Enhancing forward osmosis

Practical aspects and development of binary draw solutions

Suleman, Muhammad

2025

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MUHAMMAD SULEMAN | CHEMICAL ENGINEERING | LUND UNIVERSITY

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LUND
UNIVERSITY

LICENTIATE DISSERTATION

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To be publicly defended on 21st November 2025 at 10:00 in KC:G,
at Kemicentrum, Naturvetarvägen 14, Lund, Sweden.

Opponent
Prof. Marie Wahlgren, Lund University, Sweden.

Organization: Lund University

Document name: Licentiate Thesis **Date of issue** 2025-11-25

Sponsoring organization: This work is part of DESOLINATION project, which has received funding from the European Union´s Horizon 2020 research and innovation programme under grant agreement No. 101022686.

Author(s): Muhammad Suleman

Title and subtitle: Enhancing forward osmosis – Practical aspects and development of binary draw solutions

Abstract:

Forward osmosis (FO) and membrane distillation (MD) have emerged as promising processes for seawater desalination. One of the key factors influencing the FO process is the selection of a suitable draw solution (DS), which should exhibit high osmotic pressure and easy regeneration through a secondary process such as MD. Thermo-responsive polymers having ethylene oxide (EO) and propylene oxide (PO) as hydrophilic and hydrophobic units respectively, represent a special class of draw solutes for the FO process.

The aim of the present study is to experimentally analyse and enhance the performance of the FO process while using different commercially available copolymers as draw solutes. In this work, three different commercially available thermo-responsive polymers - Unilube® 50MB-26, Polycerin® 55GI-2601 and Pluronic® L-35 - were evaluated as draw solutes for the FO process. Synthetic seawater containing 3.5 wt.% NaCl was used as the feed solution (FS).

Initially, a series of experiments were conducted to evaluate the effect of polymer type and their concentration on the FO water flux. The experimental findings indicated that the FO water flux and percent water recovery increase with the polymer concentration. Additionally, a novel approach was established where binary DSs composed of an inorganic salt and a copolymer were introduced to enhance the FO performance. Inorganic salts such as $MgCl_2$, $CaCl_2$ and NaCl were used to prepare the binary DSs. It was confirmed that the binary DSs synergistically combined thermo-responsive and ionic properties, improving overall FO performance.

The experimental results confirmed that the osmotic draw ability of the polymeric DSs increased with the addition of inorganic salts. Particularly, the binary DS composed of 0.7M NaCl and 65 wt.% Polycerin® 55GI-2601 yielded in a higher FO water flux of 10.13 LMH, compared to the maximum water flux of 2.5 LMH using solely polymer-based DS. Overall, the proposed binary DS concept yielded higher FO flux, offering an efficient strategy for FO desalination.

Key words: Forward osmosis, Membrane Distillation, hybrid process, Draw solutions, Copolymers, Binary draw solutions, Thermo-responsive polymers.

Classification system and/or index terms (if any) Supplementary bibliographical information

Language: English **Number of pages**: 54

ISSN and key title:

ISBN:978-91-8096-132-5

Recipient's notes Price Security classification

Signature Date 2025-10-17

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Front cover photo by Muhammad Suleman

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Lund University
Lund 2025

ISBN 978-91-8096-132-5
ISBN 978-91-8096-133-2

Printed in Sweden by Media-Tryck, Lund University,
Lund, 2025

Never give up, no matter how hard life gets no matter how much pain you feel. Pain will eventually subside, nothing remains forever, so keep going and don´t give up.

- Imran Khan

Acknowledgements

During my studies, I have always had the support of the people around me, and for that I am infinitely grateful.

First, I would like to express my deepest gratitude to my supervisor, Prof. Frank Lipnizki, for his valuable support, encouragement and guidance throughout my licentiate studies. I would also like to express my gratitude to my co-supervisors, Dr. Basel Al-Rudainy and Dr. Tobias Hey for their support and guidance.

I acknowledge the financial support provided from the European Union, without which this research would not have been possible. Thanks to all my colleagues in the DESOLINATION consortium.

I would like to thank all my colleagues at the Department of Process and Life Sciences Engineering for giving me such a warm welcome, and for creating such a wonderful working environment, especially my colleagues in the Membrane Group.

A special thanks to my office mate, Edvin Bågenhalm-Ruuth, for the great and deep discussions on everything except our own research topics. Without you, our office would not have been filled with great and fruitful discussions. To all my colleagues, thank you for the informal chats and interesting discussions we shared over fika. Many thanks to Medya Hatun Tanis and Mariona Battestini Vives for always stopping by our office and ask to join for fika.

I would like to extend my special thanks to my colleague Mikael Sjölin for helping me set up the pilot plants. A special thanks to Gity Yahoo and Maria Messer for taking care of the administration issues, which was not an easy task. Thanks to Mattias Alveteg, with whom I worked as a teaching assistant. Thanks to Basel Al-Rudainy for proofreading the popular science summary in Swedish.

I would like to express my most heartfelt thanks to my friends and family. I am especially grateful to my family, Ami, Abajan, and my siblings; their unwavering support made it possible for me to complete this study. Finally, to my Zainab, for being my greatest and most important supporter, and for always making me believe in myself, no matter what the circumstances.

This journey would have been much more difficult without all of you.

Thank you, Lund University and Sweden, for your kindness and hospitality!

Preface

This licentiate dissertation is the result of an EU-funded project carried out at the Department of Process and Life Sciences Engineering at Lund University. The research was conducted within the framework of the Horizon 2020 Research and Innovation Programme under Grant Agreement No. 101022686.

This licentiate thesis is a compilation of studies on forward osmosis (FO) using commercially available thermo-responsive polymers as draw solutes and a review article on the techniques to overcome the limitations of forward osmosis and membrane distillation (MD). The work, which included laboratory-scale FO experiments, led to Paper I, presented as the original manuscript. Additionally, the comprehensive literature review of FO and MD processes, including their potential hybrid configurations, resulted in a review paper, presented as Paper II.

Abstract

Forward osmosis (FO) and membrane distillation (MD) have emerged as promising processes for seawater desalination. One of the key factors influencing the FO process is the selection of a suitable draw solution (DS), which should exhibit high osmotic pressure and easy regeneration through a secondary process such as MD. Thermo-responsive polymers having ethylene oxide (EO) and propylene oxide (PO) as hydrophilic and hydrophobic units respectively, represent a special class of draw solutes for the FO process.

The aim of the present study is to experimentally analyse and enhance the performance of the FO process while using different commercially available copolymers as draw solutes. In this work, three different commercially available thermo-responsive polymers - Unilube® 50MB-26, Polycerin® 55GI-2601 and Pluronic® L-35 - were evaluated as draw solutes for the FO process. Synthetic seawater containing 3.5 wt.% NaCl was used as the feed solution (FS).

Initially, a series of experiments were conducted to evaluate the effect of polymer type and their concentration on the FO water flux. The experimental findings indicated that the FO water flux and percent water recovery increase with the polymer concentration. Additionally, a novel approach was established where binary DSs composed of an inorganic salt and a copolymer were introduced to enhance the FO performance. Inorganic salts such as $MgCl_2$, $CaCl_2$ and NaCl were used to prepare the binary DSs. It was confirmed that the binary DSs synergistically combined thermo-responsive and ionic properties, improving overall FO performance.

The experimental results confirmed that the osmotic draw ability of the polymeric DSs increased with the addition of inorganic salts. Particularly, the binary DS composed of 0.7M NaCl and 65 wt.% Polycerin® 55GI-2601 yielded in a higher FO water flux of 10.13 LMH, compared to the maximum water flux of 2.5 LMH using solely polymer-based DS. Overall, the proposed binary DS concept yielded higher FO flux, offering an efficient strategy for FO desalination.

Popular science summary

Seawater is the most abundant available source of water on Earth; however, it contains about 3.5 wt.% salts, mostly sodium chloride. This high salinity makes it unsuitable for drinking or irrigation purposes without salt removal. Forward osmosis (FO) is a desalination technique that can be used for this purpose.

Forward osmosis is a natural membrane-based process, where a feed stream, synthetic seawater in this case, is placed on one side of a semi-permeable membrane, while a solution with high solute concentration referred as draw solution (DS) is on the other side of the membrane. Due to the osmotic difference across the membrane, the water moves from feed side to the draw side, leaving the concentrated salt brine behind. The DS becomes diluted by the incoming water and therefore requires a secondary process for regeneration to make the FO process practically viable.

The advantage of FO is that it can operate at significantly lower hydraulic pressures than reverse osmosis or nanofiltration, thereby reducing the risk of membrane fouling. However, the additional step required for DS regeneration also consumes energy, which must be considered. Moreover, there is a tendency of reverse solute leakage from the draw side to the feed side. Despite these challenges, FO is particularly useful for treating salty brines or industrial wastewaters, or as part of the hybrid systems with thermal processes such as membrane distillation (MD) as the secondary process.

In this work, thermo-responsive polymers were used for the preparation of the DS. The term ‘thermo-responsive’ refers to materials that change their behaviour with temperature variations. Each thermo-responsive polymer has a unique property called lower critical solution temperature (LCST). At temperatures above the LCST, these polymers become insoluble in water, whereas below the LCST they are soluble in water. This unique property makes the thermo-responsive polymers suitable for use as DS in the FO process. Additionally, the larger molecular size of these polymers compared to the membrane pore size effectively eliminates reverse solute leakage in the FO process.

