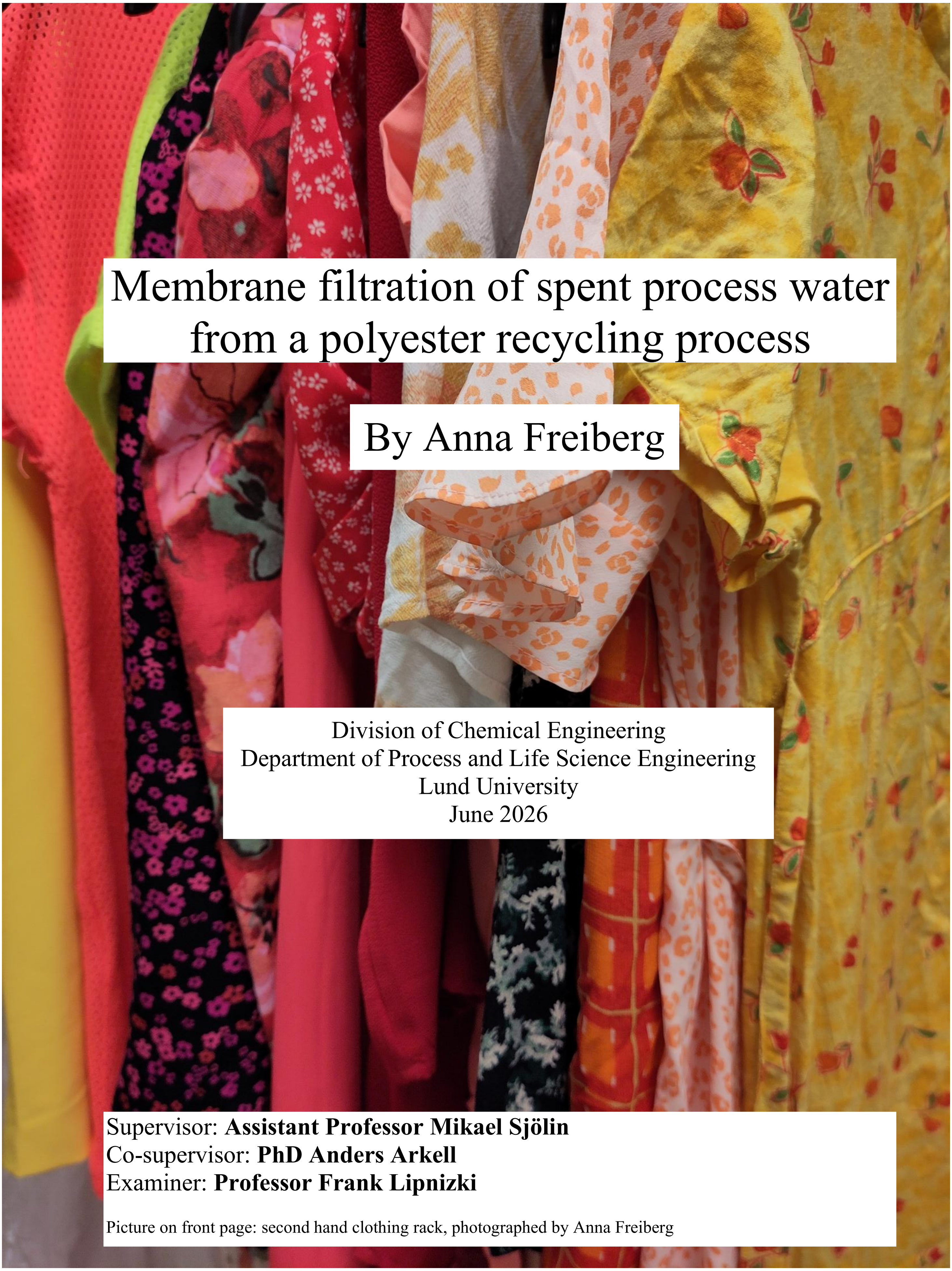

Membrane filtration of spent process water from a polyester recycling process

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Picture on front page: second hand clothing rack, photographed by Anna Freiberg

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Preface

Firstly, I would like to thank my two supervisors for all their support and guidance over the course of this project.

To Mikael Sjölin, thank you for all the work you put in, even when you were being pulled in many different directions with teaching, supervising and other projects. You always had a new idea for troubleshooting problems when things went awry and always made time for my questions, for which I am very grateful.

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Disclosure of the Use of Generative AI

This thesis has in part been produced with the assistance the generative AI model Microsoft Copilot. The AI model has been used in accordance with the KETM05 course syllabus for enhancing text quality. More specifically, I have used AI to translate the summary into Swedish and improve sentence structure and readability of text I have written. I have processed the generated text and take full responsibility for the content.

Populärvetenskaplig sammanfattning

Textilavfall är ett utbrett globalt problem med stora konsekvenser för miljön vi lever i. Endast i Europa slängs 7–7,5 miljoner ton textilier bort varje år, vilket motsvarar cirka 15 kilo textilavfall per person och år, och dessa siffror beräknas öka om ingenting görs. Textil återvinning kan vara ett sätt att reducera mängden textilavfall som hamnar i deponi eller förbränns, genom att istället använda avfallet som råvara för nyproduktion. En storskalig implementering av textil-till-textil-återvinning har potential att bidra till en minska textilindustrins koldioxidutsläpp och göra den mer hållbar.

Av alla textiler i världen är polyester den som det produceras mest av. Varje år produceras 71 miljoner ton polyester, varav 85% produceras direkt från fossila råvaror. Tänk om vi kunde ersätta detta med polyester från återvunna textiler istället? Rewin Textiles är ett textilåtervinningsföretag som har utvecklat en process för kemisk återvinning av textilavfall med hög andel polyester, med en metod som heter glykolys, eftersom den använder sig av glykol för att lösa upp och bryta ner polyestern i textilierna.

Syftet med detta examensarbete var att utvärdera hur effektiv membranfiltrering är för rening av processvatten som genereras i Rewin Textiles polyesteråtervinningsprocess. Inom membranfiltrering används ett membran som en sil för att separera partiklar och lösta ämnen från vattnet som trycks igenom membranet med hjälp av högt tryck. I studien undersöktes olika typer av membran vid olika tryck för att undersöka hur man mest effektivt kan ta bort lösta organiska ämnen och salter från vattnet. Resultatet visade att det krävdes väldigt täta membran, så kallade omvänd osmos membran, och ett högt tryck (runt 30 bar) för att rena vattnet.

En övergripande ekonomisk analys genomfördes också, som visade att reduktionsgraderna och flödena var för låga för att vara ekonomiskt hållbara. En alternativ lösning för Rewin kan vara att bygga ett mindre avloppsreningsverk på plats för att nå utsläppsgränser för organiska föroreningar. Sammantaget bidrar resultaten till en bättre förståelse av alternativen för vattenrening inom polyestertextilåtervinningsprocesser.

Summary

Textile waste is a global problem with large environmental consequences. In Europe alone, 7-7.5 million tons of textiles are thrown away each year, which corresponds to about 15 kilograms of textile waste per person per year. One way to solve the issue of textile waste is to redirect it to feedstock for new production and use recycling to close the loop of textile production. Large scale implementation of textile-to-textile recycling would also contribute to lowering the carbon footprint of the textile industry.

Rewin Textiles is a textile recycling company that has developed a process for chemically recycling post-consumer textile waste with a high polyester content, using glycolysis. The aim of this thesis was to evaluate the effectiveness of membrane filtration for the treatment of spent process water generated in Rewin Textiles' polyester recycling process. The study found that reverse osmosis membranes (RO99 and RO98pHt) showed the highest retention rates of chemical oxygen demand, COD, (all above 40%) and high salt rejection at the higher pressures. The tested UF and NF membranes with larger pore sizes were deemed unfeasible for the application because of their very low retention rates.

A short overall economic analysis was also conducted, which showed that the retention rates and fluxes were too low to be economically viable. An alternative solution for Rewin was presented, which included installing a small secondary wastewater treatment plant. Overall, the findings contribute to a better understanding of treatment options for polyester textile recycling and highlight the key challenges left to address before an economically viable membrane filtration system can be implemented.

Sammanfattning

Textilavfall är ett globalt problem med stora konsekvenser för miljön. Endast i Europa slängs 7–7,5 miljoner ton textilier bort varje år, vilket motsvarar cirka 15 kilo textilavfall per person och år. Textil återvinning kan vara ett sätt att reducera mängden textilavfall som hamnar i deponi eller förbränns, genom att istället använda avfall som råvara för nyproduktion. En storskalig implementering av textil-till-textil-återvinning har potential att minska textilindustrins koldioxidutsläpp.

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En övergripande ekonomisk analys genomfördes också, som visade att reduktionsgraderna och flödena var för låga för att vara ekonomiskt hållbara. En alternativ lösning för Rewin presenterades, som innefattade installation av ett mindre avloppsreningsverk. Sammantaget bidrar resultaten till en bättre förståelse av alternativen för vattenrening inom polyestertextilåtervinningsprocesser.

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1 Introduction

Textiles are present in every aspect of our lives, from clothing, home textiles, and furnishings to insulation in our walls, cushions in our vehicles, and personal protective equipment in our hospitals. The textile industry today produces an excessive amount of textiles; 124 million tonnes were produced in 2023, which is more than double the 58 million tonnes produced in 2000 (Textile Exchange 2024). Overproduction and overconsumption have led to a global textile waste problem.

In Europe alone, 7-7.5 million tons of textiles are thrown away each year, which corresponds to about 15 kilograms of textile waste per person per year. It is estimated that by 2030, this number could increase to 20 kilograms or 8.5-9 million tons by 2030 (Janmark et al. 2022). Recently, the EU Commission has increased its efforts to collect textile waste, along with several other directives that aim to promote sustainable and circular production of textiles (Regeringskansliet 2023). In response to this, Sweden passed a law that from 2025 all textile waste must be collected separately from household waste. However, this law was later retracted the same year, because of a lack of preparedness in infrastructure and systems to take care of the new waste (Regeringskansliet 2025).

Sweden is not the only country that is falling short of the textile collection goal. Only about 30-35% of discarded textiles are currently collected in the EU, of which most is sent to second-hand retailers to resell (Janmark et al. 2022). Second-hand stores are often overwhelmed by the amount of clothing they receive, and only a small portion is sold in the country where it is collected, according to Greenpeace (Cobbing et al. 2022). The uncollected and unsold waste is then either incinerated or ends up in landfill, often by route of exporting it to the Global South. Textiles exported to the Global South are often of such poor quality that an estimated 40% is dumped in landfill upon arrival, which has devastating effects for the local environment (Cobbing et al. 2022). Hazardous chemicals used for dyeing and finishing textiles can leak into the soil and surrounding waterways, as well as microplastics from synthetic fibres (Ndagano et al. 2025).

