the unmodified membrane with a dimension of 88.16 µm. The ADMH grafted membranes present new characteristics of the top layer with the addition of a thin layer see image (d2) from Figure 4-5 has a thickness of 103.83 µm. According to Hong et al (2017) the formation of the modifying agent layer on the top of the membrane is due to the grafting polymerisation that mainly occurs on the surface of the membrane. It confirms a successful modification of the membranes by ADMH grafting.

4.3.3 NMR Analysis

Nuclear magnetic resonance spectroscopy was used to analyse the modification in the structure of the virgin reverse osmosis membrane and the modified one. The results are presented in Figure 4-6.

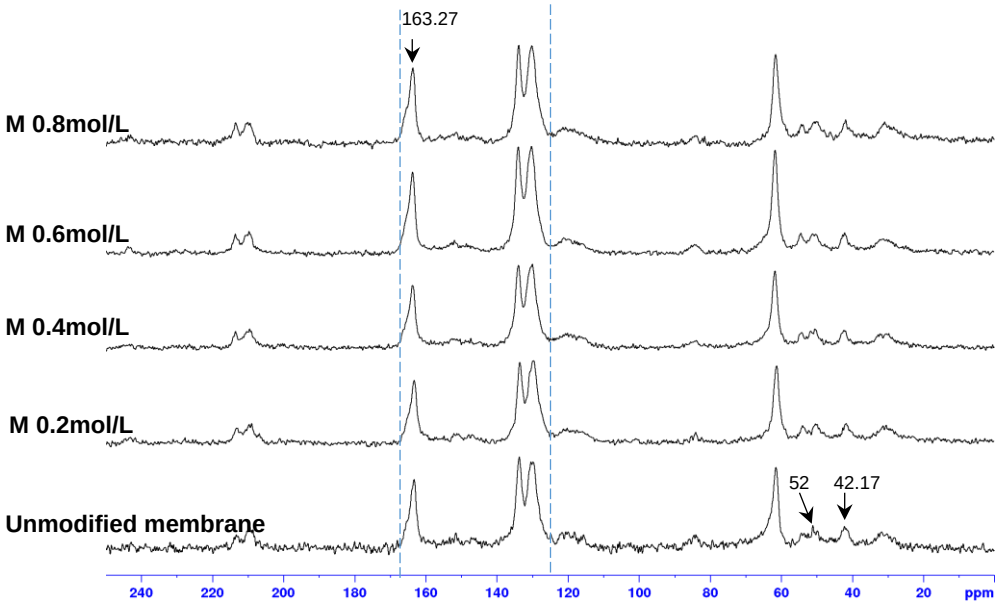


Figure 4-6: Solid C^{13} CPMAS NMR results for unmodified and all ADMH modified membranes.

The carbonyl peak at 165 ppm belongs to the to reverse osmosis membrane. Moreover, the chemical shift at 5.6–5.8 ppm was due to the methine proton in the pendant allyl groups. The spectrum of neat bulk membrane displays resonances at (110 to 165) ppm which belongs to the reverse osmosis membrane. Liu et al. (2020) presented a nuclear magnetic resonance of ADMH and identified the elemental bonds of the agent. The pick at 52 ppm represents the (C $(CH_3)_2$) of the ADMH. The pick at 42.17 ppm is the (=$CHCH_2$) bond in ADMH increasing with increasing concentration. The pick at 130.4 ppm is (=$CHCH_2$), while the pick at 163.27 ppm is the (C=O) bond in ADMH structure (refers to section 2.8 Figure 2-12 of ADMH structure). The variations observed from the membrane samples are consistent and confirm the successful graft polymerization (Liu et al., 2020).

CHAPTER 5

MEMBRANE PERFORMANCE EVALUATION - RESULTS AND DISCUSSION

5. Membrane Performance Evaluation

The results related to the membrane performance are presented in different sections as follows:

- Membrane resistance to biofouling
- Membrane salt rejection, permeability
- Membrane resistance to organic and inorganic fouling

5.1 Membrane Antimicrobial Properties (Adhesion Tests)

The biofouling experiments evaluated membrane surface resistance to microbial fouling using gram-negative E. coli bacteria and gram-positive S. aureus bacteria solutions. Both bacteria were used as model microorganisms to assess the antimicrobial, anti-biofouling ability of the modified membranes. The results are presented below.

5.1.1 Membrane Antimicrobial Properties against E. coli Bacteria

The biofouling propensity of modified and unmodified membranes was evaluated by bacterial adhesion tests using the gram-negative bacteria, E. coli according to the procedure described in section 3.3.4. The count plate method was used by consecutive dilutions to enable the determination of the mortality ratio of the membranes. Figure 5-1 shows a visual of the count plate method.

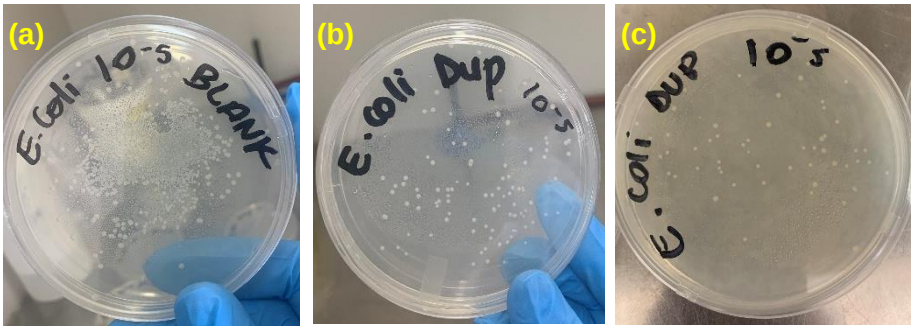


Figure 5- 1: Pictures of E. coli at dilution factor 10^{-5} (a) plated colonies from bacteria broth not in contact with membranes (b) Plated colonies from bacteria in contact with unmodified membrane (c) Plated colonies from bacteria in contact with the modified membrane.

Figure 5-1 shows the antimicrobial activity of the unmodified and modified membrane against E. coli on plates of 10^{-5} diluted E. coli solution. The visual observation of plates shows a visual difference of the number of colonies present on the plates, decreasing from (a), (b) to (c), respectively, depicting the extent of antimicrobial resistance of the membranes.

Figure 5-2 presents the mortality ratio of modified membranes compared to the pristine when tested with E. coli solution. Moreover, the degree of improvement of the modified membranes is also represented on the graph as a percentage increase or decrease in Figure 5-2.

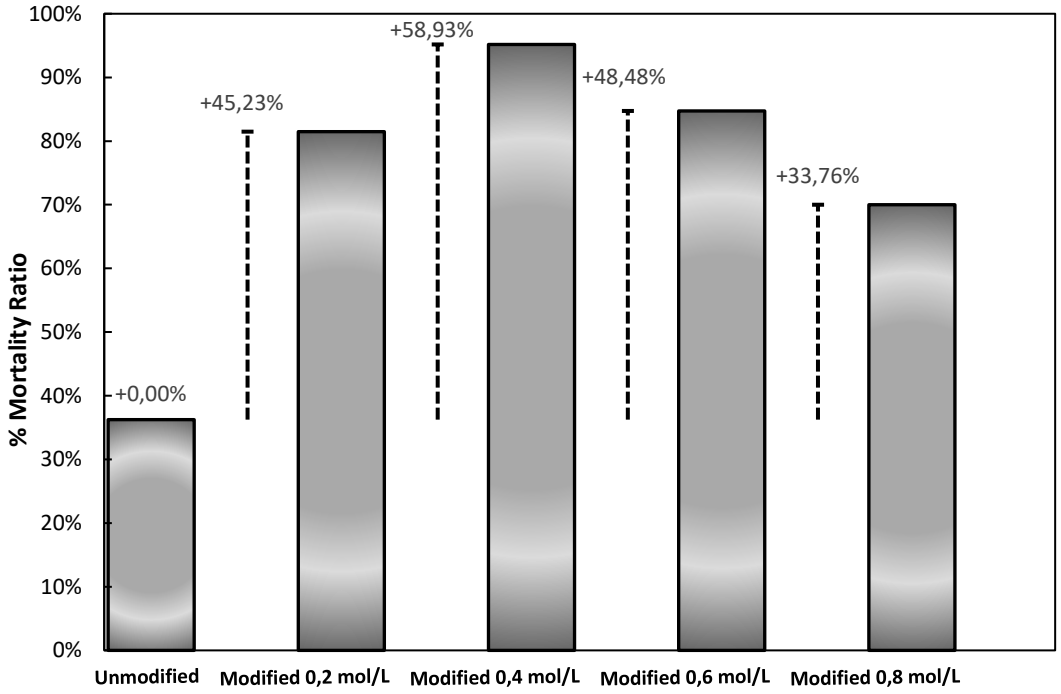


Figure 5- 2: Adhesions test results for unmodified and modified membranes against E. coli

The membranes $M_{0.2mol/L}$ and $M_{0.4mol/L}$ (modified with 0.2mol/L and 0.4mol/L concentration of ADMH) have an improved mortality ratio of 45.23% and 58.93%, respectively. The membranes $M_{0.6mol/L}$ and $M_{0.8mol/L}$ (modified with 0.6mol/L and 0.8mol/L concentration of ADMH) have an enhanced mortality ratio of 48.48% and 33.76%, respectively. It is observed that the membrane $M_{0.4mol/L}$ (modified with 0.4mol/L concentration of ADMH) had the highest improvement of 58.93% and appears to be the optimum modified membrane against E. coli. Indeed, the membrane modification exhibits better antimicrobial properties that the raw membrane (Wei et al., 2010).

5.1.2 Membrane Antimicrobial Properties against S. Aureus Bacteria

The fouling propensity of modified and unmodified membranes was evaluated by bacterial adhesion tests using the gram-positive bacteria S. aureus according to the procedure described in section 3.3.4. The count plate method was used by consecutive dilutions to determine the mortality ratio of the membranes. Figure 5-3 shows a visual observation of the count plate method.

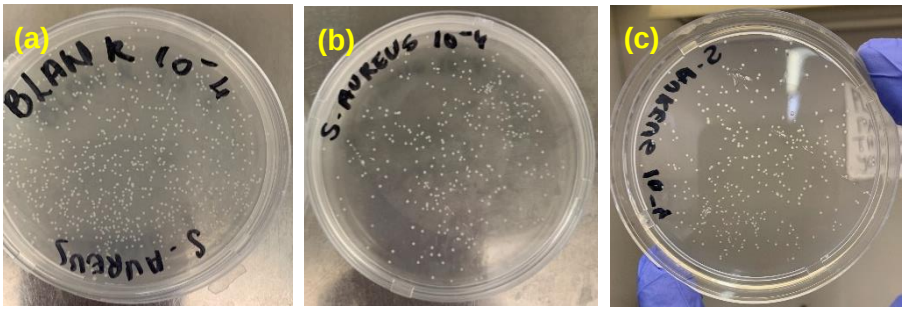


Figure 5-3: Pictures of S. aureus at dilution factor 10^{-4} (a) Plated colonies from bacteria broth not in contact with membranes (b) Plated colonies from bacteria in contact with unmodified membrane (c) Plated colonies from bacteria in contact with modified membrane

Figure 5-3 shows the antimicrobial activity of S. aureus on the unmodified RO and ADMH-modified membranes. A visual difference is observed between the plate from the solution of bacteria not in contact with the membrane (a), the unmodified membrane plate (b) and modified membrane plate (c). However, the number of colonies on the modified membrane is slightly lower than the amount on the pristine membrane. Figure 5-4 presents the antimicrobial properties of the modified membranes compared to the unmodified membrane against S. aureus in mortality ratio. Furthermore, the degree of improvement of the modified membranes is also represented on the graph as a percentage increase or decrease.

Moreover, Mushtaq et al., (2021) explained a difference in the behaviour of the bacteria. The E. coli has a negatively charged outer surface (Gram-negative bacteria type), which is repelled by the negatively charged surface of the modified membrane due to repulsive electrostatic interactions, contrary to the S. aureus, which has a positively charged outer surface (Gram-positive bacteria).

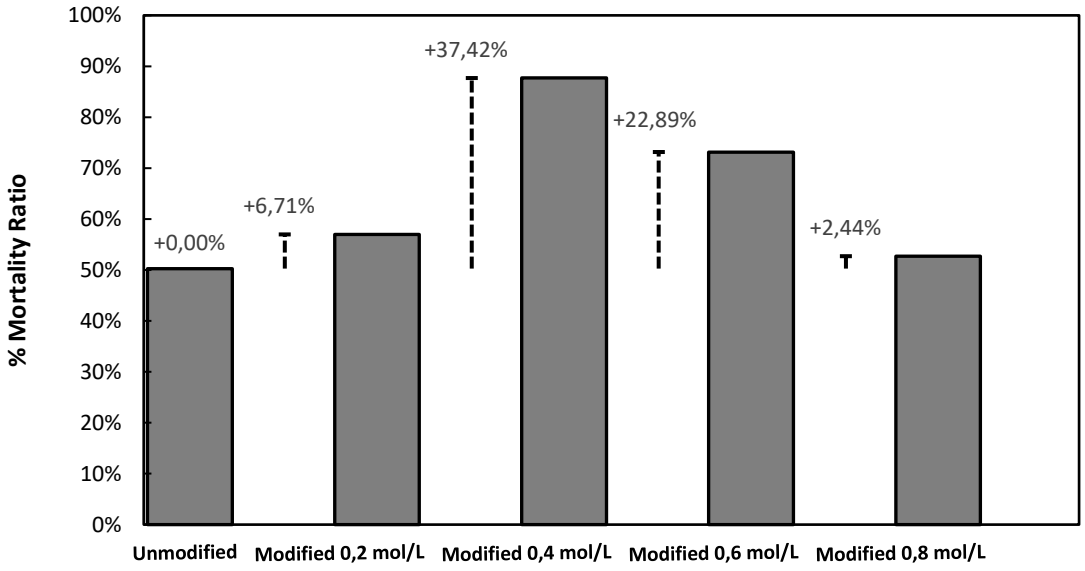


Figure 5-4: Adhesions test results for unmodified and modified membranes against S. Aureus

The membranes $M_{0.2mol/L}$, $M_{0.4mol/L}$, $M_{0.6mol/L}$, and $M_{0.8mol/L}$ (modified with 0.2mol/L, 0.4mol/L, and 0.6mol/L and 0.8mol/L concentration of ADMH) have an improved mortality ratio of 6.71%, 37.42%, 22.89% and 2.44%.

Compared to E. coli, the mortality ratio of the modified membranes is significantly lower against S. aureus. Mushtaq et al., (2021) reported a difference in the nature of the bacteria. Due to electrostatic interactions, gram-negative bacteria such as E. coli are repelled by the negatively charged surface of modified membranes. Moreover, it is observed that the membrane $M_{0.4mol/L}$ (modified with 0.4mol/L concentration of ADMH) has the highest improvement of 37.42% and appears to be the optimum modified membrane against E. coli. The success of the graft polymerization of ADMH is observed by the behaviour of the 0.4 mol/L membranes; However, the membrane samples 0.8 mol/L exhibits the lowest improvement. It could be due the impact of the time in the grafting, as discussed by Wei et al. (2010)

5.2 Membrane Salt Rejection and Permeability

The membrane performance was studied by assessing the salt rejection and flux of the membranes. The pure water flux of the modified membranes ($M_{0.2mol/L}$, $M_{0.4mol/L}$, $M_{0.6mol/L}$ and $M_{0.8mol/L}$) was used to determine the permeability of the grafted membranes at a transmembrane pressure of 15 bar. The results were compared to the unmodified membrane. M_0 and presented in Figure 5-5 below.

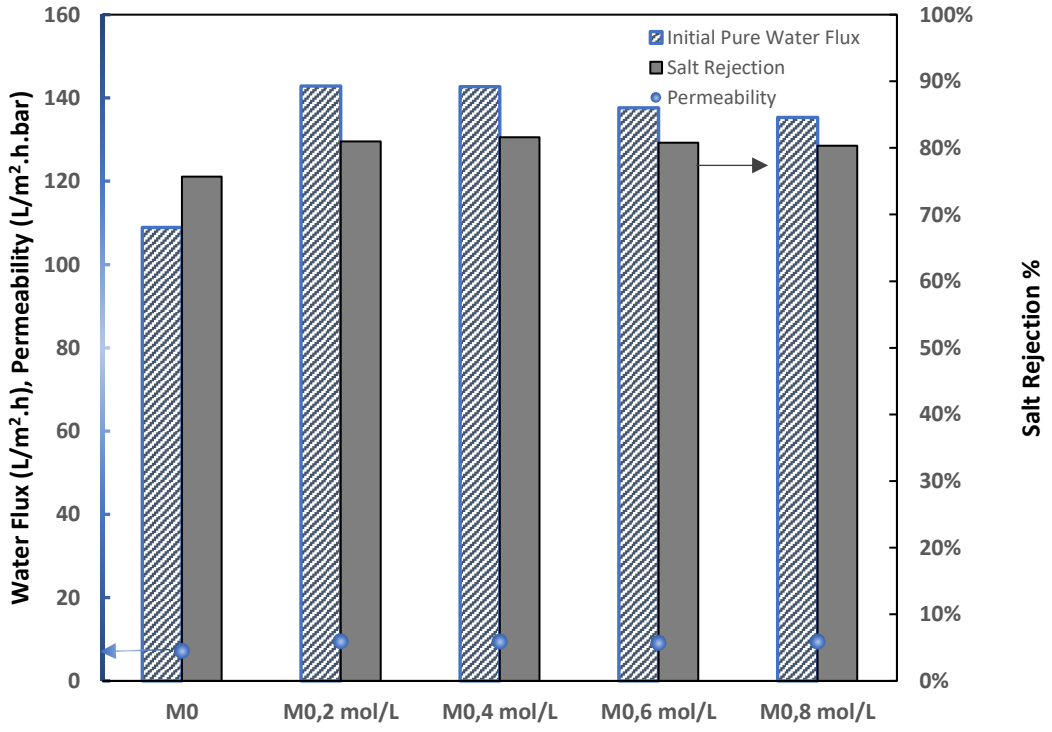


Figure 5- 5: Membrane Permeability, Water flux and Salt rejection of Unmodified and modified membranes

All experiments were conducted following the methodology and experimental conditions specified in section 3.4 and experimental data can be found in Appendix 2. The pure water flux of the membranes was found to be 108.89 $L/m^{-2}.h^{-1}$, 142.87 $L/m^{-2}.h^{-1}$, 142.67 $L/m^{-2}.h^{-1}$, 137.64 $L/m^{-2}.h^{-1}$, and 135.32 $L/m^{-2}.h^{-1}$ for the M_0, $M_{0.2mol/L}$, $M_{0.4mol/L}$, $M_{0.6mol/L}$ and $M_{0.8mol/L}$ respectively. The salt rejection for the unmodified membrane M_0 was 75.67%. According to J. Wang et al. (2015) increasing concentration of modifying agent molecules on the surface causes a decrease in the hydrogen bonds between carboxylic and amine groups of the polyamide layer of the membrane. This trend is similar the one recorded in this study. The pure water fluxes of modified membranes were higher than the pristine membrane but decreased as the concentration of ADMH increased. Wang et al., (2015) the graft polymerization of ADMH on the surface of the membrane provides an increased resistance to mass transfer across the membrane, causing the water flux changes.

Moreover, the salt rejection for the modified membranes was found to be 80.99%, 81.62%, 80.81% and 80.33% for the $M_{0.2mol/L}$, $M_{0.4mol/L}$, $M_{0.6mol/L}$ and $M_{0.8mol/L}$ membranes respectively. The permeability of the membranes after surface modification was increased significantly. It was reported that the membrane salt rejection would increase with the increase of the water flux and decrease with the increase of the salt permeation amount (Wang et al. 2015). It is due to preferred grafting site of ADMH monomer, which slightly destroys the inter chain hydrogen bonds of the aromatic polyamide chains (Wang et al., 2015).

Also, the membrane permeability of the modified membranes of 0.2mo/L, 0.4mol/L, 0.6mol/L and 0.8mol/L ADMH concentrations was 9.52 $L/m^{-2}.h^{-1}.bar$, 9.51$L/m^{-2}.h^{-1}$. bar, 9.18 $L/m^{-2}.h^{-1}.bar$ and 9.02 $L/m^{-2}.h^{-1}.bar$. A decrease of the permeability was observed with the increase of ADMH concentration; this is due to the added layer on the membrane surface after modification. Wei et al. (2010) reported that grafting time impacts the permeability by affecting the hydrophilicity of the membrane.

5.3 Membrane Biofouling Resistance Assessment

The modified and unmodified membrane samples were tested for biofouling resistance as described in section 3.4.6. The antifouling ability of ADMH-grafted membranes was evaluated in terms of flux, flux decline ratio (FDR), and flux recovery ratio (FRR). To test the FDR values of the membranes against E. coli and S. aureus, the feed solutions were fed into the reverse osmosis process according to the method explained in section 3.5 of this report. The fouled membranes then underwent a cleaning cycle, after which pure water flux was re-evaluated to determine the FRR values of the membranes. The results are in the following sections.

5.3.1 Biofouling Resistance Against E. coli

Figure 5-6 below presents the flux behaviour of the ADMH-grafted membranes during E. coli filtration.

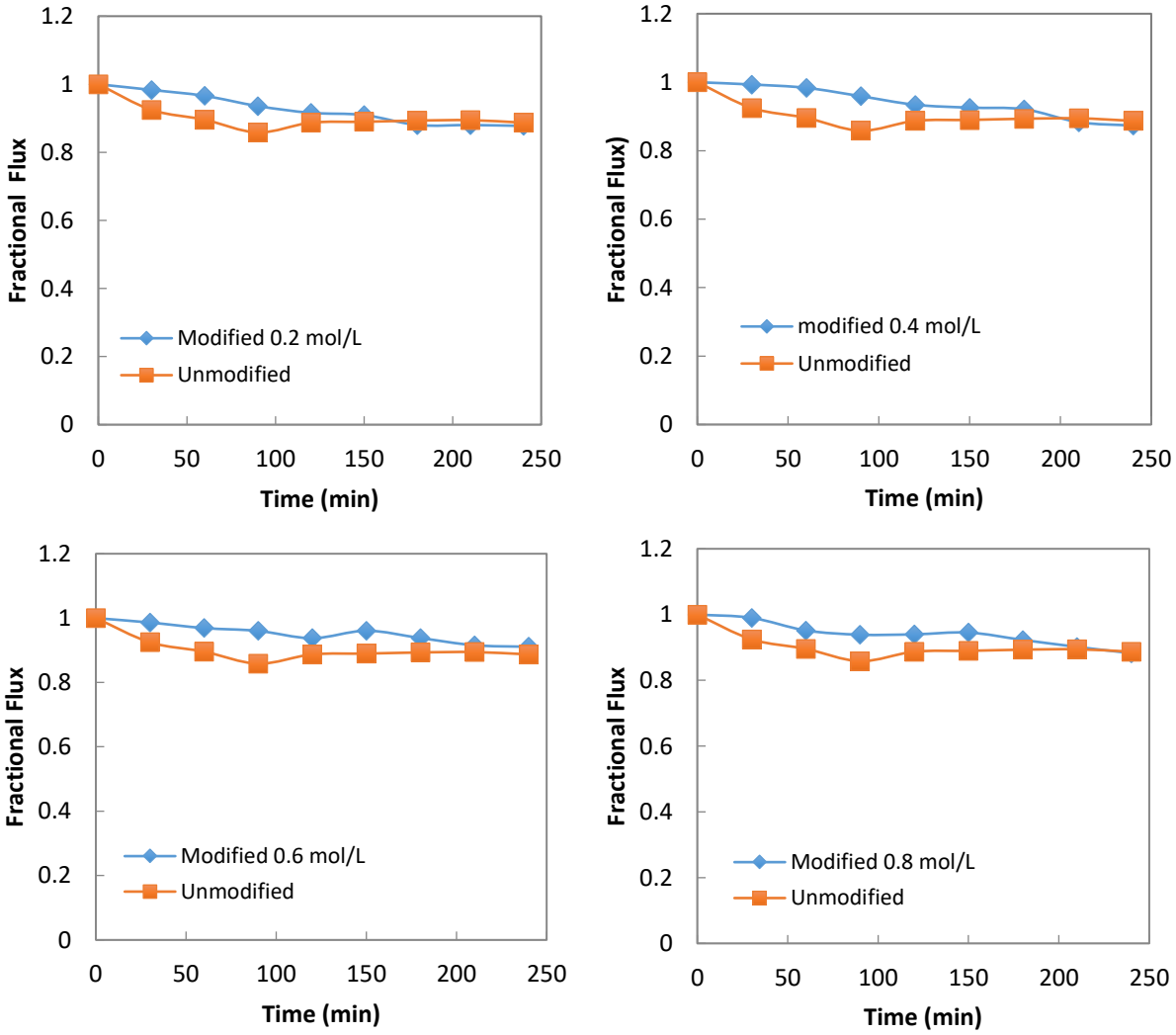


Figure 5-6: Flux of ADMH grafted membranes compared to the unmodified membrane during fouling experiment with E. coli solution

All experiments were conducted following the methodology and experimental conditions specified in section 3.5. The experimental data can be found in Appendix 2B. The values were normalised according to the feed solution's temperature changes. The normalized flux of all the membranes during E. coli biofouling experiments are presented as partial flux in Figure 5-6.

The overall trend of the fluxes of the modified membranes follows a similar trend as the unmodified membrane. The flux trend is decreasing over time, confirming the presence of microbial fouling, hence the flux decline. The fluxes of the modified membranes are higher than that of the unmodified membrane, due to the improvement of the membrane surface by graft polymerization of ADMH.