The key performance indicator of the FO process is water flux, which refers to the rate at which water passes through the membrane. Three different commercially available copolymers - Unilube® 50MB-26, Polycerin® 55GI-2601 and Pluronic® L-35 were used as draw solutes. The use of these polymers as DS resulted in lower water flux, therefore, a binary DS approach was developed, where inorganic salts were mixed with the aqueous polymer solution to enhance the osmotic potential and ultimately improve FO performance. Promising results were obtained using these binary DSs compared to the polymer-only DSs. However, a limitation of adding inorganic salts to the copolymer solution is an increase in viscosity of the DS.

Overall, the findings indicate that the use of binary DSs, presented in this study, could offer a promising strategy for developing more efficient and sustainable water purification systems based on FO.

Populärvetenskaplig sammanfattning

Havsvatten är den mest tillgängliga vattenkällan på jorden; det innehåller dock cirka 3.5 viktprocent salter, främst natriumklorid. Denna höga salthalt gör det olämpligt för dricksvatten eller bevattning utan avsaltning. Framåt-osmos (FO) är en avsaltningsmetod som kan användas för detta ändamål.

Framåt-osmos är en naturlig membranbaserad process, där en ström, i detta fall syntetiskt havsvatten, placeras på ena sidan av ett semipermeabelt membran, medan en lösning med hög löst koncentration, kallad draglösning (DS), finns på den andra sidan av membranet. På grund av det osmotiska tryckskillnaden över membranet rör sig vattnet från matningssidan till draglösningssidan, vilket lämnar den koncentrerade saltlösningen kvar. DS blir utspädd av det inkommande vattnet och kräver därför en sekundär process för regenerering för att göra FO-processen praktiskt genomförbar.

Fördelen med FO är att den kan fungera vid betydligt lägre hydrauliska tryck än omvänd osmos eller nanofiltrering, vilket minskar risken för membranbeläggning. Den extra processen som krävs för DS-regenerering förbrukar dock energi, vilket måste beaktas. Dessutom finns det en tendens till omvänd löstläckage från draglösningssidan till matningssidan. Trots dessa utmaningar är FO särskilt användbar för behandling av salta saltlösningar eller industriellt avloppsvatten, eller som en del av hybrida system med termiska processer, såsom membrandestillation (MD), som sekundär process.

I detta arbete användes termoresponsiva polymerer för framställning av DS. Begreppet "termoresponsiv" avser material som ändrar sitt beteende med temperaturvariationer. Varje termoresponsiv polymer har en unik egenskap som kallas nedre kritiska lösningstemperatur (LCST). Vid temperaturer över LCST blir dessa polymerer olösliga i vatten, medan de under LCST är lösliga i vatten. Denna unika egenskap gör de termoresponsiva polymererna lämpliga som DS i FO-processen. Dessutom eliminerar polymerernas större molekylstorlek jämfört med membranets porstorlek effektivt omvänt löstläckage i FO-processen.

Den viktigaste prestationsindikatorn för FO-processen är vattenflödet, vilket avser hastigheten med vilken vatten passerar genom membranet. Tre olika kommersiellt tillgängliga kopolymerer – Unilube® 50MB-26, Polycerin® 55GI-2601 och Pluronic® L-35 – användes som dragämnen. Användningen av dessa polymerer som DS resulterade i lägre vattenflöde, varför en binär DS-metod utvecklades, där oorganiska salter blandades med den vattenbaserade polymerlösningen för att öka det osmotiska potentialet och i slutändan förbättra FO-prestandan. Lovande resultat uppnåddes med dessa binära DS jämfört med polymer-enda DS. En begränsning med att tillsätta oorganiska salter till kopolymerlösningen är dock en ökad viskositet hos DS.

Sammanfattningsvis indikerar resultaten att användningen av binära DS, som presenteras i denna studie, kan erbjuda en lovande strategi för att utveckla mer effektiva och hållbara vattenreningssystem baserade på FO.

List of papers

This thesis comprises of the following articles, which will be referred to in the text by their Roman numerals.

Paper I **Suleman, M.;** Lipnizki, F.; Avci, A.H.; (2025). Advancing forward osmosis: Synergistic effects of thermo-responsive polymers and ionic liquids. (Manuscript submitted)

Paper II **Suleman, M.;** Al-Rudainy, B.; Lipnizki, F. Overcoming the Limitations of Forward Osmosis and Membrane Distillation in Sustainable Hybrid Processes Managing the Water–Energy Nexus. *Membranes* 2025, *15*,162. https://doi.org/10.3390/membranes15060162

My contribution to the papers

Paper I I designed and conducted all the experiments. I evaluated and interpreted the data received from all experiments. I drafted and wrote the manuscript and received comments from my co-authors.

Paper II I developed the concept together with the co-authors. I summarized and evaluated the literature and developed the schematic figures. I wrote the paper together with the co-authors.

Abbreviations

DS	Draw solution
EO	Ethylene oxide
ED	Electrodialysis
FO	Forward osmosis
FS	Feed solution
LCST	Lower critical solution temperature
MD	Membrane distillation
MVP	Mechanical vapour compression
NF	Nanofiltration
PO	Propylene oxide
PRO	Pressure retarded osmosis
PEO	Polyethylene oxide
PAG	Polyalkylene glycol
PPO	Polypropylene oxide
PEG	Polyethylene glycol
RO	Reverse osmosis

Symbols

A	Membrane area (m^2)
B	Membrane permeability coefficient (L m^{-2} h^{-1} bar^{-1})
J_w	Water flux (L m^{-2} h^{-1})
M	Solute molarity (mol. L^{-1})
n	Van't Hoff factor (-)
ΔP	Hydrostatic pressure difference (bar)
R	Universal gas constant (J mol^{-1} K^{-1})
T	Absolute temperature (K)
V_p	Volume of water permeated from feed side to draw side (L)
V_0	Initial feed solution volume (L)
ΔV_f	Change in feed volume (L)
Π	Osmotic pressure (bar)
$\Delta\Pi$	Osmotic pressure difference (bar)
Π_{DS}	Osmotic pressure of the draw solution (bar)
Π_{FS}	Osmotic pressure of the feed solution (bar)

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1 Introduction

The world´s growing population and climate change have stressed natural water resources, resulting in global freshwater scarcity [1]. According to a United Nations report, approximately 2.2 billion people lack access to safely managed freshwater [2]. To mitigate this freshwater shortage, one of the solutions is seawater desalination, which accounts for 60% of the water resources used in the desalination processes [3]. Desalination, the process of removing salt from seawater or brackish water, is now considered a promising solution to global freshwater scarcity.

Currently, reverse osmosis (RO), a pressure-driven membrane separation process, is the leading desalination technology, with more than half of the world´s desalination plants using RO [4]. This is due to its lower energy consumption and operational simplicity compared to thermal-based distillation processes [4]. Some of the thermal processes for seawater desalination include multi-stage flash distillation, multi-effect distillation, and MD, which require high maintenance and operating cost [5]. In addition to RO and MD, other membrane-based processes suitable for desalination include nanofiltration (NF), electrodialysis (ED), and FO. A classification of different desalination techniques based on their working principles is illustrated in Figure 1.

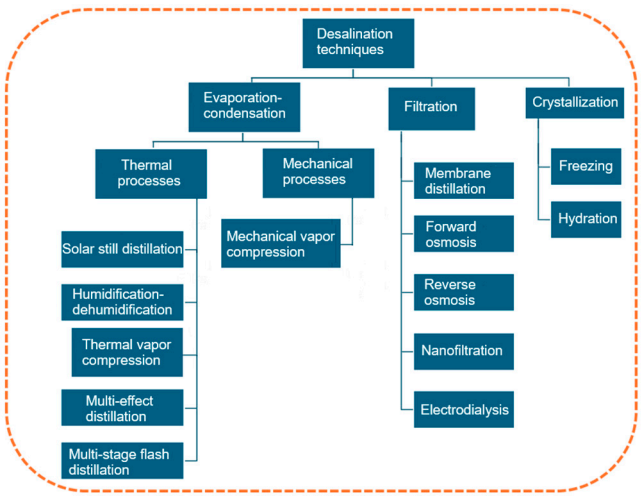

Figure 1. The classification of desalination technologies based on working principles (adapted from [6]).

Considering all the desalination processes, the process that has gained significant attention in the past decade is FO [7]. FO is a membrane separation process driven by the natural osmotic gradient across a semi-permeable membrane. Water moves from a solution with lower osmotic pressure to one with higher osmotic pressure. Unlike RO and NF, FO does not require significant hydraulic pressure, making it a comparatively low-energy consumption process [8]. The energy consumption of common desalination processes is listed in Table 1, highlighting the low energy demand of FO. In addition to its lower energy requirements, FO offers other attractive features such as lower fouling tendency due to lower hydraulic pressure compared to NF and RO [9], less frequency of membrane cleaning, which ultimately extends the FO membrane life cycle [10].

Due to the high solubility of the inorganic salts in water, they are commonly used as draw solutes in the FO process, enabling high osmotic pressure and elevated fluxes [11, 12]. However, literature also reports the use of organic compounds as draw solutes [13, 14]. These compounds are potentially beneficial for reducing the reverse solute flux due to their higher molecular weight compared to inorganic salts [15].

Among the organic compounds, thermo-responsive polymers represent a special class of regenerative draw solutes, owing to their unique property of becoming immiscible in water at temperatures above their lower critical solution temperature (LCST) [16]. In the present work, polyalkylene glycols (PAGs), which are thermo-responsive polymers, were used as draw solutes. PAGs are amphiphilic, containing both a hydrophilic segment (polyethylene oxide, also known as polyethylene glycol) and a hydrophobic segment (polypropylene oxide, also called polypropylene glycol).