One way to solve the issue of textile waste is to redirect it to feedstock for new production and use recycling to close the loop of the textile value chain. Large scale implementation of textile-to-textile recycling would also contribute to lowering the carbon footprint of the textile industry. The global CO_2 emissions of the textile industry alone are estimated to make up 3-10% of the total global greenhouse gas emissions (Berg et al. 2020). In a 2020 report from McKinsey and Global Fashion Agenda, they estimated that collection and recycling of textiles could lower emissions by 18 million tons. However, there are still many challenges to overcome: currently only less than 1% of textiles are recycled globally due to issues regarding collection, sorting, and technological challenges (Janmark et al. 2022).

Rewin Textiles is a textile recycling company that has developed a process for chemically recycling post-consumer textile waste with a high polyester content. The company is in the early stages of scale up and are set to start production in a pilot plant in 2026. Rewin's process is unique in two ways: little pretreatment is necessary and the catalyst is very effective at removing colour from the textile. However, the process can be optimised further to improve sustainability and economic viability. Spent process water could potentially be treated with membrane filtration and reused instead of sending it directly to a wastewater treatment plant.

2 Aim & Research questions

The aim of this thesis is to evaluate the effectiveness of membrane filtration for the treatment of spent process water generated in Rewin Textiles' polyester recycling process. The main research questions are:

- Which membrane is best suited to this application?
- What are the optimal parameters for membrane filtration of the wastewater?
- How technically and economically viable is membrane filtration as a wastewater treatment method?

The overall goal of the project was to evaluate whether membrane filtration can enable viable and economically sustainable reuse of process water from the polyester recycling process.

3 Literature Review

3.1 Polyester

Polyester or polyethylene terephthalate (PET), is the most popular fibre for textile production, accounting for 57% of the global textile production in 2023, which amounts to 71 million tons of textile (Textile Exchange 2024). PET is also a common material for packaging such as plastic bottles (Enking et al. 2025). Currently, less than 15% of polyester is recycled (rPET), and almost all the rPET is sourced from PET bottles. Less than 1% of recycled polyester is made from textile waste, so called fibre-to-fibre recycling (Textile Exchange 2024).

Virgin polyester is produced industrially via two distinct methods. Either ethylene glycol (MEG) reacts with dimethyl terephthalate (DMT), or MEG and terephthalic acid (TPA) react to form PET. In the DMT method, the monomer diethylene glycol terephthalate (DGT) is the intermediate product. DGT then undergoes a polycondensation polymerisation at a temperature of around 270°C to produce PET. All reactions take place in the presence of a catalyst. The TPA method is very similar, but has the monomer bis-hydroxyethyl terephthalate (BHET) as an intermediate instead (Deopura and Padaki 2015). PET is synthesised as pellets or chips that are subsequently melt-processed by an extruder to produce a filament. In textile production, these filaments are then spun directly into fibres or are subjected to a drawing process to enhance properties such as tensile strength and crystallinity (Lin 2008).

3.2 Challenges of Textile Recycling

As mentioned in the introduction, although there has been a lot of research and innovation in recent years regarding textile recycling, challenges remain. Maintaining a reliable feedstock with high purity is imperative to successfully scaling up textile recycling. However, this has proven difficult due to challenges regarding collection, sorting and textile fibre composition.

3.2.1 Collection and sorting

There is a lack of infrastructure for collecting and sorting textile waste, particularly in household waste. Household waste comes from many different individual sources and must be collected separately from mixed waste to be able to be recycled. Collection bins for textiles that are run by municipalities, charities or retailers are available in some places but are not utilised enough and can be poorly managed. In the EU only 22% of textile waste is collected for reuse or recycling (Seifali Abbas-Abadi et al. 2025).

After textile waste has been collected it must be sorted by hand in order to determine quality for resale. This first sorting step can only be done manually and is therefore often outsourced to countries with lower labour costs and subpar working conditions. In addition to manual sorting being a time-consuming task, it is also inefficient in determining textile composition as product labels can be incorrect or missing (Seifali Abbas-Abadi et al. 2025). Most recycling processes today target monofibre textiles, which makes pre-sorting by fibre composition vital. Accurate sorting can be done by automated sorting technologies that utilise near infrared (NIR), but they are not widely implemented yet (Palacios-Mateo et al. 2021). There are several companies pioneering sorting technologies for sorting using Near-Infrared (NIR) sensors for fibre composition and cameras for colour. For example, NewRetex in Denmark can currently process 10 tons of textile waste per week, with plans to expand the facility to be able to sort 40,000 tons per year ('Textile Sorting', n.d.).

3.2.2 Mixed fibre composition

Most textiles are not composed of a single fibre type but are blended with other fibres, such as polycotton, a polyester and cotton blend. Blending fibres improves the functionality of textiles and is especially popular for garments. For example, elastane is often used to add stretchiness to otherwise stiff garments like cotton jeans. Mixed fibre composition presents a challenge for textile recycling processes, as separation is difficult to achieve without degrading one of the fibres. Most fibre recycling technologies require a feed with a high composition of one unique fibre, and any other fibres present in the recycling process are regarded as contaminants (European Commission 2022).

While advancements have been made in separation and recovery of PET and cotton from polycotton textiles, other fibre blends remain extremely difficult to separate. Wool/synthetic fibre blends are an example of this, as the keratin protein structure of wool is difficult to degrade without extreme conditions, which damage the mechanical properties of the synthetic fibre (Navone et al. 2020).

3.2.3 Microplastics

The textile industry has a large environmental impact. The chemicals used in dyeing and finishing can negatively impact local ecosystems as well as human health. Recently, there has been a raised concern about the impact of microplastics on the environment and human health. There is also concern that recycled textiles may release more fibres than textiles made from virgin materials (Persson et al. 2026).

Microplastic fibres (MPFs) are threadlike plastic fragments that are released from synthetic textiles during their entire lifecycle, from manufacture to wear and laundry. Microplastics from synthetic textiles are estimated to make up 35% of the total microplastics in the oceans, and pervasive throughout all types of ecosystems (Persson et al. 2026; Chandra Manivannan et al. 2025). In a study from 2026, Persson et al. showed that repeated mechanical fibre-to-fibre recycling lead to an increased release of MPFs compared to virgin fibres during their production and wear (Persson et al. 2026).

Numerous other studies have been conducted on investigating the MPF released from thermomechanically recycled PET bottle textiles with varied results (Persson et al. 2026; Gao et al. 2024). Why some textiles release more MPFs than others is not yet fully understood and cannot be entirely explained by differences in recycling method. Structural properties and processing factors also affect MPF release patterns, and more research is needed to understand and prevent the environmental hazards of MPFs from recycled textiles (Persson et al. 2026).

3.3 Membrane filtration

Membrane filtration technology is a separation process in which components in a mixture are selectively transported through a physical barrier, the membrane. This separation is driven by a gradient across the membrane, either of pressure, concentration, temperature, or electric field. Membrane filtration had its first industrial application in the 1960s, and since then it has become widely used across pharmaceutical, food, chemical process industry, and wastewater treatment. Prior to this, membrane filtration had been used mostly in laboratories as an analytical tool, but now it is commonly used for purification and concentration of process streams (Sen and Mazumder 2025).

There are many advantages of membrane filtration over other methods of separation, such as distillation, adsorption, or crystallisation. Membrane filtration can be carried out at ambient temperature, has a small footprint area, and is easily scalable thanks to its modular set-up. This leads to smaller investment costs, lower energy demand, and reduced environmental impact compared to other processes (Sen and Mazumder 2025; Panglisch 2016).

Membrane filtration processes use different modes of operation, either batch, semi-batch, or continuous, depending on the application. Continuous processes are ideal for applications that require large volumes of feed to be processed quickly. Batch processes require refilling after each batch, which facilitates cleaning of the membrane at the same time which reduces the extent of membrane fouling (Sen and Mazumder 2025). This makes batch processes ideal for sensitive membranes and for small volumes.

In membrane processes, there are two main modes of operation: crossflow (CF) and dead-end filtration. In CF, the feed stream is parallel to the membrane surface and is divided into retentate (containing components rejected by the membrane) and permeate (the solution that permeated through the membrane) (Panglisch 2016). In dead-end filtration, the feed is forced through the membrane, using pressure, and the retentate accumulates on the membrane surface (Sen and Mazumder 2025).

There are four main types of membranes where pressure is the driving force: microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO). The membrane type is characterised by the pore size, which ranges from 100-10000 nm in the case of MF, to 10-100 nm for UF, and 0.5-5 nm for NF. RO membranes consist of a nonporous dense polymer layer and one or more porous supporting layers (Sen and Mazumder 2025). As the pore size decreases, the pressure needed to drive the separation increases. The driving force is known as the transmembrane pressure (TMP) and is defined as the difference in applied pressure between the feed and permeate (Sjölin 2023). Typical values of TMP for the different membrane types are MF and UF: $\lesssim$ 5 bar, NF: $\lesssim$ 15 bar, and RO: $\lesssim$ 100 bar (Panglisch 2016).

3.4 Applications in textile industry

Membrane filtration technology has been heavily researched in the textile industry for wastewater treatment and resource recovery. Compared to other separation processes, membrane filtration is promising because of its simplicity and ability to remove several pollutant types efficiently and at varying concentrations (Liu et al. 2025).

Already in 2000, researchers showed that nanofiltration could successfully remove disperse dyes, that had been used to dye synthetic fibres, from dye bath waste (Dhale and Mahajani 2000). After filtration, the permeate contained only water, acetic acid, and a small amount of chemical impurities, and was able to be recycled back into the dyeing process. The retentate containing the leftover dye was then treated. Since then, more progress has been made in resource recovery using membranes. Loose nanofiltration membranes have been used to selectively remove dyes, while allowing salts such as NaCl and $NaSO_4$ to permeate. Salts are used in the dyeing process to promote dye absorption on the fibre as well as dye consistency.

Loose NF membranes with larger molecular weight cut-offs (MWCOs) than the molecular weight of the dyes have still been used successfully. Due to hydrophobic interactions between aromatic rings in dye molecular structure, dyes tend to aggregate in solutions, leading to a larger molecular size. This explains why loose NF membranes can retain dyes so well, even though they have a larger pore size (Liu et al. 2025).