Zhang et al., (2013) reported that the anti-biofouling properties of ADMH are due to the firm bond created on the membrane surface, affecting the flux of the membranes. The maximum flux of 130.24 $L/m^{-2}.h^{-1}$ is achieved by the membrane grafted by the 0.2 mol/L ADMH concentration $M_{0.2mol/L}$ while the lowest flux of 107.02 $L/m^{-2}.h^{-1}$ was achieved by the unmodified membrane M_0 (Zhang et al., 2013). The presence of the flux decline reveals the presence of fouling. The FDR and FRR values are discussed in the following section. Figure 5-7 presents the FDR and FRR values of all membranes from E. coli filtration.

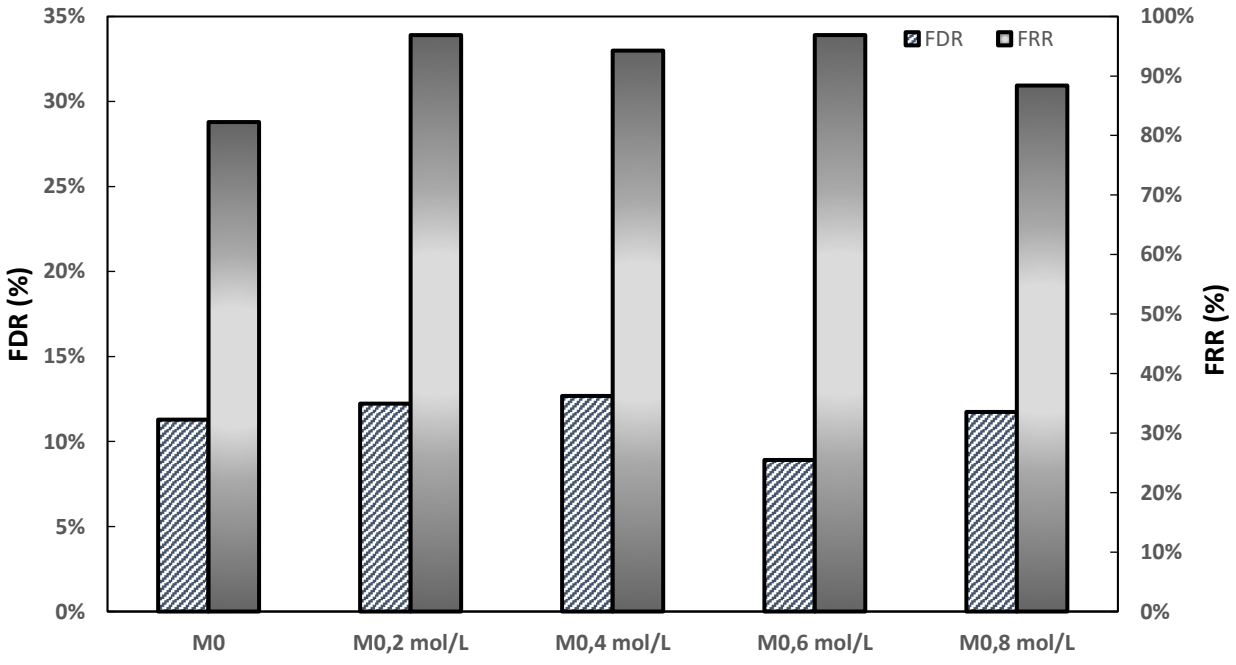


Figure 5-7: Flux decline ratio (FDR) and Flux recovery ratio (FRR) values of all membranes against E.coli

The antifouling ability of ADMH-grafted membranes was evaluated in terms of flux, flux decline ratio (FDR), and flux recovery ratio (FRR) (Kolangare et al., 2018). The higher the FDR value, the lower the biofouling resistance of the membrane; while a higher FRR percentage shows better anti. Also, the opposite trend is verifiable for the FRR value. Figure 5-7 shows that the unmodified membrane exhibits the highest FDR value of 36.24%, with an FRR value of 88.26%. Moreover, the lowest FDR value is shown by the $M_{0.6mol/L}$, with a value of 8.91%, and the highest FRR value of 96.88%. Zhang et al. (2013) reported that the fluxes of ADMH grafted membranes declined slightly due to the recovery of the inter-chain hydrogen bonds. It is observed from Figure 5-7 an increase in the FDR value from $M_{0.4mol/L}$ to $M_{0.6mol/}$ with the values of 81.12.24% and 12.68%. It is like the trend reported by Zhang et al. (2013).

5.3.2 Mathematical model relating ADMH concentration to the flux decline with time: Case of E. coli bacteria

The software Design expert was used to analyze the biofouling data of the membranes. The numerical factors are the different concentrations of ADMH, the modifying agent, and the time of the biofouling experiment.

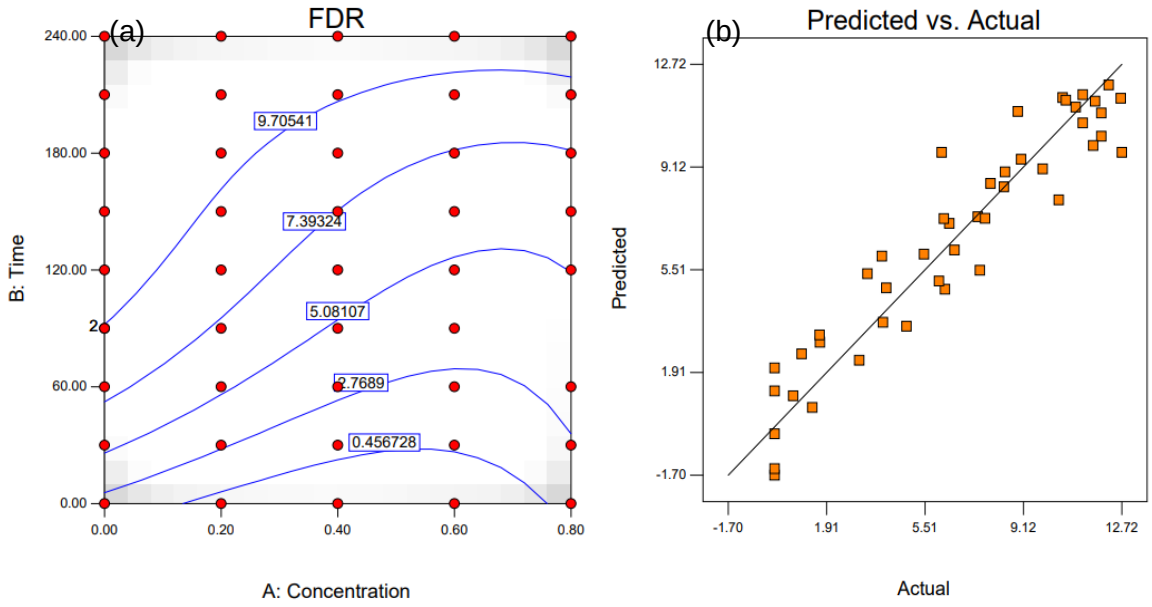


Figure 5-8: (a) Model graph membranes against biofouling (b) Predicted vs Actual of Biofouling data against E. coli

The response is the flux decline ratio (FDR) against E. coli of the membrane a different factor of time every 30 min and concentration. Graph (a) from Figure 5-8 above presents the model graph of the membranes in terms of FDR at different factor levels against E. coli biofouling.

In addition, Graph (b) from Figure 5-8 above presents the predicted values of the FDR plotted against those obtained after the experiment. It is noticed that the data points are gathered along the predicted line, representing that the experimental values are close to the expected values. Moreover, the

disparities noticed are due to the FDR behaviour discussed in section 5.3.1. The model suggested for the membrane is presented by Equation 5-1 below:

Equation 5-1: Final Equation in Terms of Coded Factors

$$FDR = +6.20 - 3.86A + 4.88B + 1.69A^2 - 1.29B^2 + 0.14AB + 1.09A^3 + 1.73B^3 - 1.67A^2B + 2.51AB^2$$

With:

Factor	Coefficient Estimate
Intercept:	6.20
A-Concentration:	-3.86
B-Time:	4.88
A^2:	1.69
B^2:	-1.29
AB:	0.14
A^3:	1.09
B^3:	1.73
A^2B:	-1.67
AB^2:	2.51

5.3.3 Biofouling Resistance Against S. aureus

Figure 5-9 presents the flux behaviour of the ADMH-grafted membranes during S. aureus filtration.

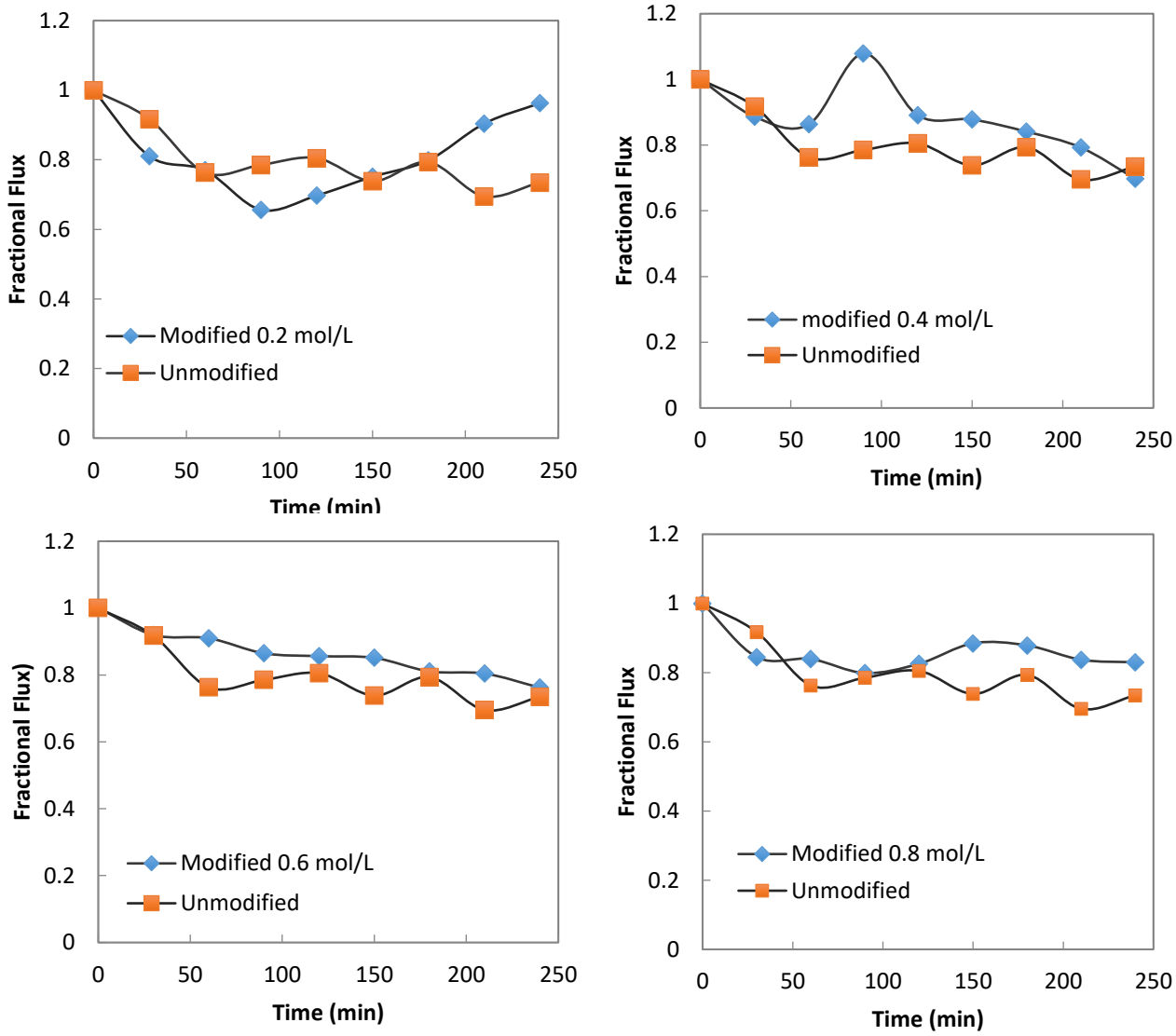


Figure 5- 9: Flux of ADMH grafted membranes compared to the unmodified membrane during fouling experimental run S. aureus

All experiments were conducted following the methodology and experimental conditions specified in section 3.5. The experimental data can also be found in Appendix 2B of this report. The values were also normalised for more accuracy, according to the changes noticed in the temperature of the feed solution. The membranes' normalised flux during S. aureus biofouling experiments is presented in Figure 5-9.

The flux is decreasing over time confirming the presence of microbial fouling by S. aureus hence causing flux decline. The overall trend of the fluxes of the modified membranes follows a similar trend as the unmodified membrane. However, it is observed that the fluxes of the modified membranes are

slightly lower than that of the unmodified membrane with a value of 33.58%, and the highest flux is 54.47% for the unmodified membrane.

Zhang et al. (2013) reported that grafted membranes have a lower flux than the raw membrane after membrane surface modification. This observation could be due to the polymerization of the aromatic layer of the grafted membrane getting more compact due to heat treatment, which is responsible for the increase in water resistance. The presence of the flux decline for all the membranes reveals the presence of fouling. In addition, the behaviour of the S. aureus bacteria being positively charged in the outer surface (Gram-positive bacteria) contributes to the impact on the flux of the negatively charged membrane (Mushtaq et al., 2021). The FDR and FRR values are discussed in the following section. Figures 5-10 below present the FDR and FRR values of all membranes from S. Aureus filtration.

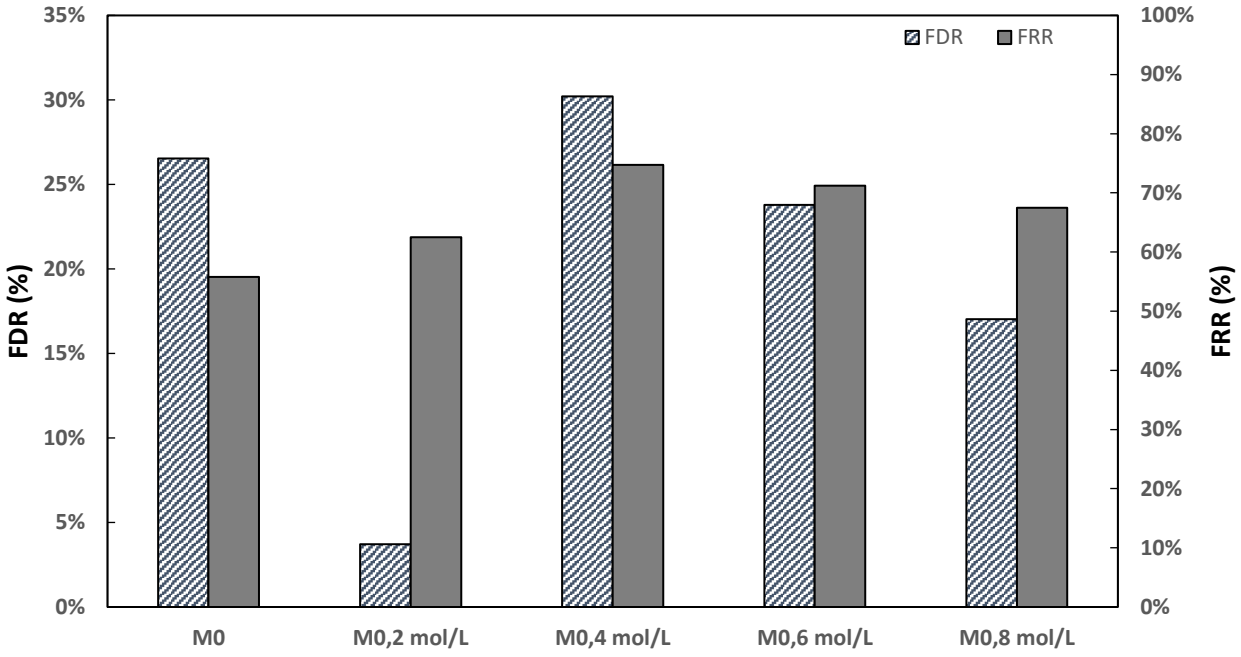


Figure 5- 10: Flux decline ratio (FDR) and Flux recovery ratio (FRR) values of all membranes against S. aureus

Figures 5-9 show that $M_{0.2mol/L}$ and $M_{0.6mol/L}$ exhibits the lowest FDR of values of 3.72% and 17.03% respectively and the FRR values of 48.39% and 69.23%. Indeed, the $M_{0.8mol/L}$ and $M_{0.6mol/L}$ membranes underwent grafting with 0.8 mol/L and 0.6 mol/L ADMH concentrations, the highest concentration used in the modification experiment. Zhang et al. (2013) reported that the anti-biofouling properties of ADMH are due to the firm bond created on the membrane surface, affecting the membranes' flux.

5.3.4 Mathematical model relating ADMH concentration to the flux decline time: Case of S. aureus bacteria

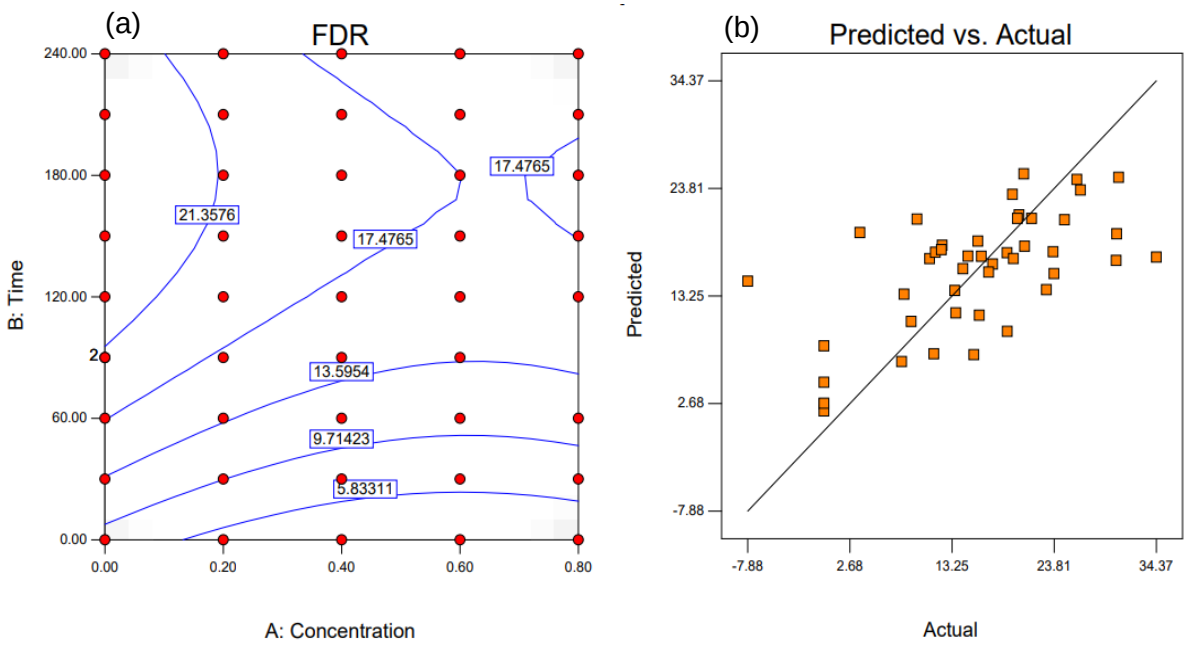


Figure 5- 11: a) Model graph membranes against biofouling (b) Predicted vs Actual of Biofouling data against S. aureus

software Design expert was used to analyze the biofouling experiments data of the membranes. The numerical factors are the different concentrations of ADMH, the modifying agent, and the time of the biofouling experiment. The response is the flux decline ratio (FDR) against S. aureus of the membrane. Graph (a) from Figure 5-8 above, presents the model graph of the membranes in terms of FDR at different concentration levels of the modifying agent.

Moreover, graph (b) from Figure 5-11 above presents the predicted values of the FDR plotted against those obtained after the experiment. It is noticed that the data points are more or less gathered along the predicted line, representing that the experimental values are relatively close to the predicted values. Moreover, the disparities noticed are due to the FDR behaviour as discussed in section 5.3.3.

The model suggested for the membrane is presented by Equation 5-2 below:

Equation 5-2: Final Equation in Terms of Coded Factors

$$FDR = +16.91 - 3.42A + 7.05B + 2.89A^2 - 7.22B^2 - 0.61AB$$

With:

Factor	Coefficient Estimate
Intercept:	16.91
A-Concentration:	-3.42
B-Time:	7.05
A^2:	2.89
B^2:	-7.22
AB:	-0.61

5.4 Inorganic and organic fouling resistance assessment with the best performing modified membrane and the pristine membrane.

From the previous results presented, the overall best-performing modified membrane was further investigated against organic and inorganic fouling. Table 5.1 below shows a table summary of the performance of membranes in the biofouling experimental runs.

Table 5-1: All membranes summarize performance table.

	Salt Rejection	Permeability ($L/m^2.h.$ bar)	Mortality Ratio		FDR		FRR	
			E. coli	S. aureus	E. coli	S. aureus	E. coli	S. aureus
M_0	76%	7,26	36,24%	50,27%	11,29%	26,53%	82,26%	48,39%
$M_{0,2mol/L}$	81%	9,52	81,48%	56,98%	12,24%	3,72%	96,88%	69,23%
$M_{0,4mol/L}$	82%	9,51	95,17%	87,69%	12,68%	30,21%	94,27%	59,70%
$M_{0,6mol/L}$	81%	9,18	84,73%	73,16%	8,91%	23,79%	96,88%	70,15%
$M_{0,8mol/L}$	80%	9,51	70%	52,71%	11,74%	17,03%	88,40%	65,67%

The best performing membranes was the $M_{0.4mol/L}$ ADMH grafted membrane as shown in Table 5-1. The membrane was then tested in reverse osmosis lab scale system according to the method specified in section 3.5.7 to assess its resistance to inorganic and organic fouling. The results are presented in the following sections.

5.4.1 Organic Fouling Resistance

An organic solution was prepared using humic acid as foulant model to assess membranes resistance to organic fouling. Figures 5-12 present the flux behaviour of ADMH-grafted and unmodified membranes during the experimental run with the organic solution.

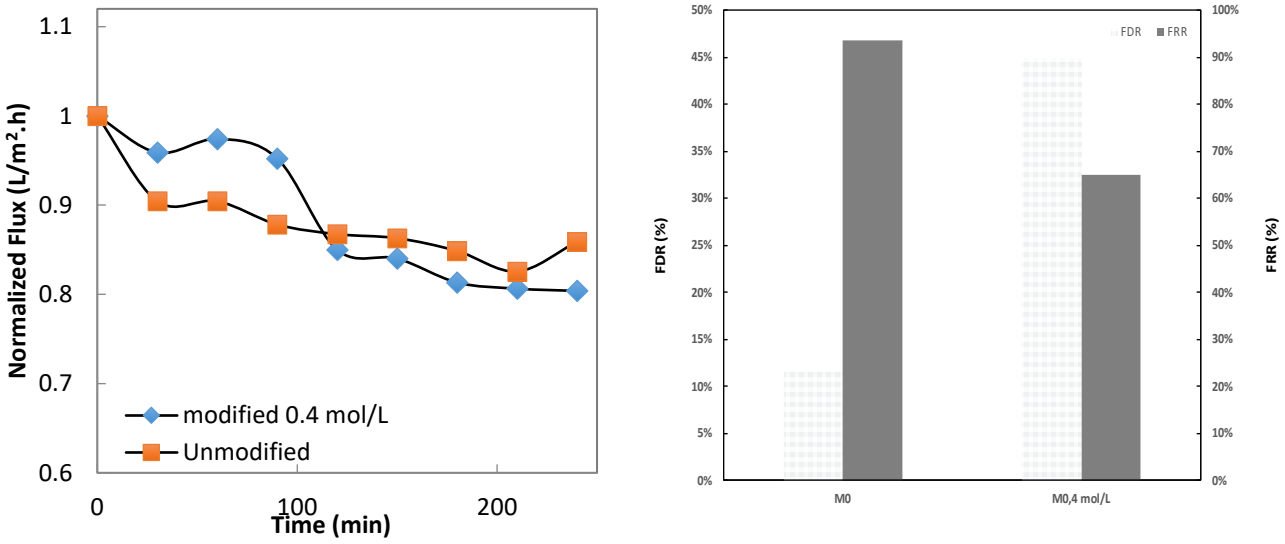


Figure 5-12: Membranes antifouling properties during organic filtration.

The overall trend of the fluxes of the modified membrane follows a similar trend to the trend of the unmodified membrane. The FDR values are 11.66% and 44.87% for the unmodified and modified membranes, respectively. The FRR values are 93.47% and 64.89 % for the unmodified and modified membranes, respectively. The modified membrane has a lower flux than the unmodified membrane. It follows the trend reported by Zhang et al. (2013). The flux of the membranes is affected by the anti-biofouling properties of ADMH due to the firm bond created on the surface of the membrane.

5.4.2 Inorganic Fouling Resistance

Figure 5-13 below present the flux behaviour of the ADMH-grafted membranes during inorganic component filtration.