Several thermo-responsive polymers have been investigated as potential DSs in the FO process [17-19]. However, the FO water flux achieved using these polymeric DSs is generally lower than that obtained with inorganic DSs [20, 21]. In a study by Xu et al. [21], FO performance was compared using 65 wt.% Pluronic® L-35 and 10 wt.% NaCl as DS, both having similar osmotic pressures (~100 bar). Seawater RO brine was used as FS. The water fluxes were 4.25 LMH and 1.22 LMH for 10 wt.% NaCl and 65 wt.% Pluronic® L-35 DS, respectively. This fourfold difference in FO water flux between a polymer-based and an electrolyte-based DS can be attributed to the higher molecular weight and viscosity of the polymer, which leads to more severe concentration polarization [22]. Nevertheless, thermo-responsive polymers offer other advantages such as lower reverse solute flux [12, 23-26] and easy regeneration via density-driven separation methods like decanters or coalescers [27, 28].

In this work, three different commercially available copolymers - Unilube® 50MB-26, Pluronic® L-35, and Polycerin® 55Gl-2601 - were investigated as DSs for FO applications. Subsequently, inorganic/polymer binary DSs were studied to evaluate

the combined effects of polymer concentration and salt additives (NaCl, $CaCl_2$ and $MgCl_2$) on FO performance. This approach aimed to synergistically combine the advantages of both the inorganic salts and thermo-responsive polymers. The main objective was to assess the enhancement in FO water flux achieved with binary DSs and to compare their draw ability against that of polymer-only DSs.

Table 1. Energy consumption in different desalination technologies.

Desalination technology	Plant capacity (m^3/day)	Energy consumption (kWh/m^3)	Ref.
RO	100,000 - 305,000	2.5 - 4.0	[29]
	NA	2.58 - 8.5	[30]
	128,000	4 – 6	[5]
MSF	50,000 - 70,000	19.58 - 27.25	[5]
MED	5,000 - 15,000	14.45 - 21.35	[5]
MVP	100 - 3,000	7 – 12	[5]
TVP	10,000 - 30,000	16.26	[5]
NF	NA	2.54 - 4.2	[31]
FO (Standalone)	NA	0.084 - 0.275	[32]
	NA	0.11	[10]
MD	1 - 15	1.58 - 2.63	[33]

MVP – mechanical vapor compression; TVC – thermal vapor compression.

1.1 Problem statement and research objectives

The growing shortage of potable water has led to considerable interest in seawater desalination, establishing it as a major research area. Among the various desalination techniques, FO and MD have shown significant potential for efficient water recovery. The DS is a critical component for efficient FO operation. Thermo-responsive polymers are a distinct type of organic draw solutes; however, the water flux achieved in FO using these polymers is generally lower than that obtained with inorganic draw solutes [21].

The main goal of this work was to provide proof-of-concept results for employing various commercially available copolymers as draw solutes, and to enhance FO performance by developing inorganic/polymer binary DSs and comparing their water flux with that of polymer-only DSs.

The specific objectives of this study are presented as follows:

- To review the literature on the limitations of standalone FO and MD processes and to examine strategies for developing a sustainable FO-MD hybrid process.

- To evaluate different commercially available copolymers as DSs for the FO process.
- To investigate the effect of DS type and their concentration on the FO water flux.
- To develop binary DSs composed of inorganic salts and thermo-responsive polymers.
- To operate the FO process using binary DSs and assess their water flux relative to polymer-based DSs.

1.2 Research methodology

The research approach adopted to fulfill these objectives of the current research is illustrated in three main steps in Figure 2. Firstly, a brief introduction and literature review was conducted, which resulted in Paper II. Next, three different commercially available copolymers - Unilube® 50MB-26, Polycerin® 55GI-2601 and Pluronic® L-35 - were tested as DSs for FO applications. Finally, binary DSs were developed to enhance the performance of the polymeric DSs, and their draw performance was compared with that of polymer-only DSs. Steps 2 and 3 together lead to the development of Paper I.

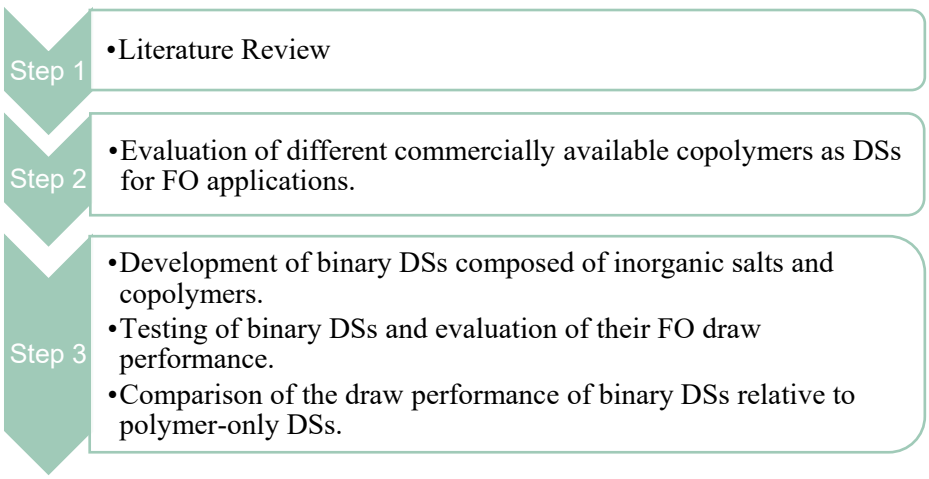

Figure 2. Research methodology of the present study.

1.3 Outline of current thesis

The topics covered in this thesis range from general aspects of FO and MD to specific challenges and opportunities related to DSs. Following the introduction and objectives presented in this chapter, Chapter 2 covers the theoretical and practical aspects of FO and MD. Moreover, Chapter 2 describes the types of DS, with particular focus on the thermo-responsive polymers implemented in the current work. Chapter 3 outlines the materials and methods used in this study. Chapter 4 presents the results of the FO experiments conducted with thermo-responsive polymers as DS, along with the results obtained using binary DSs. Additionally, the effect of inorganic salt addition on the viscosity of the aqueous polymer solution is discussed in Chapter 4. Finally, Chapters 5 and 6 present the conclusions and suggestions for future work.

2 Theoretical background

2.1 Forward Osmosis

Osmosis is the movement of water molecules across a semipermeable membrane from a region of lower solute concentration to one of higher solute concentration. The membrane allows only water molecules to pass, while rejecting solutes, and this process continues until osmotic equilibrium is reached. FO generally produces a much lower water flux than RO when using membranes of the same surface area [34]. Figure 3 illustrates the differences between RO and FO.

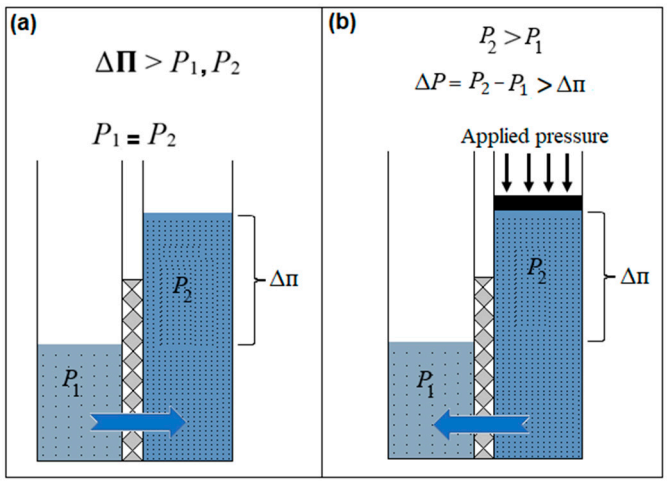

Figure 3. (a) FO, showing P_1 and P_2 as the hydraulic pressures of the dilute and concentrated solutions, respectively, and Δπ as the osmotic pressure difference. (b) RO, where P_1 and P_2 indicate the hydraulic pressures of the dilute and concentrated solutions, Δπ represents the osmotic pressure difference, and ΔP denotes the applied hydraulic pressure. Adapted from [35].

Osmotic pressure is defined as the minimum pressure required to prevent the osmotic flow of solvent molecules across a semipermeable membrane. It can be determined using both experimental and theoretical approaches. According to Van't Hoff's equation, osmotic pressure Π can be calculated as:

$$\Pi = nMRT \qquad (2.1)$$

where n is the Van't Hoff factor, M is the molarity of the solute, T is the absolute temperature, and R is the universal gas constant. It is important to note that Van't Hoff's equation is valid only for dilute solutions, where the solution behaves ideally.

2.1.1 FO theoretical model

The general equation describing the osmotic mass transport of water across a membrane is given by,

$$J_w = B(\Delta\Pi - \Delta P) \tag{2.2}$$

Equation 2.2 is applicable to any membrane-based osmotic process. In this equation, J_w represents the water flux, B is the membrane permeability coefficient, ΔΠ is the osmotic pressure difference, and ΔP denotes the hydrostatic pressure difference between the feed and draw solution. For FO, ΔP is set to zero, while ΔP = ΔΠ signifies osmotic equilibrium between the solutions. For pressure retarded osmosis (PRO), ΔΠ > ΔP whereas for RO, ΔP > ΔΠ [35].

$$J_w = B * \Delta\Pi \tag{2.3}$$

$$\Delta\Pi = \Pi_{DS} - \Pi_{FS} \tag{2.4}$$

Equation 2.3 and 2.4 represents the general simplified form for FO without accounting for the influence of internal concentration polarization and external concentration polarization. A graphical illustration of the distinctions between FO, RO, and PRO processes, along with their respective flux directions for an ideal semi-permeable membrane, is given in Figure 4.