One of the main challenges still facing membrane filtration of textile wastewater is the high rate of fouling. Dyes are especially prone to adsorbing on the membrane surface and forming a cake layer. To address this, pretreatment using UF membranes has been proposed, as well as fouling-resistant hydrophilic NF membranes (Liu et al. 2025).

3.5 Wastewater composition

Different chemical compounds are added for many purposes in textile production, including: improving processability, enhancing fibre properties like strength or softness, colour, and flame retardance (Standring et al. 2025). Over 15,000 different chemicals are used in textile production and on average 0.58 kg of chemicals are used per 1 kg of textile manufactured. Many of the chemicals used are hazardous to human health and do not biodegrade, which increases the importance of wastewater treatment in both textile production and recycling (Palacios-Mateo et al. 2021).

Disperse dyes are the most common dye type for synthetic fibres like polyester. Disperse dyes are insoluble in water and require dispersing agents and high temperatures to adhere to the fibre. However, once absorbed and bonded to the polyester fibre, the textiles retain the dye well. Disperse dyes are non-biodegradable and some dyes, such as Disperse Blue 106 and 124, have been shown to generate allergic reactions (Brandt and Gandois 2026).

Since there is no industry standard list of which additives are used in polyester production, it is impossible to know the exact contents of Rewin's process water. The feedstock Rewin uses comes from many different sources and will vary with time. It is therefore not useful to categorise the exact contents of the process water. Instead, the relative removal of contaminants will be determined by analysing chemical oxygen demand (COD), colour removal, and metal ion removal.

4 Theory

Polyester can be recycled through several different processes. There are three main types of recycling: mechanical, thermo-mechanical and chemical recycling. Several different pathways for chemical recycling have been developed, of which the most common for polyester recycling are outlined below.

4.1 Mechanical Recycling

Mechanical recycling is the process by which textiles are broken down into single fibres by tearing or garnetting. The fibres can then be spun into yarn or used in non-woven fabrics. The spinning process usually uses rotor or friction spinning because it can handle short fibres (Enking et al. 2025). Due to the shortened length, the quality of mechanically recycled fibres is lower than for virgin fibres, which limits the applications possible. For this reason, mechanical recycling often results in open-loop downcycling, meaning that the recycled material is not spun into new yarn but used for a less valuable purpose (Seifali Abbas-Abadi et al. 2025). Examples of downcycling are low-grade blankets, insulation materials and rags (Ndagano et al. 2025).

The advantages of mechanical recycling are that it is a well-developed technology that requires little water, few chemicals and less energy than other methods (Seifali Abbas-Abadi et al. 2025). Another advantage is the ability to process mixed fibre types. Unknown fibre compositions can be downcycled, but to achieve a blended fibre product, the textile waste must be correctly sorted before recycling, by fibre type and colour. Alternatively, an undyeing step could be added, but this is currently being researched (Enking et al. 2025).

4.2 Thermo-mechanical recycling

Thermo-mechanical recycling is a method that can be used for synthetic polymers. Plastics are remelted using an extruder and then pushed through a perforated plate and cut into granulates or strands. The molecular structure of the polymer is preserved, which leads to a higher quality fibre than simple mechanical recycling (Enking et al. 2025). Thermo-mechanical recycling has a relatively low energy consumption and has been shown to be commercially viable for non-textile waste (PET bottles). There are still challenges when it comes to textile-to-textile recycling with this method, as feedstock is limited due to the requirement of high single polymer type purity (Janmark et al. 2022). Recycling PET-bottles into textiles is becoming less viable, since the EU directive on reducing single-use plastic waste. PET-bottles are suitable for food-grade recycling and the EU aims to have a closed-loop recycling system for PET packaging (European Commission 2022). This will put pressure on the industry to develop fibre-to-fibre recycling technologies instead.

4.3 Chemical Recycling

Chemical recycling is the process of depolymerising fibres into monomers and subsequently re-polymerising them without compromising the quality of the fibre. Theoretically, infinite recyclability of plastics is possible with chemical recycling but in practise at least three recovery cycles is what is expected (Uekert et al. 2023). Often a mechanical tearing or shredding pre-treatment step is used to prepare textile waste for chemical recycling, which makes the process more effective (Enking et al. 2025). For polyester recycling, there are three main types: hydrolysis, methanolysis, and glycolysis. There have been other methods reported such as pyrolysis, gasification and aminolysis but these are less common and will not be focused on in this review (Ndagano et al. 2025).

4.3.1 Hydrolysis

Hydrolysis converts PET to TPA and EG by reaction with water in an alkaline, acidic or neutral environment. Neutral hydrolysis is carried out at high temperatures (200-300°C) and pressure (1-4 MPa) (Babaei et al. 2024). Neutral hydrolysis cannot handle impurities in the polyester feed and therefore requires an extra purification step compared to acid or alkaline hydrolysis. This, coupled with the high operating cost have meant that no neutral hydrolysis method has been scaled up or patented so far (Abedsoltan 2023). Acid hydrolysis usually uses high temperatures, and sulphuric acid or nitric acid, which can be recovered. Alkaline hydrolysis uses concentrated sodium hydroxide or potassium hydroxide as a base catalyst, which is consumed in the process. After this, an acidification step must be done to recover the TPA (Ndagano et al. 2025). The advantages of hydrolysis include a very high yield of TPA (close to 100%). Since no harsh chemicals are needed for hydrolysis, alkaline hydrolysis has been shown to be able to separate out cotton and viscose fibres from degraded polyester when performed under milder conditions. This presents an interesting route for potential recycling of blended fibre textiles (Peterson et al. 2022). Two US-based companies, including Ambercycle and Circ, have successfully proven this technology at pilot scale and are currently scaling up to commercial scale, however neither is fully operational yet (Schuster 2025). The Circ facility will be the first of its kind, since they will be able to recycle post-consumer polycotton textile waste at 70,000 ton per year (Borneman 2025).

4.3.2 Enzymatic Hydrolysis

Enzymatic hydrolysis is a depolymerisation method using enzymes as catalysts. First, PET reacts with the enzyme PETase in a solvent to form MHET and TPA. Then another enzyme, MHETase, reacts with MHET to form TPA and EG. The enzymatic hydrolysis reactions are very slow and carried out at mild conditions so as not to degrade the enzyme (Enking et al. 2025). Enzymatic hydrolysis can also be used to recycle cotton by depolymerising cellulose into glucose, by using different enzymes. Since the enzymes are selective, this method can be used to separate polycotton blends into pure fibres for recycling or even to recycle both at the same time, as shown in a 2023 study by Kaabel *et al.* The researchers were able to hydrolyse TPA (up to 30 ± 2 % yield) and glucose (up to 83 ± 4 % yield) by the corresponding enzymes (Kaabel et al. 2023). The yield for polyester recycling is still quite low compared to other methods, in part due to the difficulty for enzymes to access the highly crystalline structures inside the PET fibres. If the method is to be viable commercially, the yield must be increased, as well as improvements made in decreasing reaction times and producing thermally stable enzymes (Enking et al. 2025). Currently, enzymatic hydrolysis is only used at pilot scale, by companies like Gr3n in Italy and Carbios in France (Schuster 2025).

4.3.3 Methanolysis

The methanolysis recycling method depolymerises polyester into dimethyl terephthalate (DMT) using methanol as a solvent. Similar methods exist using other alcohols such as ethanol or butanol (Ndagano et al. 2025). Methanolysis uses a transesterification reaction, which requires a metal salt catalyst such as zinc-, magnesium or cobalt acetate. Jiaren New Materials established the world's first commercial textile-to-textile recycling plant in Zhejiang, China with the methanolysis method. Currently, Jiaren has a processing capacity of 40,000 tons of textile waste per year, with an output of 30,000 tons of recycled DMT, chips and yarn (Jiaren New Mater., n.d.). Jiaren is currently the only producer of recycled textile-to-textiles at this scale and has plans to expand their capacity in coming years. Other companies, like Loop Industries, have also been successful in producing textile-to-textile recycled polyester with methanolysis (ACCESS Newswire 2025). Loop Industries has several large-scale recycling facilities planned and has started construction on a 70,000 ton/year facility in Ulsan, South Korea. However, this facility will not focus entirely on textile recycling, but a mixed feedstock containing plastic packaging waste as well as textiles (Nasdaq 2023).

4.3.4 Glycolysis

Glycolysis is the process of depolymerising PET into BHET by reaction with glycol (most commonly MEG but diethylene glycol, propylene glycol, or di-propylene glycol can also be used). The reaction takes place in the presence of a catalyst at temperatures of around 200°C. Since it is an equilibrium reaction, an excess of MEG is needed to shift the reaction to the BHET product. Reported yields range from 60-99% depending on the catalyst and how yield was calculated (Enking et al. 2025). An advantage of glycolysis, compared to the other methods already described, is that BHET is an intermediate in polyester production and requires less energy to repolymerise than TPA/DMT & MEG (Enking et al. 2025).

Glycolysis is a widely researched process that was patented in 1965 and has been used in commercial facilities for plastic recycling (Abedsoltan 2023). For textile-to-textile recycling, there are several companies, such as Rewin Textiles and ReJu (France), who have demonstrated the technology at lab scale. Pilot scale production has also been shown successful by CuRe (Netherlands). Garbo and Saipem have received €15.5 million in EU funding to build an industrial-scale facility by 2029 for chemical recycling of PET by their patented glycolysis technology. Their facility will not only recycle textiles, but focus on complex, hard-to-recycle PET waste in general (Saipem 2025). Although no large commercial facilities are operational yet, rapid progress is being made in this area, and the coming years could see a breakthrough in the amount of T2T recycled polyester is available.

4.4 Environmental impact of different recycling methods

The environmental impact of textile recycling is hard to quantify, since there are so many factors to consider. Life cycle assessments (LCAs) can be used as a method to measure the environmental impact of a process or product from raw material to end of life. In general, conducted LCAs have shown that recycling polyester reduces carbon dioxide emissions. However, the different types of recycling methods have very different impacts, mostly depending on how energy-intensive the process is (Abagnato et al. 2024). In a LCA case study, authors Shen *et al.* present mechanical recycling as emitting by far the least CO_2, about a quarter of the virgin polyester emissions. Chemical recycling emitted substantially more CO_2, with glycolysis being somewhat better than methanolysis (Shen et al. 2010). This is supported by a 2023 study by Uekert *et al.* that claims glycolysis to outperform enzymatic hydrolysis and methanolysis by 1.1-3.2 times when it comes to greenhouse gas emissions, energy use and toxicity (Uekert et al. 2023).

