Ultrasonication of Spiral Wound Membranes to Mitigate Fouling in Reverse Osmosis

KTH Thesis Report

ELIOT DIKLEV

Author

Eliot Diklev
Chemical Engineering for Energy and Environment
KTH Royal Institute of Technology

Place for Project

Bluewater
Stockholm, Sweden

Examiner

Kerstin Forsberg
Division of Resource Recovery
KTH Royal Institute of Technology

Supervisors

Ahmed Fawzy

Bluewater

Abstract

The purpose of this study was to investigate an alternative fouling mitigation technique to flushing, that can efficiently remove biological fouling. Ultrasound was investigated as a possible method of removing fouling from a reverse osmosis spiral wound membrane. Previous research had suggested ultrasound to be efficient on flat sheet membranes but not on spiral wound membranes, due to the packing density. Therefore, this study conducted experiments on spiral wound membranes with ultrasound, as to get an understanding of its effects within the spiral wound membrane. Firstly, the time dependency of ultrasound was investigated, and showed similar results to that of previous research, that the ultrasound was efficient within a matter of minutes. Secondly, two membranes were subject to treatment once a day over the span of 12 days, with an exception for days 6 and 7. One was treated with ultrasound and one with flushing, and the microbiological contamination in the permeate was then analysed. The ultrasonically treated membrane produced less contamination throughout the 12 days. However, more experiments and analysis would be required to confirm this, as time constraints did not allow for repetitions. An economic assessment was also performed, as to evaluate the feasibility implementing ultrasound on a commercial scale. This is a weigh-off between water cost and energy cost, which is dependant on geographical location. Overall, the results indicate that the water saved costs more than the energy required though, which is favourable for the implementation of ultrasonic treatment. To conclude, the ultrasonic treatment showed better results than flushing within a matter of minutes, and also economically had an advantage but the cost of energy to water is relative to geographical location.

Sammanfattning

Syftet med den här studien var att undersöka en alternativ slamningsreducerande teknik till spolning, som effektivt kan ta bort biologisk påväxt. Ultraljud undersöktes som en möjlig metod för att ta bort igenslamningen från omvänd osmos med ett spirallindat membran. Tidigare forskning har föreslagit att ultraljud skulle kunna vara effektivt på platta membran men inte på spirallindade membran, på grund av packningsdensiteten som spirallindan medför. Därför genomförde denna studie experiment på spirallindade membran med ultraljud, för att få en förståelse av dess effekter inom det spirallindade membranet. För det första undersöktes tidsberoendet av ultraljud, vilket visade liknande resultat som tidigare forskning, att ultraljudet uppnådde effekt inom några minuter. För det andra behandlades två membran en gång om dagen under 12 dagar, med undantag för dag 6 och 7. Ett behandlades med ultraljud och ett med spolning, och den mikrobiologiska kontamineringen i permeatet analyserades sedan. Det ultraljudsbehandlade membranet producerade mindre kontaminering under de 12 dagarna. Det krävs dock fler experiment och analyser för att bekräfta detta, eftersom att tidsbegränsningar inte möjliggjorde repetitioner. En ekonomisk evaluering genomfördes också för att utvärdera möjligheten att implementera ultraljud i kommersiell skala. Den ekonomiska aspekten är en avvägning mellan vattenkostnad och energikostnad, som är beroende av geografiskt läge. Överlag indikerar resultaten att det sparade vattnet kostar mer än den energi som krävs, vilket är fördelaktigt för implementering av ultraljudsbehandling. Sammanfattningsvis visade ultraljudsbehandlingen bättre resultat än spolning inom några minuter, och hade även en ekonomisk fördel, men kostnaden för energi till vatten är beroende av geografisk plats.

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Eliot Diklev

Contents

Acronyms

CP Concentration Polarization. 14, 18

EPS Extracellular Polymeric Substances. 9

GPD Gallons Per Day. 4, 21

MF Microfiltration. 7, 8, 10

NF Nanofiltration. 7, 8, 10

RO Reverse Osmosis. 1, 2, 4, 5, 7–12, 14–18, 20–25, 30, 36, 37

SDG Sustainable Development Goals. 1, 2, 23, 24

SEM Scanning Electron Microscopy. 15

SWM Spiral Wound Membrane. 4, 9–16, 18–25, 30, 36, 37

UF Ultrafiltration. 7, 8, 10, 15

UN United Nations. 1, 23, 24

UTS Under-the-Sink. 5, 12–14, 16, 18

VSEP Vibratory Shear Enhanced Processing. 18

Nomenclature

π Osmotic Pressure

C Molar Concentration of Non-Permeable Solute

cfu Colony Forming Units

K Kelvin

mL Milliliter

psi Pound Force per Square Inch

R Universal Gas Constant

T Absolute Temperature

1 Introduction

1.1 Background

The access to water is recognised by the United Nations (UN) as a basic human right. The UN states that this right should encompass sufficient, safe, acceptable, physically accessible and affordable water [1]. However, far from everyone is provided this basic human right, and currently 2.1 billion people are derived of this right globally [2]. Therefore, the UN has also included it as one of its 17 Sustainable Development Goals (SDG), goals which are set to be achieved by 2030 [3]. Access to water is covered by SDG 6 - "Clean Water and Sanitation", which includes the criteria "ensure availability and sustainable management of water and sanitation for all" [3]. At the current rate, however, SDG 6 will not be achieved by 2030 and significantly increased efforts are necessary to reach it [4].

To combat contaminated water and make it safe to drink, a variety of treatments are available. In this study, however, Reverse Osmosis (RO) is the method which will be subject for further investigation. RO is a separation process, in which water is purified and deionized, as it passes through a semipermeable membrane under pressure [5]. This membrane does, however, get fouled during operation, and even more so during intermittent usage [6]. The rate and type of fouling is dependent on feed water quality, such as chemical and biological composition [7]. Generally, this fouling is dealt with either mechanically or chemically. Chemical disinfection can be used to rid the membrane of fouling, but produces secondary pollution and poses a safety risk [8]. Furthermore, the most commonly used RO membrane is a polyamide membrane, which is sensitive to free chlorine, other halogen-based oxidants, as well as other strong oxidants [9]. Exposure of these chemicals to the membrane would degrade the membrane, reduce rejection and cause the need for replacement prematurely, in comparison to its intrinsic lifespan [9]. An alternative, less intrusive method to chemical disinfection could achieve a longer lifespan of the membrane, and a reduced maintenance cost. Flushing and reverse flushing of the membrane with water is an existing solution, where water is rejected from the membrane but with it carrying foulants away from the membrane and thus cleaning it. Although flushing presents a good method of cleaning the membrane, it does,

however, also have the downside of consuming additional water and or permeate [9]. With the scarcity of water, an alternative mechanical solution that would reduce the need for chemical and minimize water utilization is of interest. Thereby, making it more affordable, acceptable and safe, which is in line with SDG 6.

The efficiency and energy consumption of the system is on the quality of the feed water, whether it be seawater, brackish water or fresh water. The market for RO was in 2017 approximately 6.5 billion USD and expected to grow to 9.2 billion USD to 2022 with a compound annual growth rate of 7.25% [10]. A market which can provide more safe water to people, however, the high maintenance cost of filters limits the affordability and thereby presents an obstacle to the market growth [11]. An extension of membrane lifespan could potentially offer more people safe water, through a reduced operating cost. Water treated with RO is potable, however, the lack of ions may cause a difference in taste [12]. Potable water from water treatment plants has many criteria for a variety of which, which can be seen in Table 1 in the Appendix [13].

1.2 Problem Formulation

Access to clean and safe drinking water is a basic human right, yet is not guaranteed everywhere in the world. Contaminated water poses a great health risk, and the need for purification is necessary in many places. The use of water purification systems, such as RO systems, can purify contaminated water, but with the downside of having a limited membrane lifespan. A short lifespan generates waste to landfills and costs for the consumer.

Reducing the cost of RO membrane could increase the access to clean water for more, as it has been identified a limiting factor to the market growth [14]. The intrinsic lifespan of a membrane is largely unaffected by cleaning mechanisms, as it degrades over time nevertheless. However, the fouling of the membrane can be reduced through cleaning, thereby prolonging the actual lifespan of the membrane [9]. Ultrasonic treatment provides a potential way of cleaning the membrane without the addition of detrimental chemicals [15]. Understanding the mechanisms and properties of ultrasonic waves have and how they could clean a membrane could provide an efficient cleaning

method to the fouling phenomena seen in membrane technology.

1.3 Research Question

The aim of this thesis is to evaluate following research question and the sub-questions connected to it.

- *Research Question: How can the implementation of ultrasonic treatment of reverse osmosis spiral wound membrane contribute to enhancement of the system process?*

In order to answer the research question three additional sub-question have been formulated, to create more easily answered questions which individually contribute to the original research question.

- *Sub-question 1: What effect does ultrasonic treatment have on the biological fouling on the membrane?*

- *Sub-question 2: How does time duration of ultrasonic application affect the results, in terms of microbiological fouling?*

- *Sub-question 3: How does the implementation and utilisation of ultrasonic treatment into a reverse osmosis system affect the economics of purified water?*

1.4 Delimitations

In order to delimit the scope of this study, the application of ultrasound has been limited to the use of an ultrasonic water bath and not direct application through the use of transducers. This delimitation was largely due to time constraints, financial reasons and availability. Although transducers would serve a more realistic approach of integrating ultrasound a the system, using the ultrasonic water bath serves as a proof of concept and could motivate the future research or implementation of transducers.

Additionally, the study is delimited to a single frequency and does not encompass frequency regulation. Although frequency regulation is an interesting variable to take into account, it could not

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be investigated due to the lack of availability of multi-frequency ultrasonic water baths and time constraints. A range of frequencies could have broaden the perspective of the results and a deeper understanding of the phenomena in relation to RO SWM. However, in this study only a frequency of 40 kHz have been used. Similarly, the power of the ultrasound could not be regulated either and was set to 600 W for a water bath which holds 30 litres of water. Power and frequency regulation could potentially highlight the most energy efficient method in cleaning the membrane, but will have to be done in future research should it be needed.

This study is delimited to a particular membrane, namely the membrane used in Bluewater's machine "Cleone", which is a aromatic polyamide membrane. Therefore, making the generalization of these results onto other membranes, whether it be other material or configuration, questionable. Similarly, this is a smaller membrane of 50 Gallons Per Day (GPD), which also could pose an issue when scaling up these results. However, this was the most realistic approach to use material that Bluewater already have available commercially and similarly available for experiments.

Furthermore, another important factor of this project is the geographical delimitation. Tap water in Sweden have been used, both to foul the membranes during operation and also as the water which have been purified. The inlet water determines much of the fouling, but due to time constraints and financial reasons this has only been used from one source. Thus, making the results of ultrasonic treatment in other regions uncertain as the fouling could be different and, therefore, also behave differently to ultrasonic treatment. Likewise, the optimum time and power of the ultrasound could vary between locations. However, the economics have considered prices of both water and energy consumption of different locations.

1.5   Expected Outcomes

The outcomes of this thesis is expected to show whether the use of ultrasounds can reduce fouling of a RO SWM, and if it could reach levels of biological contamination low enough to reach the limits of drinking water. Previous research has been non-conclusive on the technical matter, both in terms of how well it is working and whether the membrane is damaged or not [16, 17, 18]. The potential

of ultrasounds has, however, been highlighted. The economical aspect will also be evaluated, whether it is economically justified to implement the use of ultrasound to clean the membrane. Subject to this economical analysis will be water consumption, energy consumption and cost of parts. Furthermore, previous research has been more directed to industrial sized membranes rather than UTS RO systems, which could affect both technical and economical aspects [8]. As this thesis examines small-scale RO systems, it could provide insight to an area where the use of ultrasound is both technically and economically feasible.

To conclude, the expected outcome of this study aims to determine whether ultrasound can be used to maintain a clean membrane. In turn, this also affects water usage and energy consumption, which will be used to evaluate economical feasibility. It will serve as a guideline to Bluewater whether or not ultrasonically cleaned membranes is a viable option to pursue, while adding additional information to the academic community.

1.6   Disposition

To clarify the structure of this report, a short description of the following chapters are presented here.