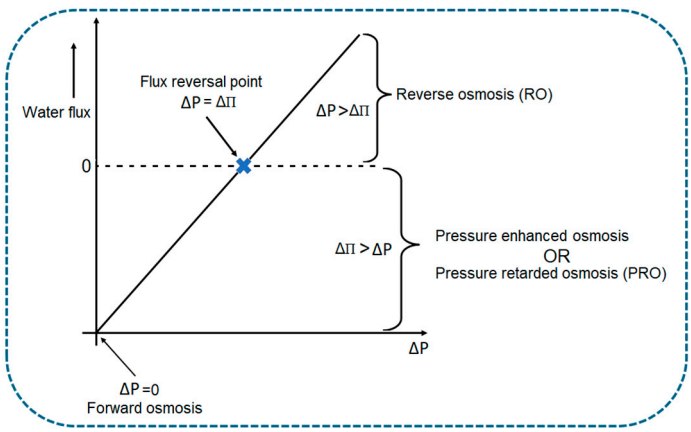

Figure 4. Differences in FO, RO, pressure enhanced osmosis, and PRO methods according to flux direction and pressure differential (Adapted from [36]).

2.2 Membrane distillation

MD is a purification technique that uses a porous, hydrophobic membrane to enable the transport of vapor across the membrane. The membrane separates the FS and permeate side, which are maintained at different temperatures. The vapor pressure gradient between the feed and permeate sides is responsible for vapor transport through the membrane pores. MD is commonly used for clean water production and for the concentration of solutions [37].

The MD process offers many appealing features, especially when integrated with low-grade heat source, such as: low operating pressure and temperature, simple membrane construction, minimal extra energy consumption when waste heat is available, theoretically 100% salt rejection, high potential for using low-grade energy sources, and no extensive pretreatment requirement [38-41].

Depending on the application, MD can be operated in four main configurations: vacuum membrane distillation, direct contact membrane distillation, sweeping gas membrane distillation, and air gap membrane distillation [42-45]. These configurations differ primarily in how the vapours are collected on the permeate side. Figure 5 (a-d) illustrates the fundamentals of these four MD configurations.

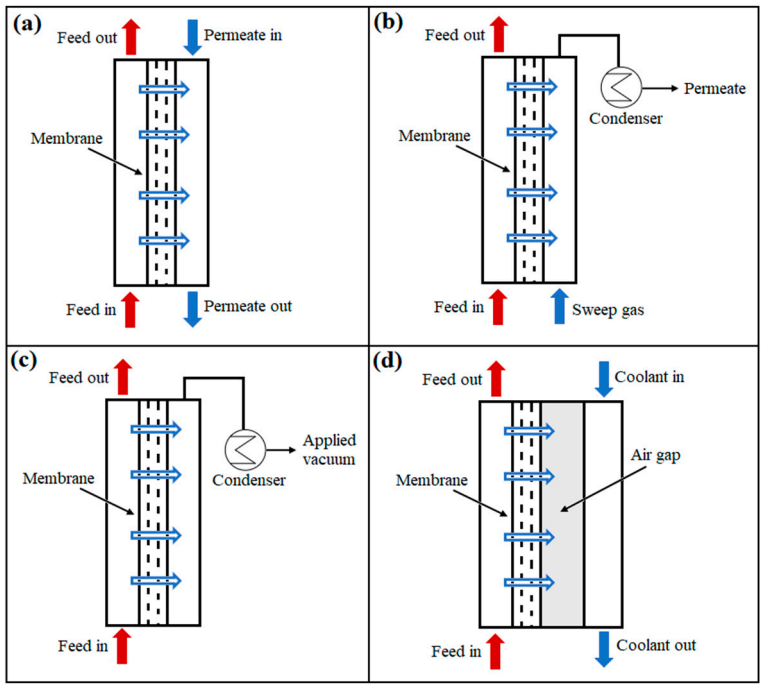

Figure 5. MD configurations; a: direct contact membrane distillation, b: sweeping gas membrane distillation, c: vacuum membrane distillation, d: air gap membrane distillation.

The integration of MD as a secondary process with FO to regenerate the DS and address the individual limitations of each standalone process is presented in detail in Paper II.

2.3 Draw solution

A major challenge in FO is the careful selection and regeneration of an appropriate DS. The performance of the FO process is largely determined by the choice of an optimal DS.

2.3.1 Characteristics of a DS

Selecting an appropriate DS requires careful consideration of several key factors. The most important criterion is high osmotic pressure, as the net FO flux is directly proportional to the osmotic gradient. According to Van't Hoff's equation (Equation 1), the osmotic pressure of an ideal solution depends on the Van't Hoff factor and the molar concentration, M. The nature of the solute does not influence the gas constant or temperature. Consequently, an effective DS must possess high solubility to generate sufficient osmotic pressure and achieve higher FO flux. NaCl and $MgCl_2$ are commonly used draw solutes due to their high water solubility, which leads to elevated osmotic pressures [35, 46, 47]. Compared to polymers or nanoparticles, the higher diffusion rates of NaCl and $MgCl_2$ make them more effective as draw solutes. Some of the key characteristics of an ideal DS are outlined in Figure 6.

Figure 6. Key characteristics of a DS.

2.3.2 Classification of draw solutes

Draw solutes can be classified according to their intrinsic properties or the methods used for their regeneration.

Inorganic salts

Inorganic salts are commonly used as draw solutes due to their high solubility in water, which enables greater osmotic pressures and enhanced water flux [11]. Among these, NaCl is the most widely used draw solute because of its high solubility, low viscosity even at high concentrations, and non-toxic nature [48]. Furthermore, NaCl is abundant, cost-effective, and can be readily reconcentrated using thermally driven membrane processes, such as MD, or pressure-driven processes, such as RO. Besides NaCl, other common inorganic salts used as draw solutes include $MgCl_2$, $CaCl_2$, KCl, KNO_3, and NH_4Cl etc [49-51].

Organic compounds

In addition to inorganic salts, organic compounds can also be considered as DSs for FO [52]. Polyacrylic acid sodium, aspartic acid, polyethyleneimine, dimethyl ether, and sodium polystyrene sulfonate are some of the organic compounds used as draw solutes for FO, reported in previous studies [52-56]. These compounds offer several advantages, including higher water flux and lower reverse solute flux, due to their relatively higher molecular weights compared to simple inorganic compounds [15].

Thermo-responsive polymers

Thermo-responsive polymers are a special class of organic compounds. Their ability to respond to temperature changes in aqueous solutions make them attractive draw solutes, as this property can simplify the regeneration process [57, 58]. These polymers possess a LCST, which governs their solubility in water. Below the LCST, they form a homogeneous, single-phase aqueous solution, whereas above this temperature, they undergo phase separation and become insoluble in water [15]. Following phase separation, the polymers can be concentrated using density-driven techniques such as decanters and coalescers.

Other categories of materials suitable for use as draw solutes include magnetic nanoparticles [14], highly charged ionic compound [59], and hydrogels [60], among others. All these types of draw solutes, along with their respective regeneration techniques, are presented in detail in Paper II.

3 Materials and methods

As a first step, experiments were conducted to compare the performance of HPC3205SI hollow fiber membrane module provided by Toyobo (Osaka, Japan) and HFFO®2 hollow fiber module (Aquaporin Inside®, Denmark). Unilube® 50MB-26 copolymer was used for these experiments. The aim was to identify a high-performance membrane for subsequent experimental studies. Following this, experiments were carried out to investigate the effects of polymer type and concentration on FO performance. Three different commercially available thermo-responsive polymers - Unilube® 50MB-26, Pluronic® L-35, and Polycerin® 55Gl-2601 - were evaluated in terms of DS performance for the FO process. These experiments were conducted using the Aquaporin Inside® hollow fibre R&D membrane module. Finally, the effects of binary DSs on FO water flux were investigated at laboratory scale.

3.1 Membranes

The following commercial hollow fiber membranes were utilized in the present study.

3.1.1 HPC3205SI hollow fiber membrane module

The cellulose triacetate (CTA) hollow fibre membrane module was provided by Toyobo (Osaka, Japan). The module was 830 mm long, with an outer fibre diameter of 200 µm and an inner fibre diameter of 105 µm. The effective membrane area was 31.5 m^2.

3.1.2 HFFO®2 hollow fiber membrane module

The HFFO®2 biomimetic hollow fiber membrane module comprising an active layer of polyamide thin film composite with integrated aquaporin proteins was provided by Aquaporin Inside® (Lyngby, Denmark). The element contains approximately 13,000 single hollow fibre membranes, with an internal fibre diameter of 0.20 mm and an effective membrane area of 2.3 m^2.

3.1.3 Hollow fiber R&D membrane module

The hollow fibre R&D module was provided by Aquaporin Inside® (Lyngby, Denmark). It is made of the same HFFO®2 material, with an internal fiber diameter of 0.2 mm, but has a much smaller effective membrane area of 400 cm^2. The lumen side of the membrane is composed of thin film composite embedded with Aquaporin proteins.

The experiments were conducted in FO mode, with the active layer facing the FS. Initially, DI water was flushed through the membranes for 1 hour to remove the storage liquid prior to use. The DS was circulated through the shell side of the hollow fibre membrane module, while the FS was passed through the active lumen side of the membrane.

Photographs of the hollow fibre membrane modules used in this study is shown in Figure 7.