4.5 Rewin recycling process

Rewin utilises glycolysis in their polyester recycling process; a simplified process flow diagram is shown in figure 1.

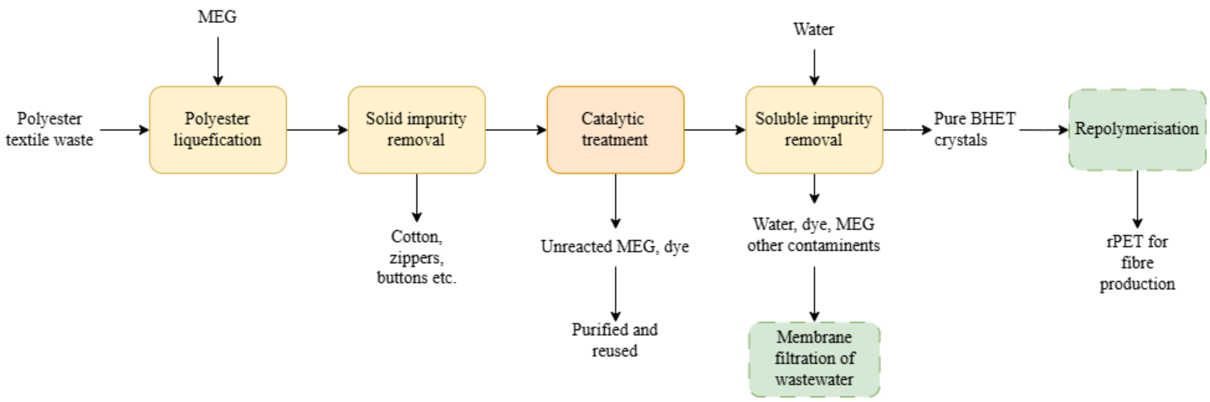

Figure 1 Simplified flow diagram of Rewins polyester recycling process, adapted from (Arkell 2026).

First, polyester is liquefied, by vapour injecting MEG into high polyester content textile waste, at a temperature of 190-250°C, which fully depolymerises the polyester into oligomers (Wene and Jakobsson 2024). After this, the solution is filtered to remove any solid impurities such as buttons, zippers and cotton. Then the solution is fed into the catalytic reactor, where the oligomers depolymerise further into BHET using an active fibre based filter catalyst (Wene and Jakobsson 2025). The solution is then cooled, which separates BHET and remaining oligomers from MEG by precipitation. The MEG stream is then recovered and reused after purification. Finally, soluble impurities are removed and BHET is purified using water to dissolve, filter and crystallise BHET. Here, membrane filtration of the wastewater could be introduced after soluble impurity removal to further improve Rewin's process. The purified BHET crystals can then be repolymerised into rPET using established commercial processes.

Rewins process addresses some of the common challenges of textile recycling. One example of this is that since MEG is heated to a vapour, it can penetrate the polyester fibre structure without excessive pre-treatment like ball-milling.

4.6 Basic principles of membrane filtration

The capacity of a membrane is commonly described by the flux. Flux, J_i, (kg/m^{2}s) is the flow rate of a component *i* across the membrane and is given by the equation one below, where *m* is mass (kg), *A* is membrane area (m^2) and *t* is time (s).

$$J_i = \frac{m_i}{A \cdot t} \tag{1}$$

Depending on the application, flux can also be expressed in terms of molar flow rate Jn_i (given in mol/m^{2}s), or volumetric flow rate Jv_i (given in L/m^{2}s). Flux can also be described in terms of driving force and flux-reducing parameters, which is given in equation 2 below (Sjölin 2023).

$$J = \frac{\text{TMP} - \Pi}{\mu(R_m + R_f + R_{cp})} \tag{2}$$

Where Π is osmotic pressure, μ is viscosity, and R_m, R_f and R_{cp} are the filtration resistance of the membrane, fouling and concentration polarisation, respectively. Concentration polarisation describes the phenomenon of the resistance that occurs when solutes form a stagnant boundary layer of higher concentration on the membrane surface (Sjölin 2023). This is illustrated in figure

2. This leads to the concentration in the bulk of the liquid (C_b) being lower than in the boundary layer at the membrane surface (C_m). The concentration polarisation naturally reduces flux, by reducing the amount of solvent that can pass through the membrane. This flux reduction is unavoidable, but can be reversed by a reduction in TMP or an increase in CFV (Bacchin et al. 2006).

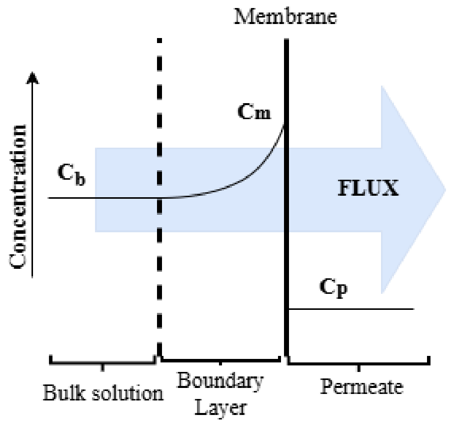

Figure 2 Concentration polarisation phenomenon. Adapted with permission from (Sjölin 2023).

When choosing which membrane to use, it is important to know how successfully it can separate specific particle sizes (Strathmann 2011). This is described by the rejection or retention coefficient R. The true retention, R_{true} is described in equation three, where C_p is the concentration of the permeate. However, since it is only feasible to sample the concentration in the bulk, the observed retention, R_{obs}, as described in equation four, is commonly used (Sjölin 2023).

$$R_{true} = \left(1 - \frac{C_p}{C_m}\right) \tag{3}$$

$$R_{obs} = \left(1 - \frac{C_p}{C_b}\right) \tag{4}$$

4.6.1 Fouling

Over time, material builds up on the membrane surface, which is known as fouling. This can take multiple forms, such as adsorption, pore blockage or cake/gel formation. Fouling leads to a reduced flux, and therefore the membrane must be cleaned to recover the membrane's capacity. Pure water flux (PWF) can be used to assess the degree of fouling and the effectiveness of cleaning. In PWF, pure water is filtered through a pristine membrane (Sjölin 2023). The degree of fouling is calculated using PWF and is shown in equation five below (Al-Rudainy et al. 2017).

$$Fouling\ grade\ (\%) = 100 \cdot \frac{PWF_{before} - PWF_{after}}{PWF_{before}} \tag{5}$$

5 Materials and Methods

5.1 BHET purification

BHET was purified and soluble impurities removed by first dissolving crude BHET in six times its own weight of deionised water. The solution was heated to 90°C and stirred for 30 mins before being filtered through a glass fibre filter to remove oligomers. After this a Norit active carbon powder (Netherlands) was added to the solution at 90°C for 30 mins and then filtered through a fresh glass fibre filter. The active carbon step was repeated twice more, and the total amount of active carbon added was 5% of the crude BHET weight.

Finally, an ion exchange resin was added to the solution and stirred at 90°C for 30 mins, before filtering the solution through a quartz microfibre filter. BHET was then crystalised by lowering the temperature slowly and letting crystallisation finalise in the fridge overnight. The formed crystals were filtered off and the filtrate was used for the subsequent membrane filtration studies.

The BHET crystals were then dissolved in the same amount of deionised water as was filtered off and recrystallised. The purified crystals were then dried in the oven for a day at 60°C and at 101°C over night.

Figure 3 To the left, crude BHET. To the right, purified and dried BHET.

5.2 Membrane filtration setup

All membrane filtration was carried out in the Albi module, a stirred cell dead-end filtration system pressurised by nitrogen gas. The pressure was controlled by a valve connected to the gas line and measured using a digital pressure gauge (DSC40.0AR, Trafag AG, Bubikon, Switzerland). The permeate was continuously bled off into a beaker on a scale (PL6001-l, Mettler Toledo Inc., Ohio, USA), which was connected to a computer and used to measure flux. The module was heated by a magnetic heating/stirrer plate (MR2002, Heidolph, Instruments GmbH & Co.KG, Schwabach, Germany). The angular velocity of the stirrer was set to 400 rpm, which can be converted to an average CFV of 0.5 m/s using the following equation (Al-Rudainy et al. 2017):

$$CFV = \frac{\int_0^{r_s} 2\pi\omega r \, dr}{r_s} = \pi\omega r_s \tag{6}$$

where ω is the stirrer angular velocity (s^{-1}), r is the position along the stirrer radius (m), and r_s is the total stirrer radius (m), which was 2.5 cm. CFV 0.5 m/s was chosen based on CFD simulations of the stirred cell module by Basel Al-Rudainy, which show that the flow is turbulent at this velocity (Al-Rudainy 2020).

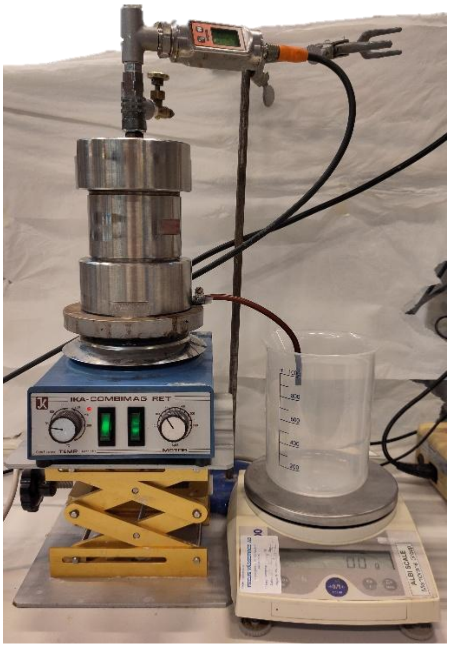

Figure 4 Albi module setup with heating/stirring plate, pressure gauge, beaker on scale.

5.3 Parameter study

A parameter study was conducted to determine which membrane should be chosen. The tested membrane pore size ranged from ultrafiltration to reverse osmosis. Specifications for each membrane are shown in table 1. Each parameter study experiment was performed using 150 ml of wastewater at 50°C with a CFV of 0.5 m/s. The pressure was varied for each experiment, and the flux was recorded at 10-second intervals by the laptop connected to the scale. For the first two membranes, a volume reduction of 33% (50 ml permeate) was made for each run. For the reverse osmosis membranes, the run was stopped at 10 ml of permeate, since the flux was so low that each run took much longer than with the other membranes. Feed and permeate samples of 5 ml were collected at the lowest and highest pressures to calculate retention.

Table 1 Tested membranes and their specifications.