Chapter 2 treats the literature review, with the current research of fouling mechanisms, ultrasonic cleaning, polyamide membranes.

Chapter 3 describes the methodology of this thesis, which includes the research approach, ethics and sustainability.

Chapter 4 presents the results of the experiments performed, and discusses the impact of these and relevance to this study.

Chapter 5 concludes this thesis through a short summary, and through the discussion of what impact this study has in its field.

Chapter 6 suggests recommendations for future research, areas where this study might have not been able to investigate due to various reasons.

Chapter 7 contains the appendix to this thesis, information which could help expand the understanding of this report but not necessarily needed in text.

2   Literature Review

2.1   Reverse Osmosis

Membrane processes consist of mainly of four different categories, namely Microfiltration (MF), Ultrafiltration (UF), Nanofiltration (NF) and RO [19]. MF, UF and NF are considered filtration processes and rely on a different separation mechanism than RO, and achieve separation through a sieving mechanism by retaining dissolved solids [19]. RO is different as it consists of a semipermeable membrane, which only allows water through under pressure while rejecting solutes at high rates [20]. The pressure required to drive this separation, the osmotic pressure, is why it is also an energy consuming process [20]. The osmotic pressure required to overcome the differences in concentrations can be visualised, as seen in Figure 1 [20].
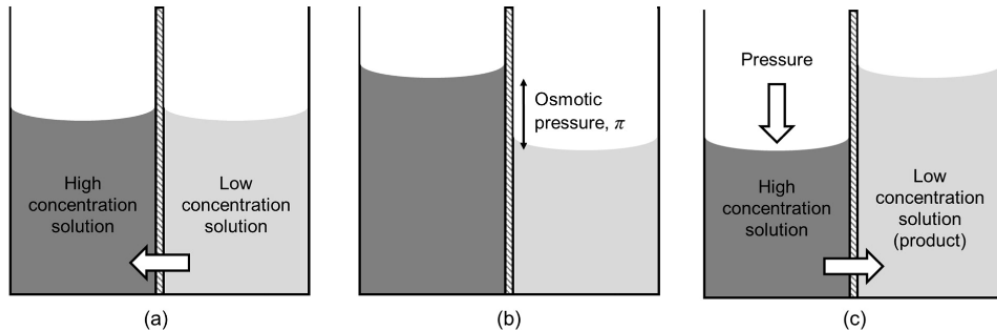
Fig. 1. Schematic of (a) osmosis (b) osmotic equilibrium (c) RO.

Figure 1: The figure illustrates how the concentration difference of solutes affect the transport phenomena of water in (a) osmosis, (b) osmotic equilibrium, and (c) reverse osmosis. The pressure applied in (c) to drive the RO process, has to overcome the osmotic pressure seen in (b) [20].

As Figure 1 illustrates, there will be a force driving the separated liquids to an osmotic equilibrium, which is dependent on the concentration. Therefore, a certain amount of pressure is needed to overcome the osmotic pressure, π, of a certain solute concentration. Depending on water composition, different pressures are required to overcome the osmotic pressure. The van't Hoff equation for ideal solutions estimates this pressure, and which can be seen in Equation 1 [20].

$$\pi = CRT \tag{1}$$

Desalination of seawater can require pressures of up to approximately 100 bar, which makes it an expensive process [20]. However, the scope of this study is the purification and removal of impurities in freshwater on tap, which requires less pressures as there is lower concentrations and contaminants.

2.2 Fouling Mechanisms

Fouling is a phenomena in membrane technology in which rejected material adheres to or otherwise blocks the membrane, thereby reducing the efficacy of the membrane. Matin et al. (2021) classified the different types of membrane fouling into four categories; inorganic, organic, biofouling, and collodial [18]. The fouling can occur in the membrane pores, internal fouling, or on the surface of the membrane, surface fouling [18, 21]. While pore fouling is common in MF and UF, it is not as evident in RO as it is compact, non-porous and semipermeable in nature but does however have a dominant issue with surface fouling instead [18, 21]. Surface fouling is, however, more easily managed and controlled, in comparison to the internal fouling [18].

The phenomena of fouling has been studied extensively, and to maintain the integrity of the RO membrane prefilters are often employed [22]. Prefilters consisting of MF, UF, and NF remove suspended solids and microorganisms to avoid particulate damage of the RO membrane [22]. These filters are not capable of removing chloride though, which degrades the crosslinks of the aromatic polyamide RO membrane [23]. To combat this issue, the implementation of activated carbon filters are common to remove chlorine and other odorous compounds [24]. Yet, fouling of the RO membrane will still occur, especially biofouling. Even though 99.9% of biological contaminants are removed the remaining 0.1% is able to grow once adhered to the membrane [25]. Inorganic, organic and colloidal fouling is not as evident in RO systems treating freshwater from taps, as most of which has been removed in earlier treatments. This is why biological fouling has been the focus of this study. Figure 2 shows the different steps of how biofouling of a membrane occurs.
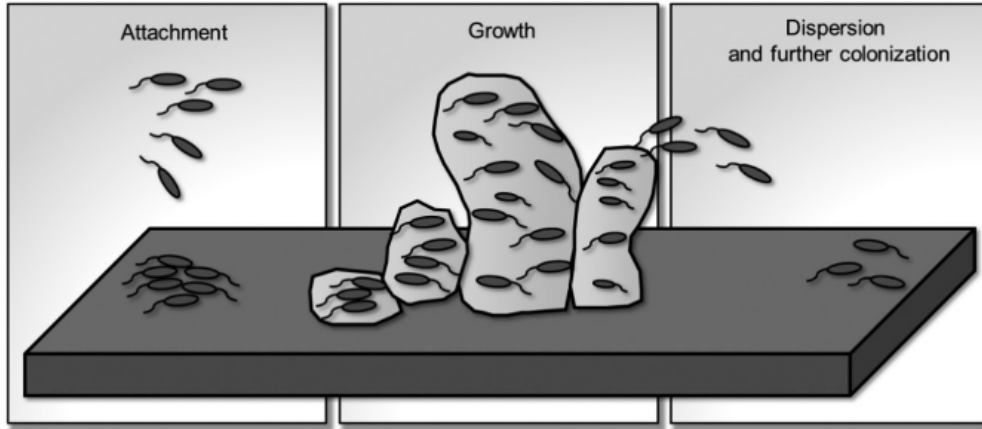
Figure 2: The figure shows how biofouling affects the RO membrane over time. The bacteria will first attach to the membrane, then grow and develop a biofilm before dispersing and form new colonies [8].

As Figure 2 shows, even though a small amount of biological contaminants make it through the prefilters, the affect will be worsened as they can grow and multiply once attached to the RO membrane. The phenomena of multiplying in biofouling is described as the "Achilles heel" of membranes according to Nguyen et al. (2012) [25]. The first step of biofouling is the attachment of a variety of microorganisms from the feed water to the membrane, which is made possible through electrokinetic and hydrophobic interactions [25, 26, 27]. After the initial adhesion, the microorganisms grow and multiply, which is possible as soluble nutrients in the feed water and organics at the membrane surface are readily available to the microorganisms as solid-water interfaces concentrate nutrients [25, 28, 29]. Furthermore, Extracellular Polymeric Substances (EPS) is produced and excreted by the microorganisms, which creates a stronger bond to the membrane and cement the microorganisms so that the reversible adhesion becomes irreversible [29]. Spacers used in RO SWM are used to produce turbulence to, but in creating turbulence the spacers also create areas of water with low flow where this biofouling can thrive [25]. This is an issue during operation of the membrane, but even more so when it is used intermittently [6]. During the pause of intermittent use, the entire membrane have beneficial conditions for growth and time for the microorganisms to anchor the excreted EPS to the membrane. A process which has to be counteracted to achieve a long lifespan of the membrane.

2.2.1 Summary

There are four different types of fouling; organic, inorganic, particulates and colloids, and biofouling. These causes the membrane to lose flow and efficiency over time. To combat this, pretreatments has been widely used, and cleaning is performed to maintain the membrane, either chemical or physical. In treatment of freshwater from tap, most inorganic, organic, particulates and colloids have been removed in previous treatment. However, due to the ability of multiplying, biofouling is the main consideration of fouling in this study.

2.3 Ultrasonic Treatment

Ultrasound is being investigated as a possible solution to the fouling phenomena occurring in membranes. Both in terms of cleaning the membrane after the fouling has occurred and mitigate fouling in order to prevent fouling from occurring in the first place. The purpose of cleaning the membrane is to increase the efficiency and also the lifespan of the membrane. This study focuses on Reverse Osmosis (RO) technology, whereas previous research has been mainly focused on membranes such as Ultrafiltration (UF), Microfiltration (MF), Nanofiltration (NF). The research of ultrasonication performed on RO membranes have been limited. The experiments which have been conducted have mostly been conducted towards single flat sheet membranes [18]. In this case Spiral Wound Membrane (SWM), which is membrane that have been rolled up and packed tightly, will be used as they are widely used commercially. The benefit of a SWM is that one can achieve a big surface are in a small volume, however, less easily cleaned. The literature review of previous research on ultrasonic treatment has been presented in chronological order, as to show the development in the area and where the focus of current research lies.

In an article by Belfort (1977), different cleaning methods are reviewed and discussed. Ultrasonics in only mentioned briefly from one article by Smith and Grube (1972) in Smith and Hill (1972). Unfortunately, this article could not be retrieved for more detailed results. Wilmoth does, however, state in a private communication that Smith and Grube has had some success in cleaning small parts of a hollow-fibre membrane using ultrasonication [30]. The article does not, however, go in further details of experimental set-up or results, which renders it rather unusable. Potts et al.

(1981), reported that direct attacks of the fouling using mechanical and ultrasonication had been tried with little success, and referred to Belfort (1977) and Cruver (1973) [31]. The article by Cruver (1973) could not, however, be retrieved to verify the results, statements made or experimental set-up used. Therefore, the reproducibility of the results presented in these articles is limited. Results can be seen as indicators but further details, such as frequency, power and application are necessary to make it useful and to achieve better results.

Relevant to this study, Kuepper (1982) used ultrasonication on an RO SWM, as well as, a single flat sheet membrane [32]. Experiments were conducted on foulants such as ferric oxide, calcium carbonate, calcium sulfate and bentonite clay. Results showed excellent results of ultrasonication on the single flat sheet but poor results for the SWM. Kuepper (1982) stated that the reason behind these contrary results was due to the packing density of the SWM, in comparison to the single flat sheet [32]. The issues with SWM presents a challenge as this is what is most commonly used commercially due to its large surface area and why it is analysed in this study. Furthermore, Kuepper (1982), suggested that flow surging is an effective way in cleaning the RO SWM. Ayers et al. (1986) presented results of cleaning a RO SWM using ultrasonication, which contradicted Kuepper (1982). Ayers et al. (1986) pointed out that the poor results achieved by Kuepper (1982), was due to the effects of acoustic resonance and cylindrical symmetric geometry [33]. This will have to be considered when performing this study, as it seemed to affect the outcome significantly. Furthermore, Ayers et al. (1986), stated that the SWM reacted quickly and positively, and after only a few minutes of ultrasonication the flow rate and pressure were back to normal [33]. This is a promising outcome of the ultrasonic treatment, although, tap water will likely experience different types of contaminants. Ayers et al. (1986) describes the experimental set-up of the ultrasonic transducers, frequency used and foulants cleaned, which is valuable information [33]. The transducers are applied on the sides of the membrane in pairs opposite each other, with a total of eight pairs. This compact design highlight the commercial application, but might not be possible to implement in this study.

Furthermore, Deqian (1987) investigated cleaning and regeneration of membranes after fouling.