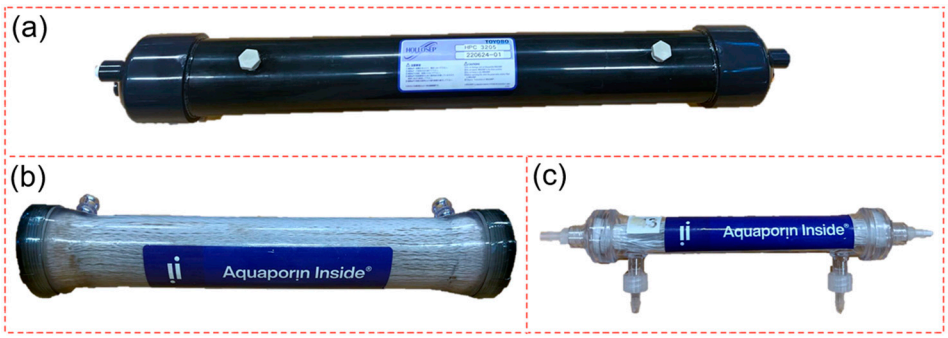

Figure 7. Membrane modules; (a) HPC3205SI (Toyobo, Japan), (b) HFFO®2 (Aquaporin, Denmark), (c) R&D membrane module (Aquaporin, Denmark).

3.2 Draw solution

Three different thermo-responsive polymers - Unilube® 50MB-26, Polycerin® 55GI-2601, and Pluronic® L-35 - were employed as DS. Unilube® 50MB-26 belongs to the class of PAG monobutyl ethers, consisting of a butyl end group attached to a random copolymer of EO and PO, with an EO content of approximately 50 wt.%. Pluronic® L-35 is a triblock copolymer composed of a central hydrophobic PO block flanked by two hydrophilic EO blocks. In contrast, Polycerin® 55Gl-2601 is a random copolymer incorporating EO, PO, and butylene oxide units. The incorporation of butylene oxide increases both the viscosity and hydrophobicity of this polymer compared with the other two. The key physicochemical properties of the copolymers are given in table 2, while the chemical structures of these polymers are described in detail in Paper I.

Commercial-grade samples of Unilube® 50MB-26, Pluronic® L-35, and Polycerin® 55Gl-2601 were procured from NOF Corporation (Tokyo, Japan), Kaimosi Biochemical Technology Co., Ltd. (Hangzhou, China), and Zhengzhou Alfa Chemical Co., Ltd. (Zhengzhou, China), respectively. $MgCl_2$, $CaCl_2$ and NaCl were obtained from Merck (Darmstadt, Germany).

To investigate the synergistic effects of salt addition on polymeric DSs, DSs with polymer concentrations of 50 wt.% and 80 wt.% were prepared using the three polymers. In addition, binary DSs were formulated by supplementing the same polymer concentrations with inorganic salts, namely $MgCl_2$, $CaCl_2$, and NaCl. This approach allowed for a direct comparison of draw performance between pure polymeric DSs and their corresponding binary DSs at the same polymer concentrations. The compositions and conductivities of the binary DSs evaluated in this study are summarized in Table 3.

Table 2. Key properties of the thermo-responsive polymers employed [61, 62].

	Unilube® 50MB-26	**Pluronic® L-35**	**Polycerin® 55Gl-2601**
Chemical structure	PEO-PPO	PEO-PPO-PEO	PEO-PPO-PBO
Type of polymer	Random	Block	Random
Molecular weight ($g.mol^{-1}$)	1850	1900	2600
Viscosity, Kinematic (mm^2/s)	310 at 20°C	375 at 25°C	560 at 20°C
PEG (wt.%)	50	50	50
LCST (°C)	50 (50 wt.% aqueous solution)	73 (1 wt.% aqueous solution)	68 (50 wt.% aqueous solution)

PEO – Polyethylene oxide; PPO – Polypropylene oxide; PEG – Polyethylene glycol.

Table 3. Compositions and conductivities of binary DSs.

DS composition	Conductivity (mS/cm)
50 wt.% Unilube® 50 MB-26 + 0.3M $MgCl_2$	6.18
65 wt.% Unilube® 50 MB-26 + 0.225M $MgCl_2$	2.17
80 wt.% Unilube® 50 MB-26 + 0.08M $MgCl_2$	0.07
50 wt.% Unilube® 50 MB-26 + 0.3M $CaCl_2$	6.22
65 wt.% Unilube® 50 MB-26 + 0.225M $CaCl_2$	2.06
80 wt.% Unilube® 50 MB-26 + 0.08M $CaCl_2$	0.101
50 wt.% Unilube® 50 MB-26 + 0.6M NaCl	8.06
80 wt.% Unilube® 50 MB-26 + 0.15M NaCl	0.199
50 wt.% Pluronic® L-35 + 0.8M $MgCl_2$	15.07
80 wt.% Pluronic® L-35 + 0.3M $MgCl_2$	0.502
50 wt.% Pluronic® L-35 + 0.8M $CaCl_2$	16.94
80 wt.% Pluronic® L-35 + 0.3M $CaCl_2$	0.676
50 wt.% Pluronic® L-35 + 1M NaCl	15.42
80 wt.% Pluronic® L-35 + 0.5M NaCl	0.853
50 wt.% Polycerin® 55GI-2601 + 0.6M $MgCl_2$	8.17
80 wt.% Polycerin® 55GI-2601 + 0.2M $MgCl_2$	0.149
50 wt.% Polycerin® 55GI-2601 + 0.6M $CaCl_2$	0.862
80 wt.% Polycerin® 55GI-2601 + 0.2M $CaCl_2$	0.172
50 wt.% Polycerin® 55GI-2601 + 1M NaCl	10.81
65 wt.% Polycerin® 55GI-2601 + 0.7M NaCl	0.262
80 wt.% Polycerin® 55GI-2601 + 0.4M NaCl	0.379

3.3 FO experimental setup

3.3.1 Pilot-scale FO setup

The initial experiments comparing the performance of the HPC3205SI and HFFO®2 hollow fiber membrane modules were performed on an FO pilot plant built by MembramProTec (Vimmerby, Sweden). During the FO experiments, the FS and DS were each used in a volume of 10 L. The experiments were conducted until osmotic equilibrium was reached. Circulation of the FS and DS were achieved using two independent vertical centrifugal pumps: VMSS 2/8 B obtained from SULZER (Wexford, Ireland). For the HFFO®2 module, the FS and DS flowrates were maintained at 60 L/h and 25 L/h, respectively. Similarly, in the HPC3205SI membrane module, the FS and DS flowrates were maintained at 40 L/h and 25 L/h, respectively, during the FO experimental operation.

Both the FS and DS were operated in recirculation mode i.e., they were contained in separate containers and pumped in a closed loop through the membrane. This allows the FS and DS to be reused and the concentrations to change over time as water permeates across the membrane. After each FO run, the membrane was rinsed

with DI water to remove any residual solutes. During rinsing, DI water was circulated through the feed and draw channels of the membrane at their respective flow rates. Rinsing continued until the conductivity in both channels reached below 10 µS/cm.

A photograph of the pilot scale FO setup located in the pilot hall at Lund University is shown in Figure 8.

Figure 8. Pilot-scale FO setup.

3.3.2 Laboratory-scale FO setup

The experimental setup used in Paper I is illustrated in Figure 9. For laboratory-scale experiments using the Aquaporin Inside® R&D module, the initial volumes of the FS and DS were 300 mL and 200 mL, respectively, and were kept constant throughout the experiments. A PL6001-L balance from Mettler-Toledo GmbH (Switzerland) was placed under the FS tank to record mass changes over time, allowing for the determination of FO flux. Circulation of the FS and DS was achieved using two independent peristaltic pumps: a WT600 (SANI Membranes A/S, Denmark) for the FS and a 530S (WATSON MARLOW Pumps, Cornwall, UK) for the DS. A magnetic stirrer was positioned at the base of the DS beaker to ensure uniform mixing. The FS and DS flow rates were maintained at 15 L/h and 6.6 L/h, respectively, as recommended by the membrane manufacturer.

After each experimental run, the membrane was rinsed with DI water until the conductivity on both the feed and draw sides reached below 10 µS/cm, ensuring complete removal of residual solutes. During membrane cleaning, the flowrates of the FS and DS were kept at 15 L/h and 6.6 L/h, respectively.

All FO experiments were carried out in triplicate, with samples collected from both the FS and DS before and after each run. FO experiments were conducted at a controlled temperature of 25°C to maintain consistent experimental conditions. Conductivity measurements of the FS and DS were recorded during the experiment.

After each FO experiment, a standard membrane performance test was conducted according to the membrane manufacturer's protocol. This involved running 500 ml of a 0.5 M NaCl DS against 500 ml of DI water as FS, until a water recovery of around 10% was obtained. Both the FS and DS were operated in a continuous recirculation mode. The water flux (J_w) was determined and compared it to the standard water flux of 11 ± 1.5 LMH specified by the membrane manufacturer for the same operating conditions.

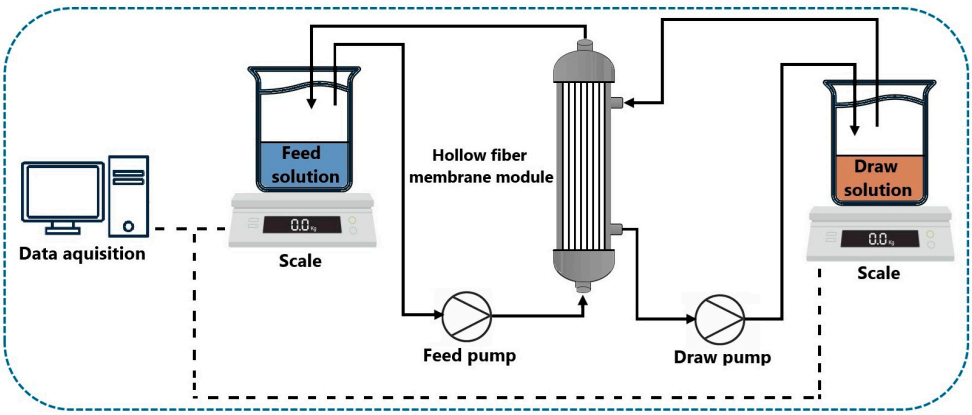

Figure 9. Schematic of the lab scale FO experimental setup.