MEMBRANE	MATERIAL	MWCO	OPERATING CONDITIONS
GR90PP, ALFA LAVAL (DENMARK)	Polyethersulphone with polypropylene support	5000 Da	1 – 10 bar 5 – 75 ℃
NF090801, SOLSEP BV (BELGIUM)	Crosslinked thin film composite on PET non-woven support	350 Da	5 – 25 bar 50 – 70 ℃
RO98 PHT, ALFA LAVAL (DENMARK)	Thin film composite polyamide with polypropylene support	-	15 – 40 bar 5 – 60 ℃
RO99, ALFA LAVAL (DENMARK)	Thin film composite polyamide with polyester support	-	15 – 40 bar 5 – 50 ℃

Sources: NF090801 specifications from (Battestini-Vives et al. 2024); Alfa Laval specifications from Alfa Laval product data sheets (Alfa Laval, n.d.-b, n.d.-a)

Membranes were conditioned using a 1 wt% Ultrasil 110 solution (Ecolab Inc., USA) for 1 hour at 50 ℃ and CFV 0.5 m/s, followed by flushing with deionised water. The pressure used for cleaning was 0.5 bar for UF, 1 bar for NF, 2 bar for RO98pHt and 10 bar for RO99.

5.4 Analysis

5.4.1 Chemical oxygen demand

Chemical oxygen demand (COD) is a measurement that indicates the amount of organic matter in wastewater by measuring the amount of oxygen that is needed to chemically oxidise pollutants in the sample. A COD test uses a strong oxidising agent to decompose contaminants in wastewater. COD measurements are expressed as the equivalent mass of oxygen required to oxidise contaminants over sample volume, mg/L (Schaschke 2014). The higher the COD measurement, the larger the amount of pollutants in the wastewater. In the EU, the chemical oxygen demand of water discharged from urban wastewater treatment plants must be under 125 mg/L (Directive (EU) 2024/3019 2024).

COD was analysed using test kit LCK 014 (HACH Lange GmbH, Germany) in the range 1000-10 000 mg/L O_2 according to manufacturer instructions.

5.4.2 Conductivity

Conductivity was measured using the Orion Star A212 conductivity meter (Thermo Fischer Scientific Inc., USA).

5.4.3 Colorimeter

The colorimeter CR-400 Konica Minolta (Konica Minolta Sensing Europe, UK) was used for all colour removal analysis. A setup to minimise refraction of light through the sample was used, since the colorimeter measures light reflected from a surface and is not specifically intended for translucent samples. A cuvette filled with 2 ml of sample was placed in a small dark box with a hole in the top, where the colorimeter was placed. The sides of the cuvette were covered with black electrical tape, and the bottom was placed against a matte white plastic surface. To avoid outside light disturbing the measurement, the colorimeter aperture was placed flush with the cuvette. Five replicates of each measurement were made, with a right-angle rotation of the cuvette between each measurement.

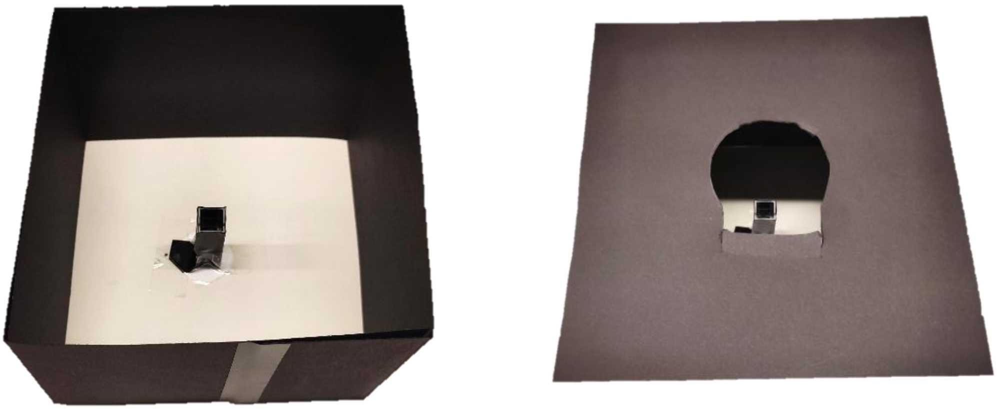

Figure 5 Colorimeter set up.

5.4.4 ICP-OES

This analysis was carried out at the Department of Biology at LTH, using the Perkin Elmer Optima 8300 (USA). First, samples are prepared using an acid digestion using concentrated nitric acid in a microwave oven. Digested samples are then diluted before analysis. The ICP-OES instrument is then used to measure the characteristic emissions spectra of each analysed metal using optical spectroscopy. To do this the instrument nebulises the samples and disperses them into an argon-plasma discharge, which excites the atoms in the sample. By determining the appropriate wavelength, and removing background interference, careful calibration can be done to quantify the composition of the sample (US EPA 2015).

5.5 Concentration study

The concentration study was performed using the optimal membrane and parameters found in the parameter study. The temperature was 50°C, TMP 30 bar, and CFV 0.5 m/s. A volume reduction of 55% was made, starting with 300 ml of wastewater. 5 ml samples of feed, permeate, and concentrate were taken and analysed using the same methods above, except ICP-OES.

Pure water flux was measured before the experiment on a pristine conditioned membrane, directly after the experiment on a fouled membrane and after cleaning. Cleaning and conditioning the membrane was done the same way for the parameter study and concentration study.

6 Results and Discussion

6.1 BHET purification

Several batches of wastewater were prepared through BHET purification. One batch was made in Rewins lab and the other by using the Albi module for filtering. The table below shows the colorimeter values for each batch. The BHET should be as white as possible to be of good quality, which would result in L*=100, a*=0, b*=0. The results show that the BHET produced in both labs is of good quality and matches the colour requirements. The most important value to compare is the b* value, as this indicates how yellow the sample is. Yellow dye is notoriously difficult to remove and therefore a small amount left in the water can discolour the BHET crystals. The BHET from the Albi module is closer to zero than the BHET produced in the Rewin lab, which confirms the robustness of the BHET purification process, since the results can be replicated with two different setups.

Table 2 Results from colour analysis on BHET samples.

BHET Rewin Lab		**Average**
	L*	92.81 ± 0.42
	a*	0.01 ± 0.02
	b*	1.37 ± 0.20
BHET Albi		
	L*	95.14 ± 0.70
	a*	-0.04 ± 0.02
	b*	0.45 ± 0.09

6.2 Parameter study

The parameter study was performed in order to screen different membrane types and determine their effectiveness for wastewater treatment and at what TMP. The CFV and temperature were kept the same for each experiment. The results of the parameter study are described in the following sections.

6.2.1 Flux

The average flux behaves as expected for the NF and UF membranes, increasing for each increase in TMP. The results can be seen in the figures below, and a full table of data can be found in the appendix.

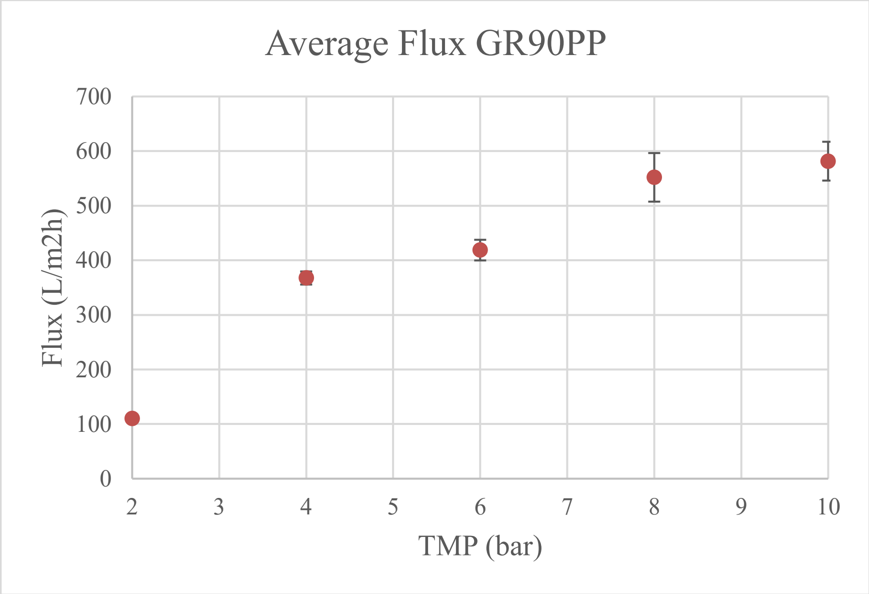

Figure 6 Results of flux measurements at increasing TMP for UF membrane.

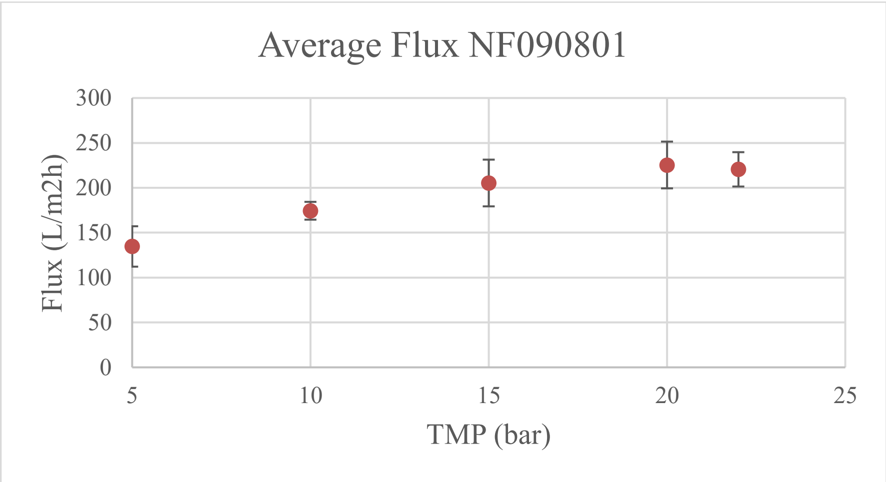

Figure 7 Results of flux measurements at increasing TMP for NF membrane.

The UF membrane exhibits the highest flux of all the membranes at 581 L/m^{2}h at the highest TMP of 10 bar, which is expected since it has the biggest pore size, shown in figure 6. The flux is also quite high for NF, in the range of 135 – 225 L/m^{2}h, shown in figure 7.

The reverse osmosis membranes behave differently from the NF and UF membranes, as they are very dense, and therefore only produce a very low flux, even at high pressures. The results can be seen in figure 8 and 9.