Deqian (1987) states that fouling is a complex issue and no simple method can remove foulants and regenerate the membrane at the same time [34]. Sonication is briefly mentioned, where it is stated that ultrasonic cavitation alone and in combination with flow surging was the most effective methods, which was referenced to Virginia and Shippey (1978). Virginia and Shippey (1978) conducted experiments on tubular RO membranes, and not SWM. It was pointed out that tubular membranes has an advantage over SWM, as tubular membranes can withstand higher pressures [35]. However, the suggested pressure utilised during ultrasonication was either zero or between 30-60 psi [35]. These pressure ranges are within the operating conditions of most commercial RO SWM, which opposes the advantaged assigned to the tubular membrane. Two different configurations of transducers were tested, the transducers were mounted on ends and sides [35]. This provides good insight into different transducer configurations, as Ayers et al. (1986) only motivated transducers mounted on the sides of the membrane. The configurations yielded similar results and no optimization into the ultrasonication was performed in the work [35]. The results indicated that both configurations achieved similar results, which is promising as the configuration might not matter as much as Ayers et al. (1986) had expressed. Virginia and Shippey (1978) stated that ultrasonication indicated great potential for "on-line" cleaning, meaning that ultrasound is applied throughout the filtration, and highlighted some benefits of physical cleaning over chemical cleaning [35]. For UTS solutions, mechanical cleaning presents a much easier and safe option to chemical cleaning, which is why ultrasonic treatment offers a possible solution. Whether "on-line" or "off-line" offers the best solution is dependent on factors such as energy consumption, water recovery rate, as well as, effect on membrane and other components.

Flemming and Schaule (1988) performed ultrasonic treatment on a piece of single flat sheet membrane, in order to examine the detachment effect on bacteria [26]. Membrane made from polyamide, polysulfone, polyethersulfone, and polyetherurea were tested in the study [26]. Results showed that ultrasonic treatment detached all adhering cells from the membrane surface [26]. Although being a piece of single flat sheet membrane, polyamide is the same material used which is promising from RO SWM. Furthermore, Flemming and Schaule (1988) showed that, if the membrane and bacteria are left in the same solution after detachment, the bacteria will attach to the membrane again [26].

Flemming and Schaule (1988) concluded that the viability of the organisms are not affected by the ultrasonic treatment [26]. This is important in using ultrasonic in SWM as flushing will have to occur at the same time to get rid of detached bacteria.

Zips et al. (1990) states that much research has been performed using ultrasonic baths, however, too many parameters differs to make different studies comparable [36]. This is a valid point, but since ultrasonic baths are easily accessible it will likely be used in this study too. Furthermore, Zips et al. (1990) mentions that younger biofilms are more easily removed than older films [36]. Similarly, the prevention of biofilms is easier than the removal of it [36]. Zips et al. (1990) also stated that the removal of the biofilm was dependent on three parameters, the intensity, the time exposure and the distance between the transducer and the membrane [36]. Zips et al. (1990) found parameters that were able to remove all of adherent cells, within minutes [36]. Although this might not be the case for SWM, these results indicate that ultrasonication is an efficient method and an evaluation of SWM should be conducted to determine its efficiency.

Flemming (1997) conducted another study on biofouling of membranes, in which ultrasonic waves was reviewed as one of many solutions [37]. Flemming (1997) states that in order to remove biofilms from membranes, the binding force between the foulant and the membrane has to be overcome [37]. The force is not particularly strong, however, is quite resistant to shear force such as running water [37]. Therefore, flushing the SWM likely has some effect but the biofilm is rather resistant to that treatment. Ultrasonic waves offers an additional force to overcome the aforementioned binding force. Likewise, Flemming (1997) suggests that biofilms could successfully be removed using ultrasonic waves, and have been successfully utilised as a method of cleaning in other fields, such as medical devices, dental instruments [37]. Membrane damage should also be considered when using ultrasonic waves, as it could potentially damage the membrane the biofilm is adhered to [37]. Furthermore, Flemming (1997) suggests that the general cleaning method consists of two steps, one chemical to weaken the biofilm and one step where mechanical forces are applied to remove the biofilm [37]. For UTS systems it would be more convient and safe to not handle any kind of chemicals but rather only rely on the mechanical step. This would likely require a higher

energy consumption to counteract the stronger, not weakened, biofilm.

Kyllönen et al. (2005) conducted a review of ultrasound enhanced membrane filtration, to combat the issues of fouling [16]. It is stated that ultrasound cannot increase the intrinsic flux of the membrane, but rather increase it through removal of cake layer and breaking the CP [16]. Furthermore, Kyllönen et al. (2005) expands on the three parameters presented by Zips et al. (1990), and presents parameters which needs to be considered when using ultrasonication as frequency, power, intensity, feed properties, membrane material, crossflow velocity, temperature, and pressure [16]. Damage on the membrane due to ultrasound is also reviewed, and found that in some cases the membrane has been damaged whereas in others remained unaffected [16]. The reason behind the damages was found to be a too high power intensity [16]. The power intensity must therefore be optimised, in order to remove as much fouling as possible while not damaging the membrane. Furthermore, it was also found that the combination of ultrasonication with other methods have been successful [16]. Combination with other techniques to yield a higher cleanliness, should be investigated further once the ultrasonic treatment has been examined. Finally, Kyllönen et al. (2005) concludes that, due to stagnation of transducer technology, the ultrasonically enhanced membranes have not been commercialized [16].

More recently, Feng et al. (2006), conducted experiments using "on-line" ultrasonication on RO flat sheet membranes [15]. Feng et al. (2006) used membranes made of polyamide, due to its importance and availability commercially [15]. Although not SWM, the same type of material could offer more insight as to how well polyamide responds to the ultrasonic treatment. The experiments were conducted with frequencies of 20 kHz with the membrane module in a water bath [15]. Water bath is an easy alternative to come by and use, and will be used as the source for the ultrasound in this study too. The membrane filtered $CaSO_4$, as well as, carboxymethyl cellulose solutions in concentrations of 500 and 1,000 mg/L [15]. The results ranged from 50.8% to 69.7% for the $CaSO_4$ solutions respectively and 264% to 113% respectively for the carboxymethyl cellulose solutions [15]. RO membranes used UTS will unlikely encounter the same degree of fouling and, therefore, not achieve as high results in the cleaning process. Furthermore, the rejection rate of the

membrane remained virtually unaffected [15]. The unaffected rejection rate not only indicates good performance of the ultrasonication but also that the membrane did not take damage during the treatment. Feng et al. (2006) perfromed SEM analysis of the membranes after the ultrasonication, which also showed that the membranes had not taken any visible damage [15]. This is essential as the membrane life is sought to be extended in this study, and high flow at the cost of premature replaced membrane would be the opposite of that.

Lin et al. (2010) expresses the inevitable obstacle fouling presents, and reviewed methods of cleaning the membrane [38]. The cleaning is divided into physical cleaning and chemical cleaning, and ultrasonic being a physical method [38]. Lin et al. (2010) only sourced one article with RO using ultrasonic treatment, and it was Feng et al. (2006), but multiple others using UF. This indicates that the area of RO and especially RO with SWM is relatively unexplored. Furthermore, Lin et al. (2010) states that lower frequencies are preferred for cleaning purposes [38]. The range of ultrasound is wide, and so limiting it to lower frequencies is a good indication as to which frequencies can be used.

Kentish and Ashokkumar (2011) reviews the ultrasonic membrane processing, and evaluates current research in the area [17]. Ultrasonic intensity is dependent on both power density and frequency, which can be increased either through a higher power density or a lower frequency [17]. Research have reported power densities between 0.05 to 83 W/cm^2 and frequencies between 20 kHz to 1 MHz [17]. For cleaning, it was found that lower frequencies on the ultrasonic spectrum was more efficient at about 20-50 kHz [17]. Similarly, it was found that conditions for cleaning the membrane were high crossflow velocity and low transmembrane pressure, in order to efficiently remove that cake layer [17]. Lower pressures allow for higher cavitational activity, reducing the need for energy to achieve this thereby reducing risks of damaging the membrane too [17]. A reduction of the energy consumption would make the implementation of ultrasonication more feasible, as the specific energy consumption would remain low. A reduction of risk to damage the membrane is an additional feature which makes it more feasible, as one of the goals is to prolong the membrane life. Some studies have had issues with damages to the membrane whereas other studies have had

no such issues, Kentish and Ashokkumar (2011) states that the damage likely originates from too high ultrasonic intensity [17].

Qasim et al. (2018) investigated the use of ultrasound to mitigate fouling of membranes, and discussed fouling mechanisms, ultrasonic waves, acoustic cavitation and collapse, and other ultrasonic-induced effects [8]. Membrane fouling is divided into four categories, namely, organic, inorganic, particulates and colloids, and microbiological organisms [8]. Microbiological organisms attach to the membrane, where they can grow and then disperse to further colonise the membrane [8]. This is the reason it is one of the biggest issues for UTS RO, as even the smallest amounts can accumulate over time. Power and frequency of the ultrasound is shown to have a large effect on the flux of the membrane, lower frequencies and higher energy seemed to yield higher flux [8]. Although these results were not specific from RO SWM, it is likely that the principles and mechanisms of the ultrasound would affect RO SWM similarly. These parameters would have to be investigated and calibrated, in order to achieve high cleaning effect while not damaging the membrane. The cavitations created by ultrasonic waves build up gradually before collapsing, generating extreme temperatures of 5000 K and pressure of 1000 atm locally [8]. These conditions, albeit very local, could potentially damage the membrane, as they exceeds the membranes operating limits. The effects of ultrasound which affects fouling of membrane are presented as acoustic streaming, microstreaming, microstreamers, and microjets, which can be seen in Figures 3-7 [8].
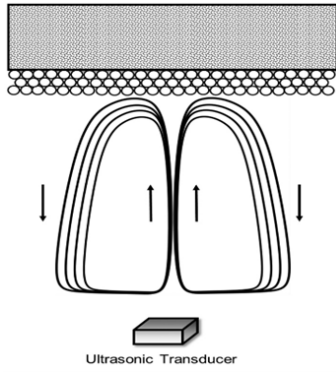
Figure 3: The figure shows how the phenomena of acoustic streaming occurs with ultrasound [8].
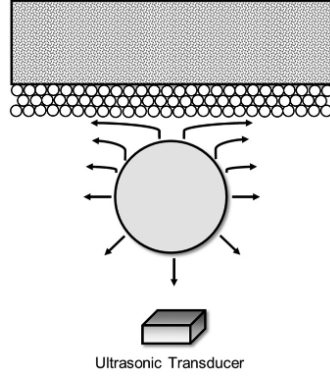
Figure 4: The figure shows how the phenomena of microstreaming during cavitation expansion [8].
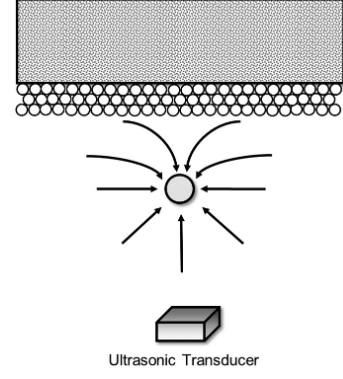
Figure 5: The figure shows how the phenomena of microstreaming during cavitation collapse [8].
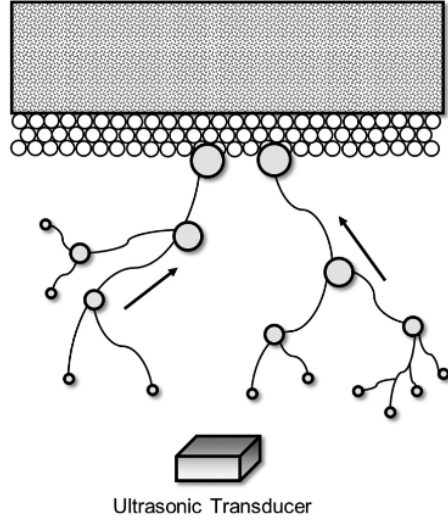
Figure 6: The figure shows how the phenomena of microstreamers occurs with ultrasound [8].
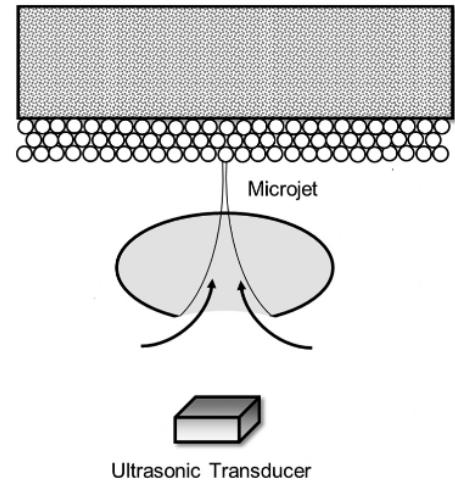
Figure 7: The figure shows how the phenomena of microjets occurs with ultrasound [8].