A photograph of the laboratory scale FO setup located in the pilot hall at Lund University is shown in Figure 10.

Figure 10. Laboratory scale FO setup.

3.4 Membrane performance evaluation

The water flux (J_w) and percent water recovery were calculated to evaluate the membrane performance. Percent water recovery was defined as the ratio of the volume permeated from feed to the draw side (V_p) and the initial FS volume (V_o). The water flux and the percent water recovery (or percent volume reduction) were determined using the following equations:

$$J_w = \frac{\Delta V_f}{A * \Delta t} \tag{3.1}$$

$$\text{Percent water recovery} = \frac{V_p}{V_0} * 100 \tag{3.2}$$

In Equation 3.1, ΔV_f represents the change in the feed volume, A is the membrane area, Δt is the elapsed time in hours during which the change in feed volume (ΔV_f) was observed. In Equation 3.2, V_p refers to the volume of water permeated from FS to DS, while V_0 is the initial FS volume.

3.5 Viscosity measurements

The dynamic viscosity of the aqueous polymer solutions was obtained through a Modular Compact Rheometer (MCR 302, Anton Paar). The rheometer was equipped with a CC27 concentric cylindrical bob, featuring a bob diameter of 26.66 mm and a cup diameter of 28.92 mm. The shear rate was gradually increased from $0.1s^{-1}$ to $1000s^{-1}$ during the measurement process. Viscosity measurements were carried out at varying concentrations and temperatures in the aqueous polymer solutions. Viscosity experiments were conducted in duplicate, and the mean values along with their standard deviations are presented in Chapter 4.

4 Results and discussion

This section summarizes the key outcomes of the current work. The results concerning the effect of membrane type are presented in Section 4.1. Subsequently, the influence of polymer type and the polymer concentration on FO water flux and water recovery are discussed in Section 4.2. The development of binary DSs and their impact on FO performance are covered in Section 4.3. Finally, Section 4.4 examines how the addition of inorganic salts influences the viscosity of the aqueous polymer solution.

4.1 Effect of membrane type on FO water flux

Figure 11 presents the FO water flux results for the HPC3205SI hollow fibre membrane module provided by Toyobo and for the HFFO®2 hollow fibre module from Aquaporin. The FS consisted of 3.5 wt.% NaCl, while the DS contained 75 wt.% Unilube® 50MB-26. Both the FS and DS were operated in recirculation mode. The experiment was conducted until osmotic equilibrium was reached. As shown in Figure 11, the HFFO®2 hollow fibre module outperformed the HPC3205SI membrane module under identical experimental conditions. Consequently, the HFFO®2 membrane module was selected for the experimental study presented in Paper I.

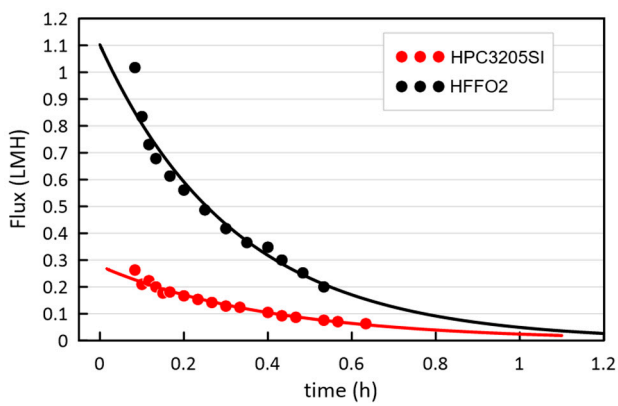

Figure 11. Comparison of HPC3205SI and HFFO®2 hollow-fibre membrane modules performance.

4.2 Types of copolymers investigated as DS

Three different thermo-responsive polymers - Unilube® 50MB-26, Pluronic® L-35 and Polycerin® 55Gl-2601, were evaluated for their DS performance in FO applications. The Aquaporin Inside® hollow fibre R&D membrane module was used throughout the experiments. Laboratory-scale experiments were conducted using 50 wt.% and 80 wt.% of the DS concentration against synthetic seawater containing 3.5 wt.% NaCl as FS.

4.2.1 Effect of polymer type and concentration on FO water flux

For polymers to exhibit LCST behaviour, a balance between the hydrophobicity and hydrophilicity interactions is essential. The effect of polymer type and their concentration on DS performance is summarized in Figure 12.

Among the three polymers, Pluronic® L-35 demonstrated the highest FO draw performance, achieving an FO water flux of 2.5 LMH at 80 wt.% DS concentration. Polycerin® 55Gl-2601 showed moderate flux behaviour, with an FO water flux of 1.625 LMH at 80 wt.% DS concentration. Unilube® 50MB-26 exhibited the lowest performance, achieving an FO water flux of only 0.495 LMH at a 50 wt.% DS concentration.

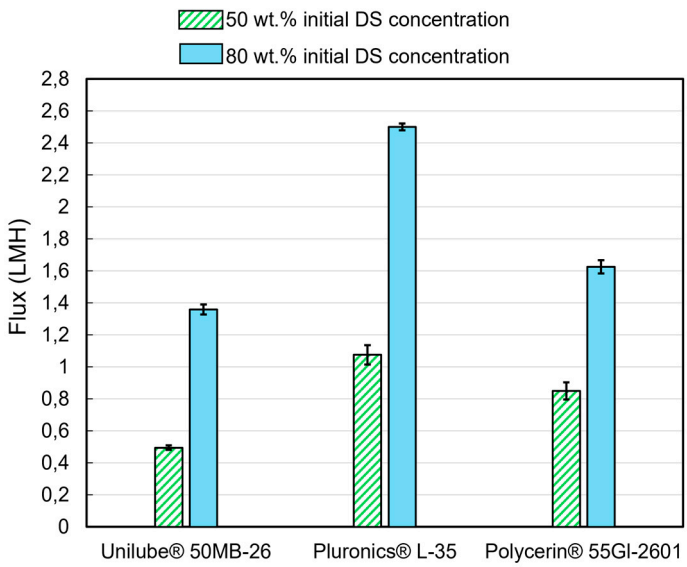

Figure 12. Effect of polymer type and concentration on the FO water flux.

As a function of concentration, higher DS concentration led to increased water flux [63], as shown in Figure 12. The osmotic gradient across the membrane is the driving force in FO, and at equal concentrations, the osmotic pressures of the polymers used in this study can be ranked as follows: Pluronic® L-35 > Polycerin® 55Gl-2601 > Unilube® 50MB-26 [61]. Therefore, the higher osmotic pressure of Pluronic® L-35 compared to the other two polymers lead to enhanced water flux.

4.2.2 Effect of polymer type and concentration on water recovery

The effect of polymer type and concentration on FO performance was further assessed in Paper I, based on percent water recovery as depicted in Figure 13. Water recovery (%) was measured at osmotic equilibrium, when the osmotic pressures on both sides of the FO membrane are assumed to be equal [64]. At an initial DS concentration of 50 wt.% and 80 wt.%, Unilube® 50MB-26 exhibited water recoveries that were approximately 41.54% and 21.33% lower, respectively, than those of Pluronic® L-35. In comparison, Pluronic® L-35 achieved water recoveries that were 15.33% and 22.99% higher than those of Polycerin® 55Gl-2601 at the same DS concentrations. The highest recorded water recovery was 49.27%, observed for Pluronic® L-35 at 80 wt.% concentration.

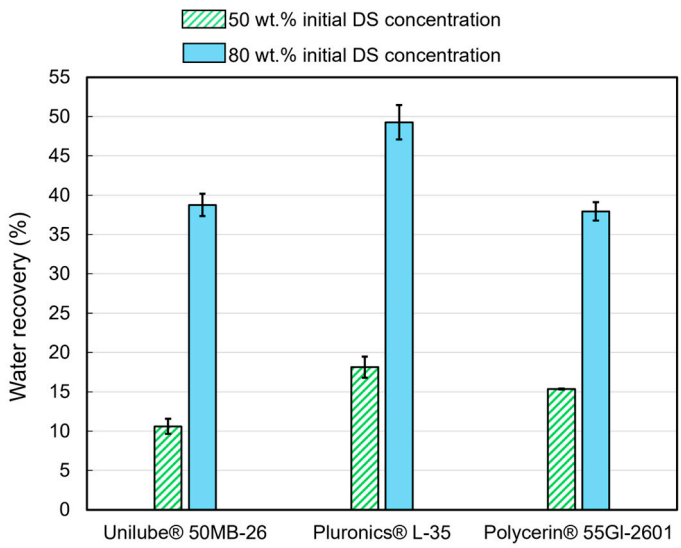

Figure 13. Effect of polymer type and concentration on percent water recovery.

Figure 14 illustrates the progression of FO water flux in relation to the corresponding water recovery rates. Over time, water permeating through the FO membrane dilutes the DS while simultaneously concentrating the FS. This process

reduces the osmotic gradient across the membrane and leads to a gradual decrease in water flux.