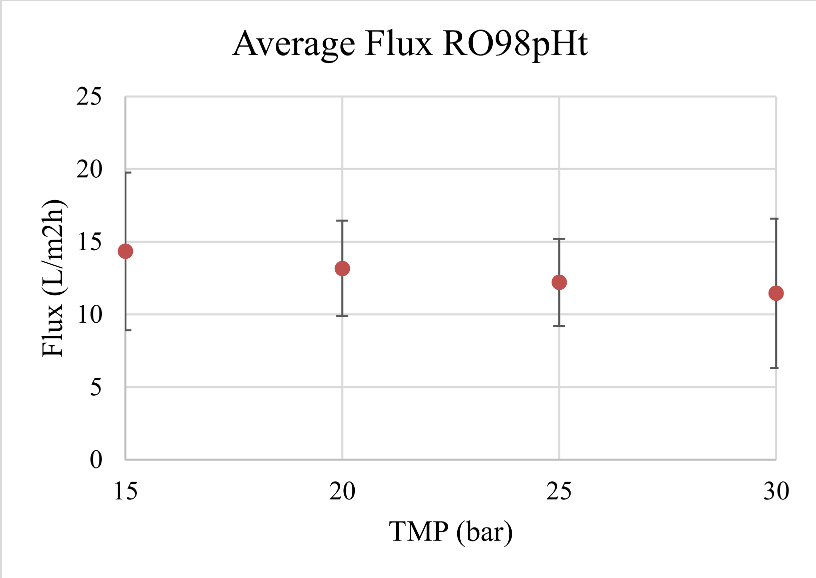

Figure 8 Results of flux measurements at increasing TMP for RO98pHt membrane.

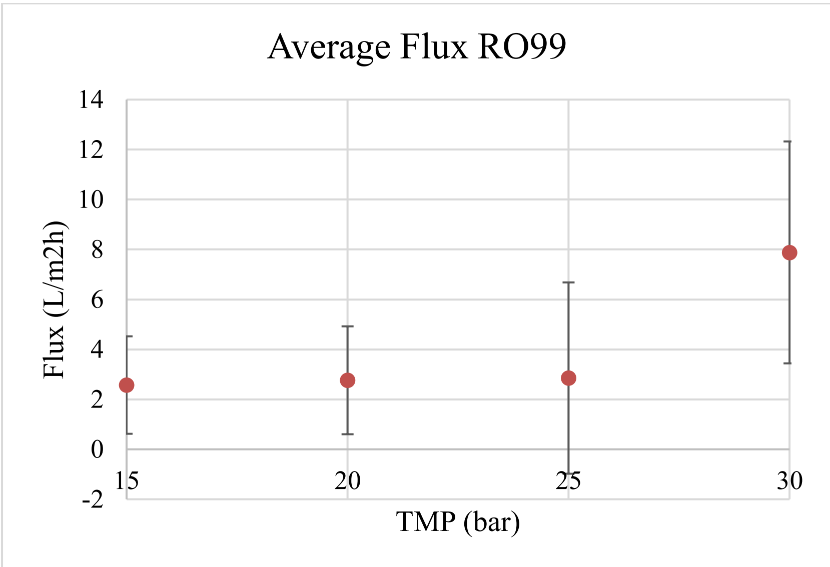

Figure 9 Results of flux measurements at increasing TMP for RO99 membrane.

As seen in figure 8, the RO98pHt membrane shows a small decrease in flux from 15 bar to 30 bar, which may indicate fouling. However, the reduction is very small (circa 3 L/m^{2}h) and within the standard deviation, as indicated by the error bars, which indicates that the trend can be attributed to experimental uncertainty rather than a confirmed fouling effect.

The RO99 membrane has a stable flux for the first three tested TMPs, increasing only slightly from 2.6 L/m^{2}h at 15 bar to 2.9 L/m^{2}h at 25 bar, shown in figure 9. Then there is a sudden increase in flux at TMP 30 bar to 7.9 L/m^{2}h. The experiment at 30 bar had to be redone, since the membrane got damaged during the first run. Therefore, the flux of 7.9 L/m^{2}h has been achieved with a freshly conditioned membrane, which could contribute to the higher flux.

Errors due to the equipment and how it is used (how tight the module is closed, how the membrane is placed, how uniformly the module is heated) also contribute to differences between experiments.

6.2.2 Chemical Oxygen Demand

The results from the parameter study COD analysis can be found in table 3. The retention R_{obs} was calculated using equation 4, where the feed concentration was used as C_b.

Table 3 Measured retention of COD for each membrane in the parameter study.

Membrane	*TMP (bar)*	R_{obs}	*Feed mg/L O_2*	*Permeate mg/L O_2*
GR90PP	2	0.08	121740	112000
	10	-0.04	122400	126800
NF090801	5	0.08	146820	135000
	22	-0.02	148000	151190
RO98 pHt	15	0.40	142080	85120
	30	0.46	117700	63880
RO99	15	0.67	120620	39680
	30	0.49	120640	61360

Due to the dead-end filtration set up, the feed cannot remain constant during the entire parameter study, as permeate and feed samples are removed in the beginning, which changes the composition of the wastewater at the end of the experiment. To mitigate this, small samples of 5 ml each were taken, and only at two pressures.

A fresh sample of wastewater was used for each membrane. However, the wastewater samples also have varying compositions as they have been produced from different textiles and in different laboratories. This is representative of the Rewin process, as their textile feed is not uniform and different batches will have different fibre compositions, dyes, etc. This will also result in slightly different concentrations of MEG in the wastewater, which makes up a large portion of the measured COD. Any membrane filtration treatment of the wastewater must be robust enough to withstand fluctuations in wastewater composition, and for this reason it was not a concern that the method allows for feed concentration to fluctuate.

The negative retention observed at the higher pressures for the UF and NF membranes is unexpected. Since the difference in COD is very small, it could be attributed to measurement inaccuracy in the pipettes or testing kit. However a replicate of the NF measurements was made showing the same results, and the UF membrane exhibits the same behaviour. It is possible that the membrane has degraded over the course of the experiment, but most likely it has to do with the Albi module not closing completely and therefore some feed was able to leak through without passing through the membrane. There were some issues with the module leaking for the NF and UF experiments which could have affected the outcome slightly. However, the retention rate of both the UF and NF membranes is so low, even at the lowest pressure, that it is not worth pursuing these as options for treatment of Rewins process water in any case.

6.2.3 Conductivity

The results of the conductivity measurements shown in table 4 show that the membrane with the highest salt retention was the RO98pHt membrane at 30 bar with 68% retention. Overall, the NF membrane performed worst, with a maximum retention of 28%, although the RO98pHt membrane had a lower retention (7%) at the lowest pressure 15 bar. RO99 exhibited more stable retention at 49% at 15 bar and 59% at 30 bar.

Table 4 Conductivity measurements showing the retention of salts for each membrane, at different pressures.

Membrane	*TMP (bar)*	*R*	*Feed (µS/cm)*	*Permeate (µS/cm)*
NF090801	5	0.16	279.5	235
	22	0.28	328.6	235.4
RO98pHt	15	0.07	165.2	152.9
	30	0.68	174.9	56.68
RO99	15	0.49	168.4	86.53
	30	0.59	192	79.45

The results of the conductivity measurements show a clear trend in increased salt retention with increased TMP. This is expected since increasing the TMP increases water transport through the membrane, while salt diffusion remains low in comparison. Overall, the results follow the expected trend of larger pore size membranes (NF) have lower retention than those with smaller (RO). The exception is the RO98pHt membrane at 15 bar, which could be explained by the differences in feed composition or the TMP being too low to overcome osmotic pressure.

6.2.4 Colorimeter

The results from the colorimeter are shown in table 5 and 6 below. The results are difficult to evaluate because of the large uncertainty in the measurements, since the colorimeter was not specifically designed for translucent samples. For example, the NF membrane exhibits quite a large change in b* value at 22 bar (-0.46) and the RO99 membrane does not (b* decreases by -0.03 and -0.08). However, visually a colour change was observed in samples from the RO99 membrane filtration, and none were observable for NF. This could be explained by the on average larger standard deviation in the NF than RO measurement. The NF samples were also among the first to be measured, so the measurement uncertainty decreased with practise.

Table 5 Results from colour analysis for UF and NF membranes.

	GR090PP 2 bar	*GR090PP 10 bar*	*NF090801 5 bar*	*NF090801 22 bar*
Feed				
*L**	39,06 ± 0,28	38,94 ± 1,04	39,70 ± 0,56	39,52 ± 0,39
*a**	0,21 ± 0,02	0,22 ± 0,02	0,14 ± 0,05	0,13 ± 0,05
*b**	2,67 ± 0,18	2,52 ± 0,23	2,57 ± 0,51	2,72 ± 0,44
Permeate				
*L**	39,19 ± 0,56	39,03 ± 0,40	39,31 ± 1,03	39,37 ± 0,83
*a**	0,21 ± 0,04	0,18 ± 0,04	0,14 ± 0,05	0,16 ± 0,04
*b**	2,65 ± 0,41	2,27 ± 0,11	2,44 ± 0,48	2,26 ± 0,26

Table 6 Results from colour analysis for RO membranes.

	RO99 15 bar	RO99 30 bar	RO98 15 bar	RO98 30 bar
Feed				
*L**	40,43 ± 0,29	39,23 ± 0,51	40,42 ± 0,86	39,93 ± 0,41
*a**	0,14 ± 0,02	0,16 ± 0,02	0,13 ± 0,05	0,11 ± 0,03
*b**	2,17 ± 0,17	2,51 ± 0,17	2,09 ± 0,20	2,19 ± 0,18
Permeate				
*L**	40,10 ± 0,25	39,34 ± 0,44	39,70 ± 0,26	40,40 ± 0,39
*a**	0,17 ± 0,02	0,15 ± 0,01	0,12 ± 0,02	0,09 ± 0,04
*b**	2,14 ± 0,19	2,43 ± 0,13	2,05 ± 0,19	1,88 ± 0,07

Interestingly, the trend of colour removal is higher for the higher TMP for each membrane, which does not correlate with the trend in COD retention, but does correlate with conductivity. Therefore, a higher COD retention does not necessarily mean that more dye was retained by the membrane. Higher COD retention could instead indicate that smaller organic molecules, like leftover ethylene glycol, are being retained. This is likely since there is a larger quantity of MEG in the spent process water (a few percent) compared to dye (ppm level). Therefore, a small retention of MEG would have a greater impact on COD than a high retention of dye.

Overall, the membrane that showed the best colour removal was RO98pHt at 30 bar, with a decrease in b* value of -0,31.