As seen in Figures 3-7, the ultrasound affect the fouling on the membrane in various different mechanisms and different forces which aids in the removal of the fouling [8]. Furthermore, Qasim et al. (2018) refers to Shu et al. (2007), rather unrelated to RO but results which shows how the flux peaks at certain powers and distance of probe [39]. A phenomena which has to be investigated of when conducting ultrasonication of membrane, finding peak power and optimum placement of

transducer.

Freire-Gormaly and Bilton (2018) examined the potential of a photovoltaic powered RO system [40]. This system share an important variable with RO UTS systems, filtration is not continuous filtration but operates intermittently. Freire-Gormaly and Bilton (2018) states that intermittent use of the membrane causes premature fouling [40]. Cleaning of the membrane in RO UTS systems is therefore critical to maintain a long lifespan of the membrane.

In a report by Liu et al. (2019), mechanisms of inorganic scaling in RO membranes, as well as, inhibition strategies were discussed. Vibratory Shear Enhanced Processing (VSEP) is a technique which utilises a shear force, generated by vibrations or through rotation, to restrict CP and thereby also inorganic scaling [41]. VSEP showed good results in inhibiting inorganic scaling while maintaining high recovery, but still limited to lab-scale [41]. Liu et al. (2019) does, however, conclude that VSEP in spiral wound membranes lacks feasibility due to difficulties in combining equipment effectively [41].

Matin et al. (2021) states that the use of ultrasonic waves to treat or enhance RO membranes is still in experimental stages and also with flat sheet membranes [18]. Furthermore, Matin et al. (2021) highlighted the economic downside of on-line ultrasonic enhancement as the increased flux did not correspond to the cost of running the transducers [18]. Although not completely comparable, the continuous cost of running ultrasonic transducers on a small scale would quickly add to the cost of water. Thus, the option of point action could present a more economically viable alternative, as previous articles have indicated that ultrasonic treatment have the potential of restoring heavily fouled membrane in matter of minutes. Matin et al. (2021) concludes that ultrasonic waves could potentially offer a more eco-friendly method of fouling control [18]

Horrigan and Freire-Gormaly (2022) performed a model analysis of the effects of ultrasonication of the feed channel temperature [6]. Temperature increase was in the range of 0.01-0.1 K, but the boundary layer was, however, not analysed [6]. These temperature differences are well within the margins of the operating temperature for an RO SWM. Horrigan and Freire-Gormaly (2022) also

compared the difference in ultrasonication using a water bath and applying to the feed channel [6]. The difference is of great importance as a water bath might be a solution for lab experiments but attaching transducers could be a more commercial solution. Horrigan and Freire-Gormaly (2022) stated that the water and module structure resulted in 90% attenuation of the ultrasonic power [6]. The attenuation effect has to be considered when conducting experiments in water bath with the pressure housing of the SWM. To overcome this obstacle, the loss of power should be compensated for by using a bath with higher power.

2.3.1 Summary

To summarise the literature review of the ultrasonic treatment, ultrasound is a physical cleaning process that consists of four different phenomena which can remove foulants. These four phenomena are acoustic streaming, microstreaming, microstreamers, and microjets. Ultrasonic treatment can be performed either "on-line", during the process as fouling mitigation, or "off-line", as a point action to periodically to restore the properties. Previous research have presented varying results, which have been directed towards different foulants and more towards industry and not necessarily specific to this case. Furthermore has damage to the membrane been observed in some cases while no damage has occurred in others, and is believed to be linked to the power of the ultrasonic waves.

3 Methodology

3.1 Approach

For this study, empirical research has been performed with an experimental approach to validate the hypothesis of using ultrasound to enhance the cleaning process of an RO SWM. From the start, the focus has been to enhance and optimize current RO technologies at Bluewater. The main issue with current membrane technologies is the fouling of the membrane, which has been the center of attention in this study. This study has, therefore, strived to test an examine a solution to this issue.

An initial literature review was conducted on the topic of fouling mitigation and removal, as to counteract the main issue with RO membranes. The initial literature review provided insight into current state of the art technologies and the current state of research, within the field of membrane processes. Ultrasound was then investigated as a possible mechanical method to mitigate fouling, and articles regarding that topic was reviewed to understand the state of that technology and also examine existing patents around it.

The literature review was then used to develop an experimental protocol, in order to test the hypothesis. Unfortunately, the experimental design was limited by time constraints and availability of material. Therefore, initial plans to test flux of membrane over time, in connection to the cleaning treatment of the membrane as a confirmation of the improvement, was not included. Time dependency of the ultrasonic treatment was tested initially, under less controlled circumstances, to confirm the statements made in literature that a few minutes would be sufficient. Power and frequency, which the literature review showed to have impact on both cleaning efficacy and damage to membrane, could not be controlled either as the water bath available had a set power and frequency. So, with this information at hand, an experimental procedure was developed, with a consideration for these limitations.

3.2 Experimental Procedure

The experimental procedure which was used in this thesis, has been developed through the literature review and several initial experiments to determine a fair comparison between current anti-fouling techniques and the ultrasonic treatment. Initial experiments included a comparison of no reject tests, flushing tests and integrated in the current machine. A more extensive study was then performed over the course of two weeks, using two brand new RO SWM rated for 50 GPD. Both membranes were connected to the Cleone machine, and flushed to eliminate the preservation agent it was stored with before initial sampling. The first samples were taken before any different treatments were performed on either membrane to establish equal starting point in terms of fouling. After which, both of the membranes were subject to treatment. The reject of the membrane being treated with ultrasound was not connected back to the Cleone machine whereas the one which was not treated with ultrasound was. This was done in order to achieved a similar effect to what is used currently, which includes an initial reject flush and continuous running reject water in a ratio of 3:1 to permeate. For the membrane treated with ultrasound, this was performed for 3 minutes with reject completely closed, however of which the last 10 seconds the reject was completely opened to perform a high flow flush. Samples of the membrane subject to ultrasonic treatment was taken at two points, one during cleaning and one after. For the membrane without ultrasonic treatment only one sample was taken, which was the water produced for drinking.

3.3 Literature Review

A literature review is paramount to establish current theories and evidences within a particular area, in order to motivate the study and justify its research question [42]. The topic of this thesis started broad, as did the literature review. As the topic was narrowed down to a research question, the literature review was narrowed down too. The final literature review seen in this paper has been reworked and adapted to the final research question. Peer-reviewed articles constitutes the majority of literature reviewed in this thesis, however grey articles occurs to some degree too. The technical review includes a few grey articles, research done by appointment of authorities such as the U.S. Army and Navy. Articles regarding the economics does, however, consists of mainly grey

articles, as there have been little data available in peer-reviewed articles.

The literature review does not only serve to establish what the current research and evidences are, but also to highlight the gaps that exist in the research. With gaps identified, one can move on to identify on how to fill these gaps. By filling gaps in the research, the study can serve a purpose of usefulness and relevance. Previous research has mostly been focused around flat sheet membranes and with purpose of scaling up to industrial processes, which many articles stated lacked economic viability. This study, however, examines ultrasonication of RO SWM on a small scale and with shorter time periods of treatment, rather than continuous.

3.4   Data Gathering

Data collected in this report has been gathered using 500 mL samples of permeate water using sterile bottles, which has been analysed for microbiological contaminants. The data was gathered in a two stage process. While the samples were collected at KTH, the results were obtained through analysis performed by Eurofins Pegasuslab AB (Uppsala), SWEDEN, ISO/IEC 17025:2017 SWEDAC 2085. Eurofins retrieved the results with respective standards; SS-EN ISO 6222:1999, ISO 6222 mod, SS 028167-2, SS 028167-2 mod. Of interest to this report has been cultivatable microorganisms at 22 °C and 37 °C, achieved with both aforementioned ISO standards. Results provided from Eurofins can be seen in 7 Appendix, Figures 20-30. To avoid additional growth during transportation and handling, collected samples have been shortly stored in a fridge before being packed in an isolated styrofoam box with ice packs. The pick up of samples have been arranged the same day as samples were taken, and time between sampling and analysis have never exceeded 12 hours.

3.5   Collaboration

This thesis was performed in collaboration with Bluewater, a Stockholm based water purification company. Bluewater is a manufacturer of RO systems with different technologies and operates across the globe. The author have, however, produced all the material in this report and possess full ownership of it. Bluewater have through the collaboration supported the thesis through super-

vision, advice, provided information regarding their technology and supplied their systems. The author have not been financially compensated for the work in any way, but has however started working for Bluewater in other areas during this thesis.

3.6 Ethics

The Swedish Research Council has developed a list of general rules for good research practice, derived from the ethical norms and values of society [43]. This list of general rules can be seen in the list below.

1. "You shall tell the truth about your research."

2. "You shall consciously review and report the basic premises of your studies."

3. "You shall openly account for your methods and results."

4. "You shall openly account for your commercial interests and other associations."

5. "You shall not make unauthorised use of the research results of others."

6. "You shall keep your research organised, for example through documentation and filing."

7. "You shall strive to conduct your research without doing harm to people, animals or the environment."

8. "You shall be fair in your judgement of others' research."

This thesis strives to comply with this list of general rules, in order to keep the ethics of this research and its findings at a high level. This list of ethic guidelines have been considered throughout the entirety of this study, to make sure the study is as compliant as possible.

3.7 Sustainability

For this project a sustainability assessment has been performed to determine the impact of the use of ultrasonic waves on RO SWM. Figure 8 shows the UN's SDGs and are rated depending on how that specific goal is affect by the purpose of this thesis.
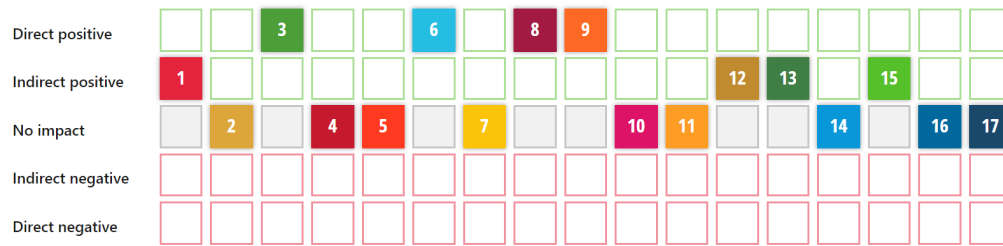
Figure 8: Assessment of UN's SDGs with respect to the implementation of ultrasound in an RO system, with purpose of cleaning the membrane. This figure was made using the SDG Impact Assessment Tool.

There are four SDGs which are directly impacted by the use of ultrasonic treatment of RO SWM, namely SDGs 3, 6, 8, and 9. These SDGs encompass "3. Good health and well-being", "6. Clean water and sanitation", "8. Decent work and economic growth" and "9. Industry, innovation and infrastructure". With the aim of reducing cost of purified water and thereby making it available for more people, this project has a direct positive impact on SDGs 3, and 6. Furthermore, the use of ultrasound to reduce wasted water and thereby improving resource efficiency and consumption, it has a direct positive impact on SDG 8. Finally, it has a direct positive impact on SDG 9 through upgrading of technology to make it more sustainable and resource-use efficient. To conclude, this project has constantly had the sustainability, economic, social and environmental aspects in mind throughout the entire study.