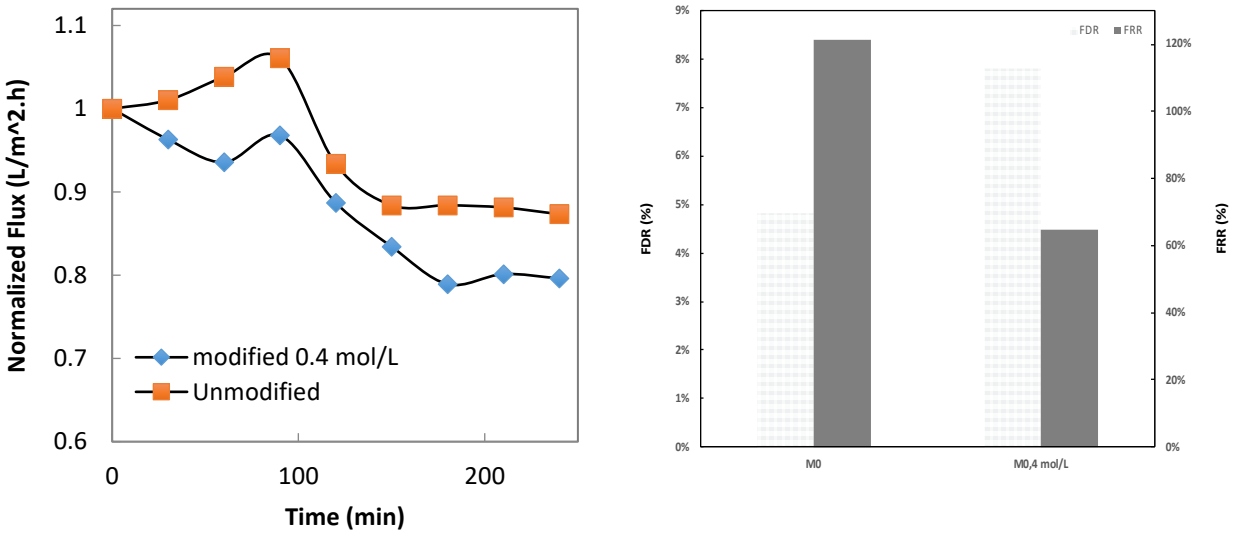


Figure 5-13: Membranes antifouling properties during inorganic filtration.

The FDR values are 4.82% and 7.80% for the unmodified and modified membranes, respectively. The highest FRR value is attributed to the unmodified membrane. The modified membrane has a lower flux than the unmodified membrane. This observation also follows the trend reported by Zhang et al. (2013) that the flux of the membranes is affected by the anti-biofouling properties of ADMH due to the firm bond created on the surface of the membrane.

CHAPTER 6

CONCLUSION AND RECOMMENDATIONS

6. Conclusion and Recommendations

6.1 Conclusion

Fouling stands as a significant challenge to the treatment processes of wastewater. It causes a decrease in membrane performance and hinders wastewater treatment processes. The grafting of a thin film reverse osmosis membrane using ADMH was investigated in this study.

The modifying agent was successfully synthesized following the Gabriel's reaction with a maximum mass yield of 73.2%. After synthesis the agent was characterized by FTIR which spectra revealed characteristics peaks at 3090 cm^{-1} and 1772 cm^{-1} which showed the strong stretching vibration of the = CH bond and a stretching vibrations of the C = O bond in ADMH respectively.The ADMH was then used to improve the resistance of the membrane to microbes. Different concentrations of 0.2mol/L, 0.4mol/L, 0.6mol/L and 0.8mol/L were used to enhance the membrane's antimicrobial properties by graft polymerization on the surface of the membrane.

The ADMH was found to be successfully grafted on the membrane by SEM, FTIR and NMR characterization methods. The SEM images revealed a change on the surface of the membrane with irregular characteristics on the surface. In contrast, the cross-sectional images revealed the formation of a layer on the top layer of the membrane. The FTIR demonstrated an increase in the peaks and the appearance of new picks at 3107 cm^{-1}, a C=O bond in the ADMH modifying agent. The NMR revealed the bands present in ADMH with ppm concentration increase at 130.4 pp, which is the bond (=$CHCH_2$) present in ADMH.

The membrane underwent antimicrobial assessment with consecutive E. coli and S. aureus adhesion test. Against E. coli the membranes $M_{0.2mol/L}$ and $M_{0.4mol/L}$ (modified with 0.2mol/L and 0.4mol/L concentration of ADMH) revealed an improved mortality ratio of 45.23% and 33.76% respectively. Meanwhile, the membranes $M_{0.6mol/L}$ and $M_{0.8mol/L}$ (modified with 0.6mol/L and 0.8mol/L concentration of ADMH) have shown an improved mortality ratio of 48.48% and 58.93% respectively. Against S. aureus, the membranes $M_{0.2mol/L}$, $M_{0.4mol/L}$, $M_{0.6mol/L}$ and $M_{0.8mol/L}$ (modified with 0.2mol/L, 0.4mol/L, and 0.6mol/L and 0.8mol/L concentration of ADMH) have demonstrated an improved mortality ratio of 6.71%, 37.42%, 22.89% and 2.44%. This antimicrobial test demonstrated the improved antimicrobial properties after the grafting of ADMH on the membrane surface. Also, the membrane's biofouling resistance was further tested using a reverse osmosis a membrane cell apparatus with synthetic feed made of microbial solution. It was found that that $M_{0.2mol/L}$ and $M_{0.6mol/L}$ exhibited the lowest FDR of values of 3.72% against S. aureus and 8.91% against E. coli respectively and their FRR values of 69.23% and 96.88%. The $M_{0.4mol/L}$ shows FRR value of 94.27% against E. coli bacteria and 59.70%

against S aureus. The membranes were then further investigated in organic and inorganic fouling filtration tests. Also, a model for the treated membrane against Gram negative bacteria E. coli and gram-positive S. aureus was suggested using Design Expert, showing the behaviour of the FDR response of the membrane at various numerical factors of concentrations and biofouling time. Furthermore, results revealed that the modification enhanced membrane resistance to biofouling while approximately maintaining its resistance to organic and inorganic fouling. The salt rejection of the modified membranes increased slightly as compared to the unmodified membrane. The membrane permeability of modified membranes was higher than the membrane, however, it was found to decrease with an increase in ADMH concentration.

Overall, the study showed the behaviour of the ADMH against gram positive and gram-negative bacteria with short contact time and its application in fouling mitigation of reverse osmosis membranes. The study reveals the impact of ADMH for the improvement of membranes antimicrobial properties. This is a contribution to investigation of treatment of municipal wastewater by application of membrane technology, as ADMH has been recently and widely used as a novel antimicrobial agent.

6.2 Recommendations

The following recommendations are suggested for further studies of membrane surface modification method:

- The investigation of the impact of grafting time and temperature on the membrane properties
- Characterization of the modified membranes by contact angle to investigate the impact of the modification of the hydrophilicity of the membrane which stands as an important characteristic in membrane technology.
- The employment of the modified membranes with real feed municipal wastewater application to further investigate the efficiency of ADMH.

LIST OF REFERENCES

. (2021). Antifouling and Flux Enhancement of Reverse Osmosis Membrane by Grafting Poly (3-Sulfopropyl Methacrylate) Brushes. *Membranes*, *11*. https://doi.org/10.3390/membranes11030213

Ankoliya, D., Mehta, B., & Raval, H. (2018a). Advances in surface modification techniques of reverse osmosis membrane over the years. *Separation Science and Technology*, *00*(00), 1–18. https://doi.org/10.1080/01496395.2018.1483404

Barello, M., Manca, D., Patel, R., & Mujtaba, I. M. (2015). Operation and modeling of RO desalination process in batch mode. *Computers and Chemical Engineering*, *83*, 139–156. https://doi.org/10.1016/j.compchemeng.2015.05.022

Belfer, S., Purinson, Y., Fainshtein, R., Radchenko, Y., & Kedem, O. (1998). *Surface modification of commercial composite polyamide reverse osmosis membranes*. *139*, 175–181.

Benavente, L., Coetsier, C., Venault, A., Chang, Y., Causserand, C., Bacchin, P., & Aimar, P. (2016). FTIR mapping as a simple and powerful approach to study membrane coating and fouling. *Journal of Membrane Science*, *520*(July), 477–489. https://doi.org/10.1016/j.memsci.2016.07.061

Chapman, S., Leslie, G., Law, I., & Solutions, I. B. L. (n.d.). *Membrane Bioreactors (MBR) for Municipal Wastewater Treatment – An Australian Perspective*.

Choudhury, R. R., Gohil, J. M., Mohanty, S., & Nayak, S. K. (2018). *osmosis and nano fi ltration membranes †*. 313–333. https://doi.org/10.1039/c7ta08627j

Cihanoğlu, A., & Altinkaya, S. A. (2020). A facile route to the preparation of antibacterial polysulfone-sulfonated polyethersulfone ultrafiltration membranes using a cationic surfactant cetyltrimethylammonium bromide. *Journal of Membrane Science*, *594*(May 2019), 117438. https://doi.org/10.1016/j.memsci.2019.117438

Daramola, M. O., Aransiola, E. F., & Ojumu, T. V. (2012). *Potential Applications of Zeolite Membranes in Reaction Coupling Separation Processes*. *September 2015*. https://doi.org/10.3390/ma5112101

Deowan, S. A., Galiano, F., Johnson, D., Altinkaya, S. A., Gabriele, B., Hilal, N., Drioli, E., Figoli, A., Ahmed, S., Galiano, F., Hoinkis, J., Johnson, D., Altinkaya, S. A., Gabriele, B., & Hilal, N. (2016). Author ' s Accepted Manuscript. *Journal of Membrane Science*. https://doi.org/10.1016/j.memsci.2016.03.002

Department of Water Affairs and Forestry (1996), *South African Water Quality Guidelines Volume 1, Domesctic Use*, Available at: https://www.dws.gov.za/Groundwater/documents/Pol_saWQguideFRESHDomesticusevol1.pdf (Accessed:04 April 2022)

Elsevier, B. V, Alike, C. C. A., Published, A., & Terms, D. (2019). *How RO membrane permeability and other performance factors affect process cost and energy use: A review*. 0–30.

Ezugbe, E. O., & Rathilal, S. (2020). Membrane technologies in wastewater treatment: A review. In *Membranes* (Vol. 10, Issue 5). MDPI AG. https://doi.org/10.3390/membranes10050089

Federation, W. E. (n.d.). *Membrane Systems for Wastewater Treatment*.

Field, R. (2010). *Fundamentals of Fouling*. *4*.

Fiksdal, L., & Leiknes, T. (2006). *The effect of coagulation with MF / UF membrane filtration for the removal of virus in drinking water*. *279*, 364–371. https://doi.org/10.1016/j.memsci.2005.12.023

García-pacheco, R., Landaburu-aguirre, J., & Molina, S
Desalination, *434*(August 2017), 60–80. https://doi.org/10.1016/j.desal.2017.07.023

Ibrar, I.,Osamah, N., Adel, S., Ali, M., Alaa, . (2015). Transformation of end-of-life RO membranes into NF and UF membranes : Evaluation of membrane performance. *Journal of Membrane Science*, *495*, 305–315. https://doi.org/10.1016/j.memsci.2015.08.025

Goh, P. S., & Ismail, A. F. (2018). A review on inorganic membranes for desalination and wastewater treatment. A., Adnan, A., A., Ali, A. (2019) 'A Review of Fouling Mechanisms , Control Strategies and Real-Time Fouling Monitoring Techniques', 11(4). https://doi.org/10.3390/w11040695

Jiang, S., Li, Y., & Ladewig, B. P. (2017). Science of the Total Environment A review of reverse osmosis membrane fouling and control strategies. *Science of the Total Environment*, *595*, 567–583. https://doi.org/10.1016/j.scitotenv.2017.03.235

Kabir, S. M. F., Sikdar, P. P., Rahman, B. H. M. A., & Ali, B. A. (2018). Cellulose - based hydrogel materials : chemistry , properties and their prospective applications. *Progress in Biomaterials*, *0123456789*. https://doi.org/10.1007/s40204-018-0095-0

Karkhanechi, H., Takagi, R., & Matsuyama, H. (2014). Biofouling resistance of reverse osmosis membrane modified with polydopamine. *Desalination*, *336*(1), 87–96. https://doi.org/10.1016/j.desal.2013.12.033

Kasongo, G., Steenberg, C., Morris, B., Kapenda, G., Jacobs, N., and Aziz, M. (2019). Surface grafting of polyvinyl alcohol (PVA) cross-linked with glutaraldehyde (GA) to improve resistance to fouling of aromatic polyamide thin-film composite reverse osmosis membranes using municipal membrane bioreactor effluent. *Water Pract. Technol*., 14(3), 614–624.

Kolangare, I., Isloor, A., Abdul Karim, Z., Kulal, A., Ismail, A., . I., & Asiri, A. M. (2018). Antibiofouling hollow-fiber membranes for dye rejection by embedding chitosan and silver-loaded chitosan nanoparticles. *Environmental Chemistry Letters*, *17*. https://doi.org/10.1007/s10311-018-0799-3

Koros, W. J., & Fleming, G. K. (1993). *Membrane-based gas separation*. *83*.

Ladewig, B., & Al-Shaeli, M. N. Z. (2017). *Fundamentals of Membrane Bioreactors*. *November 2020*, 13–38. https://doi.org/10.1007/978-981-10-2014-8

Lau, W. J., Ismail, A. F., & Firdaus, S. (2013). Car wash industry in Malaysia : Treatment of car wash effluent using ultrafiltration and nanofiltration membranes. *SEPARATION AND PURIFICATION TECHNOLOGY*, *104*, 26–31. https://doi.org/10.1016/j.seppur.2012.11.012

Leckie, J. O. (2007). *Membrane Independent Limiting Flux for RO and NF Membranes Fouled by Humic Acid*. *41*(13), 4767–4773.

Lee, X. J., Show, P. L., Katsuda, T., Chen, W. H., & Chang, J. S. (2018). Surface grafting techniques on the improvement of membrane bioreactor: State-of-the-art advances. *Bioresource Technology*, *269*(August), 489–502. https://doi.org/10.1016/j.biortech.2018.08.090

Li, Y., & Tung, K. (2008). *The effect of curvature of a spacer-filled channel on fluid flow in spiral-wound*

membrane modules. *319*, 286–297. https://doi.org/10.1016/j.memsci.2008.03.069

Liu, X., Li, L., Chen, Z., Duan, X., Yu, Y., & Sun, L. (2020). Curing behavior, thermal, and mechanical properties of N,N′-(4,4′-diphenylmethane)bismaleimide/2,2′-diallylbisphenol A/3-allyl-5,5-dimethylhydantoin resin system. *High Performance Polymers*, *32*(6), 631–644. https://doi.org/10.1177/0954008319894034

Maddah, H., & Chogle, A. (2016). Biofouling in reverse osmosis : phenomena , monitoring , controlling and remediation. *Applied Water Science*. https://doi.org/10.1007/s13201-016-0493-1

Manouchehri, M., & Kargari, A. (2017). Water recovery from laundry wastewater by the cross fl ow micro fi ltration process : A strategy for water recycling in residential buildings. *Journal of Cleaner Production*, *168*, 227–238. https://doi.org/10.1016/j.jclepro.2017.08.211

Matin, A., Khan, Z., Zaidi, S. M. J., & Boyce, M. C. (2011). Biofouling in reverse osmosis membranes for seawater desalination : Phenomena and prevention. *DES*, *281*, 1–16. https://doi.org/10.1016/j.desal.2011.06.063

Mayyahi, A. Al. (2018). *TiO 2 Polyamide Thin Film Nanocomposite Reverses Osmosis Membrane for Water Desalination*. https://doi.org/10.3390/membranes8030066

Melin, T., Jefferson, B., Bixio, D., Thoeye, C., Wilde, W. De, & Koning, J. De. (2006). *Membrane bioreactor technology for wastewater treatment and reuse*. *187*(February 2005), 271–282. https://doi.org/10.1016/j.desal.2005.04.086

Misdan, N., Ismail, A. F., & Hilal, N. (2015). Recent advances in the development of (bio) fouling resistant thin fi lm composite membranes for desalination ☆. *DES*, 4–10. https://doi.org/10.1016/j.desal.2015.06.001

Mohammadi, T., Kazemimoghadam, M., & Saadabadi, M. (2003). *Modeling of membrane fouling and flux decline in reverse osmosis during separation of oil in water emulsions*. *157*(May), 369–375.

Mushtaq, R., Abbas M, Mushtaq, S. (2021). Antifouling and Flux Enhancement of Reverse Osmosis Membrane by Grafting Poly (3-Sulfopropyl Methacrylate) Brushes. *Membranes*, *11*. https://doi.org/10.3390/membranes11030213

Nady, N., Franssen, M. C. R., Zuilhof, H., Mohy, M. S., Boom, R., & Schroën, K. (2011). *Modi fi cation methods for poly (arylsulfone) membranes : A mini - review focusing on surface modi fi cation*. *275*, 1–9. https://doi.org/10.1016/j.desal.2011.03.010

Naghizadeh, A., Mahvi, A., & Alimohammadi, M. (2011). *Application of MBR Technology in Municipal Wastewater Treatment Application of MBR Technology in Municipal Wastewater Treatment*. *May 2014*, 2–10. https://doi.org/10.1007/s13369-010-0007-7

Nguyen, T., Roddick, F. A., & Fan, L. (2012). *Biofouling of Water Treatment Membranes: A Review of the Underlying Causes, Monitoring Techniques and Control Measures*. *July 2014*. https://doi.org/10.3390/membranes2040804

Odjadjare, E. E. O., & Okoh, A. I. (2010). Physicochemical quality of an urban municipal wastewater effluent and its impact on the receiving environment. *Environmental Monitoring and Assessment*, *170*(1–4), 383–394. https://doi.org/10.1007/s10661-009-1240-y

Osu, Y., & Okoh, A. (2017). Human enteric bacteria and viruses in five wastewater treatment plants in the Eastern Cape, South Africa. *Journal of Infection and Public Health*, *10*. https://doi.org/10.1016/j.jiph.2016.11.012

Review, A. (2020). *Membrane Technologies in Wastewater Treatment :*

Salvesen, I., & Vadstein, O. (2000). *Evaluation of plate count methods for determination of maximum specific growth rate in mixed microbial communities , and its possible application for diversity assessment*. 442–448.

Silhavy, T. J., Kahne, D., Walker, S., Kumar, K., Mella-herrera, R. A., Golden, J. W., Thanbichler, M., Kaiser, D., Robinson, M., Kroos, L., Burton, B., & Dubnau, D. (2014). *The Bacterial Cell Envelope*. https://doi.org/10.1101/cshperspect.a000414

Sangita, A., Soumendra, D., Srimoyee, S., (2022) Challenges in management of domestic wastewater for sustainable development. *Current Direction in water scarcity Research*, 6, 531-552. https://doi.org/10.1016/B978-0-323-91838-1.00019-1

Silva, A. L. C. F. M. V. (2011). *AFM analysis of the surface of nanoporous membranes : application to the nanofiltration of potassium clavulanate*. 3356–3369. https://doi.org/10.1007/s10853-010-5224-7

Stevia Technology, *Membrane Based Steviol Glycoside Purification Technology*, Viewed Oct 2020 , < https://www.steviashantanu.com/stevia-membrane-based-extraction>

Su, Y., Huang, C., Pan, J. R., Hsieh, W., & Chu, M. (2012). *Fouling Mitigation by TiO 2 Composite Membrane in Membrane Bioreactors*. *March*, 344–350. https://doi.org/10.1061/(ASCE)EE.1943-7870.0000419.

Sun, Y., & Sun, G. (2002). *Synthesis, Characterization, and Antibacterial Activities of Novel*. 8909–8912.

Tamime, R., Wyart, Y., Siozade, L., Baudin, I., Deumie, C., Glucina, K., & Moulin, P. (2011). *Membrane Characterization by Microscopic and Scattering Methods: Multiscale Structure*. 91–97. https://doi.org/10.3390/membranes1020091

Tian, J., Ernst, M., Cui, F., & Jekel, M. (2012). Correlations of relevant membrane foulants with UF membrane fouling in different waters. *Water Research*, *47*(3), 1218–1228. https://doi.org/10.1016/j.watres.2012.11.043

Turner, R., Goldrick, S., Joseph, A., Mollet, M., Turner, R., & Gruber, D. (2017). Predicting Performance of Constant Flow Depth Filtration using Constant Pressure Filtration Data Predicting performance of constant fl ow depth fi ltration using constant pressure fi ltration data. *Journal of Membrane Science*, *531*(March), 138–147. https://doi.org/10.1016/j.memsci.2017.03.002

Tuttle, A., Trahan, N., & Son, M. (2021). Growth and Maintenance of Escherichia coli Laboratory Strains. *Current Protocols*, *1*. https://doi.org/10.1002/cpz1.20

Vatanpour, V., & Zoqi, N. (2017). Surface modification of commercial seawater reverse osmosis membranes by grafting of hydrophilic monomer blended with carboxylated multiwalled carbon nanotubes. *Applied Surface Science*, *396*, 1478–1489. https://doi.org/10.1016/j.apsusc.2016.11.195

Wang, J., Wang, Z., Wang, J., & Wang, S. (2015). Improving the water flux and bio-fouling resistance of reverse osmosis (RO) membrane through surface modification by zwitterionic polymer. *Journal of Membrane Science*, *493*, 188–199. https://doi.org/10.1016/j.memsci.2015.06.036

Wei, X., Wang, Z., Zhang, Z., Wang, J., & Wang, S. (2010). Surface modification of commercial aromatic polyamide reverse osmosis membranes by graft polymerization of 3-allyl-5 , 5-

dimethylhydantoin. *Journal of Membrane Science*, *351*(1–2), 222–233. https://doi.org/10.1016/j.memsci.2010.01.054

Western Cape Provincial Gazette 7227 (2013), *Wastewater and Industrial Effffluent By-Law (2022), Available at: https://openbylaws.org.za/akn/za-cpt/act/by-law/2013/wastewater-industrial-effluent/eng@2014-02-07 (Accessed: 05 June 2022)*

Xiao, J., Xie, Y., & Cao, H. (2014). Chemosphere Organic pollutants removal in wastewater by heterogeneous photocatalytic ozonation. *CHEMOSPHERE*. https://doi.org/10.1016/j.chemosphere.2014.10.072

Yang, Z., Zhou, Y., Feng, Z., Rui, X., Zhang, T., & Zhang, Z. (2019). *A Review on Reverse Osmosis and Nanofiltration Membranes for Water Purification*. 1–22.

Yorgun, M. S., Balcioglu, I. A., & Saygin, O. (2008). *Performance comparison of ultrafiltration , nanofiltration and reverse osmosis on whey treatment*. *229*, 204–216. https://doi.org/10.1016/j.desal.2007.09.008

Zainol Abidin, M. N., Mahmoud Nasef, M., & Matsuura, T. (2022). Fouling Prevention in Polymeric Membranes by Radiation Induced Graft Copolymerization. *Polymers*, *14*(1). https://doi.org/10.3390/polym14010197

Zhang, Z., Wang, Z., Wang, J., & Wang, S. (2013). Enhancing chlorine resistances and anti-biofouling properties of commercial aromatic polyamide reverse osmosis membranes by grafting 3-allyl-5 , 5-dimethylhydantoin and N , N ′ -Methylenebis (acrylamide). *DES*, *309*, 187–196. https://doi.org/10.1016/j.desal.2012.10.019

Zhao, C., Xue, J., Ran, F., & Sun, S. (2013). Modification of polyethersulfone membranes – A review of methods. *Progress in Materials Science*, *58*, 76–150. https://doi.org/10.1016/j.pmatsci.2012.07.002

Zhou, Y., Yu, S., Gao, C., & Feng, X. (2009). *Surface modification of thin film composite polyamide membranes by electrostatic self deposition of polycations for improved fouling resistance*. *66*, 287–294. https://doi.org/10.1016/j.seppur.2008.12.021

Zhu, A., Christofides, P. D., & Cohen, Y. (2009). *On RO membrane and energy costs and associated incentives for future enhancements of membrane permeability*. *344*, 1–5. https://doi.org/10.1016/j.memsci.2009.08.006

Zipf, M. S., Pinheiro, I. G., & Conegero, M. G. (2016). Simplified greywater treatment systems: Slow filters of sand and slate waste followed by granular activated carbon. *Journal of Environmental Management*, *176*, 119–127. https://doi.org/10.1016/j.jenvman.2016.03.035

APPENDICES

Appendix 1: Sample Calculations

Appendix 1A: Sample Calculations Related to Modifying Agent Solutions.

- 3-allyl-5.5-dimethylhydantoin (ADMH) is the modifying agent used in this project, its formula is: $C_8H_{12}N_2O_2$ therefore the molecular weight is given by:

$M = (C \times 8) + (H \times 12) + (N \times 2) + (O \times 2)$

$M = (12 \times 8) + (1 \times 12) + (14 \times 2) + (16 \times 2) = 168\ g/mol$

- Calculations for 0.2 mol/L, 0.4 mol/L, 0.6 mol/L and 0.8 mol/L concentrations of ADMH, please note 1L of aqueous solutions were made for each concentration. Let:

Table 1A-1: Table of concentration and mass labels

Concentrations	Required AMDH Mass
$C_1 = 0.2\ mol/L$	m_1
$C_2 = 0.4\ mol/L$	m_2
$C_3 = 0.6\ mol/L$	m_3
$C_4 = 0.8\ mo/L$	m_4

$C_1 = \frac{n}{V}$

$n_1 = C_1 \times V$

$\frac{m_1}{M} = C_1 \times V$

$m_1 = C_1 \times V \times M$

$m_1 = 0.2\frac{mol}{L} \times 1L \times 168\frac{g}{mol}$

$m_1 = 33.6\ g$

Note: The same procedure was applied for the other concentrations (0.4 mol/L, 0.6 mol/L and 0.8 mol/L)

Appendix 1B: Sample Calculations Related to Reverse Osmosis Membrane Parameters

- **Flux calculations**

Sample calculations for preliminary results at time 30 min for 0.2 mol/L ADMH-grafted membrane against E. coli:

$$J = \frac{V}{A \times \Delta t}$$

$$J = \frac{0.0072}{0.013775 \times 0.004166667} = 125.44\ L/m^2.h$$

- **Normalized Flux calculations**

Normalizing RO data allows a more accurate comparison in terms of the performance of the membrane. The objective is to set a standard which does not depend on changing operating conditions. Indeed, the normalized data will measure the direct condition of the RO membrane and show the true performance and health level of the membrane.