6.2.5 ICP-OES Results

The results of the ICP-OES analysis are show that the metal ions present in the spent process water feed vary in concentration from so low that they are below detection, to 2.71 mg/L. For the permeate, the maximum concentration found was 1.95 mg/L. The full table of results can be found in the appendix, and a summary of the retention of each metal for each experiment in the parameter study is found in table 7. The retention has been calculated in the same way as for the other analyses in the parameter study, using feed concentration as C_b.

Table 7 Retention of different metal salts in parameter study.

	TMP (bar)	***Cd R***	***Cr R***	***Cu R***	***Fe R***	***Mn R***	***Ni R***	***Sb R***	***Ti R***	***Zn R***
NF090801	5	0,16	0,72	-0,03	0,97	0,13	0,12	0,07	0,00	0,76
	22	-0,29	0,75	-0,15	1,00	0,07	0,62	0,01	0,42	0,34
RO98	15	0,77	-4,98	0,74	0,80	0,49	0,48	0,65	0,37	0,74
	30	0,53	BDL	0,85	0,83	0,58	0,48	0,79	0,22	0,75
RO99	15	0,62	-	0,41	0,97	0,61	-0,93	0,92	0,53	0,96
	30	0,37	BDL	0,74	-	0,38	0,28	0,66	-0,03	0,74

BDL indicates that both values were below the detection limit, and missing value indicates that one of the concentrations (either feed or permeate) were below the detection limit and therefore could not be calculated. Pb was also measured, but all of these results were under the BDL, and have therefore not been included here.

The retention rates vary widely depending on which metal is being analysed, the pressure and which membrane is used. The fluctuation is expected since different membranes have different affinities for certain metal ions, depending on their charge and size. However, the variance in feed composition will also have contributed to the variance in metal salt retention, which makes it difficult to draw any overall conclusions from these results. The result for Cr at 15 bar with RO98pHt is surprising as it is not only negative but very high compared to the other results.

When looking at the median average of the different metal salt retentions, the RO membranes perform slightly better on average (0.38 – 0.66) than the NF membrane (0.13 – 0.34). However, the RO membranes do not show an increased retention with increased TMP, which the conductivity measurements seemed to indicate. This suggests that the trend of increased retention at higher TMP seen in the conductivity measurements was made up in majority of monovalent salts.

6.3 Concentration Study

The RO98pHt membrane was chosen for the study, with a TMP of 30 bar, CFV 0.5 m/s and temperature 50°C. This membrane and these parameters were decided on as they gave the largest reduction in colour, as this is the most important factor for Rewin in wastewater treatment.

The concentration study took a total time of 6 hours and 17 mins, and resulted in a volume reduction of 55%, with a permeate of 165.9 g from the starting 299.4g. The figure below shows how the flux reduced over time, from 25 L/m^{2}h, and stabilising to circa 5 L/m^{2}h.

A PWF was measured before the experiment and compared to the PWF directly after the experiment, which is described as the fouled water flux FWF. After cleaning, the PWF was measured again, and this was described as the clean water flux, CWF.

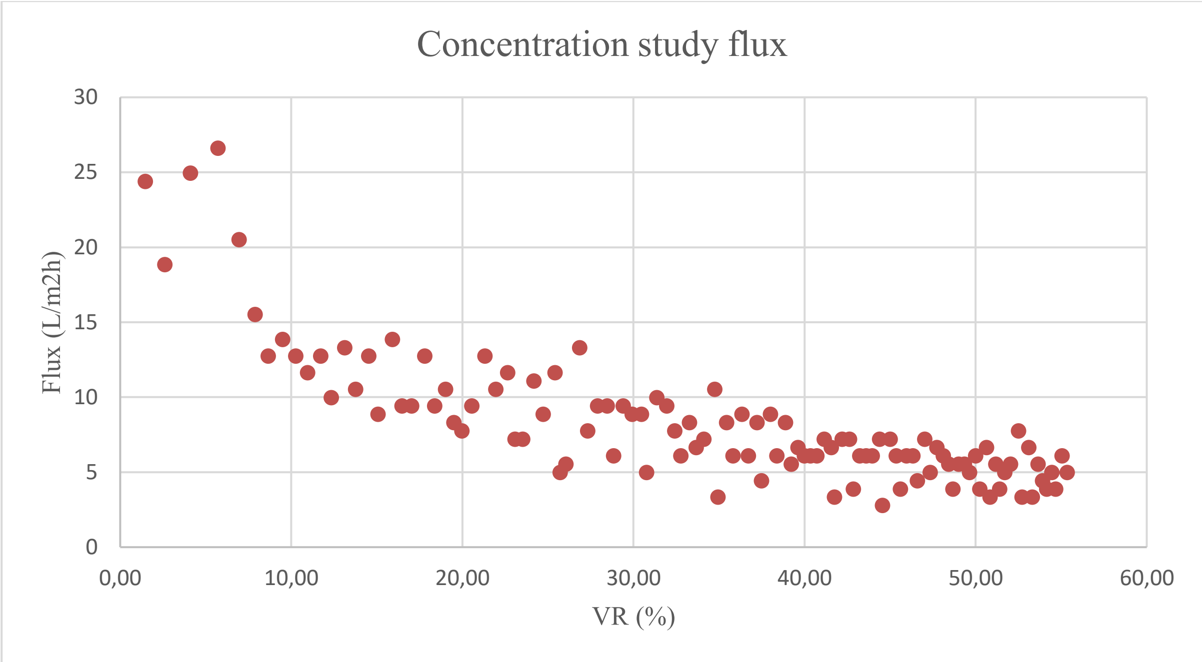

Figure 10 Flux variation over the course of the concentration study.

The flux reduces greatly over the course of the experiment, which is expected, as the longer filtration time leads to a concentration of the feed. This enhances the effect of concentration polarisation and fouling leading to a reduced flux. The flux reduces quickly at first and then gradually stabilises, indicating initial fouling, and possibly cake layer formation.

When comparing the PWF and FWF it is clear there has been fouling on the membrane, which is unsurprising since RO membranes are easily fouled, due to their pore size. The PWF came to 292.7 L/m^{2}h, which reduced to a FWF of 92.6 L/m^{2}h after the experiment. The fouling grade calculated using equation five was 68.4%, which confirms that significant fouling has occurred.

The fouled membrane was cleaned the same way it was conditioned, with 1% Ultrasil at 50°C and 2 bar for 1h. After this, the CWF was 138.0 L/m^{2}h, which is still less than half of the PWF and the fouling grad remains high at 52.9%. Since only one method of cleaning was tested, it is not certain whether the fouling still present on the membrane is irreversible or if a longer cleaning time or a different cleaning agent could remove it.

Reverse osmosis membranes are very sensitive to fouling, and therefore a nanofiltration pretreatment step could be implemented to remove larger particles and avoid pore-blocking.

6.3.1 COD and conductivity analysis

The results of the chemical oxygen demand analysis can be seen in the table below. This time, the retention was calculated using the average of the concentrate and feed concentrations as C_b instead of feed concentration, as this is more representative of what the bulk concentration was during the experiment. The COD retention R_{obs} came to 39%, which is lower than the retention achieved in the parameter study with the same conditions, which was 46%. Similarly, the salt retention was also lower in the concentration study than for the same conditions in the parameter study, 50% compared to 68%.

Table 8 Results from COD and conductivity analysis of concentration study.

Analysis	R_{obs}	***Feed***	***Permeate***	***Concentrate***
COD	0.39	125140 mg/L O_2	87910 mg/L O_2	164060 mg/L O_2
Conductivity	0.50	142.7 ± 4.1 µS/cm	91.4 ± 2.0 µS/cm	224.8 ± 6.7 µS/cm

6.3.2 Colorimeter results

The colorimeter results show a decrease in b* from feed to permeate, which confirms that colour has been removed. However, as with all colorimeter results, there is a large confidence interval which makes it difficult to draw reliable conclusions. The colour intensity of the concentrate seems to be lower than the feed, which suggests that the observed fouling was caused by adsorption of dye molecules onto the membrane surface. On the other hand, it could also be a side-effect of the uncertainty in the measurement. From observation, it seems like the concentrate has a more saturated colour than the feed, so in fact the true b* value for the concentrate should be at the upper interval.

Table 9 Results of the colour analysis of the concentration study.

	Feed	**Permeate**	**Concentrate**
L*	40.01 ± 0.40	39.92 ± 0.35	39.58 ± 0.26
a*	0.20 ± 0.03	0.14 ± 0.04	0.18 ± 0.04
b*	2.88 ± 0.21	2.40 ± 0.31	2.68 ± 0.33

6.4 Economic analysis

To answer the question if membrane filtration is a financially viable option for Rewin Textiles, in their upscaling process an overarching economic analysis was made. The economic analysis is meant to be a first estimation of the cost, since a deeper analysis is outside the scope of this thesis.

To aid the understanding of the economic value of a membrane filtration system, three scenarios will be explored in this analysis. Scenario A is no wastewater treatment at all, just sending all of the water to municipal treatment. Scenario B is to use a set up similar to the one explored in the concentration study and treat the water with RO. Scenario C is a compromise, and entails building a small secondary wastewater treatment plant onsite.

The book *Chemical Engineering – Process Design and Economics, A Practical Guide* by Ulrich and Vasudevan was used to make economic estimations for scenarios B & C. Since the book was published in 2004, all values taken from the book were adjusted for inflation using the Chemical engineering plant cost index, CEPCI. Historical values can be adjusted using equation seven, where C is the equipment cost, I is the CEPCI which is 400 in 2004 and 840 today ('Plant Cost Index Beta', n.d.).

$$C_{2026} = C_{2004} \cdot \frac{I_{2026}}{I_{2004}} \tag{7}$$

As part of this economic analysis, several assumptions have been made. The factory is assumed to have a capacity of 25 000 tons/year, and with maintenance breaks this means it will run for 8000 hrs/year. Therefore, 150 000 m^3 of wastewater will have to be treated per year, which gives an average flow of 5.21 L/s. Other assumptions were made include electricity price of 0.672 SEK/kWh and an exchange rate of 9.23$ to SEK. The plant is also assumed to be placed in Eslöv, Skåne, as this is where Rewin's pilot plant is situated.