4 Results and Discussion

4.1 Technical Results

For the technical assessment of this study, initial experiments were first conducted with aspect to the time dependency. Ultrasound was applied to the RO SWM, for a duration of about 12 minutes. The tests were performed using already fouled membranes, rather than letting them get fouled for Figures 9 and 10. The more comprehensive tests, seen in Figures 11 and 12, were conducted on brand new, unfouled membranes. Due to the sample size of 500 mL, the time between the samples was roughly 3 minutes. The first sample was taken without any kind of treatment. Results for the time dependency of the ultrasonic treatment can be seen in Figures 9 and 10, for microorganisms cultivatable at 22 °C and 37 °C respectively. Analysis data for both Figure 9 and 10 can be seen in the Appendix, in Figures 16-19.
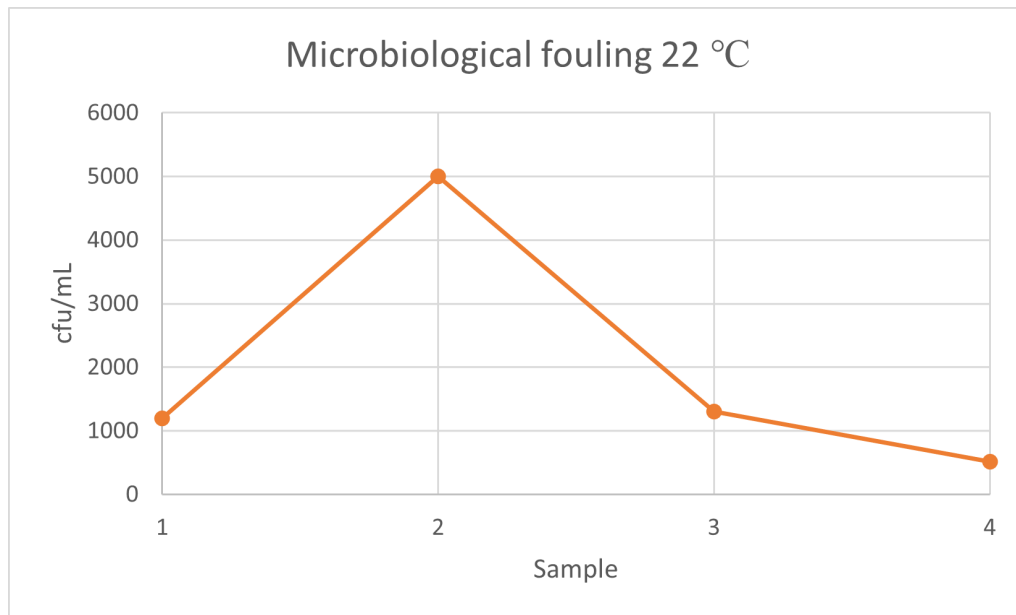
Figure 9: The figure shows the amount of microorganisms cultivatable at 22 °C for membrane during ultrasonic treatment over the time span of about 12 minutes.

As seen in Figure 9, the concentration in the permeate peaked at sample 2, which is approximately 3 minutes of ultrasonic treatment. Due to the 500 mL size of the samples, lower resolution could

not be obtained. However, a duration of 3 minutes is in line with the results found in other articles. It is possible that the time duration could be even lower, but due to time constraints and available analysis methods 3 minutes was used. The analysis could not measure over 5,000 cfu/mL, which is a limiting factor for the results from sample 2 in Figure 9. Therefore, it is not necessarily representative and could be higher than 5,000 cfu/mL. The high concentration after 3 minutes could potentially be explained by the removal of the young biofilm. Whereas the biological contamination after 3 minutes could be either older biofilms which require more energy to remove, or the remains of the agitation caused by the ultrasonication.
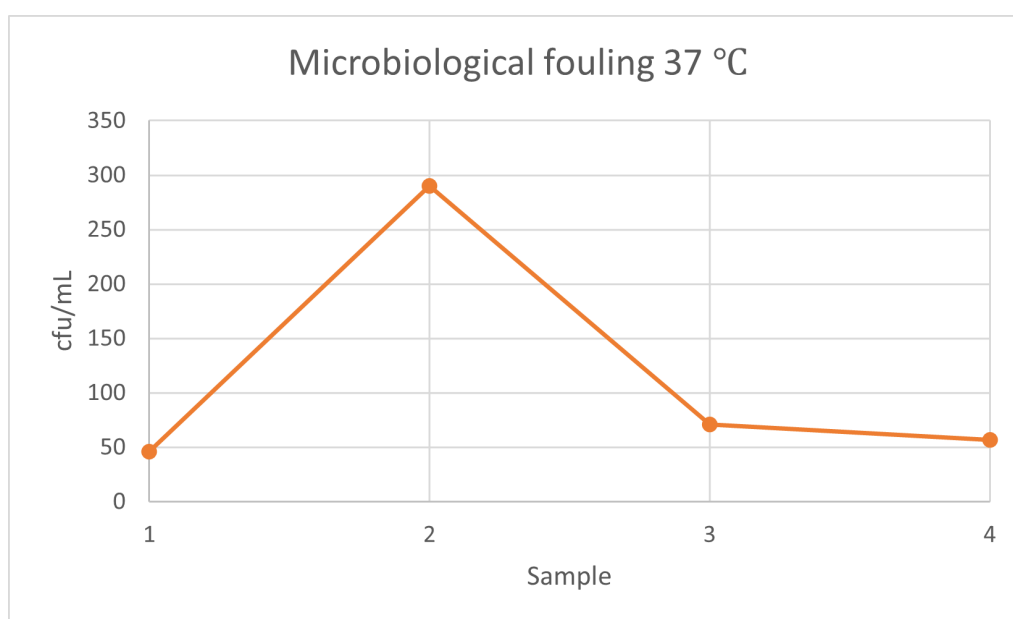
Figure 10: The figure shows the amount of microorganisms cultivatable at 37°C for membrane during ultrasonic treatment over the time span of about 12 minutes.

As seen in Figure 10, the microorganisms cultivatable at 37 °C showed similar results to the microorganisms cultivatable at 22 °C, and peaked at the second sample after around 3 minutes. Again, this was in line with the results found in the literature. As this samples were taken together with the 22 °C samples, the resolution or time span could not be decreased. Therefore, 3 minutes is the minimum which can be observed as it is the approximate time to collect 500 ml of sample. Microorganisms cultivatable at 22 °C and 37 °C changed similarly, although at different

concentrations. Therefore, it is possible that sample 2 in Figure 9 did not exceed 5,000 cfu/mL by much, as the ratios between the samples between Figures 9 and 10 are similar for sample 2 too.

The results from the more comprehensive assessment is presented as an observation over 12 days, with data collected on days 1, 3, 10 and 12. Initial plan of collecting data every other day was not possible due to Eurofins not operating on days 5-8. Data from the ultrasonic treatment was collected both during and after, to confirm that the treatment achieved a higher removal rate during the treatment than after it. Treatments were not performed on days 6 and 7, which has to be taken into consideration when evaluating these results.

The concentration of microorganisms present in the samples are presented in Figures 11 and 12, and were analysed for microorganisms cultivatable at 22 °C and 37 °C respectively. The analysis data provided from Eurofins for both Figures 11 and 12, can be found in the Appendix in Figures 20-30. Unfortunately, the measurements do not exceed 5,000 cfu/mL, which limits the comparison at higher concentrations.
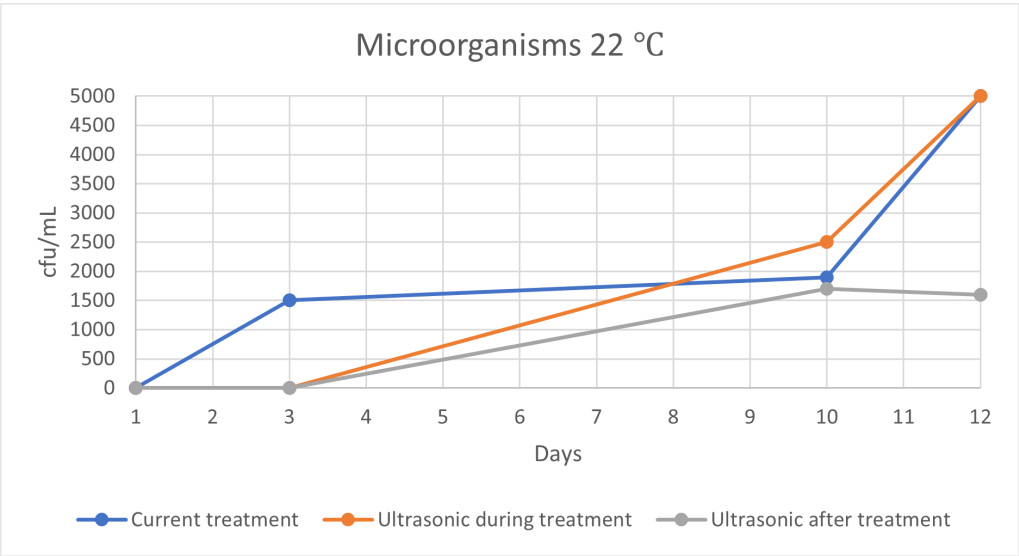

Figure 11: The figure shows the amount of microorganisms cultivatable at 22°C for membrane with current treatment, during ultrasonic treatment and after ultrasonic treatment.

As seen in Figure 11, the ultrasonic treatment outperformed the current treatment in terms of

microbiological contamination. The "current treatment" and the "ultrasonic after treatment" is essentially what will be produced as water to the tap. In terms of microbiological contamination in drinking water, it is set to a level of 100 cfu/mL in Sweden as seen in Table 1 in the Appendix. With that information at hand, only day 3 managed to produce permeate of aforementioned quality.

The results on day 3 can be explained by a variety of reasons. One of which is that younger biofilms are more readily removed than older films, as stated by Zips et al. (1990) [36]. This would be compliant with the rest of the results, however more data would be necessary to confirm this. Another possibility is that preservation agent was still present in the membrane with ultrasound but not in the membrane with the current treatment, which would limit the growth of microorganisms. An additional possibility could be that the ultrasound killed the microorganisms present in the sample, as the disinfectant properties of ultrasound has been witnessed in previous research [44]. Finally, different parameters could have varied for the two membranes, which could have influenced the results on day 3. Both membranes were flushed simultaneously, so that existing contamination from other parts and tubing in the machine would influence both membranes equally. However, due to the programming of the Cleone machine, the current treatment started as soon as water ran through it, so samples were always taken from the current treatment first. Similarly, the membranes were stored in the same fume hood, but one in water and one in air due to space limitations and available material. The water had been in stored for several days in the same ambient temperature, but could however have affected the microbiological growth of the ultrasonically treated membrane. This did, however, not seem to be the case for the following days, but should be investigated further to rule it out as a cause.

The results seen after days 6 and 7, the days without treatments, shows a sharp increase for the membrane treated with ultrasound but a rather flat increase for the current treatment. This low increase of microbiological content for the current treatment could suggest that the data point from day 3 for the current treatment was subject to error, as day 10 to 12 shows a more rapid increase. Especially as no treatment was performed during 6 and 7, the growth of microbiological contamination would be expected to grow significantly during this time. This expected growth

during the pause in treatment during day 6 and 7 is evident in the results from the ultrasonically treated membrane. As the microorganisms multiply, the curve will inevitably take the shape of an exponential function. However, for the current treatment it is data from day 3 which deviates from this exponential function.

The ultrasonic treatments shows potential over the current treatment in microorganisms cultivatable at 22 °C, although the data is not validated through repeats due to time constraints and availability of materials. The analysis from Eurofins is limited to 5,000 cfu/mL and does not record any higher concentrations, which would have been beneficial to determine the difference in efficacy between the current treatment and the ultrasonic treatment in the sample from day 12. Even though days 6 and 7 did not include treatments, the ultrasonically treated membrane decreased from day 10 to 12. This would suggest a potential recovery of the membrane over time, this would have to be analysed more in depth both long term with treatments every day and potential recovery of membranes. The permeate from the membrane after being ultrasonically treated yielded lower concentration than the current treatment. For the last day, day 12, the permeate from the current treated membrane had more than three times the concentration than the ultrasonically treated membrane.