Because the temperature effect is delineated for this specific study, a temperature correction factor (TCF) has been included to normalize the flux of the membrane. The following Table 1B-1 bellow shows the temperature correction factors according to FilmTech 's latest reverse osmosis membranes technical manual, that was used for the flux normalization as a function of the Feed Temperature (2023).

Sample calculations for preliminary results at time 30 min for 0.2 mol/L ADMH-grafted membrane against E. coli:

$$Normalized\ flux = Actual\ Flux\ \times Temperature\ Correction\ Factor$$

$$J_{Normalized} = J_{actual} \times TCF$$

$$J_{Normalized} = 125.44 \times 1.021 = 128.07\ L/m^2.h$$

Table 1B-1: Temperature correlation table (FilmTech, 2023)

Temp °C	Correction Factor	Temp °C	Correction Factor	Temp °C	Correction Factor	Temp °C	Correction Factor	Temp °C	Correction Factor
10.0	1.711	14.0	1.475	18.0	1.276	22.0	1.109	26.0	0.971
10.1	1.705	14.1	1.469	18.1	1.272	22.1	1.105	26.1	0.968
10.2	1.698	14.2	1.464	18.2	1.267	22.2	1.101	26.2	0.965
10.3	1.692	14.3	1.459	18.3	1.262	22.3	1.097	26.3	0.962
10.4	1.686	14.4	1.453	18.4	1.258	22.4	1.093	26.4	0.959
10.5	1.679	14.5	1.448	18.5	1.254	22.5	1.090	26.5	0.957
10.6	1.673	14.6	1.443	18.6	1.249	22.6	1.086	26.6	0.954
10.7	1.667	14.7	1.437	18.7	1.245	22.7	1.082	26.7	0.951
10.8	1.660	14.8	1.432	18.8	1.240	22.8	1.078	26.8	0.948
10.9	1.654	14.9	1.427	18.9	1.236	22.9	1.075	26.9	0.945
11.0	1.648	15.0	1.422	19.0	1.232	23.0	1.071	27.0	0.943
11.1	1.642	15.1	1.417	19.1	1.227	23.1	1.067	27.1	0.940
11.2	1.636	15.2	1.411	19.2	1.223	23.2	1.064	27.2	0.937
11.3	1.630	15.3	1.406	19.3	1.219	23.3	1.060	27.3	0.934
11.4	1.624	15.4	1.401	19.4	1.214	23.4	1.056	27.4	0.932
11.5	1.618	15.5	1.396	19.5	1.210	23.5	1.053	27.5	0.929
11.6	1.611	15.6	1.391	19.6	1.206	23.6	1.049	27.6	0.926
11.7	1.605	15.7	1.386	19.7	1.201	23.7	1.045	27.7	0.924
11.8	1.600	15.8	1.381	19.8	1.197	23.8	1.042	27.8	0.921
11.9	1.594	15.9	1.376	19.9	1.193	23.9	1.038	27.9	0.918
12.0	1.588	16.0	1.371	20.0	1.189	24.0	1.035	28.0	0.915
12.1	1.582	16.1	1.366	20.1	1.185	24.1	1.031	28.1	0.913
12.2	1.576	16.2	1.361	20.2	1.180	24.2	1.028	28.2	0.910
12.3	1.570	16.3	1.356	20.3	1.176	24.3	1.024	28.3	0.908
12.4	1.564	16.4	1.351	20.4	1.172	24.4	1.021	28.4	0.905
12.5	1.558	16.5	1.347	20.5	1.168	24.5	1.017	28.5	0.902
12.6	1.553	16.6	1.342	20.6	1.164	24.6	1.014	28.6	0.900
12.7	1.547	16.7	1.337	20.7	1.160	24.7	1.010	28.7	0.897
12.8	1.541	16.8	1.332	20.8	1.156	24.8	1.007	28.8	0.894
12.9	1.536	16.9	1.327	20.9	1.152	24.9	1.003	28.9	0.892
13.0	1.530	17.0	1.323	21.0	1.148	25.0	1.000	29.0	0.889
13.1	1.524	17.1	1.318	21.1	1.144	25.1	0.997	29.1	0.887
13.2	1.519	17.2	1.313	21.2	1.140	25.2	0.994	29.2	0.884
13.3	1.513	17.3	1.308	21.3	1.136	25.3	0.991	29.3	0.882
13.4	1.508	17.4	1.304	21.4	1.132	25.4	0.988	29.4	0.879
13.5	1.502	17.5	1.299	21.5	1.128	25.5	0.985	29.5	0.877
13.6	1.496	17.6	1.294	21.6	1.124	25.6	0.982	29.6	0.874
13.7	1.491	17.7	1.290	21.7	1.120	25.7	0.979	29.7	0.871
13.8	1.486	17.8	1.285	21.8	1.116	25.8	0.977	29.8	0.869
13.9	1.480	17.9	1.281	21.9	1.112	25.9	0.974	29.9	0.866

- **Salt Rejection calculations**

Sample calculations for preliminary results at time 0 min for 0.2 mol/L ADMH-grafted:

$$R = \frac{C_f - C_P}{C_f} \times 100$$

$$R = \frac{1016 - 191.8}{1016} \times 100$$

$$R = 81.12\%$$

- **Flux Decline Ratio (FDR) calculations**

Sample calculations for 0.4 mol/L ADMH-grafted membrane against inorganic:

$$FDR = \left(\frac{Jw_i - J}{Jw_i}\right) \times 100$$

$$FDR = \left(\frac{121.09 - 105.75}{129.09}\right) \times 100$$

$$FDR = 12.67\%$$

- **Flux Recovery Ratio (FRR) calculations**

Sample calculations for 0.4 mol/L ADMH-grafted membrane against inorganic:

$$FRR = \left(\frac{J_{wf}}{J_{wi}}\right)$$

$$FRR = \left(\frac{125.44}{138.38}\right) \times 100 = 90\%$$

- **Mortality Ratio**

Sample calculation for unmodified membrane antimicrobial abilities against E. coli:

$$R = \left(\frac{B - A}{B}\right) \times 100$$

$$R = \left(\frac{1.15 \times 10^7 - 7.30 \times 10^6}{1.15 \times 10^7}\right) \times 100 = 36.24\%$$

Appendix 2: Reverse Osmosis Filtration Process Data

The following experiments was run at constant operating conditions with the specific feed.

Set to a pressure of 15 bar (±3 bar) and hydraulic pressure 20 Bar with a constant flow rate of 2L/min.

Appendix 2A: Preliminaries Data Pure Water Filtration Data Pure Water Flux & Salt Rejection

- **Unmodified Membrane (M_0)**

Table 2A- 1: Unmodified membrane preliminary data feed specifications (1)

FEED SPECIFICATIONS
Pure Water
Volume = 15L
Temp =18°C
Conductivity= 5.4 µS

Table 2A- 2: Unmodified membrane preliminary data (1)

Time (min)	**Time interval (Δt) (s)**	**Permeate V (mL)**	**Permeate V (L)**	**Time interval (Δt) (h)**	**Flow rate (L/h)**	**Flux (L/m^2.h)**	**Permeability (L/m^2.h.Bar)**
0	15	6,2	0,0062	0,004166667	1,488	108,0217786	7,201451906
30	15	6,2	0,0062	0,004166667	1,488	108,0217786	7,201451906
60	15	6,1	0,0061	0,004166667	1,464	106,2794918	7,085299456
90	15	6,2	0,0062	0,004166667	1,488	108,0217786	7,201451906
120	15	6,4	0,0064	0,004166667	1,536	111,5063521	7,433756806
150	15	6,4	0,0064	0,004166667	1,536	111,5063521	7,433756806
180	15	6,4	0,0064	0,004166667	1,536	111,5063521	7,433756806
210	15	6,3	0,0063	0,004166667	1,512	109,7640653	7,317604356
240	15	6,2	0,0062	0,004166667	1,488	108,0217786	7,201451906
270	15	6,1	0,0061	0,004166667	1,464	106,2794918	7,085299456
						108,892922	**7,259528131**

Table 2A-3: Unmodified membrane preliminary data feed specifications (2)

FEED SPECIFICATIONS
500 ppm NaCl solution
Volume = 15L
Temp =18°C
Conductivity= 5.4 µS

Table 2A-4: Unmodified membrane preliminary data (2)

	FEED			**BRINE**		**PERMEATE**				
Time (min)	EC (mS)	TDS(g/L)	Temp (°C)	EC (µS)	TDS(g/L)	EC (µS)	TDS(g/L)	Temp (°C)	Volume (mL)	Time interval (Δt) (s)
0	864	0,633	19,1	434,6	0,336	36,1	0,0286	16,8	6,1	15
30	892	0,643	19,9	464,3	0,3162	65,1	0,0495	16,8	6,1	15
60	918	0,651	20,7	0,886	0,631	114,4	0,0875	16,9	6,2	15
90	531	0,659	21,5	455	0,3282	62,8	0,0453	17,2	6,1	15
120	993	0,67	21,9	466,9	0,321	59	0,047	17,2	6,1	15
150	998	0,681	22,4	464,1	0,3225	66,7	0,0486	17,2	6	15
180	967	0,691	22,5	464,7	0,3181	132,8	0,0996	17,3	6,1	15
210	1046	0,704	23,1	480	0,3279	145,8	0,1068	17,4	5,9	15
240	1064	0,71	23,4	490,6	0,3558	155,8	0,1213	17,5	6	15
270	97,4	0,465	23,8	490,3	0,349	157,7	0,1228	17,5	5,9	15
310	1093	0,584	23,8	561	0,361	164,4	0,1266	17,5	5,9	15

Table 2A- 5: Unmodified membrane preliminary data (3)

Time interval (Δt) (h)	**Volume (L)**	**Flow Rate (L/h)**	**Flux (L/m^2.h)**	**Salt Rejection Ratio (%)**
0,004166667	0,0061	1,464	106,2794918	95,82%
0,004166667	0,0061	1,464	106,2794918	92,70%
0,004166667	0,0062	1,488	108,0217786	87,54%
0,004166667	0,0061	1,464	106,2794918	88,17%
0,004166667	0,0061	1,464	106,2794918	94,06%
0,004166667	0,006	1,44	104,5372051	93,32%
0,004166667	0,0061	1,464	106,2794918	86,27%
0,004166667	0,0059	1,416	102,7949183	86,06%
0,004166667	0,006	1,44	104,5372051	85,36%
0,004166667	0,0059	1,416	102,7949183	-61,91%
0,004166667	0,0059	1,416	102,7949183	84,96%
			105,1707639	**75,67%**

- **0.2 mol/L Modified membrane ($M_{0.2mol/L}$)**

Table 2A-6: 0.2 mol/L modified membrane preliminary data feed specifications (1)

FEED SPECIFICATIONS
Pure Water
Volume = 9L
Temp =21°C
Conductivity= 5.4 µS

Table 2A- 7: 0.2 mol/L modified membrane preliminary data (1)

Time (min)	**Time interval (Δt) (s)**	**Permeate V (mL)**	**Permeate (L)**	**Time interval (Δt) (h)**	**Flow rate (L/h)**	**Flux (L/m^2.h)**	**Permeability (L/m^2.h.Bar)**
0	15	8,1	0,0081	0,004166667	1,944	141,1252269	9,408348457
30	15	8	0,008	0,004166667	1,92	139,3829401	9,292196007
60	15	8,1	0,0081	0,004166667	1,944	141,1252269	9,408348457
90	15	8,1	0,0081	0,004166667	1,944	141,1252269	9,408348457
120	15	8,1	0,0081	0,004166667	1,944	141,1252269	9,408348457
150	15	8,3	0,0083	0,004166667	1,992	144,6098004	9,640653358
180	15	8,2	0,0082	0,004166667	1,968	142,8675136	9,524500907
210	15	8,2	0,0082	0,004166667	1,968	142,8675136	9,524500907
240	15	8,7	0,0087	0,004166667	2,088	151,5789474	10,10526316
						142,8675136	**9,524500907**

Table 2A-8: 0.2 mol/L modified membrane preliminary data feed specifications (2)

FEED SPECIFICATIONS
500 ppm NaCl solution
Volume = 10L
Temp = 19°C
Conductivity= 5.4 µS

Table 2A-9: 0.2 mol/L modified membrane preliminary data (2)

	FEED			BRINE		PERMEATE				
Time (min)	**EC (µS)**	**TDS(g/L)**	**Temp (°C)**	**EC (µS)**	**TDS(g/L)**	**EC (µS)**	**TDS(g/L)**	**Temp (°C)**	**Volume (mL)**	**Time interval (Δt) (s)**
0	1016	0,649	17,6	996	0,648	191,8	0,1631	17,7	8,4	15
30	1075	0,71	19,6	1079	0,681	301	0,1956	18	6,8	15
60	1175	0,762	20,9	1165	0,757	271,1	0,1753	18,4	6,4	15
90	1195	0,827	21,9	1234	0,802	254,5	0,1649	18,7	6,4	15
120	1396	0,836	22,8	1347	0,875	255,9	0,1707	19,2	6,6	15
150	1480	0,996	23,2	1462	0,958	225,8	0,1636	20	6,6	15
180	1699	0,896	23,7	1690	1,098	270,9	0,1757	20,3	6,4	15
210	1902	1,238	23,8	1934	1,1258	265,2	0,1737	20,4	6	15
240	1353	0,888	25,1	2192	1,1422	252,2	0,1811	20,5	6	15
270	1567	0,88	25,5	2599	1,681	263	0,1828	20,6	6	15

Table 2A-10: 0.2 mol/L modified membrane preliminary data (3)

Time interval (Δt) (h)	Volume (L)	Flow Rate (L/h)	Flux (L/m^2.h)	Salt Rejection Ratio (%)
0,004166667	0,0084	2,016	146,3520871	81,12%
0,004166667	0,0068	1,632	118,4754991	72,00%
0,004166667	0,0064	1,536	111,5063521	76,93%
0,004166667	0,0064	1,536	111,5063521	78,70%
0,004166667	0,0066	1,584	114,9909256	81,67%
0,004166667	0,0066	1,584	114,9909256	84,74%
0,004166667	0,0064	1,536	111,5063521	84,06%
0,004166667	0,006	1,44	104,5372051	86,06%
0,004166667	0,006	1,44	104,5372051	81,36%
0,004166667	0,006	1,44	104,5372051	83,22%
			114,2940109	**80,99%**

- **0.4 mol/L Modified membrane ($M_{0.4\ mol/L}$)**

Table 2A-11: 0.4 mol/L modified membrane preliminary data feed specifications (1)

FEED SPECIFICATIONS
Pure Water
Volume = 9L
Temp =20°C
Conductivity= 5.4 µS

Table 2A-12: 0.4 mol/L modified membrane preliminary data (1)

Time (min)	Time interval (Δt) (s)	Permeate V (mL)	Permeate V (L)	Time interval (Δt) (h)	Flow rate (L/h)	Flux (L/m^2.h)	Permeability (L/m^2.h.Bar)
0	15	8,3	0,0083	0,004166667	1,992	144,6098004	9,640653358
30	15	8,1	0,0081	0,004166667	1,944	141,1252269	9,408348457
60	15	8	0,008	0,004166667	1,92	139,3829401	9,292196007
90	15	8,1	0,0081	0,004166667	1,944	141,1252269	9,408348457
120	15	8,1	0,0081	0,004166667	1,944	141,1252269	9,408348457
150	15	8,2	0,0082	0,004166667	1,968	142,8675136	9,524500907
180	15	8,1	0,0081	0,004166667	1,944	141,1252269	9,408348457
210	15	8,2	0,0082	0,004166667	1,968	142,8675136	9,524500907
240	15	8,6	0,0086	0,004166667	2,064	149,8366606	9,989110708
						142,6739262	**9,51159508**

Table 2A-13: 0.4 mol/L modified membrane preliminary data feed specifications (2)

FEED SPECIFICATIONS
500 ppm NaCl solution
Volume = 10L
Temp = 20°C
Conductivity= 5.4 µS

Table 2A-14: 0.4 mol/L modified membrane preliminary data (2)

	FEED			**BRINE**		**PERMEATE**				
Time (min)	**EC (µS)**	**TDS(g/L)**	**Temp (°C)**	**EC (µS)**	**TDS(g/L)**	**EC (µS)**	**TDS(g/L)**	**Temp (°C)**	**Volume (mL)**	**Time interval (Δt) (s)**
0	1014	0,64	20	991	0,637	187,2	0,1602	20,1	8,2	15
30	1070	0,679	20,6	1068	0,672	227,1	0,1856	20,3	7,2	15
60	1150	0,742	20,9	1149	0,74	256,2	0,1906	20,3	7,2	15
90	1192	0,817	21,7	1194	0,721	260,1	0,2002	21,1	7,1	15
120	1380	0,816	22,5	1292	0,798	266,1	0,2101	21,2	7,1	15
150	1502	1,012	22,8	1481	0,859	223,1	0,1812	21,4	7	15
180	1689	1,052	23,1	1650	0,962	269,3	0,1805	21,8	7	15
210	1904	1,238	23,6	1934	1,011	261,2	0,169	22,2	7	15
240	1354	0,886	24,9	1960	1,126	255,6	0,1856	22,6	6,9	15
270	1560	1,112	25,1	2460	1,523	270,2	0,189	22,9	6,7	15

Table 2A-15: 0.4 mol/L modified membrane preliminary data (3)

Time interval (Δt) (h)	Volume (L)	Flow Rate (L/h)	Flux (L/m^2.h)	Salt Rejection Ratio (%)
0,004166667	0,0082	1,968	142,8675136	81,54%
0,004166667	0,0072	1,728	125,4446461	78,78%
0,004166667	0,0072	1,728	125,4446461	77,72%
0,004166667	0,0071	1,704	123,7023593	78,18%
0,004166667	0,0071	1,704	123,7023593	80,72%
0,004166667	0,007	1,68	121,9600726	85,15%
0,004166667	0,007	1,68	121,9600726	84,06%
0,004166667	0,007	1,68	121,9600726	86,28%
0,004166667	0,0069	1,656	120,2177858	81,12%
0,004166667	0,0067	1,608	116,7332123	82,68%
			124,399274	**81,62%**

- **0.6 mol/L Modified membrane ($M_{0.6\ mol/L}$)**

Table 2A-16: 0.6 mol/L modified membrane preliminary data feed specifications (1)

FEED SPECIFICATIONS
Pure Water
Volume = 9L
Temp =20°C
Conductivity= 5.4 µS

Table 2A-17: 0.6 mol/L modified membrane preliminary data (1)

Time (min)	Time interval (Δt) (s)	Permeate V (mL)	Permeate V (L)	Time interval (Δt) (h)	Flow rate (L/h)	Flux (L/m^2.h)	Permeability (L/m^2.h.Bar)
0	15	7,9	0,0079	0,004166667	1,896	137,6406534	9,176043557
30	15	8	0,008	0,004166667	1,92	139,3829401	9,292196007
60	15	8,1	0,0081	0,004166667	1,944	141,1252269	9,408348457
90	15	8,1	0,0081	0,004166667	1,944	141,1252269	9,408348457
120	15	7,9	0,0079	0,004166667	1,896	137,6406534	9,176043557
150	15	7,9	0,0079	0,004166667	1,896	137,6406534	9,176043557
180	15	7,8	0,0078	0,004166667	1,872	135,8983666	9,059891107
210	15	7,8	0,0078	0,004166667	1,872	135,8983666	9,059891107
240	15	7,6	0,0076	0,004166667	1,824	132,4137931	8,827586207
						137,6406534	**9,176043557**

Table 2A-18: 0.6 mol/L modified membrane preliminary data feed specifications (2)

FEED SPECIFICATIONS
500 ppm NaCl solution
Volume = 10L
Temp = 20.1°C
Conductivity= 5.4 µS

Table 2A-19: 0.6 mol/L modified membrane preliminary data (2)

	FEED			BRINE		PERMEATE				
Time (min)	**EC (µS)**	**TDS(g/L)**	**Temp (°C)**	**EC (µS)**	**TDS(g/L)**	**EC (µS)**	**TDS(g/L)**	**Temp (°C)**	**Volume (mL)**	**Time interval (Δt) (s)**
0	1029	0,692	20	985	0,585	201,2	0,1556	20,2	8,1	15
30	1065	0,705	20,4	1005	0,623	249,1	0,1765	20,3	8	15
60	1145	0,729	20,7	1059	0,673	231,2	0,1899	20,2	8	15
90	1198	0,741	21,2	1120	0,706	253,1	0,1906	20,5	7,9	15
120	1405	0,902	21,6	1360	0,78	249,6	0,1952	20,6	7,9	15
150	1533	1,051	22,1	1492	0,821	254,3	0,2103	20,9	7,9	15
180	1679	1,066	22,8	1595	0,915	281,2	0,212	21,1	7,8	15
210	1994	1,23	23,1	1879	0,998	291,3	0,2322	21,4	7,8	15
240	1299	0,961	23,6	1960	1,199	298,3	0,2398	21,9	7,8	15
270	1592	1,23	24,9	2320	1,495	302,6	0,241	22,1	7,6	15

Table 2A-20: 0.6 mol/L modified membrane preliminary data (3)

Time interval (Δt) (h)	Volume (L)	Flow Rate (L/h)	Flux (L/m^2.h)	Salt Rejection Ratio (%)
0,004166667	0,0081	1,944	141,1252269	80,45%
0,004166667	0,008	1,92	139,3829401	76,61%
0,004166667	0,008	1,92	139,3829401	79,81%
0,004166667	0,0079	1,896	137,6406534	78,87%
0,004166667	0,0079	1,896	137,6406534	82,23%
0,004166667	0,0079	1,896	137,6406534	83,41%
0,004166667	0,0078	1,872	135,8983666	83,25%
0,004166667	0,0078	1,872	135,8983666	85,39%
0,004166667	0,0078	1,872	135,8983666	77,04%
0,004166667	0,0076	1,824	132,4137931	80,99%
			137,292196	**80,81%**

- **0.8 mol/L Modified membrane ($M_{0.8\ mol/L}$)**

Table 2A-21: 0.8 mol/L modified membrane preliminary data feed specifications (1)

FEED SPECIFICATIONS
Pure Water
Volume = 9L
Temp =20°C
Conductivity= 5.4 µS

Table 2A-22: 0.8 mol/L modified membrane preliminary data (1)

Time (min)	**Time interval (Δt) (s)**	**Permeate V (mL)**	**Permeate V (L)**	**Time interval (Δt) (h)**	**Flow rate (L/h)**	**Flux (L/m^2.h)**	**Permeability (L/m^2.h.Bar)**
0	15	8,1	0,0081	0,004166667	1,944	141,1252269	9,408348457
30	15	7,9	0,0079	0,004166667	1,896	137,6406534	9,176043557
60	15	7,9	0,0079	0,004166667	1,896	137,6406534	9,176043557
90	15	7,8	0,0078	0,004166667	1,872	135,8983666	9,059891107
120	15	7,9	0,0079	0,004166667	1,896	137,6406534	9,176043557
150	15	7,8	0,0078	0,004166667	1,872	135,8983666	9,059891107
180	15	7,5	0,0075	0,004166667	1,8	130,6715064	8,711433757
210	15	7,5	0,0075	0,004166667	1,8	130,6715064	8,711433757
240	15	7,5	0,0075	0,004166667	1,8	130,6715064	8,711433757
						135,3176044	**9,021173624**

Table 2A-23: 0.8 mol/L modified membrane preliminary data feed specifications (2)

FEED SPECIFICATIONS
500 ppm NaCl solution
Volume = 10L
Temp = 20.1°C
Conductivity= 5.4 µS

Table 2A-24: 0.8 mol/L modified membrane preliminary data (2)

	FEED			BRINE		PERMEATE				
Time (min)	**EC (µS)**	**TDS(g/L)**	**Temp (°C)**	**EC (µS)**	**TDS(g/L)**	**EC (µS)**	**TDS(g/L)**	**Temp (°C)**	**Volume (mL)**	**Time interval (Δt) (s)**
0	1013	0,598	20,2	858	0,495	220,2	0,2264	20,1	8	15
30	1059	0,639	20,4	910	0,509	236,9	0,2786	20,4	7,9	15
60	1102	0,7	20,9	980	0,579	242,6	0,2931	20,8	7,4	15
90	1293	0,724	21,3	1250	0,596	258,2	0,3216	20,9	7,4	15
120	1389	0,821	21,7	1280	0,656	260,3	0,3156	21,9	7,3	15
150	1433	0,895	22,2	1359	0,789	267,3	0,3369	22,1	7,3	15
180	1598	0,912	22,7	1599	0,889	274,8	0,3452	22,3	7,2	15
210	1836	1,125	23,2	1690	0,996	283,4	0,3965	22,4	7,2	15
240	1408	0,856	23,5	1802	1,119	294,3	0,4123	22,6	7,1	15
270	1523	0,902	24,1	1997	1,328	300,1	0,4256	22,9	7,1	15

Table 2A-25: 0.8 mol/L modified membrane preliminary (3)