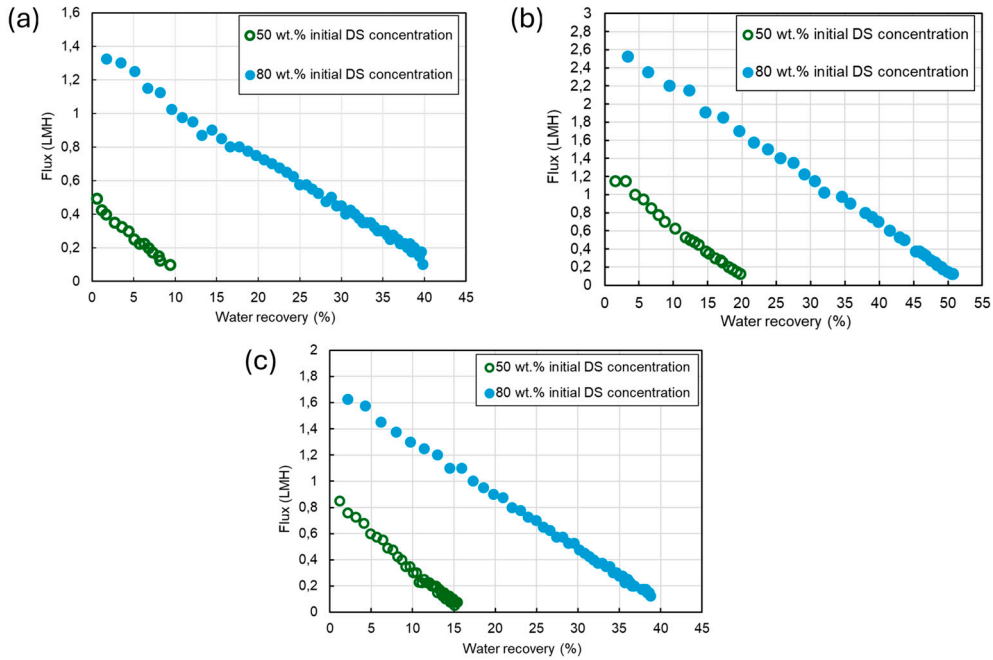

Figure 14. Water flux versus percent water recovery in FO: (a) Unilube® 50MB-26, (b) Pluronic® L-35 and (c) Polycerin® 55GI-2601.

4.3 FO performance of binary DSs

To assess the affinity of thermo-responsive polymers for inorganic salts at room temperature, the maximum solubility of the inorganic salts in aqueous polymer solutions was measured at different concentrations, with the aim of synergistically exploiting the high osmotic pressure of salts in binary DSs [65].

Polymeric DSs were prepared by dissolving the polymer in DI water under stirring for one hour. Inorganic salts were then added to obtain binary (polymer-salt) DSs, followed by an additional hour of stirring before measurement. To minimize aggregate formation, inorganic salts were introduced only after complete dissolution of the polymer in DI water [66].

4.3.1 Unilube® 50MB-26

The synergistic effect on FO water flux resulting from the combined use of Unilube® 50MB-26 and inorganic salts as draw solutes is illustrated in Figure 15. Binary DS demonstrated higher FO water flux compared to the polymer-only DS. At 50 wt.% Unilube® 50MB-26 with 0.3M $MgCl_2$, the FO water flux was 3.89 LMH, increasing slightly to 4.48 LMH for 0.3M $CaCl_2$. However, at 50 wt.% Unilube® 50MB-26 with 0.6M NaCl, the flux reached its maximum value of 5.66 LMH, indicating significantly better performance for NaCl compared to divalent salts at the same polymer concentration. This enhanced flux associated with NaCl-based binary DS can be attributed to the higher solubility and osmotic pressure of NaCl, which strongly influences the water transport through the FO membrane.

Increasing the Unilube® 50MB-26 concentration to 65 wt.% resulted in a slight improvement in water flux for $MgCl_2$ and $CaCl_2$. Specifically, water flux increased to 4.63 LMH and 4.12 LMH for 65 wt.% of Unilube® 50MB-26 combined with 0.225M $MgCl_2$ and $CaCl_2$, respectively.

At 80 wt.% polymer concentration, FO water flux decreased for all three inorganic salts, likely due to reduced salt solubility at higher polymer concentrations, which lowers the osmotic pressure, and the increased polymer viscosity causing severe concentration polarization [21, 67]. At 80 wt.% Unilube® 50MB-26, the observed flux was 2.98 LMH for 0.08M $MgCl_2$, representing the lowest flux recorded across all tested conditions. Similarly, $CaCl_2$ at 0.08M resulted in a reduced flux of 3.29 LMH. In case of NaCl, at 80 wt.% Unilube® 50MB-26 with 0.15M NaCl, a water flux of 3.58 LMH was achieved. While this value is lower than at 50 wt.% polymer concentration, it remains higher than the fluxes observed with divalent salts under the same polymer concentration.

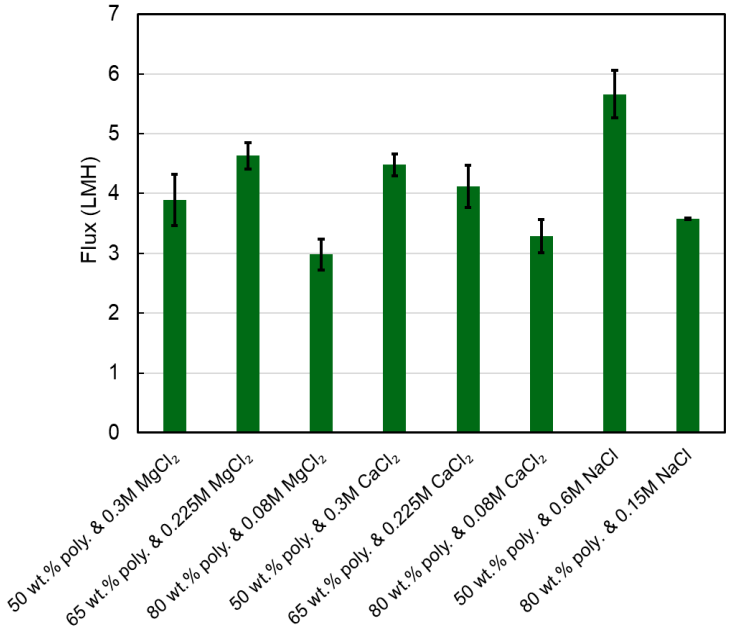

Figure 15. Water flux for FS with 3.5 wt.% NaCl and various Unilube® 50MB-26-based binary DS compositions.

4.3.2 Pluronic® L-35

Figure 16 shows the FO water flux for binary DSs based on Pluronic® L-35. Increasing salt concentration had a greater impact on flux than increasing polymer concentration. For instance, 80 wt.% Pluronic® L-35 with 0.3M $MgCl_2$ yielded 5.06 LMH, whereas 50 wt.% Pluronic® L-35 with 0.8M $MgCl_2$ reached 7.5 LMH. A similar trend was observed with $CaCl_2$.

When NaCl was used as a supplement salt in Pluronic® L-35-based DSs, water flux values were significantly higher than those observed with divalent salts. With 50 wt.% Pluronic® L-35 and 1M NaCl, the flux reached a maximum of 9.83 LMH, reflecting NaCl's superior solubility at lower polymer concentrations and its positive impact on DS performance. Similarly, at 80 wt.% Pluronic® L-35 with 0.5M NaCl, the flux remained relatively high at 7.45 LMH. However, it should be noted that enhancing polymeric DS performance with NaCl restricts regeneration options to processes such as MD and RO, since commercial NF and ultrafiltration membranes exhibit very low NaCl rejections [68]. Overall, NaCl addition to polymeric DSs consistently outperformed $CaCl_2$ and $MgCl_2$, regardless of polymer type or concentration.

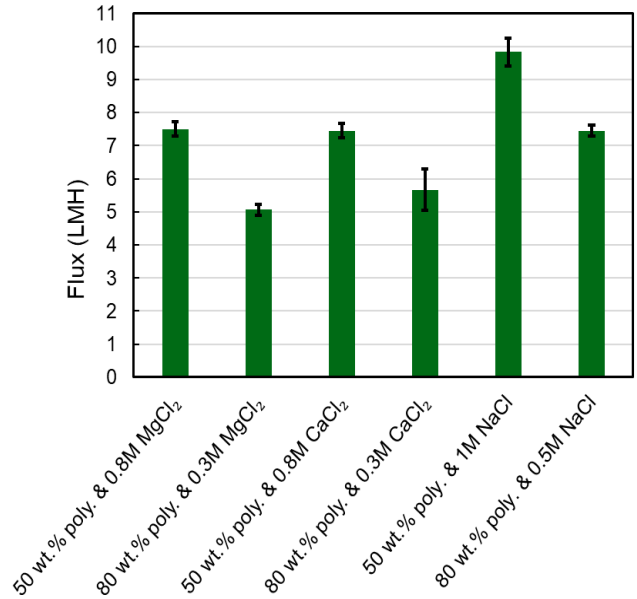

Figure 16. Water fluxes for FS with 3.5 wt.% NaCl and various Pluronics® L-35-salt binary DS compositions.

4.3.3 Polycerin® 55Gl-2601

Figure 17 illustrates the FO water flux for binary DSs composed of Polycerin® 55Gl-2601 and inorganic salts. The highest flux, 10.13 LMH, was obtained with 65 wt.% Polycerin® 55Gl-2601 combined with 0.7M NaCl, indicating that increasing polymer concentration imposes a significant limitation on the water flux in FO systems utilizing binary DS.