The flush of both treatments is able to remove large amount of contaminants, however was not measured partially due to exceeding 5,000 cfu/mL during trials and partially because the water produced from the current treatment was not feasible to measure. However, the sample during the ultrasonic treatment is an indication that the ultrasound is capable of releasing biofouling from the membrane. It had higher measurements over the current treatment, which was followed by lower concentrations after the treatment. It is, however, possible that this is caused by the extended time of use to sample both during and after. The current treatment has an initial flush, although shorter in total in any case. Nevertheless, daily tests over longer time periods would be required to fully establish that the ultrasonic treatment can outperform the current treatment.
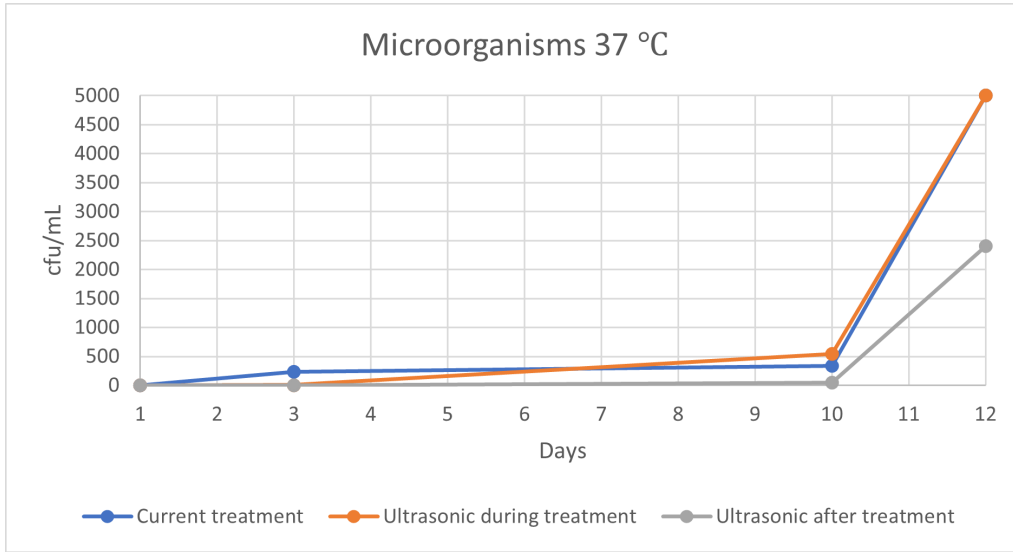
Figure 12: The figure shows the amount of microorganisms cultivatable at 37°C for membrane with current treatment, during ultrasonic treatment and after ultrasonic treatment.

As seen in Figure 12, the results of the microorganisms cultivatable at 37 °C yielded a similar result to the microorganisms cultivatable at 22 °C in Figure 11. The ultrasonically treated membrane yielded permeate with less microbiological contamination, after treatment. The microorganisms cultivatable at 37 °C showed a more distinct growth spurt between day 10 and 12, in comparison to the other days.

4.2 Economics

Besides the technical assessment of ultrasonic treatment of RO SWM, the economic aspect also has to be considered for it to become a viable commercial product. As Bluewater is a commercial company and strives to deliver products to the market, therefore, this thesis also evaluates the economics of operating the ultrasonic treatment. The evaluation does not take into account the implementation cost of ultrasonic transducers, as commercially available transducers are roughly of 9 USD [45]. There are other costs related to implementing ultrasonic transducers, such as cables, hardware and software. However, the levelised cost of water over the lifespan of the machine, which is 10 years according to Bluewater, would not affect the cost of permeate significantly. Furthermore,

long term effects of ultrasound on both membrane and machine has not been evaluated and has therefore not been considered in this economic assessment. Therefore, only the operational costs, in other words energy and water, have been considered.

The energy prices have been ranged from 0 to 0.37 USD/kWh, which includes the highest and lowest prices worldwide as of 2021 from 0.01 to 0.36 USD/kWh [46]. Similarly, the water prices have been varied from 0 to 7.1 USD/m^3, which encompass the highest and lowest prices around the world of 0.04 to 6.7 USD/m^3 [47, 48]. The sensitivity analysis of energy and water prices can bee seen in Figure 13, where the normalised price of 1 is 0.185 USD/kWh and 3.55 USD/m^3 respectively for energy and water. Figure 13 shows the difference between the current treatment of flushing and the ultrasonic treatment. Furthermore, the added energy consumption of the ultrasonic treatment was assumed to be 10% of the water bath consumption of 600 W, as Horrigan and Freire-Gormaly (2022) suggests in their article [6]. Additionally, the economic calculations are based on a full capacity usage of Cleone, which is 190 liters/day, and the energy consumption was assumed to be an average of 27 W, as Bluewater stated that it ranges from 23 W to 31 W [49].
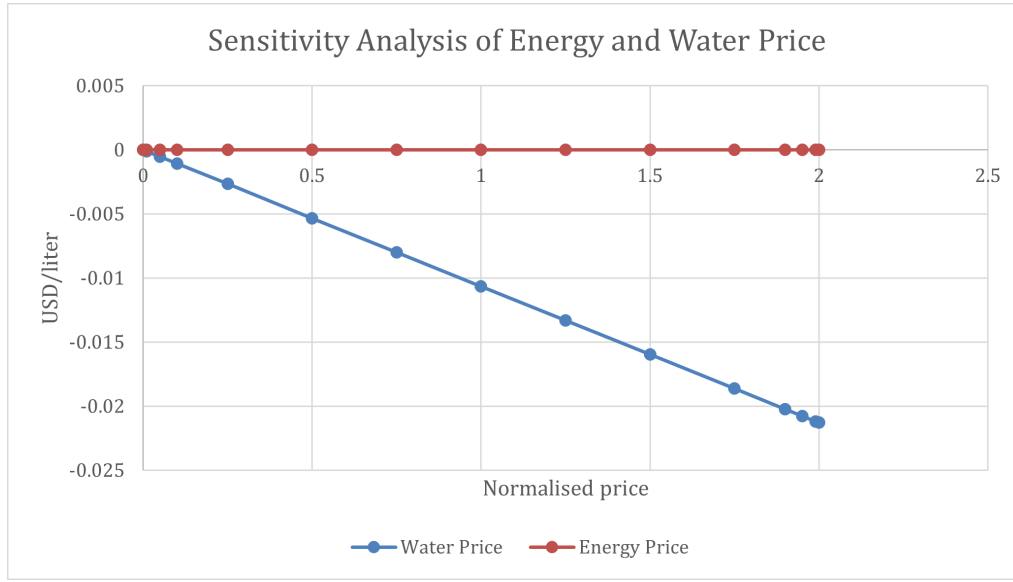
Figure 13: The figure shows a sensitivity analysis of water price and energy prices. The X-axis shows variation of a normalised price, and the Y-axis shows how the price difference between current treatment and ultrasonic treatment affected by water respectively energy price influences the permeate cost.

As Figure 13 shows, the cost of permeate is more sensitive to the water price rather than the energy price. This is due to reducing water consumption efficiently while consuming only a small amount of energy, which is shown more clearly in Figures 14 and 15. With Figure 13 at hand, one can determine in which areas the use of ultrasonic treatment would be economically feasible, as one can compare the energy price to the water price and determine whether it has a positive or negative outcome on the cost of permeate. To summarise, the effect of water is roughly a factor four due to the reduction of 3:1 reject to permeate ratio, whereas the energy consumption is the addition of transducers of 60 W for 3 minutes a day.

Figures 14 and 15 show the variation in price and consumption of operating means water and energy, resulting in the cost of permeate. Unlike Figure 13, the prices in these figures is not normalised but show the actual price and represent the differences between consumption and cost more clearly as the treatments are separated.
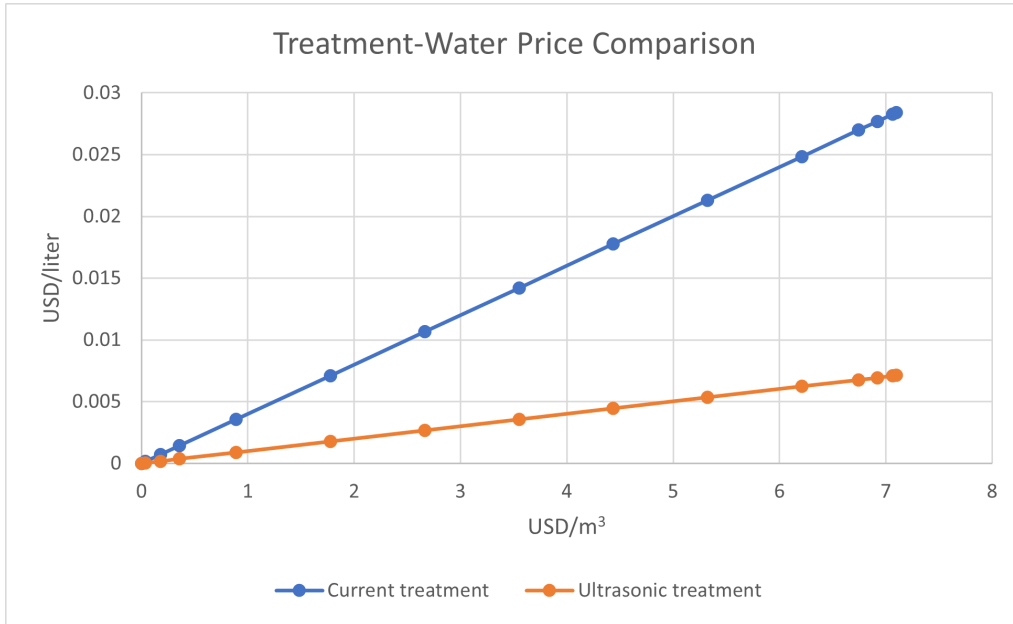
Figure 14: The figure shows a treatment and water price comparison and how much the price variation of water contributes to the cost of permeate. The relationship between the two treatments are linear, and cost of permeate between the two treatments increases with increasing water price.

The differences in water consumption between the two treatments is constant, which can be seen in Figure 14 as the function is linear when the price is increased. However, the linear function varies greatly depending on price, which is of relevance when comparing markets around the globe. The economics behind the water consumption assume that one cleaning cycle of ultrasonic treatment is sufficient for one day, which consumes 0.5 liters to flush. The amount of water used during the flushing could also vary depending on water inlet pressure. However, with the mere consumption of 0.5 liters used per day to reject in comparison to the current 570 liters rejected, there is room to perform the cleaning cycle several times per day from the water point of view. Additional cleaning cycles would also have to be confirmed with the energy aspect, so that the total cost of energy consumption and water consumption does not outweigh the current treatment.
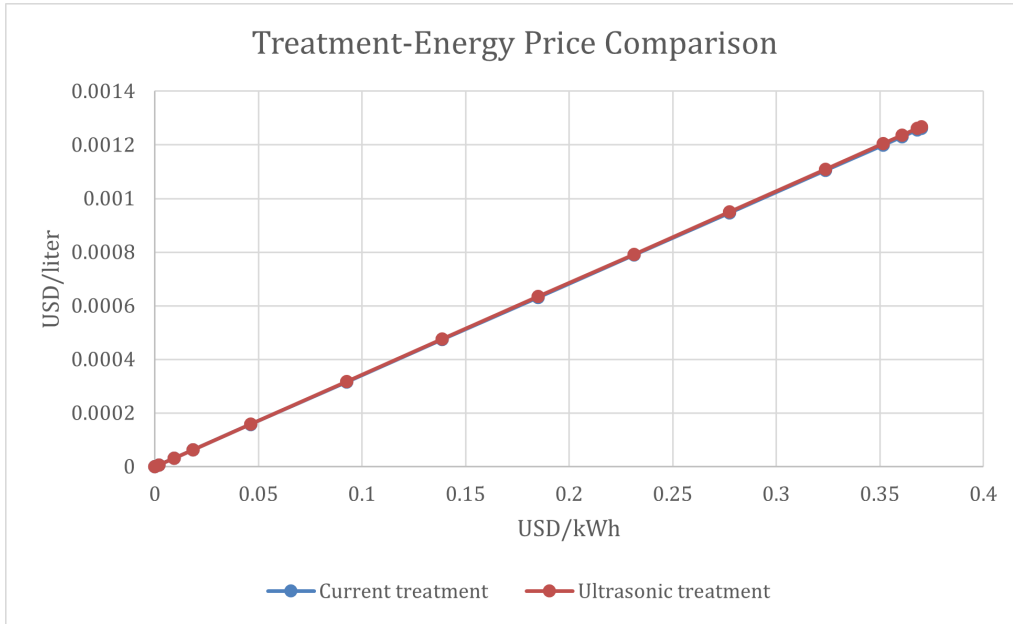
Figure 15: The figure shows a treatment and energy price comparison and how much the price variation of energy contributes to the cost of permeate. The relationship between the two treatments are linear with the addition of 60 W for 3 minutes for the ultrasonic treatment. The cost of permeate difference between the two treatments increases with increasing energy price.