Time interval (Δt) (h)	**Volume (L)**	**Flow Rate (L/h)**	**Flux (L/m^2.h)**	**Salt Rejection Ratio (%)**
0,004166667	0,008	1,92	139,3829401	78,26%
0,004166667	0,0079	1,896	137,6406534	77,63%
0,004166667	0,0074	1,776	128,9292196	77,99%
0,004166667	0,0074	1,776	128,9292196	80,03%
0,004166667	0,0073	1,752	127,1869328	81,26%
0,004166667	0,0073	1,752	127,1869328	81,35%
0,004166667	0,0072	1,728	125,4446461	82,80%
0,004166667	0,0072	1,728	125,4446461	84,56%
0,004166667	0,0071	1,704	123,7023593	79,10%
0,004166667	0,0071	1,704	123,7023593	80,30%
			128,7549909	**80,33%**

Appendix 2B: Biofouling Experiments Data Against E. coli

- **Unmodified Membrane**

Table 2B-1: Unmodified membrane biofouling experiments data against E. coli speed specifications (1)

FEED SPECIFICATIONS
Pure Water Before Filtration
Volume = 15L
Temp =24.2°C
Conductivity= 5.4 µS

Table 2B-2: Unmodified membrane biofouling experiments data against E.coli (1)

Time (min)	**Time interval (Δt) (s)**	**Permeate V (mL)**	**Permeate V (L)**	**Time interval (Δt) (h)**	**Flow rate (L/h)**	**Flux (L/m^2.h)**
0	15	7,2	0,0072	0,004166667	1,728	125,4446461
10	15	6,8	0,0068	0,004166667	1,632	118,4754991
20	15	6,6	0,0066	0,004166667	1,584	114,9909256
30	15	6,8	0,0068	0,004166667	1,632	118,4754991
40	15	6,6	0,0066	0,004166667	1,584	114,9909256
50	15	6,6	0,0066	0,004166667	1,584	114,9909256
60	15	6,4	0,0064	0,004166667	1,536	111,5063521
70	15	6,2	0,0062	0,004166667	1,488	108,0217786
80	15	6,1	0,0061	0,004166667	1,464	106,2794918
90	15	6,3	0,0063	0,004166667	1,512	109,7640653
100	15	6,2	0,0062	0,004166667	1,488	108,0217786
110	15	6,2	0,0062	0,004166667	1,488	108,0217786
120	15	6,2	0,0062	0,004166667	1,488	108,0217786
						112,8465727

Table 2B- 3: Unmodified membrane biofouling experiments data against E. coli speed specifications (2)

FEED SPECIFICATIONS
Volume: 2L Broth + 4 x E.coli Broth 250 mL During Filtration
Conductivity= 272.5 µS
Temp= 24.0 °C
pH= 7.49

Table 2B-4: Unmodified membrane biofouling experiments data against E. coli (2)

	FEED			BRINE		PERMEATE				
Time (min)	**EC (µS)**	**TDS(g/L)**	**Temp (°C)**	**EC (µS)**	**TDS(g/L)**	**EC (µS)**	**TDS(g/L)**	**Temp (°C)**	**Volume (mL)**	**Time interval (Δt) (s)**
0	254,6	0,1662	24	254,1	0,1662	3,6	0,0024	23,1	6,8	15
30	263,5	0,1709	24,5	267,5	0,1756	3,2	0,0022	23	6,4	15
60	279,8	0,1846	24,5	292,5	0,1891	3,3	0,0022	22,8	6,2	15
90	309,5	0,1952	24,8	297,9	0,1975	3,4	0,0023	22,6	6,1	15
120	316,4	0,206	25	321,5	0,2096	3,6	0,0024	22,7	6,2	15
150	343,4	0,224	24,7	351,7	0,239	3,7	0,0026	22,6	6,2	15
180	362,1	0,237	24,6	374,1	0,245	3,6	0,0024	22,1	6,2	15
210	390,3	0,248	24,1	393,1	0,2589	3,7	0,0025	21,9	5,9	15
240	410,2	0,255	24,8	414,6	0,26366	3,8	0,0027	21,9	6,2	15

Table 2B-5: Unmodified membrane biofouling experiments data against E. coli (3)

Time interval (Δt) (h)	**Volume (L)**	**Flow Rate (L/h)**	**Flux (L/m^2.h)**	**Normalized Flux**	**FDR**
0,004166667	0,0068	1,632	118,4754991	122,6221416	0,00%
0,004166667	0,0064	1,536	111,5063521	113,4019601	7,52%
0,004166667	0,0062	1,488	108,0217786	109,8581488	10,41%
0,004166667	0,0061	1,464	106,2794918	107,0234483	12,72%
0,004166667	0,0062	1,488	108,0217786	108,777931	11,29%
0,004166667	0,0062	1,488	108,0217786	109,1019964	11,03%
0,004166667	0,0062	1,488	108,0217786	109,5340835	10,67%
0,004166667	0,0059	1,416	102,7949183	109,6821779	10,55%
0,004166667	0,0062	1,488	108,0217786	108,777931	11,29%
			108,7961283	**110,9755354**	**9,50%**

Table 2B-6: Unmodified membrane biofouling experiments data against E. coli speed specifications (3)

FEED SPECIFICATIONS
Pure Water After Filtration
Volume = 15L
Temp =24.1°C
Conductivity= 5.4 µS

Table 2B 7: Unmodified membrane biofouling experiments data against E. coli (4)

Time (min)	Time interval (Δt) (s)	Permeate V (mL)	Permeate V (L)	Time interval (Δt) (h)	Flow rate (L/h)	Flux (L/m^2.h)	FRR
0	15	5	0,005	0,004166667	1,2	87,11433757	69,44%
10	15	5,1	0,0051	0,004166667	1,224	88,85662432	75,00%
20	15	4,9	0,0049	0,004166667	1,176	85,37205082	74,24%
30	15	5,1	0,0051	0,004166667	1,224	88,85662432	75,00%
40	15	5,1	0,0051	0,004166667	1,224	88,85662432	77,27%
50	15	5,2	0,0052	0,004166667	1,248	90,59891107	78,79%
60	15	5,1	0,0051	0,004166667	1,224	88,85662432	79,69%
70	15	5,1	0,0051	0,004166667	1,224	88,85662432	82,26%
80	15	5,2	0,0052	0,004166667	1,248	90,59891107	85,25%
90	15	5,1	0,0051	0,004166667	1,224	88,85662432	80,95%
100	15	5,2	0,0052	0,004166667	1,248	90,59891107	83,87%
110	15	5,2	0,0052	0,004166667	1,248	90,59891107	83,87%
120	15	5,1	0,0051	0,004166667	1,224	88,85662432	82,26%
						88,99064638	**79,07%**

- **0.2 mol/L Modified membrane ($M_{0.2\ mol/L}$)**

Table 2B-8: 0.2 mol/L membrane biofouling experiments data against E. coli speed specifications (1)

FEED SPECIFICATIONS
Pure Water Before Filtration
Volume = 15L
Temp =24.1°C
Conductivity= 4.8 µS

Table 2B-9: 0.2 mol/L membrane biofouling experiments data against E. coli (1)

Time (min)	**Time interval (Δt) (s)**	**Permeate V (mL)**	**Permeate V (L)**	**Time interval (Δt) (h)**	**Flow rate (L/h)**	**Flux (L/m^2.h)**
0	15	7	0,007	0,004166667	1,68	121,9600726
10	15	7,1	0,0071	0,004166667	1,704	123,7023593
20	15	7,1	0,0071	0,004166667	1,704	123,7023593
30	15	7,3	0,0073	0,004166667	1,752	127,1869328
40	15	6,8	0,0068	0,004166667	1,632	118,4754991
50	15	7	0,007	0,004166667	1,68	121,9600726
60	15	7	0,007	0,004166667	1,68	121,9600726
70	15	7,1	0,0071	0,004166667	1,704	123,7023593
80	15	6,8	0,0068	0,004166667	1,632	118,4754991
90	15	6,6	0,0066	0,004166667	1,584	114,9909256
100	15	6,7	0,0067	0,004166667	1,608	116,7332123
110	15	6,6	0,0066	0,004166667	1,584	114,9909256
120	15	6,5	0,0065	0,004166667	1,56	113,2486388
						120,0837638

Table 2B-10: 0.2 mol/L membrane biofouling experiments data against E. coli speed specifications (2)

FEED SPECIFICATIONS
Volume: 2L Broth + 4 x E.coli Broth 250 mL During Filtration
Conductivity= 271.4 µS
Temp= 24.2 °C
pH= 7.28

Table 2B-11: 0.2 mol/L membrane biofouling experiments data against E. coli (2)

	FEED			BRINE		PERMEATE				
Time (min)	**EC (µS)**	**TDS(g/L)**	**Temp (°C)**	**EC (µS)**	**TDS(g/L)**	**EC (µS)**	**TDS(g/L)**	**Temp (°C)**	**Volume (mL)**	**Time interval (Δt) (s)**
0	253,6	0,1598	24,3	253,2	0,1521	3,5	0,0023	23,4	7,3	15
30	260,9	0,1626	24,4	261,8	0,1701	3,4	0,0023	23,3	7,2	15
60	275,7	0,1788	24,5	286,2	0,1809	3,4	0,0022	23,3	7,1	15
90	299,2	0,1854	24,6	291,3	0,1889	3,3	0,0022	23,2	6,9	15
120	315,7	0,196	24,8	317,9	0,1912	3,5	0,0024	23	6,8	15
150	342,8	0,2133	25	349,2	0,1977	3,6	0,0024	22,9	6,8	15
180	358,7	0,2319	25,1	368,5	0,2411	3,6	0,0025	22,8	6,6	15
210	381,2	0,2381	25,1	382,7	0,2497	3,7	0,0028	22,7	6,6	15
240	405,6	0,2496	25,2	431,7	0,2901	3,7	0,0028	22,4	6,6	15

Table 2B- 12: 0.2 mol/L membrane biofouling experiments data against E. coli (3)

Time interval (Δt) (h)	**Volume (L)**	**Flow Rate (L/h)**	**Flux (L/m^2.h)**	**Normalized Flux**	**FDR**
0,004166667	0,0073	1,752	127,1869328	130,2394192	0,00%
0,004166667	0,0072	1,728	125,4446461	128,0789837	1,66%
0,004166667	0,0071	1,704	123,7023593	125,8052995	3,40%
0,004166667	0,0069	1,656	120,2177858	121,9008348	6,40%
0,004166667	0,0068	1,632	118,4754991	119,3048276	8,40%
0,004166667	0,0068	1,632	118,4754991	118,4754991	9,03%
0,004166667	0,0066	1,584	114,9909256	114,6459528	11,97%
0,004166667	0,0066	1,584	114,9909256	114,6459528	11,97%
0,004166667	0,0066	1,584	114,9909256	114,30098	12,24%
			119,830611	**120,8219722**	**7,23%**

Table 2B-13: 0.2 mol/L membrane biofouling experiments data against E. coli speed specifications (3)

FEED SPECIFICATIONS
Pure Water After Filtration
Volume = 15L
Temp =24.3°C
Conductivity= 7.4 µS

Table 2B- 14: 0.2 mol/L membrane biofouling experiments data against E. coli (4)

Time (min)	Time interval (Δt) (s)	Permeate V (mL)	Permeate V (L)	Time interval (Δt) (h)	Flow rate (L/h)	Flux (L/m^2.h)	FRR
0	15	6,8	0,0068	0,004166667	1,632	118,4754991	97,14%
10	15	6,8	0,0068	0,004166667	1,632	118,4754991	95,77%
20	15	6,7	0,0067	0,004166667	1,608	116,7332123	94,37%
30	15	6,7	0,0067	0,004166667	1,608	116,7332123	91,78%
40	15	6,8	0,0068	0,004166667	1,632	118,4754991	100,00%
50	15	6,7	0,0067	0,004166667	1,608	116,7332123	95,71%
60	15	6,7	0,0067	0,004166667	1,608	116,7332123	95,71%
70	15	6,7	0,0067	0,004166667	1,608	116,7332123	94,37%
80	15	6,6	0,0066	0,004166667	1,584	114,9909256	97,06%
90	15	6,6	0,0066	0,004166667	1,584	114,9909256	100,00%
100	15	6,6	0,0066	0,004166667	1,584	114,9909256	98,51%
110	15	6,6	0,0066	0,004166667	1,584	114,9909256	100,00%
120	15	6,5	0,0065	0,004166667	1,56	113,2486388	100,00%
						116,3311462	**96,96%**

- **0.4 mol/L Modified membrane ($M_{0.4\ mol/L}$)**

Table 2B- 15: 0.4 mol/L membrane biofouling experiments data against E. coli speed specifications (1)

FEED SPECIFICATIONS
Pure Water Before Filtration
Volume = 15L
Temp =24.3°C
Conductivity= 4.6 µS

Table 2B-16: 0.2 mol/L membrane biofouling experiments data against E. coli (1)

Time (min)	Time interval (Δt) (s)	Permeate V (mL)	Permeate V (L)	Time interval (Δt) (h)	Flow rate (L/h)	Flux (L/m^2.h)
10	15	7,1	0,0071	0,004166667	1,704	123,7023593
20	15	7,2	0,0072	0,004166667	1,728	125,4446461
30	15	7,2	0,0072	0,004166667	1,728	125,4446461
40	15	7,2	0,0072	0,004166667	1,728	125,4446461
50	15	7	0,007	0,004166667	1,68	121,9600726
60	15	6,9	0,0069	0,004166667	1,656	120,2177858
70	15	6,9	0,0069	0,004166667	1,656	120,2177858
80	15	6,9	0,0069	0,004166667	1,656	120,2177858
90	15	6,9	0,0069	0,004166667	1,656	120,2177858
100	15	6,9	0,0069	0,004166667	1,656	120,2177858
110	15	6,7	0,0067	0,004166667	1,608	116,7332123
120	15	6,7	0,0067	0,004166667	1,608	116,7332123
						121,5580064

Table 2B-17: 0.4 mol/L membrane biofouling experiments data against E. coli speed specifications (2)

FEED SPECIFICATIONS
Volume: 2L Broth + 4 x E.coli Broth 250 mL During Filtration
Conductivity= 262.1 µS
Temp= 24.2 °C
pH= 7.12

Table 2B-18: 0.4 mol/L membrane biofouling experiments data against E. coli (2)

	FEED			BRINE		PERMEATE				
Time (min)	EC (µS)	TDS(g/L)	Temp (°C)	EC (µS)	TDS(g/L)	EC (µS)	TDS(g/L)	Temp (°C)	Volume (mL)	Time interval (Δt) (s)
0	248,9	0,1534	24,1	241,9	0,1489	3,1	0,0021	23,1	7,1	15
30	251,2	0,1582	24,3	249,4	0,1556	3,1	0,0021	23,2	7,1	15
60	258,7	0,1603	24,6	260,2	0,1625	3,2	0,0022	22,9	7,1	15
90	267,4	0,1695	24,9	278,1	0,1739	3,3	0,0023	22,7	7	15
120	291,3	0,1787	25,3	303,3	0,1812	3,4	0,0024	22,6	6,9	15
150	324,7	0,2078	25,6	345,2	0,1989	3,5	0,0024	22,4	6,9	15
180	337,9	0,2276	25,8	364,1	0,2254	3,5	0,0025	22,2	6,9	15
210	348,8	0,2267	26,2	388,2	0,2379	3,6	0,0028	22	6,7	15
240	398,9	0,2299	26,6	421,6	0,2668	3,6	0,0028	21,9	6,7	15

Table 2B-19: 0.4 mol/L membrane biofouling experiments data against E. coli (3)

Time interval (Δt) (h)	Volume (L)	Flow Rate (L/h)	Flux (L/m^2.h)	Normalized Flux	FDR
0,004166667	0,0071	1,704	123,7023593	127,5371325	0,00%
0,004166667	0,0071	1,704	123,7023593	126,671216	0,68%
0,004166667	0,0071	1,704	123,7023593	125,4341924	1,65%
0,004166667	0,007	1,68	121,9600726	122,3259528	4,09%
0,004166667	0,0069	1,656	120,2177858	119,1358258	6,59%
0,004166667	0,0069	1,656	120,2177858	118,0538657	7,44%
0,004166667	0,0069	1,656	120,2177858	117,4527768	7,91%
0,004166667	0,0067	1,608	116,7332123	112,6475499	11,67%
0,004166667	0,0067	1,608	116,7332123	111,3634846	12,68%
			120,7985481	**120,0691107**	**5,86%**

Table 2B-20: 0.4 mol/L membrane biofouling experiments data against E. coli speed specifications (3)

FEED SPECIFICATIONS
Pure Water After Filtration
Volume = 15L
Temp =24.3°C
Conductivity= 6.8 µS

Table 2B-21: 0.2 mol/L membrane biofouling experiments data against E. coli (4)

Time (min)	Time interval (Δt) (s)	Permeate V (mL)	Permeate V (L)	Time interval (Δt) (h)	Flow rate (L/h)	Flux (L/m^2.h)	FRR
0	15	6,9	0,0069	0,004166667	1,656	120,2177858	97,18%
10	15	6,9	0,0069	0,004166667	1,656	120,2177858	95,83%
20	15	6,8	0,0068	0,004166667	1,632	118,4754991	94,44%
30	15	6,7	0,0067	0,004166667	1,608	116,7332123	93,06%
40	15	6,8	0,0068	0,004166667	1,632	118,4754991	97,14%
50	15	6,7	0,0067	0,004166667	1,608	116,7332123	97,10%
60	15	6,5	0,0065	0,004166667	1,56	113,2486388	94,20%
70	15	6,5	0,0065	0,004166667	1,56	113,2486388	94,20%
80	15	6,2	0,0062	0,004166667	1,488	108,0217786	89,86%
90	15	6,4	0,0064	0,004166667	1,536	111,5063521	92,75%
100	15	6,4	0,0064	0,004166667	1,536	111,5063521	95,52%
110	15	6,4	0,0064	0,004166667	1,536	111,5063521	95,52%
120	15	6,3	0,0063	0,004166667	1,512	109,7640653	90,30%
						114,5888594	**94,39%**

- **0.6 mol/L Modified membrane ($M_{0.6\ mol/L}$)**

Table 2B-22: 0.6 mol/L membrane biofouling experiments data against E. coli speed specifications (1)

FEED SPECIFICATIONS
Pure Water Before Filtration
Volume = 15L
Temp =24.2°C
Conductivity= 5.2 µS

Table 2B-23: 0.6 mol/L membrane biofouling experiments data against E. coli (1)

Time (min)	**Time interval (Δt) (s)**	**Permeate V (mL)**	**Permeate V (L)**	**Time interval (Δt) (h)**	**Flow rate (L/h)**	**Flux (L/m^2.h)**
0	15	7	0,007	0,004166667	1,68	121,9600726
10	15	7	0,007	0,004166667	1,68	121,9600726
20	15	7	0,007	0,004166667	1,68	121,9600726
30	15	6,8	0,0068	0,004166667	1,632	118,4754991
40	15	7	0,007	0,004166667	1,68	121,9600726
50	15	7	0,007	0,004166667	1,68	121,9600726
60	15	6,9	0,0069	0,004166667	1,656	120,2177858
70	15	6,9	0,0069	0,004166667	1,656	120,2177858
80	15	6,8	0,0068	0,004166667	1,632	118,4754991
90	15	6,8	0,0068	0,004166667	1,632	118,4754991
100	15	6,9	0,0069	0,004166667	1,656	120,2177858
110	15	6,7	0,0067	0,004166667	1,608	116,7332123
120	15	6,7	0,0067	0,004166667	1,608	116,7332123
						120,2177858

Table 2B-24: 0.6 mol/L membrane biofouling experiments data against E. coli speed specifications (2)

FEED SPECIFICATIONS
Volume: 2L Broth + 4 x E.coli Broth 250 mL During Filtration
Conductivity= 270.1 µS
Temp= 24.7 °C
pH= 7.58

Table 2B-25: 0.6 mol/L membrane biofouling experiments data against E. coli (2)

	FEED			BRINE		PERMEATE				
Time (min)	**EC (µS)**	**TDS(g/L)**	**Temp (°C)**	**EC (µS)**	**TDS(g/L)**	**EC (µS)**	**TDS(g/L)**	**Temp (°C)**	**Volume (mL)**	**Time interval (Δt) (s)**
0	261,2	0,1625	24,5	250,9	0,1554	3,2	0,0022	24,1	6,9	15
30	273,2	0,1697	24,9	269,8	0,168	3,3	0,0023	24	6,9	15
60	279,1	0,1758	25	282,7	0,1759	3,3	0,0023	23,9	6,8	15
90	285,3	0,1823	25,3	297,5	0,1807	3,4	0,0024	23,7	6,8	15
120	296,8	0,1856	25,6	304,9	0,1868	3,4	0,0024	23,5	6,7	15
150	331,3	0,215	25,8	339,6	0,1923	3,5	0,0026	23,1	6,9	15
180	349,4	0,2307	26,1	370,9	0,2186	3,5	0,0026	22,9	6,8	15
210	367,2	0,2396	26,4	399,7	0,2481	3,6	0,0027	22,7	6,7	15
240	412,9	0,2417	26,6	412,3	0,2545	3,7	0,0028	22,4	6,7	15

Table 2B-26: 0.6 mol/L membrane biofouling experiments data against E. coli (3)

Time interval (Δt) (h)	**Volume (L)**	**Flow Rate (L/h)**	**Flux (L/m^2.h)**	**Normalized Flux**	**FDR**
0,004166667	0,0069	1,656	120,2177858	122,2614882	0,00%
0,004166667	0,0069	1,656	120,2177858	120,5784392	1,38%
0,004166667	0,0068	1,632	118,4754991	118,4754991	3,10%
0,004166667	0,0068	1,632	118,4754991	117,4092196	3,97%
0,004166667	0,0067	1,608	116,7332123	114,6320145	6,24%
0,004166667	0,0069	1,656	120,2177858	117,4527768	3,93%
0,004166667	0,0068	1,632	118,4754991	114,6842831	6,20%
0,004166667	0,0067	1,608	116,7332123	111,9471506	8,44%
0,004166667	0,0067	1,608	116,7332123	111,3634846	8,91%
			118,4754991	**116,5338173**	**4,68%**

Table 2B-27: 0.6 mol/L membrane biofouling experiments data against E. coli speed specifications (3)

FEED SPECIFICATIONS
Pure Water After Filtration
Volume = 15L
Temp =24.4°C
Conductivity= 7.2 µS

Table 2B-28: 0.6 mol/L membrane biofouling experiments data against E. coli (4)

Time (min)	Time interval (Δt) (s)	Permeate V (mL)	Permeate V (L)	**Time interval (Δt) (h)**	**Flow rate (L/h)**	**Flux (L/m^2.h)**	**FRR**
0	15	6,7	0,0067	0,004166667	1,608	116,7332123	95,71%
10	15	6,7	0,0067	0,004166667	1,608	116,7332123	95,71%
20	15	6,7	0,0067	0,004166667	1,608	116,7332123	98,53%
30	15	6,7	0,0067	0,004166667	1,608	116,7332123	97,14%
40	15	6,8	0,0068	0,004166667	1,632	118,4754991	97,14%
50	15	6,8	0,0068	0,004166667	1,632	118,4754991	98,55%
60	15	6,8	0,0068	0,004166667	1,632	118,4754991	95,65%
70	15	6,6	0,0066	0,004166667	1,584	114,9909256	97,06%
80	15	6,6	0,0066	0,004166667	1,584	114,9909256	98,53%
90	15	6,7	0,0067	0,004166667	1,608	116,7332123	95,65%
100	15	6,6	0,0066	0,004166667	1,584	114,9909256	98,51%
110	15	6,6	0,0066	0,004166667	1,584	114,9909256	98,51%
120	15	6,6	0,0066	0,004166667	1,584	114,9909256	96,88%
						116,4651682	**97,20%**

- **0.8 mol/L Modified membrane ($M_{0.8\ mol/L}$)**

Table 2B-29: 0.8 mol/L membrane biofouling experiments data against E. coli feed specifications (1)

FEED SPECIFICATIONS
Pure Water Before Filtration
Volume = 15L
Temp =23.3°C
Conductivity= 5.1 µS

Table 2B- 30: 0.8 mol/L membrane biofouling experiments data against E. coli (1)

Time (min)	Time interval (Δt) (s)	Permeate V (mL)	Permeate V (L)	Time interval (Δt) (h)	Flow rate (L/h)	Flux (L/m^2.h)
0	15	6,8	0,0068	0,004166667	1,632	118,4754991
10	15	6,7	0,0067	0,004166667	1,608	116,7332123
20	15	6,9	0,0069	0,004166667	1,656	120,2177858
30	15	7	0,007	0,004166667	1,68	121,9600726
40	15	7	0,007	0,004166667	1,68	121,9600726
50	15	7,1	0,0071	0,004166667	1,704	123,7023593
60	15	7	0,007	0,004166667	1,68	121,9600726
70	15	6,9	0,0069	0,004166667	1,656	120,2177858
80	15	6,9	0,0069	0,004166667	1,656	120,2177858
90	15	6,8	0,0068	0,004166667	1,632	118,4754991
100	15	6,8	0,0068	0,004166667	1,632	118,4754991
110	15	6,7	0,0067	0,004166667	1,608	116,7332123
120	15	6,7	0,0067	0,004166667	1,608	116,7332123
						119,9274047

Table 2B-31: 0.8 mol/L membrane biofouling experiments data against E. coli feed specifications (2)

FEED SPECIFICATIONS
Volume: 2L Broth + 4 x E.coli Broth 250 mL During Filtration
Conductivity= 269.1 µS
Temp= 23.7 °C
pH= 7.35

Table 2B-32: 0.8 mol/L membrane biofouling experiments data against E. coli (2)