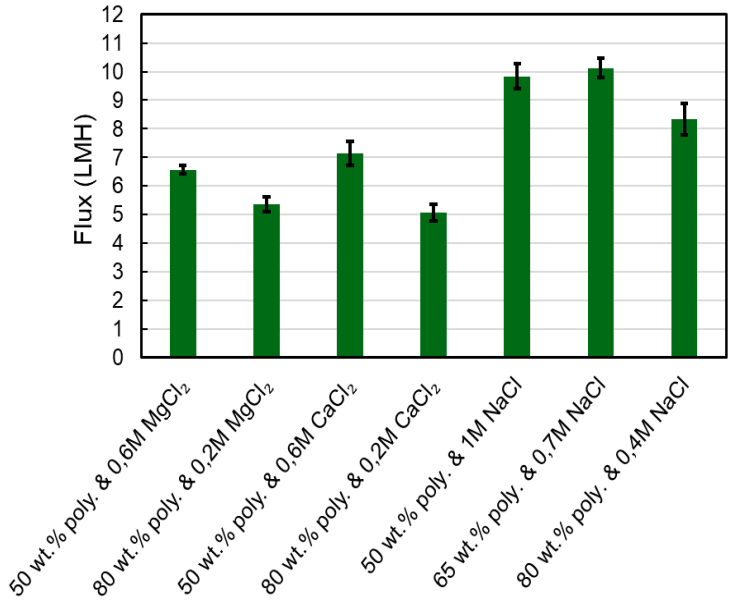

Figure 17. Water flux for FS with 3.5 wt.% NaCl versus various Polycerin® 55Gl-2601- salt binary DSs.

4.4 Viscosities

The FO performance is significantly influenced by the viscosity of the polymeric DS [69, 70]. Therefore, the effect of polymer concentration, DS temperature and inorganic salt addition on the viscosity of the polymers were investigated in Paper I.

4.4.1 Effect of polymer concentration and operating temperature

For FO applications, low viscosity is preferred for copolymers to mitigate concentration polarization [21]. From the experiments, it was observed that increasing polymer concentration in the DS led to a corresponding increase in dynamic viscosity, particularly at temperatures below the LCST of the respective copolymer. As shown in Figure 18a, the viscosity of Unilube® 50MB-26 copolymer at 50 wt.% concentration decreased with increasing temperature up to approximately 45°C, beyond which it begins to rise. This behaviour can be attributed to the relatively low LCST of the Unilube® 50MB-26, reported at the literature as 41.75°C and 50°C, at polymer concentrations of 20 wt.% and 50 wt.%, respectively [61]. For Polycerin® 55Gl-2601 and Pluronic® L-35, the literature reported LCSTs are 68°C and 78-82°C, respectively, at polymer concentrations of

50 wt.% and 10 wt.% [61]. The higher LCST of Pluronic® L-35 is further reflected in the continuous decrease in viscosity with increasing temperature, as illustrated in Figure 18a.

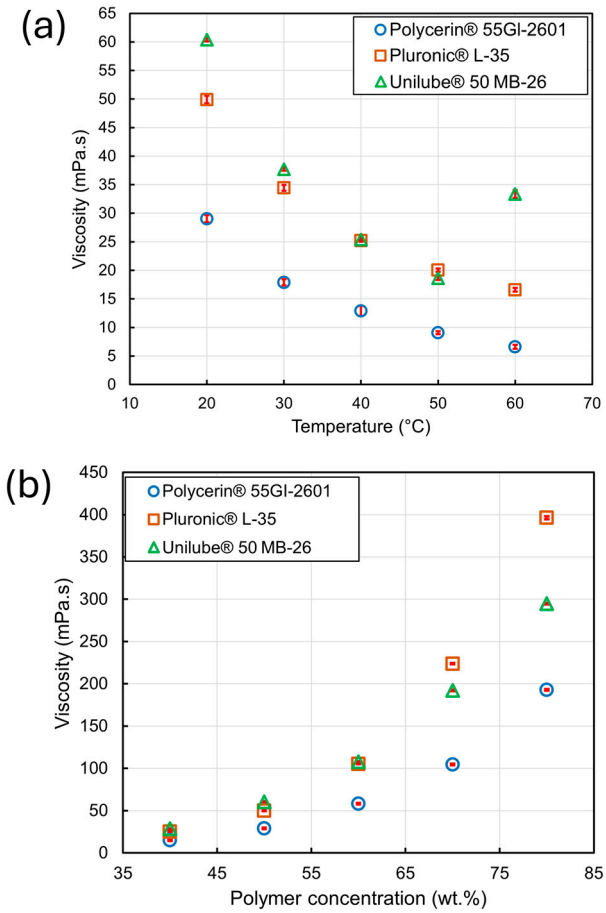

Figure 18. Viscosities of aqueous solutions of Polycerin® 55GI-2601, Pluronic® L-35 and Unilube® 50MB-26 polymers (a) with increasing temperature at 50 wt.% polymer concentration, (b) with increasing polymer concentration at temperature of 20°C. Experiments were performed in duplicate (n = 2), and the maximum standard deviation observed was ± 1.73.

4.4.2 Effect of inorganic salt on polymer concentration

To evaluate the effect of inorganic salt on the polymer viscosity, the viscosities of binary DSs containing 50 wt.% copolymer were measured upon addition of NaCl at concentrations ranging from 0.1 to 0.5M, in 0.1 M increments. A comparison with the viscosities of pure polymeric DSs at the same polymer concentration and

temperature shows a substantial increase in viscosity, as illustrated in Figure 19. The maximum increase was observed for Polycerin® 55Gl-2601, where the viscosity increased from 29.05 mPa·s to 58.5 mPa·s upon addition of 0.5 M NaCl. Therefore, the performance of binary DSs in FO is limited by the fact that the increased viscosity enhances concentration polarization, which ultimately impacts FO performance.

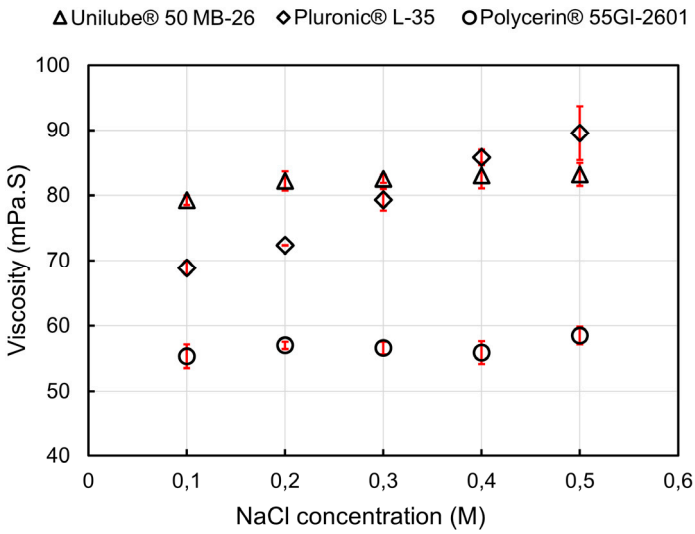

Figure 19. Effect of inorganic salt on the viscosity of aqueous solutions of Polycerin® 55Gl-2601, Pluronic® L-35 and Unilube® 50MB-26 copolymers. The copolymer concentration and solution temperature were kept constant at 50 wt.% and 20°C, respectively. Experiments were performed in duplicate (n = 2), and the maximum standard deviation observed was ± 4.16.

5 Conclusions

This thesis describes studies on the use of thermo-responsive polymers as DSs for FO applications. The experimental investigations conducted have contributed to further understanding of the effects of polymer type and concentration on FO performance. The findings also include the formulation of binary DSs composed of thermo-responsive polymers and selected inorganic salts. Laboratory-scale experiments provided valuable insights for the initial assessment of membrane selection. Furthermore, the performance of binary DSs was compared to that of polymer-only DSs. $MgCl_2$, $CaCl_2$, and NaCl were used as the inorganic salt components in the binary DSs.

Variations in the EO and PO content, as well as the polymer concentration in the DSs, were found to influence the FO water flux. The tested polymers demonstrated potential as DSs for the FO process, however, their relatively lower water fluxes limit broader FO applications. As a result, binary DSs were evaluated to address the low water flux associated with polymer-only DS. The proposed binary DS system showed improved FO performance, achieving a maximum FO water flux of 10.13 LMH for a binary DS composed of 0.7 M NaCl and 65 wt.% Polycerin® 55GI-2601, compared to a maximum flux of 2.5 LMH for polymer-only DS. However, the presence of inorganic salts in the aqueous polymer solution negatively affects the DS viscosity, potentially leading to increased concentration polarization and reduced FO efficiency.

6 Future research

The findings presented in this thesis suggest that thermo-responsive polymers have potential as DSs for FO applications. Additionally, the use of binary DSs helped overcome the limitation of lower FO water fluxes observed with the tested polymers. However, the binary DSs require further evaluation, including the effect of inorganic salt addition on the LCSTs of these polymers. A more thorough analysis of the interactions between the inorganic salts and the polymers, taking LCSTs into consideration would help in assessing the need for regeneration of these binary DSs.

Regeneration remains a primary concern, and therefore further research is required to explore the regeneration strategies for these DSs - such as combining a coalescer with NF or ultrafiltration. This is essential, as continuous regeneration of the DS is a requirement for the FO process.

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Printed by Media-Tryck, Lund 2025 NORDIC SWAN ECOLABEL 3041 0903

ISBN: 978-91-8096-132-5

Chemical Engineering
Faculty of Engineering
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