As seen in Figure 15, the relative difference to the actual energy cost is so small that the lines appears superimposed. However, the current treatment is slightly lower in energy consumption, which is more visible in Figure 13. The difference between the current treatment and the ultrasonic treatment is the addition of 60 W for 3 minutes a day, which is an increase of less than 0.5% to the current energy consumption of 648 Wh/day. What this analysis does not consider, though, is that the variability in energy consumption is largely due to fouling of the membrane. In other words, a cleaner membrane would likely reduce the energy consumption, despite the additional energy to the transducers, if sufficient defouling is achieved. Though for this to be evaluated further data would have to be required, both flow of water and energy consumption of the pump. However, the continuous running reject water of the current treatment could potentially keep the fouling more even than short treatments of ultrasound, which could level out the energy consumption too. Further analysis of both treatments and also a long term analysis of their performance would be

necessary to ensure an economic evaluation with higher precision.

To conclude the economic evaluation, the ultrasonic treatment has potential to be economically viable given the measured parameters. There could be geographical areas where the energy price is too high in comparison to the water price, which would render it unfavorable. However, there are also other aspects that have not been considered in this study that would have to be taken into account to establish a more accurate economic evaluation. Aspects such as how the cleaning treatment affects the energy consumption, water flow, and damages that could potentially be caused by ultrasonic treatment.

5 Conclusion

5.1 Research Question: How can the implementation of ultrasonic treatment of reverse osmosis spiral wound membrane contribute to enhancement of the system process?

The results from this study indicates that ultrasonic treatment of RO SWM could provide a more efficient cleaning mechanism than flushing, which is currently used in Bluewater's Cleone machine. The ultrasonic treatment did not manage to sustain the criteria of drinking water standards when performed on a brand new, unfouled membrane, in terms of biological contamination. However, the results suggests that the ultrasonic treatment was able to remove more contamination from the SWM than the current treatment. By removing more fouling from the SWM, it is likely that water can permeate more easily and thereby at a lower pressure. However, this needs additional confirmation in terms of energy consumption and flow measurements. Experiments with different time duration for ultrasonic treatment showed similar results to the literature review and had a distinct peak at around 3 minutes, which is the time that was used for succeeding experiments. The following, more comprehensive, experiments demonstrated a lower microbiological concentration for the ultrasonically treated membrane throughout the 12 days, and for both microorganisms cultivatable at 22 °C and 37 °C. These results would, however, need further testing as the results are not repeated nor continuously treated as there was a gap in treatment over days 6 and 7. To conclude the main research question, the results indicate that the implementation of ultrasonic treatment of the SWM could reduce water consumption, an potentially increase the cleaning efficiency.

5.2 Sub-Questions

5.2.1 Sub-Question 1

As the literature suggested, the ultrasound was able to produce forces which could remove contaminants in a short period of time. The discussed issue of packing density of the SWM, did not prevent the ultrasound from removing contaminants but the efficiency could potentially have

been affected. Ultrasound has also been discussed as a possible disinfectant, which could also have affected the analysis of the results. Overall, the ultrasound achieved a higher removal than the current flushing system, and damage is unlikely in the present study as the permeate concentration was lower for the ultrasonic treated membrane. Although, temperature differences could have affect this again. Damages in connection with ultrasound would allow ions through the membrane, and to confirm that the membrane is not damaged conductivity test should be performed.

5.2.2 Sub-Question 2

The result of the ultrasonically treated membrane with regards to time, showed that the bulk of fouling which the ultrasound removed was achieved within 3 minutes. After approximately 3 minutes, the concentration of contaminants decreased. This is well aligned with previous research which also suggested that ultrasound could clean membranes within minutes.

5.2.3 Sub-Question 3

The economic aspects of using ultrasound as a treatment to reduce and mitigate fouling showed potential viability. The cost of transducers were assumed to be negligible in comparison to the amount of treated water. Therefore, only the operational conditions were taken into account, in other words the energy consumption and water consumption costs. Energy consumption has been assumed at 90% of that of the water bath, in line with the suggested values from literature. Furthermore, given that this is treatment of freshwater, which comes at a cost, the rejected flush water can be balanced against the energy consumption of the ultrasonic transducers. However, this is dependant on the geographical costs of water and energy, which could prove it viable in one location but not another.

5.3 Contributions

The contributions of this study and its findings include the utilisation of ultrasound to mitigate fouling in RO SWM. Previous research have shown results on flat sheet memebranes, while the packing density of SWMs have been argued to be an issue in literature. This study demonstrated that it does have effect on the microbiological content within a tightly packed SWM. Furthermore,

previous research has been focused around implementing ultrasound on an industrial scale which was determined not to be economically viable, this study has identified economic viability within the area of small scale water purification.

6   Future recommendations

Although the treatment showed good results in keeping the microbiological fouling at a minimum, additional analysis of the treatment would be required to get a more comprehensive understanding of its effect. The treatment reduced the microbiological content of the permeate, but another important factor would be the analysis of the flux. The flux could determine how the reduction of reject water and ultrasonic treatment affect not only the microbiological content in the permeate but how it affects fouling at the membrane surface and energy consumption in turn.

As this study was limited by power and frequency, future research should investigate and identify optimum power and frequency to mitigate fouling. Similarly, with the implementation of transducers, the power and frequency should be evaluated to determine whether the transducers change the effect on the fouling.

The application of ultrasound could potentially have unwanted affects both to the membrane and other parts of the equipment. A long term application study of its effects would be necessary to identify any issues of using ultrasound over a longer period of time, although not witnessed in this study, it would be essential to run ultrasound during a total time of expected life of membrane. Damage to the membrane would be counteracting to the purpose of prolonging the lifespan of the membrane. Wear and tear of other parts would also defeat the purpose of providing cleaning through ultrasound.

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7   Appendix

Provnummer:	177-2022-03280842		Ankomsttemp °C Mikro		5	
Provbeskrivning:			Provtagningsdatum		2022-03-28	
Matris:	Mineralvatten		Mikrob. analys påbörjad		2022-03-28 21:04	
Provet ankom:	2022-03-28		Provtagare		Ahmed Fawzy	
Utskriftsdatum:	2022-04-04					
Provmärkning:	UST 1.1					
Analys		**Resultat**	**Enhet**	**Mäto.**	**Metod/ref**	
Odlingsbara mikroorganismer 22°C		**1200**	cfu/ml		SS-EN ISO 6222:1999	a)
Odlingsbara mikroorganismer 37°C		**46**	cfu/ml		ISO 6222 mod	a)
Koliforma bakterier 37°C		**< 1**	cfu/250 ml		SS 028167-2	a)
Escherichia coli		**< 1**	cfu/250 ml		SS 028167-2 mod.	a)

Figure 16: This figure shows the first analysis of the time dependency of ultrasound performed on an already fouled membrane.

Provnummer:	177-2022-03280843		Ankomsttemp °C Mikro		5	
Provbeskrivning:			Provtagningsdatum		2022-03-28	
Matris:	Mineralvatten		Mikrob. analys påbörjad		2022-03-28 21:04	
Provet ankom:	2022-03-28		Provtagare		Ahmed Fawzy	
Utskriftsdatum:	2022-04-04					
Provmärkning:	UST 1.2					
Analys		**Resultat**	**Enhet**	**Mäto.**	**Metod/ref**	
Odlingsbara mikroorganismer 22°C		**> 5000**	cfu/ml		SS-EN ISO 6222:1999	a)
Odlingsbara mikroorganismer 37°C		**290**	cfu/ml		ISO 6222 mod	a)
Koliforma bakterier 37°C		**< 1**	cfu/250 ml		SS 028167-2	a)
Escherichia coli		**< 1**	cfu/250 ml		SS 028167-2 mod.	a)

Figure 17: This figure shows the second analysis of the time dependency of ultrasound performed on an already fouled membrane.

Provnummer:	177-2022-03280844			Ankomsttemp °C Mikro	5	
Provbeskrivning:				Provtagningsdatum	2022-03-28	
Matris:	Mineralvatten			Mikrob. analys påbörjad	2022-03-28 20:14	
Provet ankom:	2022-03-28			Provtagare	Ahmed Fawzy	
Utskriftsdatum:	2022-04-04					
Provmärkning:	UST 1.3					
Analys		Resultat	Enhet	Mäto.	Metod/ref	
Odlingsbara mikroorganismer 22°C		1300	cfu/ml		SS-EN ISO 6222:1999	a)
Odlingsbara mikroorganismer 37°C		71	cfu/ml		ISO 6222 mod	a)
Koliforma bakterier 37°C		< 1	cfu/250 ml		SS 028167-2	a)
Escherichia coli		< 1	cfu/250 ml		SS 028167-2 mod.	a)

Figure 18: This figure shows the third analysis of the time dependency of ultrasound performed on an already fouled membrane.

Provnummer:	177-2022-03280845			Ankomsttemp °C Mikro	5	
Provbeskrivning:				Provtagningsdatum	2022-03-28	
Matris:	Mineralvatten			Mikrob. analys påbörjad	2022-03-28 20:14	
Provet ankom:	2022-03-28			Provtagare	Ahmed Fawzy	
Utskriftsdatum:	2022-04-04					
Provmärkning:	UST 1.4					
Analys		Resultat	Enhet	Mäto.	Metod/ref	
Odlingsbara mikroorganismer 22°C		520	cfu/ml		SS-EN ISO 6222:1999	a)
Odlingsbara mikroorganismer 37°C		57	cfu/ml		ISO 6222 mod	a)
Koliforma bakterier 37°C		< 1	cfu/250 ml		SS 028167-2	a)
Escherichia coli		< 1	cfu/250 ml		SS 028167-2 mod.	a)

Figure 19: This figure shows the fourth analysis of the time dependency of ultrasound performed on an already fouled membrane.

Provnummer:	177-2022-04110958			Ankomsttemp °C Mikro	6	
Provbeskrivning:				Provtagningsdatum	2022-04-11	
Matris:	Övrigt rent vatten			Mikrob. analys påbörjad	2022-04-11 19:54	
Provet ankom:	2022-04-11			Provtagare	Ahmed Fawzy	
Utskriftsdatum:	2022-04-25					
Provmärkning:	RF 1.1					

Analys	Resultat	Enhet	Mäto.	Metod/ref	
Odlingsbara mikroorganismer 22°C	1	cfu/ml		SS-EN ISO 6222:1999	a)
Odlingsbara mikroorganismer 37°C	< 1	cfu/ml		ISO 6222 mod	a)
Koliforma bakterier 37°C	< 1	cfu/250 ml		SS 028167-2	a)
Escherichia coli	< 1	cfu/250 ml		SS 028167-2 mod.	a)

Kommentar/bedömning från Eurofins Pegasuslab AB:
Mikrobiologisk kommentar
Provtagningsdatum/tid har ej angivits. Om tid mellan provtagning och analysstart överstiger 12 timmar, kan analysresultaten påverkas.

Figure 20: This figure shows the analysis of the membrane without ultrasonic treatment, before treatment started to establish clean membranes.

Provnummer:	177-2022-04131836			Ankomsttemp °C Mikro	7	
Provbeskrivning:				Provtagningsdatum	2022-04-13	
Matris:	Övrigt rent vatten			Mikrob. analys påbörjad	2022-04-13 19:01	
Provet ankom:	2022-04-13			Provtagare	Ahmed fawzy	
Utskriftsdatum:	2022-04-29					
Provmärkning:	RF1.2					

Analys	Resultat	Enhet	Mäto.	Metod/ref	
Odlingsbara mikroorganismer 22°C	1500	cfu/ml		SS-EN ISO 6222:1999	a)
Odlingsbara mikroorganismer 37°C	230	cfu/ml		ISO 6222 mod	a)
Koliforma bakterier 37°C	< 1	cfu/250 ml		SS 028167-2	a)
Escherichia coli	< 1	cfu/250 ml		SS 028167-2 mod.	a)

Kommentar/bedömning från Eurofins Pegasuslab AB:
Mikrobiologisk kommentar
Provtagningsdatum/tid har ej angivits. Om tid mellan provtagning och analysstart överstiger 12 timmar, kan analysresultaten påverkas.