	FEED			**BRINE**		**PERMEATE**				
Time (min)	**EC (µS)**	**TDS(g/L)**	**Temp (°C)**	**EC (µS)**	**TDS(g/L)**	**EC (µS)**	**TDS(g/L)**	**Temp (°C)**	**Volume (mL)**	**Time interval (Δt) (s)**
0	268,2	0,1681	23,2	255,8	0,1602	3,1	0,0025	22,9	6,7	15
30	271	0,1705	23,9	260,3	0,1652	3,1	0,0026	22,8	6,8	15
60	274,9	0,1806	24,2	268,2	0,1671	3,2	0,0028	22,6	6,6	15
90	279,6	0,1825	24,6	276,2	0,1723	3,3	0,0028	22,5	6,6	15
120	283,7	0,1851	25	286,2	0,1775	3,4	0,0029	22,3	6,7	15
150	289,9	0,1965	25,3	291,6	0,1826	3,5	0,003	22,1	6,8	15
180	297,8	0,2024	25,6	297,1	0,1858	3,5	0,0031	21,9	6,7	15
210	299,7	0,2396	25,9	306,8	0,1903	3,6	0,0032	21,7	6,6	15
240	308,8	0,2421	26,1	315,2	0,1924	3,6	0,0032	21,5	6,5	15

Table 2B- 33: 0.8 mol/L membrane biofouling experiments data against E. coli (3)

Time interval (Δt) (h)	Volume (L)	Flow Rate (L/h)	Flux (L/m^2.h)	Normalized Flux	FDR
0,004166667	0,0067	1,608	116,7332123	124,2041379	0,00%
0,004166667	0,0068	1,632	118,4754991	122,9775681	0,99%
0,004166667	0,0066	1,584	114,9909256	118,2106715	4,83%
0,004166667	0,0066	1,584	114,9909256	116,6007985	6,12%
0,004166667	0,0067	1,608	116,7332123	116,7332123	6,02%
0,004166667	0,0068	1,632	118,4754991	117,4092196	5,47%
0,004166667	0,0067	1,608	116,7332123	114,6320145	7,71%
0,004166667	0,0066	1,584	114,9909256	112,0011615	9,82%
0,004166667	0,0065	1,56	113,2486388	109,6246824	11,74%
			116,1524501	**116,9326074**	**5,85%**

Table 2B-34: 0.8 mol/L membrane biofouling experiments data against E. coli feed specifications (3)

FEED SPECIFICATIONS
Pure Water After Filtration
Volume = 15L
Temp =24.3°C
Conductivity= 6.2 µS

Table 2B- 35: 0.8 mol/L membrane biofouling experiments data against E. coli (4)

Time (min)	Time interval (Δt) (s)	Permeate V (mL)	Permeate V (L)	Time interval (Δt) (h)	Flow rate (L/h)	Flux (L/m^2.h)	FRR
0	15	6,2	0,0062	0,004166667	1,488	108,0217786	91,18%
10	15	6,2	0,0062	0,004166667	1,488	108,0217786	92,54%
20	15	6,1	0,0061	0,004166667	1,464	106,2794918	88,41%
30	15	6,2	0,0062	0,004166667	1,488	108,0217786	88,57%
40	15	6,1	0,0061	0,004166667	1,464	106,2794918	87,14%
50	15	6	0,006	0,004166667	1,44	104,5372051	84,51%
60	15	6	0,006	0,004166667	1,44	104,5372051	85,71%
70	15	6	0,006	0,004166667	1,44	104,5372051	86,96%
80	15	6	0,006	0,004166667	1,44	104,5372051	86,96%
90	15	6,2	0,0062	0,004166667	1,488	108,0217786	91,18%
100	15	6,1	0,0061	0,004166667	1,464	106,2794918	89,71%
110	15	6	0,006	0,004166667	1,44	104,5372051	89,55%
120	15	6	0,006	0,004166667	1,44	104,5372051	89,55%
						106,0114477	**88,61%**

Appendix 2C: Biofouling Performance Data Against S. aureus

- **Unmodified Membrane**

Table 2C- 1: Unmodified membrane biofouling experiments data against S. Aureus feed specifications (1)

FEED SPECIFICATIONS
Pure Water Before Filtration
Volume = 15L
Temp =24.2°C
Conductivity= 4.4 µS

Table 2C- 2: Unmodified membrane biofouling experiments data against S. Aureus (1)

Time (min)	**Time interval (Δt) (s)**	**Permeate V (mL)**	**Permeate V (L)**	**Time interval (Δt) (h)**	**Flow rate (L/h)**	**Flux (L/m^2.h)**
0	15	7,2	0,0072	0,004166667	1,728	125,4446461
10	15	6,8	0,0068	0,004166667	1,632	118,4754991
20	15	6,6	0,0066	0,004166667	1,584	114,9909256
30	15	6,8	0,0068	0,004166667	1,632	118,4754991
40	15	6,6	0,0066	0,004166667	1,584	114,9909256
50	15	6,6	0,0066	0,004166667	1,584	114,9909256
60	15	6,4	0,0064	0,004166667	1,536	111,5063521
70	15	6,2	0,0062	0,004166667	1,488	108,0217786
80	15	6,1	0,0061	0,004166667	1,464	106,2794918
90	15	6,3	0,0063	0,004166667	1,512	109,7640653
100	15	6,2	0,0062	0,004166667	1,488	108,0217786
110	15	6,2	0,0062	0,004166667	1,488	108,0217786
120	15	6,2	0,0062	0,004166667	1,488	108,0217786
						112,8465727

Table 2C-3: Unmodified membrane biofouling experiments data against S. Aureus feed specifications (2)

FEED SPECIFICATIONS
Volume: 2L Broth + 4 x E.coli Broth 250 mL During Filtration
Conductivity= 11.45 mS
Temp= 21.3 °C
pH= 8.15

Table 2C-4: Unmodified membrane biofouling experiments data against S. Aureus (2)

	FEED			**BRINE**		**PERMEATE**				
Time (min)	EC (µS)	TDS(g/L)	Temp (°C)	EC (µS)	TDS(g/L)	EC (µS)	TDS(g/L)	Temp (°C)	Volume (mL)	Time interval (Δt) (s)
0	9740	6,6	22,8	10090	6,86	83,1	0,045	22,5	2,9	15
30	10480	6,9	24,3	10590	6,89	114,6	0,0781	22,9	2,8	15
60	10550	6,8	25,2	10830	7	134,5	0,0906	23	2,4	15
90	10630	6,88	25,6	11110	6,93	178,3	0,1198	24	2,5	15
120	10740	6,89	26,1	11250	6,95	174,9	0,1153	24,2	2,6	15
150	11200	7,1	26,3	11420	6,94	180,2	0,1185	24,2	2,4	15
180	11030	6,94	26,6	11400	6,94	205	0,1343	24,4	2,6	15
210	11460	6,98	26,9	11450	7,13	237,8	0,0731	24,3	2,3	15
240	10800	6,8	26,5	11330	7,04	238,1	0,0102	23,8	2,4	15

Table 2C- 5: Unmodified membrane biofouling experiments data against S. Aureus (3)

Time interval (Δt) (h)	**Volume (L)**	**Flow Rate (L/h)**	**Flux (L/m^2.h)**	**Normalized Flux**	**FDR**
0,004166667	0,0029	0,696	50,52631579	54,46736842	0,00%
0,004166667	0,0028	0,672	48,78402904	49,95484574	8,28%
0,004166667	0,0024	0,576	41,81488203	41,56399274	23,69%
0,004166667	0,0025	0,6	43,55716878	42,77313975	21,47%
0,004166667	0,0026	0,624	45,29945554	43,84987296	19,49%
0,004166667	0,0024	0,576	41,81488203	40,22591652	26,15%
0,004166667	0,0026	0,624	45,29945554	43,21568058	20,66%
0,004166667	0,0023	0,552	40,07259528	37,86860254	30,47%
0,004166667	0,0024	0,576	41,81488203	40,01684211	26,53%
			44,33151845	**43,7706957**	**19,64%**

Table 2C-6: Unmodified membrane biofouling experiments data against S. Aureus feed specifications (3)

FEED SPECIFICATIONS
Pure Water After Filtration
Volume = 15L
Temp =24.1°C
Conductivity= 5.4 µS

Table 2C-7: Unmodified membrane biofouling experiments data against S. Aureus (4)

Time (min)	**Time interval (Δt) (s)**	**Permeate V (mL)**	**Permeate V (L)**	**Time interval (Δt) (h)**	**Flow rate (L/h)**	**Flux (L/m^2.h)**	**FRR**
0	15	4	0,004	0,004166667	0,96	69,69147005	55,56%
10	15	4,2	0,0042	0,004166667	1,008	73,17604356	61,76%
20	15	4	0,004	0,004166667	0,96	69,69147005	60,61%
30	15	3,6	0,0036	0,004166667	0,864	62,72232305	52,94%
40	15	3,8	0,0038	0,004166667	0,912	66,20689655	57,58%
50	15	3,8	0,0038	0,004166667	0,912	66,20689655	57,58%
60	15	3,4	0,0034	0,004166667	0,816	59,23774955	53,13%
70	15	3,8	0,0038	0,004166667	0,912	66,20689655	61,29%
80	15	3,6	0,0036	0,004166667	0,864	62,72232305	59,02%
90	15	3,4	0,0034	0,004166667	0,816	59,23774955	53,97%
100	15	3,2	0,0032	0,004166667	0,768	55,75317604	51,61%
110	15	3,2	0,0032	0,004166667	0,768	55,75317604	51,61%
120	15	3	0,003	0,004166667	0,72	52,26860254	48,39%
						62,99036716	**55,77%**

- **0.2 mol/L Modified membrane ($M_{0.2\ mol/L}$)**

Table 2C-8: 0.2 mol/L membrane biofouling experiments data against S. Aureus feed specifications (1)

FEED SPECIFICATIONS
Pure Water Before Filtration
Volume = 15L
Temp =24.1°C
Conductivity= 4.8 µS

Table 2C-9: 0.2 mol/L membrane biofouling experiments data against S. Aureus (1)

Time (min)	**Time interval (Δt) (s)**	**Permeate V (mL)**	**Permeate V (L)**	**Time interval (Δt) (h)**	**Flow rate (L/h)**	**Flux (L/m^2.h)**
0	15	7	0,007	0,004166667	1,68	121,9600726
10	15	7,1	0,0071	0,004166667	1,704	123,7023593
20	15	7,1	0,0071	0,004166667	1,704	123,7023593
30	15	7,3	0,0073	0,004166667	1,752	127,1869328
40	15	6,8	0,0068	0,004166667	1,632	118,4754991
50	15	7	0,007	0,004166667	1,68	121,9600726
60	15	7	0,007	0,004166667	1,68	121,9600726
70	15	7,1	0,0071	0,004166667	1,704	123,7023593
80	15	6,8	0,0068	0,004166667	1,632	118,4754991
90	15	6,6	0,0066	0,004166667	1,584	114,9909256
100	15	6,7	0,0067	0,004166667	1,608	116,7332123
110	15	6,6	0,0066	0,004166667	1,584	114,9909256
120	15	6,5	0,0065	0,004166667	1,56	113,2486388
						120,0837638

Table 2C-10: 0.2 mol/L membrane biofouling experiments data against S. Aureus feed specifications (2):

FEED SPECIFICATIONS
Volume: 2L Broth + 4 x E.coli Broth 250 mL During Filtration
Conductivity= 5.12 mS
Temp= 21.8 °C
pH= 6.52

Table 2C-11: 0.2 mol/L membrane biofouling experiments data against S. Aureus (2)

	FEED			**BRINE**		**PERMEATE**				
Time (min)	**EC (µS)**	**TDS(g/L)**	**Temp (°C)**	**EC (µS)**	**TDS(g/L)**	**EC (µS)**	**TDS(g/L)**	**Temp (°C)**	**Volume (mL)**	**Time interval (Δt) (s)**
0	10120	6,8	23,6	10150	6,72	90,5	0,1315	22,2	2,8	15
30	10180	6,79	24	10450	6,67	165,7	0,1132	22,5	2,3	15
60	10300	7	24,2	10610	6,89	182,1	0,1245	22,9	2,2	15
90	10140	6,62	23	10000	6,45	209,6	0,1358	22,3	1,8	15
120	10390	6,84	24,3	10380	6,75	212,8	0,1469	22,4	2	15
150	10100	6,63	24,9	10490	6,75	204,7	0,1389	22,5	2,2	15
180	10290	6,69	24,8	10480	6,83	225,2	0,1525	22,6	2,4	15
210	10630	7,07	24,4	10670	6,87	301,8	0,1823	22,4	2,6	15
240	10600	7,02	24,7	10810	6,76	461,8	0,2453	22,3	2,8	15

Table 2C- 12: 0.2 mol/L membrane biofouling experiments data against S. Aureus (3)

Time interval (Δt) (h)	**Volume (L)**	**Flow Rate (L/h)**	**Flux (L/m^2.h)**	**Normalized Flux**	**FDR**
0,004166667	0,0028	0,672	48,78402904	51,17444646	0,00%
0,004166667	0,0023	0,552	40,07259528	41,47513612	18,95%
0,004166667	0,0022	0,528	38,33030853	39,40355717	23,00%
0,004166667	0,0018	0,432	31,36116152	33,58780399	34,37%
0,004166667	0,002	0,48	34,84573503	35,68203267	30,27%
0,004166667	0,0022	0,528	38,33030853	38,44529946	24,87%
0,004166667	0,0024	0,576	41,81488203	40,85313975	20,17%
0,004166667	0,0026	0,624	45,29945554	46,2507441	9,62%
0,004166667	0,0028	0,672	48,78402904	49,27186933	3,72%
			40,84694495	**41,793781**	**18,33%**

Table 2C-13: 0.2 mol/L membrane biofouling experiments data against S. Aureus feed specifications (3)

FEED SPECIFICATIONS
Pure Water After Filtration
Volume = 15L
Temp =24.3°C
Conductivity= 7.4 µS

Table 2C-14: 0.2 mol/L membrane biofouling experiments data against S. Aureus (4)

Time (min)	**Time interval (Δt) (s)**	**Permeate V (mL)**	**Permeate V (L)**	**Time interval (Δt) (h)**	**Flow rate (L/h)**	**Flux (L/m^2.h)**	**FRR**
0	15	4	0,004	0,004166667	0,96	69,69147005	57,14%
10	15	4,1	0,0041	0,004166667	0,984	71,43375681	57,75%
20	15	4,2	0,0042	0,004166667	1,008	73,17604356	59,15%
30	15	4,1	0,0041	0,004166667	0,984	71,43375681	56,16%
40	15	4,1	0,0041	0,004166667	0,984	71,43375681	60,29%
50	15	4,2	0,0042	0,004166667	1,008	73,17604356	60,00%
60	15	4,4	0,0044	0,004166667	1,056	76,66061706	62,86%
70	15	4,6	0,0046	0,004166667	1,104	80,14519056	64,79%
80	15	4,4	0,0044	0,004166667	1,056	76,66061706	64,71%
90	15	4,4	0,0044	0,004166667	1,056	76,66061706	66,67%
100	15	4,5	0,0045	0,004166667	1,08	78,40290381	67,16%
110	15	4,5	0,0045	0,004166667	1,08	78,40290381	68,18%
120	15	4,5	0,0045	0,004166667	1,08	78,40290381	69,23%
						75,05235237	**62,62%**

- **0.4 mol/L Modified membrane ($M_{0.4\ mol/L}$)**

Table 2C-15: 0.4 mol/L membrane biofouling experiments data against S. Aureus feed specifications (1)

FEED SPECIFICATIONS
Pure Water Before Filtration
Volume = 15L
Temp =24.3°C
Conductivity= 4.6 µS

Table 2C-16: 0.4 mol/L membrane biofouling experiments data against S. Aureus (1)

Time (min)	**Time interval (Δt) (s)**	**Permeate V (mL)**	**Permeate V (L)**	**Time interval (Δt) (h)**	**Flow rate (L/h)**	**Flux (L/m^2.h)**
10	15	7,1	0,0071	0,004166667	1,704	123,7023593
20	15	7,2	0,0072	0,004166667	1,728	125,4446461
30	15	7,2	0,0072	0,004166667	1,728	125,4446461
40	15	7,2	0,0072	0,004166667	1,728	125,4446461
50	15	7	0,007	0,004166667	1,68	121,9600726
60	15	6,9	0,0069	0,004166667	1,656	120,2177858
70	15	6,9	0,0069	0,004166667	1,656	120,2177858
80	15	6,9	0,0069	0,004166667	1,656	120,2177858
90	15	6,9	0,0069	0,004166667	1,656	120,2177858
100	15	6,9	0,0069	0,004166667	1,656	120,2177858
110	15	6,7	0,0067	0,004166667	1,608	116,7332123
120	15	6,7	0,0067	0,004166667	1,608	116,7332123
						121,5580064

Table 2C-17: 0.4 mol/L membrane biofouling experiments data against S. Aureus feed specifications (2)

FEED SPECIFICATIONS
Volume: 2L Broth + 4 x E.coli Broth 250 mL During Filtration
Conductivity= 12.45 mS
Temp= 23.3 °C
pH= 6.95

Table 2C-18: 0.4 mol/L membrane biofouling experiments data against S. Aureus (2)

	FEED			**BRINE**		**PERMEATE**				
Time (min)	EC (µS)	TDS(g/L)	Temp (°C)	EC (µS)	TDS(g/L)	EC (µS)	TDS(g/L)	Temp (°C)	Volume (mL)	Time interval (Δt) (s)
0	9510	6,29	24	9640	6,32	209,3	0,1406	23	2,1	15
30	9560	6,32	24,6	9680	6,29	148,7	0,0968	23,6	1,9	15
60	9500	6,4	25,4	9940	6,4	125,3	0,0837	23,8	1,9	15
90	9810	6,28	25,8	10030	6,28	146	0,09	24,1	2,4	15
120	10350	6,33	26,1	10100	6,33	146,2	0,0968	24,1	2	15
150	10030	6,34	26,6	10140	6,34	142	0,0939	24	2	15
180	10220	6,42	26,3	10320	6,42	170,8	0,1126	24	1,9	15
210	9850	6,28	26,5	10060	6,28	164,6	0,109	24	1,8	15
240	10280	6,36	26,9	10160	6,36	170,9	0,1137	23,8	1,6	15

Table 2C-19: 0.4 mol/L membrane biofouling experiments data against S. Aureus (3)

Time interval (Δt) (h)	**Volume (L)**	**Flow Rate (L/h)**	**Flux (L/m^2.h)**	**Normalized Flux**	**FDR**
0,004166667	0,0021	0,504	36,58802178	37,86860254	0,00%
0,004166667	0,0019	0,456	33,10344828	33,56689655	11,36%
0,004166667	0,0019	0,456	33,10344828	32,7062069	13,63%
0,004166667	0,0024	0,576	41,81488203	40,85313975	-7,88%
0,004166667	0,002	0,48	34,84573503	33,73067151	10,93%
0,004166667	0,002	0,48	34,84573503	33,24283122	12,22%
0,004166667	0,0019	0,456	33,10344828	31,84551724	15,91%
0,004166667	0,0018	0,432	31,36116152	30,01263158	20,75%
0,004166667	0,0016	0,384	27,87658802	26,42700544	30,21%
			34,07138536	**33,3615003**	**11,90%**

Table 2C-20: 0.4 mol/L membrane biofouling experiments data against S. Aureus feed specifications (3)

FEED SPECIFICATIONS
Pure Water After Filtration
Volume = 15L
Temp =24.3°C
Conductivity= 6.8.4 µS

Table 2C-21: 0.4 mol/L membrane biofouling experiments data against S. Aureus (4)

Time (min)	**Time interval (Δt) (s)**	**Permeate V (mL)**	**Permeate V (L)**	**Time interval (Δt) (h)**	**Flow rate (L/h)**	**Flux (L/m^2.h)**	**FRR**
0	15	7,1	0,0071	0,004166667	1,704	123,7023593	100,00%
10	15	5,6	0,0056	0,004166667	1,344	97,56805808	77,78%
20	15	6	0,006	0,004166667	1,44	104,5372051	83,33%
30	15	5,6	0,0056	0,004166667	1,344	97,56805808	77,78%
40	15	5,7	0,0057	0,004166667	1,368	99,31034483	81,43%
50	15	5	0,005	0,004166667	1,2	87,11433757	72,46%
60	15	4,8	0,0048	0,004166667	1,152	83,62976407	69,57%
70	15	5,1	0,0051	0,004166667	1,224	88,85662432	73,91%
80	15	4,8	0,0048	0,004166667	1,152	83,62976407	69,57%
90	15	4,7	0,0047	0,004166667	1,128	81,88747731	68,12%
100	15	4,8	0,0048	0,004166667	1,152	83,62976407	71,64%
110	15	4,6	0,0046	0,004166667	1,104	80,14519056	68,66%
120	15	4	0,004	0,004166667	0,96	69,69147005	57,33%
						90,86695519	**74,74%**

- **0.6 mol/L Modified membrane ($M_{0.6\ mol/L}$)**

Table 2C-22: 0.6 mol/L membrane biofouling experiments data against S. Aureus feed specifications (1)

FEED SPECIFICATIONS
Pure Water Before Filtration
Volume = 15L
Temp =24.3°C
Conductivity= 5.2 µS

Table 2C-23: 0.6 mol/L membrane biofouling experiments data against S. Aureus (1)

Time (min)	**Time interval (Δt) (s)**	**Permeate V (mL)**	**Permeate V (L)**	**Time interval (Δt) (h)**	**Flow rate (L/h)**	**Flux (L/m^2.h)**
0	15	7	0,007	0,004166667	1,68	121,9600726
10	15	7	0,007	0,004166667	1,68	121,9600726
20	15	7	0,007	0,004166667	1,68	121,9600726
30	15	6,8	0,0068	0,004166667	1,632	118,4754991
40	15	7	0,007	0,004166667	1,68	121,9600726
50	15	7	0,007	0,004166667	1,68	121,9600726
60	15	6,9	0,0069	0,004166667	1,656	120,2177858
70	15	6,9	0,0069	0,004166667	1,656	120,2177858
80	15	6,8	0,0068	0,004166667	1,632	118,4754991
90	15	6,8	0,0068	0,004166667	1,632	118,4754991
100	15	6,9	0,0069	0,004166667	1,656	120,2177858
110	15	6,7	0,0067	0,004166667	1,608	116,7332123
120	15	6,7	0,0067	0,004166667	1,608	116,7332123
						120,2177858

Table 2C-24: 0.6 mol/L membrane biofouling experiments data against S. Aureus feed specifications (2)

FEED SPECIFICATIONS
Volume: 2L Broth + 4 x E.coli Broth 250 mL During Filtration
Conductivity= 12.3 mS
Temp= 23.9 °C
pH= 8.2

Table 2C-25: 0.6 mol/L membrane biofouling experiments data against S. Aureus (2)

	FEED			**BRINE**		**PERMEATE**				
Time (min)	EC (µS)	TDS(g/L)	Temp (°C)	EC (µS)	TDS(g/L)	EC (µS)	TDS(g/L)	Temp (°C)	Volume (mL)	Time interval (Δt) (s)
0	8310	5,92	24	8200	5,11	192	0,0893	23,3	2,7	15
30	8700	6,11	24,2	8800	5,42	178,3	0,0954	23,5	2,5	15
60	9200	6,21	24,5	9630	6,1	159,6	0,1039	23,7	2,5	15
90	9820	6,32	24,8	10040	6,38	145,9	0,1098	23,9	2,4	15
120	9900	6,39	25,1	10170	6,7	141,9	0,1173	24,2	2,4	15
150	11100	7,05	25,3	10030	6,8	180,7	0,1298	24,4	2,4	15
180	11400	7,23	25,5	11200	6,81	187,6	0,1159	24,7	2,3	15
210	11600	7,36	25,8	11900	6,85	178,9	0,1206	24,9	2,3	15
240	11800	7,51	26,1	12300	6,92	156,9	0,1297	25,2	2,2	15

Table 2C-26: 0.6 mol/L membrane biofouling experiments data against S. Aureus (3)

Time interval (Δt) (h)	**Volume (L)**	**Flow Rate (L/h)**	**Flux (L/m^2.h)**	**Normalized Flux**	**FDR**
0,004166667	0,0027	0,648	47,04174229	48,68820327	0,00%
0,004166667	0,0025	0,6	43,55716878	44,77676951	8,03%
0,004166667	0,0025	0,6	43,55716878	44,29764065	9,02%
0,004166667	0,0024	0,576	41,81488203	42,10758621	13,52%
0,004166667	0,0024	0,576	41,81488203	41,68943739	14,37%
0,004166667	0,0024	0,576	41,81488203	41,43854809	14,89%
0,004166667	0,0023	0,552	40,07259528	39,47150635	18,93%
0,004166667	0,0023	0,552	40,07259528	39,15092559	19,59%
0,004166667	0,0022	0,528	38,33030853	37,10373866	23,79%
			42,00846945	**42,08048397**	**13,57%**

Table 2C-27: 0.6 mol/L membrane biofouling experiments data against S. Aureus feed specifications (3)

FEED SPECIFICATIONS
Pure Water After Filtration
Volume = 15L
Temp =24.3°C
Conductivity= 7.2 µS

Table 2C-28: 0.6 mol/L membrane biofouling experiments data against S. Aureus (4)