6.4.1 Scenario A – Municipal water treatment

The first option for Rewin is to not treat their wastewater at all and instead send all of it to a municipal wastewater treatment plant. Since the COD, and therefore the biological oxygen content BOD, is so high, this becomes very expensive very quickly. The emission limit of BOD in the Skåne region is 260 g/m^3 and the average feed composition of wastewater can be estimated to 60 000 g/m^3 BOD (half of COD). These emissions alone would cost Rewin 76 million SEK every year. A summary of the costs for scenario A can be found in the table below and a more detailed breakdown of costs is in the appendix.

Table 10 Summary of costs for scenario A.

Scenario A – Operational costs		
Water and fees	7 219 472	SEK/yr
Contaminated wastewater treatment	75 989 280	SEK/yr
Total	83 208 752	SEK/yr
Scenario A – Capital costs		
Water deionising equipment*	151 818	SEK

** Source: (www.alibaba.com, n.d.)*

6.4.2 Scenario B – RO membrane filtration

Based on the results of the parameter study, a membrane filtration system of several steps was designed. First, there is a nanofiltration step to remove the larger particles and keep fouling on the subsequent RO membranes low. This was then followed by five reverse osmosis filtration steps, using the RO99 membrane as it showed the highest retention of COD. The retention was assumed to be the same as in the parameter study, however the fluxes were changed to more accurately reflect a spiral wound, crossflow module. The design specifications of each membrane module and the single module cost can be seen in the following table.

Table 11 Specifications of membrane system.

	NF	**RO99**
Flux (L/m2h)	100	10
Area total (m2)	187.5	1875.0
Module Area (m2)	35	35
No. modules	5	54
Single module cost (SEK)	10 000	10 000

The total capital cost of the membrane filtration system came to 6.5 million SEK, which includes the cost of installation, membranes, pumps, piping, cleaning systems, and control panel. The cost of replacing membranes was estimated to be 10% of the membrane filtration system cost, resulting in a cost of 650 000 SEK per year, if they are replaced each year. Other operational costs, such as electricity, staff, retentate wastewater discharge fines or make-up freshwater costs, have not been included here and are left to future studies.

6.4.3 Scenario C – Small secondary wastewater treatment plant

A common way to treat wastewater that has a high BOD is by secondary treatment, which includes oxidising organic compounds using active sludge, combined with filtration. Installing a small secondary wastewater treatment plant that has a capacity of 0.005 m^3/s would cost 9.69 million SEK (Ulrich and Vasudevan 2004). The cost for installing a standardised secondary wastewater treatment plant was taken directly from the aforementioned book by Ulrich and Vasudevan, 2004 and the sizing is based solely on the waterflow and is not tailored to the specific contents of the wastewater.

In addition to this, there would be additional operational costs associated with running the treatment plant, such as electricity, staff, and replacement membranes and maintenance. There would also be the additional cost of purchasing fresh water as well as water distillation equipment, as in scenario A, since the cleaned water would meet discharge limits but not be of high enough quality for reuse. A summary of these costs can be found in table 12 below.

Table 12 Summary of costs for scenario C.

Scenario C – Operational costs		
Water and fees	7 219 472	SEK/yr
Scenario C – Capital costs		
Water deionising equipment	151 818	SEK
Installed wastewater treatment plant	9 691 500	SEK
TOTAL	9 843 318	SEK

The costs for in installing a wastewater treatment plant should only be seen as a rough estimate, as the contents of Rewin's spent process water is very different from a municipal wastewater, which the cost is based on. Municipal wastewater has a BOD of 110-350 mg/L, compared to Rewins 60 000 mg/L (Metcalf and Eddy 2014). More research is needed in order to determine the proper dimensions for an active sludge treatment plant.

6.4.4 Conclusions of economic analysis

The results of the economic analysis show that the chosen wastewater treatment solution will have a large impact on the financial viability of upscaling Rewin's process. The first option, scenario A, is unrealistic since the high BOD levels lead to extremely high annual costs of 76 million SEK. Even if the company could afford these costs for a few years, in the long term it is not economically sustainable. Placing the factory in another part of Sweden, where the price of water is cheaper, could cut the freshwater costs by about half, which would lower the other major cost in this scenario, but the emissions cost is unavoidable if water is not treated.

Treating wastewater is the only viable option, and both scenarios B and C present technically viable options, although with markedly different costs. The membrane filtration system in scenario B presents the greatest opportunity for water reuse and low capital cost. Scenario C, secondary wastewater treatment, allows for water to be discharged at a similar capital cost but without yearly fees for emissions for waste stream disposal, which makes scenario C stand out as the most economically sustainable option.

In the future, a more detailed economic analysis of the operational costs of scenarios B & C should be made before a final decision is made. It is also possible that the membrane filtration set up could be improved, resulting in higher fluxes and more efficient pollutant removal, which would lower costs. An optimal solution may be to combine secondary wastewater treatment with membrane filtration in order to reuse as much water as possible while keeping the costs reasonable.

7 Conclusions

The aim of this thesis was to evaluate the effectiveness of membrane filtration treatment of wastewater from Rewin Textiles polyester recycling process.

A parameter study was conducted in which differences in membrane performance were observed. As expected, the membranes with larger pore sizes, UF and NF, obtained very low retention rates and were not suitable for wastewater treatment, except as a pre-treatment step to prevent fouling. In contrast, the reverse osmosis membranes showed the highest retention rates of COD (all above 40%) and high salt rejection at the higher pressures.

The RO98pHt membrane was selected for the concentration study, at the optimal conditions TMP of 30 bar, CFV 0.5 m/s and temperature 50°C. The study resulted in a COD retention of 0.39 salt rejection of 0.5 and colour removal of delta b*= 0.48. These retentions are still quite low and show that further work is needed to improve the optimisation of the parameters for membrane filtration. The flux reduced significantly over the course of the concentration study, due to fouling on the membrane, which had a fouling grade of 68.4%. This would cause problems in upscaling this system, and suggest that other, more fouling resistant RO membranes would be better suited to this application.

From an application perspective, the retention rates and fluxes are currently too low to be economically viable. The economic analysis showed that an alternative solution for Rewin could be installing a small secondary wastewater treatment plant. However, further work is needed to confirm these costs.

Overall, this thesis contributes to a better understanding of treatment options for polyester textile recycling and highlights the key challenges left to address before a viable membrane filtration system can be implemented.

8 Future Work

Based on the results of this study, further research is needed to improve the efficiency and reliability of membrane filtration for the treatment of wastewater from polyester textile recycling, before it can be scaled up.

Future studies should focus on reverse osmosis membranes and could investigate the effects of changing the CFV and temperature on membrane performance. Experiments using a crossflow module instead of dead-end filtration could contribute to a better understanding of how membranes will behave in a scaled-up process. Taken together with a deeper economic analysis, future experiments could provide insight into whether multi-stage membrane filtration is a viable option. Since the retention rates were so low, it is recommended to evaluate alternative separation processes to membrane filtration for treating the spent process water.

In addition to this, it is recommended that the analysis methods are adjusted to limit the uncertainty in measurement and interpretation. Instead of the CR-400 Konica Minolta, an alternative colorimeter instrument that is specifically designed for translucent samples should be used to take colour measurements. Alternative methods of colour analysis, such as UV-VIS spectrophotometry could be explored. For this to be successful, a blank that accurately represents spent process water without dyes is needed. This would ensure that spectrophotometer only measures the absorption of the dye particles; not the other contaminants in the spent process water.

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Appendix

Flux

Measured average flux for each membrane in parameter study at different pressures

Membrane	TMP (bar)	Flux (L/m2h)	Standard deviation
NF090801	5	134,7	22,5
	10	174,4	9,9
	15	205,3	26,0
	20	225,4	26,0
	22	220,5	19,1
GR90PP	2	110,2	7,1
	4	367,5	12,0
	6	418,6	18,9
	8	551,9	44,5
	10	581,5	35,5
RO98pHt	15	14,3	5,4
	20	13,2	3,3
	25	12,2	3,0
	30	11,5	5,1
RO99	15	2,6	2,0
	20	2,8	2,2
	25	2,9	3,8
	30	7,9	4,4

Economics

SCENARIO A - OPERATIONAL COSTS PER YEAR				
Municipal water	44,84	SEK/m3	6726000	SEK/year
Industry fee	169 405	SEK/year	169405	SEK/year
Base fee	3 499,00	SEK/year	3499	SEK/year
Plot fee per 100 m2	195,00	SEK/year/100m2	97500	SEK/year
Dagvatten fee per m2	3,87	SEK/year/m2	193500	SEK/year
Electricity for deionisation	5,50	kW	29568	SEK/year
BOD contamination fee	8,48	SEK/kg	75989280	SEK/year
Nitrogen contamination fee	42,80	SEK/kg	0	SEK/year
Phosphorus contamination fee	282,00	SEK/kg	0	SEK/year

ICP-OES Results

Prov	Cd 228.802 (mg/L)	Cr 267.716 (mg/L)	Cu 327.393 (mg/L)	Fe 238.204 (mg/L)	Mn 257.610 (mg/L)	Ni 231.604 (mg/L)	Sb 206.836 (mg/L)	Ti 334.940 (mg/L)	Zn 206.200 (mg/L)	Pb 220.353 (mg/L)
15F R098	0,018	0,001	0,073	0,096	0,039	0,015	0,909	0,001	1,557	BDL
15P R098	0,004	0,008	0,019	0,019	0,020	0,007	0,317	0,001	0,408	BDL
30F R098	0,009	BDL	0,042	0,013	0,042	0,017	0,803	0,001	1,297	BDL
30P R098	0,004	BDL	0,006	0,002	0,018	0,009	0,166	0,001	0,325	BDL
30C R098	0,004	0,007	0,060	0,003	BDL	0,023	0,991	0,005	1,647	BDL
15F R099	0,006	BDL	0,039	0,084	0,035	0,014	0,848	0,001	1,498	BDL
15P R099	0,002	0,005	0,023	0,002	0,014	0,027	0,071	0,001	0,066	BDL
30F R099	0,003	BDL	0,034	0,059	0,029	0,011	0,751	0,001	1,182	BDL
30P R099	0,002	BDL	0,009	BDL	0,018	0,008	0,255	0,001	0,311	BDL
30C R099	0,002	BDL	0,031	0,034	0,026	0,010	0,685	0,001	0,957	BDL
5F NF	0,004	0,007	0,108	0,012	0,030	0,012	2,089	0,001	2,711	BDL
5P NF	0,003	0,002	0,111	0,000	0,026	0,010	1,951	0,001	0,642	BDL
22F NF	0,003	0,005	0,091	0,009	0,025	0,030	1,973	0,001	0,833	BDL
22P NF	0,003	0,001	0,105	BDL	0,023	0,011	1,947	0,001	0,551	BDL