Figure 21: This figure shows the analysis of the membrane without ultrasonic treatment, at day 3 of treatment.

Provnummer:	177-2022-04201712		Provtagningsdatum		2022-04-20	
Provbeskrivning:			Mikrob. analys påbörjad		2022-04-20 21:29	
Matris:	Mineralvatten		Provtagare		Ahmed Fawzy	
Provet ankom:	2022-04-20					
Utskriftsdatum:	2022-05-04					
Provmärkning:	RF 1.3					
Analys		Resultat	Enhet	Mäto.	Metod/ref	
Odlingsbara mikroorganismer 22°C		1900	cfu/ml		SS-EN ISO 6222:1999	a)
Odlingsbara mikroorganismer 37°C		340	cfu/ml		ISO 6222 mod	a)
Koliforma bakterier 37°C		< 1	cfu/250 ml		SS 028167-2	a)
Escherichia coli		< 1	cfu/250 ml		SS 028167-2 mod.	a)

Figure 22: This figure shows the analysis of the membrane without ultrasonic treatment, at day 10 of treatment however with no treatment during day 6 and 7.

Sample code:	177-2022-04221784		Arrival temp °C Micro		7	
Description:			Sampling date		2022-04-22	
Matrix	Tap water		Start date of analysis		2022-04-22 21:56	
Received:	2022-04-22		Sampler		Ahmed Fawzy	
Report date:	2022-05-19					
Start of analysis	2022-04-22					
Client Sample:	RF 1.4					
Analysis		Result	Unit	Unc.	Method	
Aerobic Plate Count 22°C		> 5000	cfu/ml		ISO 6222 mod.	a)
Slow-growing bacteria		> 5000	cfu/ml		ISO 6222 mod.	a)
Coliforms 35°C		< 1	cfu/100 ml		SS 028167-2 mod.	a)
Escherichia coli		< 1	cfu/100 ml		SS 028167-2 mod.	a)

Comment/conclusion from Eurofins Pegasuslab AB:
Microbiological comment
Suitable with remarks according to SLV FS 2001:30.
due to a high number of slow-growing bacteria (7 days, 22°C).
due to a high aerobic plate count (3 days, 22°C).
Time/date for sampling has not been given. If the time from sampling to start of analysis exceeds 12 hours, the results could be affected.

Figure 23: This figure shows the analysis of the membrane without ultrasonic treatment, at day 12 of treatment however with no treatment during day 6 and 7.

Provnummer:	177-2022-04110959		Ankomsttemp °C Mikro		6	
Provbeskrivning:			Provtagningsdatum		2022-04-11	
Matris:	Övrigt rent vatten		Mikrob. analys påbörjad		2022-04-11 19:54	
Provet ankom:	2022-04-11		Provtagare		Ahmed Fawzy	
Utskriftsdatum:	2022-04-25					
Provmärkning:	USF 1.1					

Analys	Resultat	Enhet	Mäto.	Metod/ref	
Odlingsbara mikroorganismer 22°C	< 1	cfu/ml		SS-EN ISO 6222:1999	a)
Odlingsbara mikroorganismer 37°C	< 1	cfu/ml		ISO 6222 mod	a)
Koliforma bakterier 37°C	< 1	cfu/250 ml		SS 028167-2	a)
Escherichia coli	< 1	cfu/250 ml		SS 028167-2 mod.	a)

Kommentar/bedömning från Eurofins Pegasuslab AB:
Mikrobiologisk kommentar
Provtagningsdatum/tid har ej angivits. Om tid mellan provtagning och analysstart överstiger 12 timmar, kan analysresultaten påverkas.

Figure 24: This figure shows the analysis of the membrane with ultrasonic treatment, before treatment started to establish clean membranes.

Provnummer:	177-2022-04131837		Ankomsttemp °C Mikro		7	
Provbeskrivning:			Provtagningsdatum		2022-04-13	
Matris:	Övrigt rent vatten		Mikrob. analys påbörjad		2022-04-13 19:01	
Provet ankom:	2022-04-13		Provtagare		ahmed fawzy	
Utskriftsdatum:	2022-04-29					
Provmärkning:	USF 1.2					

Analys	Resultat	Enhet	Mäto.	Metod/ref	
Odlingsbara mikroorganismer 22°C	3	cfu/ml		SS-EN ISO 6222:1999	a)
Odlingsbara mikroorganismer 37°C	5	cfu/ml		ISO 6222 mod	a)
Koliforma bakterier 37°C	< 1	cfu/250 ml		SS 028167-2	a)
Escherichia coli	< 1	cfu/250 ml		SS 028167-2 mod.	a)

Kommentar/bedömning från Eurofins Pegasuslab AB:
Mikrobiologisk kommentar
Provtagningsdatum/tid har ej angivits. Om tid mellan provtagning och analysstart överstiger 12 timmar, kan analysresultaten påverkas.

Figure 25: This figure shows the analysis of the membrane with ultrasonic treatment during treatment, at day 3 of treatment.

Provnummer:	177-2022-04201713		Provtagningsdatum	2022-04-20	
Provbeskrivning:			Mikrob. analys påbörjad	2022-04-20 21:29	
Matris:	Mineralvatten		Provtagare	Ahmed Fawzy	
Provet ankom:	2022-04-20				
Utskriftsdatum:	2022-05-04				
Provmärkning:	USF 1.3				

Analys	Resultat	Enhet	Mäto.	Metod/ref	
Odlingsbara mikroorganismer 22°C	2500	cfu/ml		SS-EN ISO 6222:1999	a)
Odlingsbara mikroorganismer 37°C	540	cfu/ml		ISO 6222 mod	a)
Koliforma bakterier 37°C	< 1	cfu/250 ml		SS 028167-2	a)
Escherichia coli	< 1	cfu/250 ml		SS 028167-2 mod.	a)

Figure 26: This figure shows the analysis of the membrane without ultrasonic treatment during treatment, at day 10 of treatment however with no treatment during day 6 and 7.

Sample code:	177-2022-04221785		Arrival temp °C Micro	7	
Description:			Sampling date	2022-04-22	
Matrix	Tap water		Start date of analysis	2022-04-22 21:56	
Received:	2022-04-22		Sampler	Ahmed Fawzy	
Report date:	2022-05-19				
Start of analysis	2022-04-22				
Client Sample:	USF 1.4				

Analysis	Result	Unit	Unc.	Method	
Aerobic Plate Count 22°C	> 5000	cfu/ml		ISO 6222 mod.	a)
Slow-growing bacteria	> 5000	cfu/ml		ISO 6222 mod.	a)
Coliforms 35°C	< 1	cfu/100 ml		SS 028167-2 mod.	a)
Escherichia coli	< 1	cfu/100 ml		SS 028167-2 mod.	a)

Comment/conclusion from Eurofins Pegasuslab AB:
Microbiological comment
Suitable with remarks according to SLV FS 2001:30.
due to a high number of slow-growing bacteria (7 days, 22°C).
due to a high aerobic plate count (3 days, 22°C).
Time/date for sampling has not been given. If the time from sampling to start of analysis exceeds 12 hours, the results could be affected.

Figure 27: This figure shows the analysis of the membrane without ultrasonic treatment during treatment, at day 12 of treatment however with no treatment during day 6 and 7.

Provnummer:	177-2022-04131838		Ankomsttemp °C Mikro		7	
Provbeskrivning:			Provtagningsdatum		2022-04-13	
Matris:	Övrigt rent vatten		Mikrob. analys påbörjad		2022-04-13 19:01	
Provet ankom:	2022-04-13		Provtagare		ahmed fawzy	
Utskriftsdatum:	2022-04-29					
Provmärkning:	USF 2.2					

Analys	Resultat	Enhet	Mäto.	Metod/ref	
Odlingsbara mikroorganismer 22°C	< 1	cfu/ml		SS-EN ISO 6222:1999	a)
Odlingsbara mikroorganismer 37°C	< 1	cfu/ml		ISO 6222 mod	a)
Koliforma bakterier 37°C	< 1	cfu/250 ml		SS 028167-2	a)
Escherichia coli	< 1	cfu/250 ml		SS 028167-2 mod.	a)

Kommentar/bedömning från Eurofins Pegasuslab AB:
Mikrobiologisk kommentar
Provtagningsdatum/tid har ej angivits. Om tid mellan provtagning och analysstart överstiger 12 timmar, kan analysresultaten påverkas.

Figure 28: This figure shows the analysis of the membrane with ultrasonic treatment after treatment, at day 3 of treatment.

Provnummer:	177-2022-04201714		Provtagningsdatum		2022-04-20	
Provbeskrivning:			Mikrob. analys påbörjad		2022-04-20 21:29	
Matris:	Mineralvatten		Provtagare		Ahmed Fawzy	
Provet ankom:	2022-04-20					
Utskriftsdatum:	2022-05-04					
Provmärkning:	USF 2.3					

Analys	Resultat	Enhet	Mäto.	Metod/ref	
Odlingsbara mikroorganismer 22°C	1700	cfu/ml		SS-EN ISO 6222:1999	a)
Odlingsbara mikroorganismer 37°C	43	cfu/ml		ISO 6222 mod	a)
Koliforma bakterier 37°C	< 1	cfu/250 ml		SS 028167-2	a)
Escherichia coli	< 1	cfu/250 ml		SS 028167-2 mod.	a)

Figure 29: This figure shows the analysis of the membrane with ultrasonic treatment after treatment, at day 10 of treatment however with no treatment during day 6 and 7.

Sample code:	**177-2022-04221786**		Arrival temp °C Micro		7	
Description:			Sampling date		2022-04-22	
Matrix	Tap water		Start date of analysis		2022-04-22 21:56	
Received:	2022-04-22		Sampler		Ahmed Fawzy	
Report date:	2022-05-19					
Start of analysis	2022-04-22					
Client Sample:	**USF 2.4**					

Analysis	Result	Unit	Unc.	Method	
Aerobic Plate Count 22°C	**1600**	cfu/ml		ISO 6222 mod.	a)
Slow-growing bacteria	**2400**	cfu/ml		ISO 6222 mod.	a)
Coliforms 35°C	**< 1**	cfu/100 ml		SS 028167-2 mod.	a)
Escherichia coli	**< 1**	cfu/100 ml		SS 028167-2 mod.	a)

Comment/conclusion from Eurofins Pegasuslab AB:
Microbiological comment
Suitable with remarks according to SLV FS 2001:30.
due to a high aerobic plate count (3 days, 22°C).
Time/date for sampling has not been given. If the time from sampling to start of analysis exceeds 12 hours, the results could be affected.

Figure 30: This figure shows the analysis of the membrane with ultrasonic treatment after treatment, at day 12 of treatment however with no treatment during day 6 and 7.

Compound	Unit	Limit
Temperature	$°C$	20
Colour	mg/l	15
Turbidity	FNU	0.5
Conductivity	mS/s	250
Total Organic Carbon	mg/l	5.5
Smell	-	weak
Taste	-	weak
pH	-	6.5-9.5
Alkalinity	mg/l	-
Hardness	$°dH$	15
Calcium	mg/l	100
Magnesium	mg/l	30
Sodium	mg/l	100
Potassium	mg/l	-
Iron	mg/l	0.100
Manganese	mg/l	0.050
Aluminium	mg/l	0.100
Copper	mg/l	0.20
Lead	mg/l	0.010
Cadmium	mg/l	0.0050
Quicksilver	mg/l	0.0010
Aresenic	mg/l	0.010
Pesticides	mg/l	0.00050
Polyaromatic hydrocarbons	mg/l	0.00010
Trihalomethanes	mg/l	0.050
Sulfate	mg/l	100
Chloride	mg/l	100
Flouride	mg/l	1.5
Ammonia	mg/l	0.50
Nitrite	mg/l	0.10
Total active chlorine	mg/l	0.4
Microorganisms, 22 °C, 3 days	$per\ ml$	10
Microorganisms, 22 °C, 7 days	$per\ ml$	5000
Coliform bacteria, 35 °C	$per\ 100\ ml$	proven
Escherichia coli	$per\ 100\ ml$	proven
Clostridium perfringens	$per\ 100\ ml$	proven

Table 1: This table contains the Swedish limits for compounds in drinking water [13].