Time (min)	Time interval (Δt) (s)	Permeate V (mL)	Permeate V (L)	**Time interval (Δt) (h)**	**Flow rate (L/h)**	**Flux (L/m^2.h)**	**FRR**
0	15	5,2	0,0052	0,004166667	1,248	90,59891107	74,29%
10	15	5,1	0,0051	0,004166667	1,224	88,85662432	70,00%
20	15	4,9	0,0049	0,004166667	1,176	85,37205082	73,53%
30	15	5	0,005	0,004166667	1,2	87,11433757	71,43%
40	15	5	0,005	0,004166667	1,2	87,11433757	70,00%
50	15	4,9	0,0049	0,004166667	1,176	85,37205082	71,01%
60	15	4,9	0,0049	0,004166667	1,176	85,37205082	71,01%
70	15	4,9	0,0049	0,004166667	1,176	85,37205082	72,06%
80	15	4,9	0,0049	0,004166667	1,176	85,37205082	70,59%
90	15	4,8	0,0048	0,004166667	1,152	83,62976407	69,57%
100	15	4,8	0,0048	0,004166667	1,152	83,62976407	71,64%
110	15	4,8	0,0048	0,004166667	1,152	83,62976407	70,15%
120	15	4,7	0,0047	0,004166667	1,128	81,88747731	71,24%
						85,64009493	**71,27%**

- **0.8 mol/L Modified membrane ($M_{0.8\ mol/L}$)**

Table 2C-29: 0.8 mol/L membrane biofouling experiments data against S. Aureus feed specifications (1)

FEED SPECIFICATIONS
Pure Water Before Filtration
Volume = 15L
Temp =23.3°C
Conductivity= 5.1 µS

Table 2C-30: 0.8 mol/L membrane biofouling experiments data against S. Aureus (1)

Time (min)	**Time interval (Δt) (s)**	**Permeate V (mL)**	**Permeate V (L)**	**Time interval (Δt) (h)**	**Flow rate (L/h)**	**Flux (L/m^2.h)**
0	15	6,8	0,0068	0,004166667	1,632	118,4754991
10	15	6,7	0,0067	0,004166667	1,608	116,7332123
20	15	6,9	0,0069	0,004166667	1,656	120,2177858
30	15	7	0,007	0,004166667	1,68	121,9600726
40	15	7	0,007	0,004166667	1,68	121,9600726
50	15	7,1	0,0071	0,004166667	1,704	123,7023593
60	15	7	0,007	0,004166667	1,68	121,9600726
70	15	6,9	0,0069	0,004166667	1,656	120,2177858
80	15	6,9	0,0069	0,004166667	1,656	120,2177858
90	15	6,8	0,0068	0,004166667	1,632	118,4754991
100	15	6,8	0,0068	0,004166667	1,632	118,4754991
110	15	6,7	0,0067	0,004166667	1,608	116,7332123
120	15	6,7	0,0067	0,004166667	1,608	116,7332123
						119,9274047

Table 2C-31: 0.8 mol/L membrane biofouling experiments data against S. Aureus feed specifications (2)

FEED SPECIFICATIONS
Volume: 2L Broth + 4 x E.coli Broth 250 mL During Filtration
Conductivity= 13.1 mS
Temp= 23.1 °C
pH= 7.98

Table 2C-32: 0.8 mol/L membrane biofouling experiments data against S. Aureus (2)

	FEED			**BRINE**		**PERMEATE**				
Time (min)	EC (µS)	TDS(g/L)	Temp (°C)	EC (µS)	TDS(g/L)	EC (µS)	TDS(g/L)	Temp (°C)	Volume (mL)	Time interval (Δt) (s)
0	8820	6,2	23,3	8600	5,86	209,3	0,0937	22,8	2,8	15
30	9110	6,37	23,7	8930	6,22	180,9	0,0989	22,3	2,4	15
60	9260	6,49	23,9	9480	6,31	177,1	0,1026	21,9	2,4	15
90	9700	6,58	24,1	9920	6,46	165,2	0,1098	21,7	2,3	15
120	9940	6,79	24,4	10700	6,75	158,6	0,1129	21,4	2,4	15
150	10200	7,13	24,7	10980	6,9	149,6	0,1185	21,1	2,6	15
180	10800	7,39	24,9	11800	7,16	164,2	0,1207	20,8	2,6	15
210	11200	7,95	25,2	12100	7,34	153,9	0,1236	20,6	2,5	15
240	11900	8,21	25,5	13290	7,6	139,8	0,1286	20,9	2,5	15

Table 2C-33: 0.8 mol/L membrane biofouling experiments data against S. Aureus (3)

Time interval (Δt) (h)	**Volume (L)**	**Flow Rate (L/h)**	**Flux (L/m^2.h)**	**Normalized Flux**	**FDR**
0,004166667	0,0028	0,672	48,78402904	51,71107078	0,00%
0,004166667	0,0024	0,576	41,81488203	43,69655172	15,50%
0,004166667	0,0024	0,576	41,81488203	43,40384755	16,06%
0,004166667	0,0023	0,552	40,07259528	41,31484574	20,10%
0,004166667	0,0024	0,576	41,81488203	42,69299456	17,44%
0,004166667	0,0026	0,624	45,29945554	45,75245009	11,52%
0,004166667	0,0026	0,624	45,29945554	45,4353539	12,14%
0,004166667	0,0025	0,6	43,55716878	43,29582577	16,27%
0,004166667	0,0025	0,6	43,55716878	42,90381125	17,03%
			43,55716878	**44,46741682**	**14,01%**

Table 2C-34: 0.8 mol/L membrane biofouling experiments data against S. Aureus feed specifications (3)

FEED SPECIFICATIONS
Pure Water After Filtration
Volume = 15L
Temp =24.3°C
Conductivity= 6.2 µS

Table 2C-35: 0.8 mol/L membrane biofouling experiments data against S. Aureus (2)

Time (min)	**Time interval (Δt) (s)**	**Permeate V (mL)**	**Permeate V (L)**	**Time interval (Δt) (h)**	**Flow rate (L/h)**	**Flux (L/m^2.h)**	**FRR**
0	15	4,9	0,0049	0,004166667	1,176	85,37205082	72,06%
10	15	4,8	0,0048	0,004166667	1,152	83,62976407	71,64%
20	15	4,8	0,0048	0,004166667	1,152	83,62976407	69,57%
30	15	4,9	0,0049	0,004166667	1,176	85,37205082	70,00%
40	15	4,7	0,0047	0,004166667	1,128	81,88747731	67,14%
50	15	4,7	0,0047	0,004166667	1,128	81,88747731	66,20%
60	15	4,6	0,0046	0,004166667	1,104	80,14519056	65,71%
70	15	4,6	0,0046	0,004166667	1,104	80,14519056	66,67%
80	15	4,5	0,0045	0,004166667	1,08	78,40290381	65,22%
90	15	4,6	0,0046	0,004166667	1,104	80,14519056	67,65%
100	15	4,5	0,0045	0,004166667	1,08	78,40290381	66,18%
110	15	4,4	0,0044	0,004166667	1,056	76,66061706	65,67%
120	15	4,4	0,0044	0,004166667	1,056	76,66061706	65,67%
						80,94932291	**67,64%**

Appendix 2D: Organic and Inorganic Fouling Performance Against Sodium Bicarbonate and Humic Acid

Organic Fouling

- **Unmodified Membrane**

Table 2D-1: Unmodified membrane biofouling experiments data against Humic Acid feed specifications (1)

FEED SPECIFICATIONS
Pure Water Before Filtration
Volume = 15L
Temp =23.3°C
Conductivity= 4.9 µS

Table 2D-2: Unmodified membrane biofouling experiments data against Humic Acid (1)

Time (min)	Time interval (Δt) (s)	Permeate V (mL)	Permeate V (L)	Time interval (Δt) (h)	Flow rate (L/h)	Flux (L/m^2.h)
0	15	7	0,007	0,004166667	1,68	121,9600726
10	15	7,2	0,0072	0,004166667	1,728	125,4446461
20	15	6,8	0,0068	0,004166667	1,632	118,4754991
30	15	8,6	0,0086	0,004166667	2,064	149,8366606
40	15	7,8	0,0078	0,004166667	1,872	135,8983666
50	15	7,2	0,0072	0,004166667	1,728	125,4446461
60	15	7,8	0,0078	0,004166667	1,872	135,8983666
70	15	8	0,008	0,004166667	1,92	139,3829401
80	15	7,6	0,0076	0,004166667	1,824	132,4137931
90	15	7,6	0,0076	0,004166667	1,824	132,4137931
100	15	7,8	0,0078	0,004166667	1,872	135,8983666
110	15	8,2	0,0082	0,004166667	1,968	142,8675136
120	15	8	0,008	0,004166667	1,92	139,3829401
						133,4859696

Table 2D-3: Unmodified membrane biofouling experiments data against Humic Acid specifications (2)

FEED SPECIFICATIONS
Volume: 10L Humic acid (100 mg/L)
Conductivity= 253.7 µS
Temp= 22.0 °C
pH= 9.92

Table 2D-4: Unmodified membrane biofouling experiments data against Humic Acid (2)

	FEED			BRINE		PERMEATE			
Time (min)	EC (µS)	TDS(g/L)	Temp (°C)	EC (µS)	TDS(g/L)	EC (µS)	TDS(g/L)	Temp (°C)	Volume (mL)
0	38,9	0,0268	22	19,2	0,0127	1,9	0,0014	23,8	7,4
30	42,1	0,0269	24,9	42,8	0,0279	1,5	0,0012	23,9	7,4
60	43,7	0,0285	24,9	46,5	0,0295	1,7	0,0012	24,8	7,4
90	50,3	0,0321	25,9	56,1	0,032	2,1	0,0014	24,1	7,4
120	56	0,0359	26,3	59,5	0,0372	2,2	0,0015	24,2	7,4
150	64,3	0,0413	26,5	61,8	0,0402	2	0,0013	24,4	7,4
180	71,5	0,0452	26,6	78,2	0,0495	1,8	0,0013	24,1	7,3
210	74,9	0,0477	26,1	94,3	0,0586	2,3	0,0016	23,9	7
240	101,1	0,0648	25,7	109,9	0,0686	2,5	0,0016	23,8	7,2

Table 2D-5: Unmodified membrane biofouling experiments data against Humic Acid (3)

Time interval (Δt) (s)	Time interval (Δt) (h)	Volume (L)	Flow Rate (L/h)	Flux (L/m^2.h)	Normalized Flux	FDR
15	0,004166667	0,0074	1,776	128,9292196	142,9825045	0,00%
15	0,004166667	0,0074	1,776	128,9292196	129,3160073	9,56%
15	0,004166667	0,0074	1,776	128,9292196	129,3160073	9,56%
15	0,004166667	0,0074	1,776	128,9292196	125,5770599	12,17%
15	0,004166667	0,0074	1,776	128,9292196	124,0299093	13,26%
15	0,004166667	0,0074	1,776	128,9292196	123,3852632	13,71%
15	0,004166667	0,0073	1,752	127,1869328	121,3363339	15,14%
15	0,004166667	0,007	1,68	121,9600726	118,0573503	17,43%
15	0,004166667	0,0072	1,728	125,4446461	122,8103085	14,11%
		0,0066		**127,5741077**	**126,3123049**	**11,66%**

Table 2D-6: Unmodified membrane biofouling experiments data against Humic Acid feed specifications (3)

FEED SPECIFICATIONS
Pure After Filtration
Volume = 15L
Temp =24.1°C
Conductivity= 5.4 µS

Table 2D-7: Unmodified membrane biofouling experiments data against Humic Acid (4)

Time (min)	**Time interval (Δt) (s)**	**Permeate V (mL)**	**Permeate V (L)**	**Time interval (Δt) (h)**	**Flow rate (L/h)**	**Flux (L/m^2.h)**	**FRR**
0	15	7,1	0,0071	0,004166667	1,704	123,7023593	101,43%
10	15	7,2	0,0072	0,004166667	1,728	125,4446461	100,00%
20	15	7	0,007	0,004166667	1,68	121,9600726	102,94%
30	15	6,9	0,0069	0,004166667	1,656	120,2177858	80,23%
40	15	6,8	0,0068	0,004166667	1,632	118,4754991	87,18%
50	15	7,3	0,0073	0,004166667	1,752	127,1869328	101,39%
60	15	7,4	0,0074	0,004166667	1,776	128,9292196	94,87%
70	15	7,4	0,0074	0,004166667	1,776	128,9292196	92,50%
80	15	7,2	0,0072	0,004166667	1,728	125,4446461	94,74%
90	15	7,1	0,0071	0,004166667	1,704	123,7023593	93,42%
100	15	7,1	0,0071	0,004166667	1,704	123,7023593	91,03%
110	15	7,1	0,0071	0,004166667	1,704	123,7023593	86,59%
120	15	7,1	0,0071	0,004166667	1,704	123,7023593	88,75%
						124,2384476	**93,47%**

- **0.4 modified membrane ($M_{0.4\ mol/L}$)**

Table 2D-8: 0.4 mol/L modified membrane biofouling experiments data against Sodium Bicarbonate feed specifications (1)

FEED SPECIFICATIONS
Pure Water Before Filtration
Volume = 15L
Temp =24.3°C
Conductivity= 4.6 µS

Table 2D-9: 0.4 mol/L modified membrane biofouling experiments data against Sodium Bicarbonate (1)

Time (min)	**Time interval (Δt) (s)**	**Permeate V (mL)**	**Permeate V (L)**	**Time interval (Δt) (h)**	**Flow rate (L/h)**	**Flux (L/m^2.h)**
10	15	7,1	0,0071	0,004166667	1,704	123,7023593
20	15	7,2	0,0072	0,004166667	1,728	125,4446461
30	15	7,2	0,0072	0,004166667	1,728	125,4446461
40	15	7,2	0,0072	0,004166667	1,728	125,4446461
50	15	7	0,007	0,004166667	1,68	121,9600726
60	15	6,9	0,0069	0,004166667	1,656	120,2177858
70	15	6,9	0,0069	0,004166667	1,656	120,2177858
80	15	6,9	0,0069	0,004166667	1,656	120,2177858
90	15	6,9	0,0069	0,004166667	1,656	120,2177858
100	15	6,9	0,0069	0,004166667	1,656	120,2177858
110	15	6,7	0,0067	0,004166667	1,608	116,7332123
120	15	6,7	0,0067	0,004166667	1,608	116,7332123
						121,5580064

Table 2D-10: 0.4 mol/L modified membrane biofouling experiments data against Sodium Bicarbonate feed specifications (2)

FEED SPECIFICATIONS
Volume: 12L Humic acid (100 mg/L)
Conductivity= 254.5 µS
Temp= 23.0 °C
pH= 10.09

Table 2D-11: 0.4 mol/L modified membrane biofouling experiments data against Sodium Bicarbonate (2)

	FEED			**BRINE**		**PERMEATE**			
Time (min)	EC (µS)	TDS(g/L)	Temp (°C)	EC (µS)	TDS(g/L)	EC (µS)	TDS(g/L)	Temp (°C)	Volume (mL)
0	258,2	0,1739	23,1	257,9	0,1724	15,5	0,0104	22,8	8,8
30	267,5	0,178	23,6	274,6	0,182	15,2	0,0102	23	5,6
60	285,9	0,1894	24,1	294,7	0,1927	14,5	0,0097	23,2	5,6
90	306,8	0,201	24,4	309,9	0,2017	13,9	0,0093	23,2	5,1
120	328,5	0,2155	24,6	324,7	0,2105	13,1	0,0089	23,2	4,3
150	337,8	0,2242	24	332,2	0,22	12,4	0,0084	23,1	4
180	352,6	0,2346	23,6	354,3	0,2314	11,6	0,0078	23,1	4
210	371	0,2461	24	380,9	0,2481	11,4	0,0077	22,8	4
240	374,1	0,2464	24,9	370,2	0,2511	11,3	0,0076	22,9	3,5

Table 2D-12: 0.4 mol/L modified membrane biofouling experiments data against Sodium Bicarbonate (3)

Time interval (Δt) (s)	**Time interval (Δt) (h)**	**Volume (L)**	**Flow Rate (L/h)**	**Flux (L/m^2.h)**	**Normalized Flux**	**FDR**
15	0,004166667	0,0088	2,112	153,3212341	163,5937568	0,00%
15	0,004166667	0,0056	1,344	97,56805808	102,3488929	37,44%
15	0,004166667	0,0056	1,344	97,56805808	100,5926679	38,51%
15	0,004166667	0,0051	1,224	88,85662432	90,72261343	44,54%
15	0,004166667	0,0043	1,032	74,91833031	75,96718693	53,56%
15	0,004166667	0,004	0,96	69,69147005	72,13067151	55,91%
15	0,004166667	0,004	0,96	69,69147005	73,10635209	55,31%
15	0,004166667	0,004	0,96	69,69147005	72,13067151	55,91%
15	0,004166667	0,0035	0,84	60,9800363	61,16297641	62,61%
				86,92075015	**90,19508772**	**44,87%**

Table 2D-13: 0.4 mol/L modified membrane biofouling experiments data against Sodium Bicarbonate feed specifications (3)

FEED SPECIFICATIONS
Pure After Filtration
Volume = 15L
Temp =24.1°C
Conductivity= 5.2 µS

Table 2D-14: 0.4 mol/L modified membrane biofouling experiments data against Sodium Bicarbonate (4)

Time (min)	**Time interval (Δt) (s)**	**Permeate V (mL)**	**Permeate V (L)**	**Time interval (Δt) (h)**	**Flow rate (L/h)**	**Flux (L/m^2.h)**	**FRR**
0	15	4	0,004	0,004166667	0,96	69,69147005	56,34%
10	15	4,4	0,0044	0,004166667	1,056	76,66061706	61,11%
20	15	4,5	0,0045	0,004166667	1,08	78,40290381	62,50%
30	15	4,4	0,0044	0,004166667	1,056	76,66061706	61,11%
40	15	4,4	0,0044	0,004166667	1,056	76,66061706	62,86%
50	15	4,4	0,0044	0,004166667	1,056	76,66061706	63,77%
60	15	4,7	0,0047	0,004166667	1,128	81,88747731	68,12%
70	15	4,7	0,0047	0,004166667	1,128	81,88747731	68,12%
80	15	4,6	0,0046	0,004166667	1,104	80,14519056	66,67%
90	15	4,2	0,0042	0,004166667	1,008	73,17604356	60,87%
100	15	4,9	0,0049	0,004166667	1,176	85,37205082	73,13%
110	15	4,8	0,0048	0,004166667	1,152	83,62976407	71,64%
120	15	4,7	0,0047	0,004166667	1,128	81,88747731	67,36%
						78,67094793	**64,89%**

Inorganic Fouling

- **Unmodified membrane**

FEED SPECIFICATIONS
Pure Water Before Filtration
Volume = 20L
Temp =21.1°C
Conductivity= 4.1 µS

Time (min)	Time interval (Δt) (s)	Permeate V (mL)	Permeate V (L)	Time interval (Δt) (h)	Flow rate (L/h)	Flux (L/m^2.h)
0	15	6,2	0,0062	0,004166667	1,488	108,0217786
10	15	6,2	0,0062	0,004166667	1,488	108,0217786
20	15	6,2	0,0062	0,004166667	1,488	108,0217786
30	15	6,2	0,0062	0,004166667	1,488	108,0217786
40	15	6	0,006	0,004166667	1,44	104,5372051
50	15	6,2	0,0062	0,004166667	1,488	108,0217786
60	15	6,2	0,0062	0,004166667	1,488	108,0217786
70	15	6	0,006	0,004166667	1,44	104,5372051
80	15	6	0,006	0,004166667	1,44	104,5372051
90	15	6	0,006	0,004166667	1,44	104,5372051
100	15	6	0,006	0,004166667	1,44	104,5372051
110	15	6,2	0,0062	0,004166667	1,488	108,0217786
120	15	6,2	0,0062	0,004166667	1,488	108,0217786
						106,681558

FEED SPECIFICATIONS
Volume: 20L Humic Acid (100 mg/L)
Conductivity= 108.5 µS
Temp= 23.7 °C
pH= 8.54

	FEED			**BRINE**		**PERMEATE**				
Time (min)	EC (µS)	TDS (g/L)	Temp (°C)	EC (µS)	TDS (g/L)	EC (µS)	TDS (g/L)	Temp (°C)	Volume (mL)	Time interval (Δt) (s)
0	108,8	0,0707	22,6	109,6	0,0713	4,1	0,0027	23,3	6,4	15
30	114,8	0,0747	23,2	118,8	0,0773	5	0,0033	22,6	6,6	15
60	116,2	0,0775	24,1	123,5	0,0802	4,2	0,0027	22,8	7	15
90	126,8	0,0827	24,3	130,3	0,0874	4,2	0,0027	22,9	7,2	15
120	131,3	0,0856	24,6	135,4	0,0878	3,9	0,0027	22,9	6,4	15
150	140,1	0,0911	25,3	141,2	0,0921	4,2	0,0027	23,1	6,2	15
180	146,6	0,0952	25,3	150,8	0,0984	4,2	0,0028	23,1	6,2	15
210	153,4	0,1002	25,4	159,1	0,1036	5	0,0032	23,2	6,2	15
240	163,3	0,1065	25,4	168,9	0,11	4,4	0,0029	23,2	6,2	15

Time interval (Δt) (s)	**Time interval (Δt) (h)**	**Volume (L)**	**Flow Rate (L/h)**	**Flux (L/m^2.h)**	**Normalized Flux**	**FDR**
15	0,004166667	0,0064	1,536	111,5063521	121,0958984	0,00%
15	0,004166667	0,0066	1,584	114,9909256	122,3503448	-1,04%
15	0,004166667	0,007	1,68	121,9600726	125,7408348	-3,84%
15	0,004166667	0,0072	1,728	125,4446461	128,4553176	-6,08%
15	0,004166667	0,0064	1,536	111,5063521	113,067441	6,63%
15	0,004166667	0,0062	1,488	108,0217786	107,0495826	11,60%
15	0,004166667	0,0062	1,488	108,0217786	107,0495826	11,60%
15	0,004166667	0,0062	1,488	108,0217786	106,7255172	11,87%
15	0,004166667	0,0062	1,488	108,0217786	105,7533212	12,67%
				113,0550514	**115,2542045**	**4,82%**

FEED SPECIFICATIONS
Pure After Filtration
Volume = 15L
Temp =24.1°C
Conductivity= 5.4 µS

Time (min)	Time interval (Δt) (s)	Permeate V (mL)	Permeate V (L)	**Time interval (Δt) (h)**	**Flow rate (L/h)**	**Flux (L/m^2.h)**	**FRR**
0	15	7,3	0,0073	0,004166667	1,752	127,1869328	117,74%
10	15	7,5	0,0075	0,004166667	1,8	130,6715064	120,97%
20	15	7,4	0,0074	0,004166667	1,776	128,9292196	119,35%
30	15	7,3	0,0073	0,004166667	1,752	127,1869328	117,74%
40	15	7	0,007	0,004166667	1,68	121,9600726	116,67%
50	15	7,8	0,0078	0,004166667	1,872	135,8983666	125,81%
60	15	7,8	0,0078	0,004166667	1,872	135,8983666	125,81%
70	15	7,6	0,0076	0,004166667	1,824	132,4137931	126,67%
80	15	7,4	0,0074	0,004166667	1,776	128,9292196	123,33%
90	15	7,4	0,0074	0,004166667	1,776	128,9292196	123,33%
100	15	7,4	0,0074	0,004166667	1,776	128,9292196	123,33%
110	15	7,4	0,0074	0,004166667	1,776	128,9292196	119,35%
120	15	7,2	0,0072	0,004166667	1,728	125,4446461	116,13%
						129,3312858	**121,25%**

- **0.4 mol/L modified Membrane($M_{0.4\ mol/L}$)**

FEED SPECIFICATIONS
Pure Water Before Filtration
Volume = 15L
Temp =24.6°C
Conductivity= 4.6 µS

Time (min)	Time interval (Δt) (s)	Permeate V (mL)	Permeate V (L)	Time interval (Δt) (h)	Flow rate (L/h)	Flux (L/m^2.h)
10	15	7,1	0,0071	0,004166667	1,704	123,7023593
20	15	7,2	0,0072	0,004166667	1,728	125,4446461
30	15	7,2	0,0072	0,004166667	1,728	125,4446461
40	15	7,2	0,0072	0,004166667	1,728	125,4446461
50	15	7	0,007	0,004166667	1,68	121,9600726
60	15	6,9	0,0069	0,004166667	1,656	120,2177858
70	15	6,9	0,0069	0,004166667	1,656	120,2177858
80	15	6,9	0,0069	0,004166667	1,656	120,2177858
90	15	6,9	0,0069	0,004166667	1,656	120,2177858
100	15	6,9	0,0069	0,004166667	1,656	120,2177858
110	15	6,7	0,0067	0,004166667	1,608	116,7332123
120	15	6,7	0,0067	0,004166667	1,608	116,7332123
						121,5580064

FEED SPECIFICATIONS
Volume: 12L Sodium Bicarbonate (100 mg/L)
Conductivity= 127 µS
Temp= 23.7 °C
pH= 9.09

	FEED			**BRINE**		**PERMEATE**				
Time (min)	EC (µS)	TDS (g/L)	Temp (°C)	EC (µS)	TDS(g/L)	EC (µS)	TDS (g/L)	Temp (°C)	Volume (mL)	Time interval (Δt) (s)
0	124,7	0,0837	23,4	132,6	0,0876	5,6	0,0037	23,5	7,6	15
30	142,3	0,0937	24,5	146,1	0,0949	4	0,0027	23,9	7,6	15
60	157	0,101	25,4	163,8	0,1052	4,1	0,0027	24,3	7,6	15
90	179,8	0,114	26	183,9	0,1168	4	0,0026	24,6	8	15
120	204,9	0,13	26,3	212,8	0,1338	4,5	0,0029	24,8	7,4	15
150	199,2	0,1255	27	235,1	0,1467	4,3	0,0028	25,4	7,1	15
180	280,8	0,178	27,9	286,4	0,1779	5,5	0,0035	25,7	6,9	15
210	325,6	0,203	27,4	339,9	0,2097	5,3	0,0034	25,8	6,9	15
240	403,1	0,2501	27,6	414,8	0,2565	5,3	0,0035	25,8	9,7	15

Time interval (Δt) (s)	**Time interval (Δt) (h)**	**Volume (L)**	**Flow Rate (L/h)**	**Flux (L/m^2.h)**	**Normalized Flux**	**FDR**
15	0,004166667	0,0076	1,824	132,4137931	139,8289655	0,00%
15	0,004166667	0,0076	1,824	132,4137931	134,6648276	3,69%
15	0,004166667	0,0076	1,824	132,4137931	130,8248276	6,44%
15	0,004166667	0,008	1,92	139,3829401	135,3408348	3,21%
15	0,004166667	0,0074	1,776	128,9292196	124,0299093	11,30%
15	0,004166667	0,0071	1,704	123,7023593	116,6513249	16,58%
15	0,004166667	0,0069	1,656	120,2177858	110,3599274	21,08%
15	0,004166667	0,0069	1,656	120,2177858	112,0429764	19,87%
15	0,004166667	0,0097	2,328	169,0018149	156,4956806	-11,92%
				133,1881428	**128,9154749**	**7,80%**

FEED SPECIFICATIONS
Pure Water After Filtration
Volume = 15L
Temp =24.1°C
Conductivity= 5.2 µS

Time (min)	Time interval (Δt) (s)	Permeate V (mL)	Permeate V (L)	Time interval (Δt) (h)	Flow rate (L/h)	Flux (L/m^2.h)	FRR
0	15	4	0,004	0,004166667	0,96	69,69147005	56,34%
10	15	4,4	0,0044	0,004166667	1,056	76,66061706	61,11%
20	15	4,5	0,0045	0,004166667	1,08	78,40290381	62,50%
30	15	4,4	0,0044	0,004166667	1,056	76,66061706	61,11%
40	15	4,4	0,0044	0,004166667	1,056	76,66061706	62,86%
50	15	4,4	0,0044	0,004166667	1,056	76,66061706	63,77%
60	15	4,7	0,0047	0,004166667	1,128	81,88747731	68,12%
70	15	4,7	0,0047	0,004166667	1,128	81,88747731	68,12%
80	15	4,6	0,0046	0,004166667	1,104	80,14519056	66,67%
90	15	4,2	0,0042	0,004166667	1,008	73,17604356	60,87%
100	15	4,9	0,0049	0,004166667	1,176	85,37205082	73,13%
110	15	4,8	0,0048	0,004166667	1,152	83,62976407	71,64%
120	15	4,7	0,0047	0,004166667	1,128	81,88747731	67,36%
						78,67094793	**64,89%**

Appendix 3: Microbial Experiments Related Data

Appendix 3A: Bacterial Adhesions Test Data

Unmodified Membrane

Table 3A-1: Unmodified membranes antimicrobial tests data against E .coli

	Dilution Factor	N° of colonies on plate	Reciprocal of dilution sample	N° bacteria/mL
E. coli Blank (Broth Control)	1,00E-05	105	1,00E+05	1,05E+07
E. coli Blank (Broth Control) DUP	1,00E-05	124	1,00E+05	1,24E+07
AVERAGE				**1,15E+07**
E. coli in contact with the membrane	1,00E-06	9	1,00E+06	9,00E+06
E. coli in contact with the membrane DUP	1,00E-05	56	1,00E+05	5,60E+06
AVERAGE				**7,30E+06**

Table 3A- 2: Unmodified membranes antimicrobial tests data against S. aureus

	Dilution Factor	N° of colonies on plate	Reciprocal of dilution sample	N° bacteria/mL
S. Aureus Blank (Broth Control)	1,00E-05	81	1,00E+05	8,10E+06
S. Aureus Blank (Broth Control) DUP	1,00E-06	3	1,00E+06	3,00E+06
AVERAGE				**5,55E+06**
S. Aureus in contact with the membrane	1,00E-04	322	1,00E+04	3,22E+06
S. Aureus in contact with the membrane DUP	1,00E-05	23	1,00E+05	2,30E+06
AVERAGE				**2,76E+06**

Table 3A- 3: Summary antimicrobial tests unmodified membranes

	TOTAL	N° bacteria/mL
B	E. coli in solution (not in contact with membrane)	1,15E+07
A	E. coli in contact with the membrane	7,30E+06
B1	S. Aureus in solution (not in contact with membrane)	5,55E+06
A1	S. Aureus in contact with the membrane	2,76E+06

ADMH-Modified Membranes against E. coli

Table 3A- 4: Modified membranes antimicrobial tests data against E .coli

E. coli Blank (Broth Control)	Dilution Factor	N° of colonies on plate	Reciprocal of dilution sample	N° bacteria/mL
	1,00E-06	246	1,00E+06	2,46E+08
E. coli Blank (Broth Control) DUP	**Dilution Factor**	**N° of colonies on plate**	**Reciprocal of dilution sample**	**N° bacteria/mL**
	1,00E-05	180	1,00E+05	1,80E+07
	1,00E-06	92	1,00E+06	9,20E+07
AVERAGE				**1,19E+08**

0,2mol/L ADMH	Dilution Factor	N° of colonies on plate	Reciprocal of dilution sample	N° bacteria/mL
E. coli in contact with membrane	1,00E-05	81	1,00E+05	8,10E+06
0,2mol/ ADMH DUP1	**Dilution Factor**	**N° of colonies on plate**	**Reciprocal of dilution sample**	**N° bacteria/mL**
E. coli in contact with membrane DUP	1,00E-03	168	1,00E+03	1,68E+05
	1,00E-04	94	1,00E+04	9,40E+05
	1,00E-05	87	1,00E+05	8,70E+06
	1,00E-06	92	1,00E+06	9,20E+07
AVERAGE				**2,20E+07**

0,4mol/L ADMH	Dilution Factor	N° of colonies on plate	Reciprocal of dilution sample	N° bacteria/mL
E. coli in contact with membrane (saline water)	1,00E-05	155	1,00E+05	1,55E+07
0,4mol/L ADMH DUP1	**Dilution Factor**	**N° of colonies on plate**	**Reciprocal of dilution sample**	**N° bacteria/mL**
E. coli in contact with membrane (saline water) DUP1	1,00E-03	255	1,00E+03	2,55E+05
	1,00E-04	143	1,00E+04	1,43E+06
AVERAGE				**5,73E+06**

0,6mol/L ADMH	Dilution Factor	N° of colonies on plate	Reciprocal of dilution sample	N° bacteria/mL
E. coli in contact with membrane (saline water)	1,00E-04	210	1,00E+04	2,10E+06
0,6mol/L ADMH DUP1	**Dilution Factor**	**N° of colonies on plate**	**Reciprocal of dilution sample**	**N° bacteria/mL**
E. coli in contact with membrane (saline water) DUP1	1,00E-03	270	1,00E+03	2,70E+05
	1,00E-06	52	1,00E+06	5,20E+07
AVERAGE				**1,81E+07**

0,8 mol/L ADMH	Dilution Factor	N° of colonies on plate	Reciprocal of dilution sample	N° bacteria/mL
E. coli in contact with membrane (saline water)	1,00E-04	180	1,00E+04	1,80E+06
	1,00E-05	130	1,00E+05	1,30E+07
0,8mol/L ADMH DUP1	**Dilution Factor**	**N° of colonies on plate**	**Reciprocal of dilution sample**	**N° bacteria/mL**
E. coli in contact with membrane (saline water) DUP1	1,00E+06	92	1,00E+06	9,20E+07
AVERAGE				**3,56E+07**

Table 3A- 5: Summary Modified membranes antimicrobial tests data against E .coli

	TOTAL	N° bacteria/mL
B	E. coli in solution (not in contact with membrane)	1,19E+08
A1	E. coli in contact with membrane 0,2mol/L	2,20E+07
A2	E. coli in contact with membrane 0,4mol/L	5,73E+06
A3	E. coli in contact with membrane 0,6mol/L	1,81E+07
A4	E. coli in contact with membrane 0,8mol/L	3,56E+07

ADMH-Modified Membranes against S. aureus

Table 3A-6: Modified membranes antimicrobial tests data against S. aureus

Bacteria	Dilution factor	N° of colonies on plate	Reciprocal of dilution sample	N° bacteria/mL
S. Aureus Blank (Broth Control)	1,00E-05	71	1,00E+05	7,10E+06
S. Aureus Blank (Broth Control) DUP	1,00E-06	28	1,00E+06	2,80E+07
AVERAGE				1,76E+07

0,2mol/L ADMH	Dilution Factor	N° of colonies on plate	Reciprocal of dilution sample	
S. Aureus in contact with membrane (saline water)	1,00E-05	62	1,00E+05	6,20E+06
0,2mol/ ADMH DUP1	**Dilution Factor**	**N° of colonies on plate**		
S. Aureus in contact with membrane (saline water) DUP	1,00E-05	89	1,00E+05	8,90E+06
AVERAGE				7,55E+06

0,4mol/L ADMH	Dilution Factor	N° of colonies on plate	Reciprocal of dilution sample	
S. Aureus in contact with membrane (saline water)	1,00E-05	34	1,00E+05	3,40E+06
0,4mol/L ADMH DUP1	**Dilution Factor**	**N° of colonies on plate**		
S. Aureus in contact with membrane (saline water) DUP1	1,00E-04	92	1,00E+04	9,20E+05
AVERAGE				2,16E+06

0,6mol/L ADMH	Dilution Factor	N° of colonies on plate	Reciprocal of dilution sample	

S. Aureus in contact with membrane (saline water)	1,00E-04	102	1,00E+04	1,02E+06
0,6mol/L ADMH DUP1	**Dilution Factor**	**N° of colonies on plate**		
S. Aureus in contact with membrane (saline water) DUP1	1,00E-05	84	1,00E+05	8,40E+06
AVERAGE				4,71E+06

0,8 mol/L ADMH	**Dilution Factor**	**N° of colonies on plate**	**Reciprocal of dilution sample**	
S. Aureus in contact with membrane (saline water)	1,00E-05	112	1,00E+05	1,12E+07
0,8mol/L ADMH DUP1	**Dilution Factor**	**N° of colonies on plate**		
S. Aureus in contact with membrane (saline water) DUP1	1,00E-06	54	1,00E+05	5,40E+06
AVERAGE				8,30E+06

Table 3A-7: Summary modified membranes antimicrobial tests data against S. aureus

Membranes	**B**	**A**
Modified 0,2 mol/L	1,76E+07	7,55E+06
Modified 0,4 mol/L	1,76E+07	2,16E+06
Modified 0,6 mol/L	1,76E+07	4,71E+06
Modified 0,8 mol/L	1,76E+07	8,30E+06

Appendix 3B: Optical Density Study – Bacteria Growth Curves

The optical density of the microbes in broth was used to determine the growing microbial population of E. coli in nutrient broth during adhesion test. Observing the bacteria growth according to the growth curves of the bacteria. The same method was used for microbial feed preparation in biofouling test.

Growth curve based on OD for E. coli:

Table 3B-1: Optical density data for E. coli

Time (min)	E. Coli OD (ABS)	E. Coli OD DUP (ABS)
0	0	0
15	0,03	0,04
30	0,045	0,059
45	0,086	0,101
60	0,145	0,162
75	0,215	0,243
90	0,289	0,309
105	0,337	0,348
120	0,38	0,402
Corresponding CFU/mL After Plating Broth	1.05×10^7	1.24×10^7

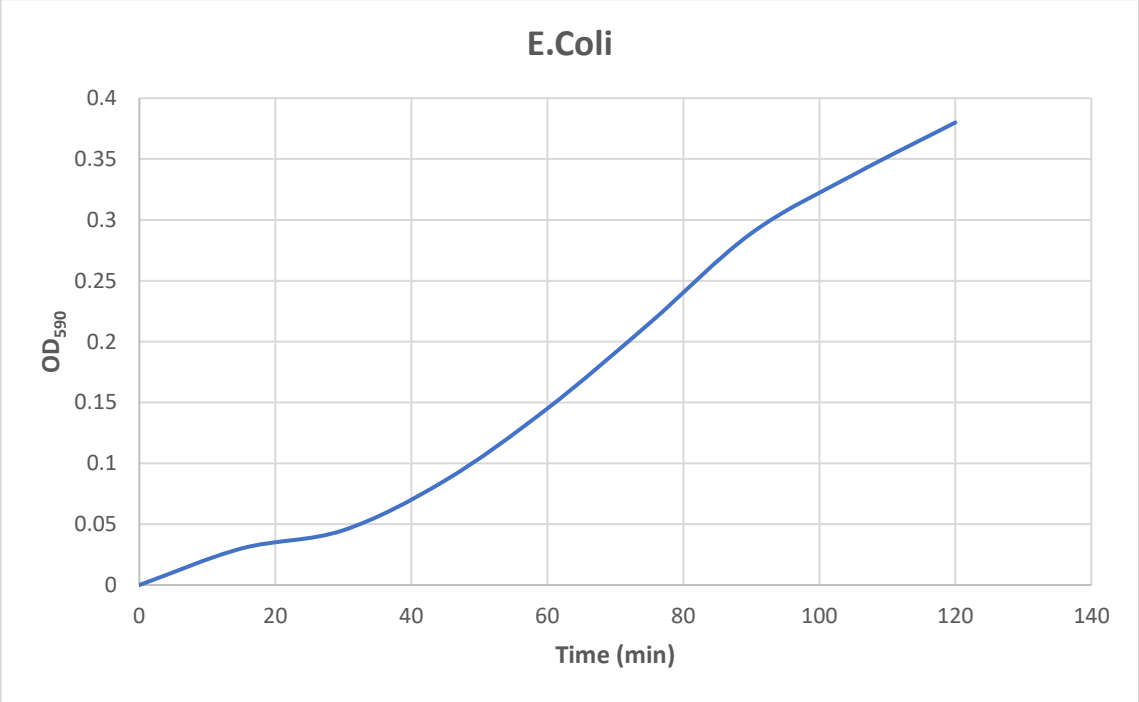


Figure 3B-1: Growth curve E. coli (1)

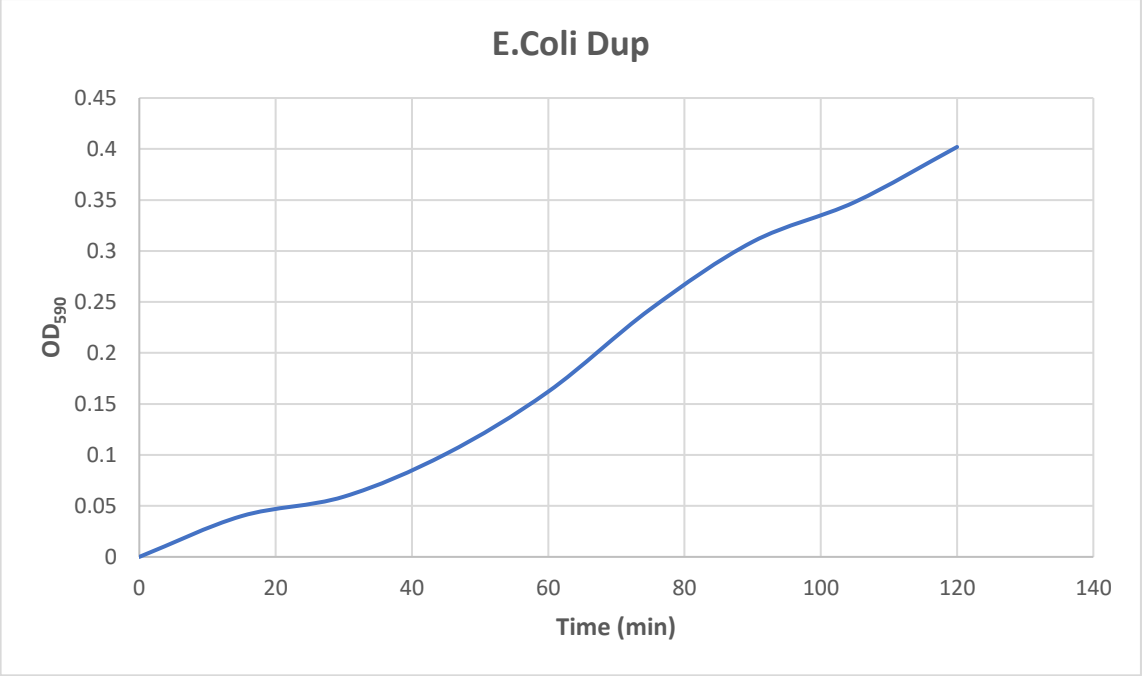


Figure 3B-2: Growth curve E. coli (2)

Growth curve based on OD for S. aureus:

Table 3B-2: Optical density data for S. aureus

Time	S. Aureus OD (ABS)	S. Aureus OD DUP (ABS)
0	0	0
60	0,042	0,045
90	0,042	0,046
120	0,045	0,047
Corresponding CFU/ mL After Plating Broth	$\mathbf{8.10 \times 10^6}$	$\mathbf{3.00 \times 10^6}$

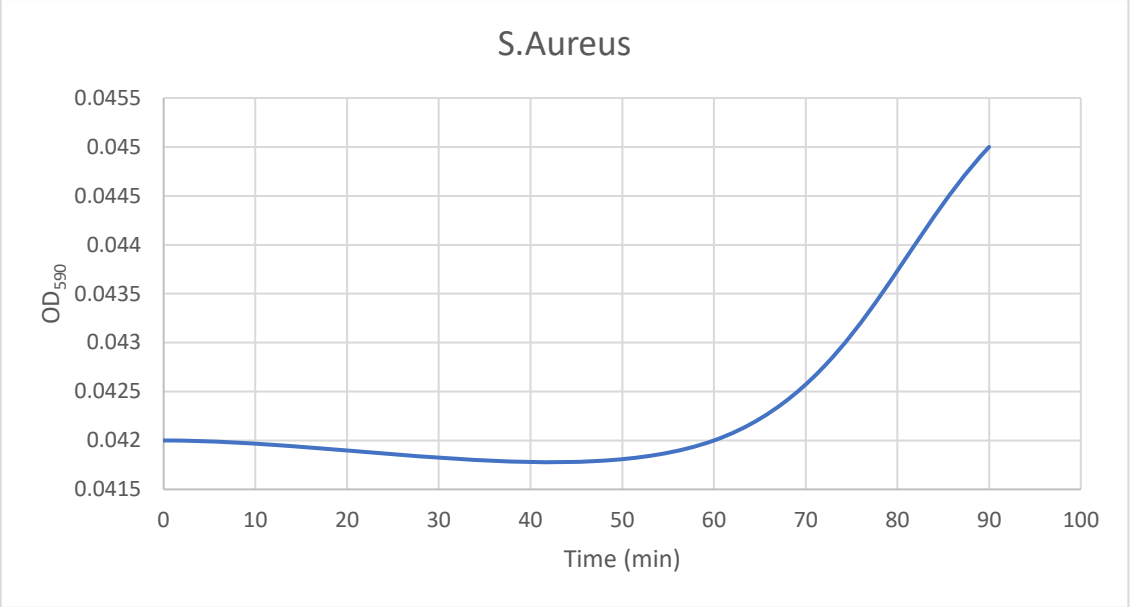


Figure 3B-3: Growth curve S. aureus (1)

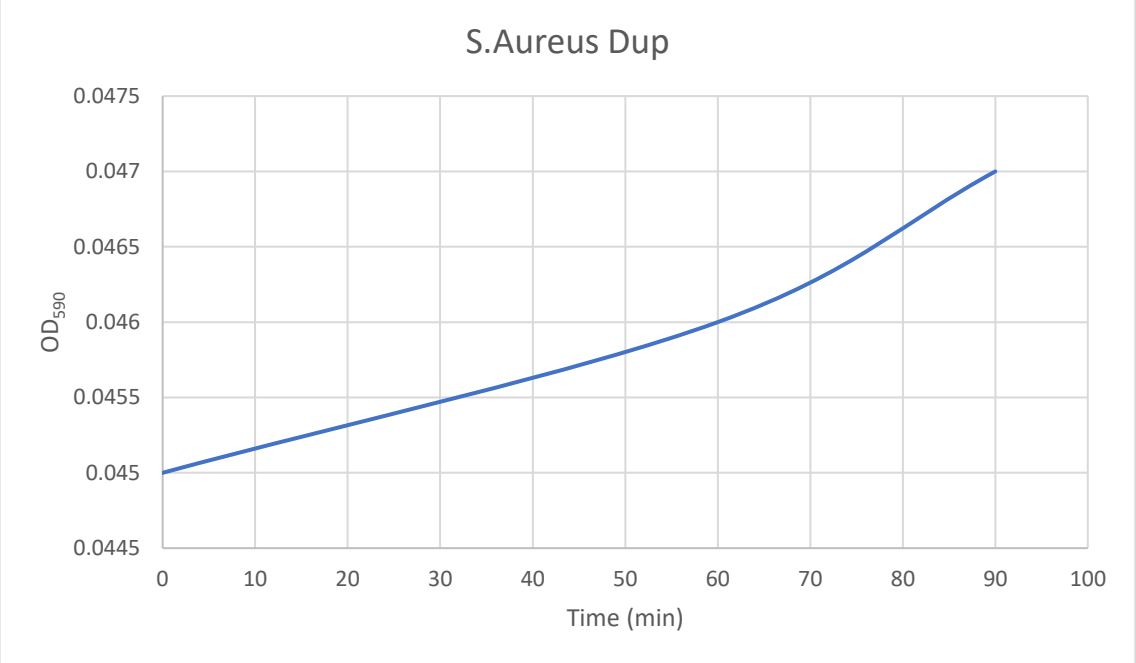


Figure 3B-4: Growth curve S. aureus (2)

Appendix 4: Design of Experiment Data

Appendix 4A: ANNOVA report for Biofouling Against E. coli

Response: FDR

ANOVA for Response Surface Cubic Model Analysis of variance table [Partial sum of squares]

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
Model	684.12	9	76.01	31.85	< 0.0001	significant
A	*32.52*	*1*	*32.52*	*13.63*	*0.0008*	
B	*53.73*	*1*	*53.73*	*22.51*	*< 0.0001*	
A^2	*22.07*	*1*	*22.07*	*9.25*	*0.0045*	
B^2	*9.89*	*1*	*9.89*	*4.15*	*0.0494*	
AB	*0.20*	*1*	*0.20*	*0.082*	*0.7762*	
A^3	*2.40*	*1*	*2.40*	*1.01*	*0.3228*	
B^3	*5.16*	*1*	*5.16*	*2.16*	*0.1502*	
A^2B	*9.17*	*1*	*9.17*	*3.84*	*0.0579*	
AB^2	*18.69*	*1*	*18.69*	*7.83*	*0.0083*	
Residual	83.53	35	2.39			
Lack of Fit	*61.75*	*34*	*1.82*	*0.083*	*0.9985*	*not significant*
Pure Error	*21.78*	*1*	*21.78*			
Cor Total	767.65	44				

The Model F-value of 31.85 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise.

Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case A, B, A^2, B^2, AB^2 are significant model terms.

Values greater than 0.1000 indicate the model terms are not significant.

If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model.

The "Lack of Fit F-value" of 0.08 implies the Lack of Fit is not significant relative to the pure error. There is a 99.85% chance that a "Lack of Fit F-value" this large could occur due to noise. Non-significant lack of fit is good -- we want the model to fit.

Std. Dev.	1.54	R-Squared	0.8912
Mean	6.63	Adj R-Squared	0.8632
C.V.	23.32	Pred R-Square	0.8022
PRESS	151.83	Adeq Precision	18.805

The "Pred R-Squared" of 0.8022 is in reasonable agreement with the "Adj R-Squared" of 0.8632.

"Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. Your ratio of 18.805 indicates an adequate signal. **This model can be used to navigate the design space.**

Appendix 4B: ANNOVA report for Biofouling against S aureus

Response: FDR

ANOVA for Response Surface Quadratic Model Analysis of variance table [Partial sum of squares]

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
Model	1605.80	5	321.16	5.50	0.0006	significant
A	*260.04*	*1*	*260.04*	*4.46*	*0.0412*	
B	*930.02*	*1*	*930.02*	*15.94*	*0.0003*	
A2	*65.21*	*1*	*65.21*	*1.12*	*0.2969*	
B2	*312.62*	*1*	*312.62*	*5.36*	*0.0260*	
AB	*3.43*	*1*	*3.43*	*0.059*	*0.8096*	
Residual	2275.33	39	58.34			
Lack of Fit	*2274.25*	*38*	*59.85*	*55.39*	*0.1062 not significant*	
Pure Error	*1.08*	*1*	*1.08*			
Cor Total	3881.14	44				

The Model F-value of 5.50 implies the model is significant. There is only a 0.06% chance that a "Model F-Value" this large could occur due to noise.

Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case A, B, B2 are significant model terms.
Values greater than 0.1000 indicate the model terms are not significant.
If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model.

The "Lack of Fit F-value" of 55.39 implies the Lack of Fit is not significant relative to the pure error. There is a 10.62% chance that a "Lack of Fit F-value" this large could occur due to noise. Non-significant lack of fit is good -- we want the model to fit.

Std. Dev.	7.64	R-Squared	0.4137
Mean	15.49	Adj R-Squared	0.3386
C.V.	49.32	Pred R-Square	0.2328
PRESS	2977.74	Adeq Precision	8.349

The "Pred R-Squared" of 0.2328 is in reasonable agreement with the "Adj R-Squared" of 0.3386.
"Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. Your ratio of 8.349 indicates an adequate signal. **This model can be used to navigate the design space.**