**MASTER THESIS**

**KE200X**
**CHEMICAL ENGINEERING FOR ENERGY AND ENVIRONMENT**

# Optimisation of an ultrafiltration unit on a bench-scale plant

## A comparison between carbon and sand filtrate

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# MASTER THESIS

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# Abstract

The municipal association Norrvatten is one of Sweden's largest drinking water producers and distributes over 50 million $m^3$ of drinking water to around 700 000 inhabitants in northern Stockholm. The water is treated in the Görväln plant, which has since 2016 planned to expand its capacity and improve its water quality. One researched area for improving the treatment process is implementing membrane technology. In this project, experiments are performed as a continued work of integrating ultrafiltration with coagulation on a bench-scale plant. The purpose is to optimise the operating parameters (coagulant dosage, pH & alkalinity, retention time, and mixing) and compare the ultrafiltration removal efficiency for two types of feed water (carbon and sand filtrate).

A lower coagulant dosage of 2.5 mg Al/L resulted in removal efficiencies on average of 18.9 % TOC removal and 21.3 % $UV_{254}$ reduction. Compared to the higher dosage of 3.8 mg Al/L, the removal efficiency was only decreased with 2 % TOC and 3 % $UV_{254}$. Therefore, a lower dosage is a more suitable option. Although, more data needs to be collected for a more reliable optimal dosage. In addition, for the scaling up of the pilot, automatic dosage control needs to be implemented as the coagulant dosage is difficult to control as a parameter.

pH showed the best removal efficiency in the range of 6.8 to 7.2 and minimised aluminium residue in the permeate. It verifies that flock formation is pH-dependent and optimal close to 7. The efficiency also depended on the alkalinity, with the optimal alkalinity between 40 to 50 mg $HCO_3$/L. Higher alkalinity decreased the efficiency, which supports the theory that too basic water hinders flock formation. With minimum dosage of 5 mL 0.01 M $Na_2CO_3$/L untreated water, the required alkalinity could be achieved without affecting the amount of aluminium in the permeate residue.

The retention time and mixing configuration did not result in an optimum adjustment. However, with no retention time at a coagulant dosage of 0 mg Al/mL, the efficiency was reduced drastically to 2 % TOC removal and 6 % $UV_{254}$ reduction.

The placement after the carbon filter showed no adverse signs on the removal efficiency compared with placing it after the sand filter. The TMP of the membrane increased over time from 0.02 to 0.06 bar, and higher fluctuations in TMP were noted in the last experiment compared to the first. The differences were identical for both carbon and sand filtrate, strengthening the decision to place the ultrafiltration unit after the carbon filter.

# Sammanfattning

Kommunalförbundet Norrvatten är en av Sveriges största producenter av dricksvatten och förser över 50 miljoner vatten till över 700 000 invånare i norra Stockholm. Vattnet är renat i Görvälnverket som har sedan år 2016 planlagt en expansion av verkets kapacitet och kvalité. Ett fokusområde för att förbättra reningsprocessen är implementering av membranteknik.

I det här projektet har experiment utförts som ett fortsatt arbete av att integrera ultrafiltration med koagulering på en mikropilot. Syftet med projektet är att optimera driftparameterar (koaguleringsdos, pH och alkalitet, uppehållstid och omblandning) för processen och jämföra pilotens effektivitet för två typer av matarvatten (kol- och sandfiltrat).

En lägre koaguleringsdos på 2.5 mg Al/L resulterade i en 18.9 % avskiljning av TOC och 21.3 % minskning i $UV_{254}$. I jämförelse med en högre dos på 3.8 mg Al/L, var effektiviteten 2 % bättre för TOC och 3 % bättre för $UV_{254}$. Till följd av en låg ökning i effektivitet för en högre koagulantdos påvisar en lägre dosering ett bättre alternativ. Dessutom är det rekommenderat att vid uppskalandet av piloten mer försök genomförs för att få mer pålitliga data och att automatisk dosering implementeras eftersom dosering av koagulant var en svårkontrollerad parameter.

pH inom intervallet 6.8 till 7.2 visade vara mest optimal för att minimera mängden aluminiumrester i permeatet. Experimenten på pH konstaterar att flockning är pH beroende och optimalt vid pH 7. Effektiviteten var också beroende av alkaliteten. Där bäst alkalinitet anpassades till mellan 40 och 50 mg $HCO_3$/L, med högre än 50 mg $HCO_3$/L minskade effektiviteten av avskiljningen, vilket tyder på sämre flockning vid basiska förhållanden. Karbonatdosering av 5 mL 0.01 M $Na_2CO_3$/L obehandlat vatten uppnådde önskad alkalinitet och minimerade aluminiumrester i permeatet.

Uppehållstiden och konfigurationen av blandning indikerade ingen optimal justering. Emellertid, en jämförelse av försök med uppehållstiden och försök utan koaguleringdos visade dramatisk minskning i effektivitet till endast 2 % TOC avskiljning och 6 % $UV_{254}$ minskning.

Placering av ultrafiltrationsenheten efter kolfiltret jämfört med efter sandfiltret visade inga tecken på nedsatt effektivitet. Transmembrantrycket över membranet ökade över den experimenterade perioden från 0.02 till 0.06 bar och fluktuerade under drift mellan det första och sista försöket. Det var däremot ingen skillnad i trycket mellan kolfilter och sandfilter, vilket styrker beslutet att placera ultrafiltrationsenheten efter kolfiltret.

# List of abbreviations

DBP – Disinfectant by-products

DOC – Dissolved organic carbon

DOM – Dissolved organic matter

fDOM – Fluorescent dissolved organic matter

FEED – Water sample before the inlet of the membrane, taken 45 min after start-up.

HF – Hollow fibre

IN – Water sample from the feed at the start.

KMS – Twisted ribbon elements

MF – Microfiltration

MQ - Ultrapure Milli-Q water

NOM – Natural organic matter

NF – Nanofiltration

PAC – Polyaluminium Chloride

PERM1 – Permeate sample taken 30 min after start-up.

PERM2 – Permeate sample taken 30 min after start-up.

PES – Polyether sulphone

PS – Polysulphone

POC – Particulate organic carbon

PVDF – Polyvinylidene fluoride

RO – Reverse osmosis

SF - Sand filtrate

SMV – Corrugated plate elements

TMP – Transmembrane pressure

TOC – Total organic carbon

UF – Ultrafiltration

$UV_{254}$ – Ultraviolet absorbance at wavelength 254 nm

# List of tables

# List of figures

# Table of contents

# 1 Introduction

The municipal association Norrvatten produces and distributes over 50 million m$^3$ of drinking water to around 700 000 inhabitants in northern Stockholm. The water is taken from Mälaren, Sweden's third-largest lake. The lake is a good source of raw water and contains several healthy minerals but also numerous contaminants. The water is treated in the Görväln plant, which has since 2016 planned to expand its capacity and improve its water quality (Norrvatten, n.d.a).

The vision of Norrvatten is to supply healthy drinking water with social and environmental benefits in focus. It includes offering available water without interruptions and supplying a capacity that can handle unexpected disturbances. It also aims to provide high-quality drinking water that is safe for consumption. Finally, it contains a sustainable production and distribution of drinking water (Norrvatten, 2021).

Projections point to an increasing population and decreasing raw water quality in Mälaren. Therefore, an expansion of the treatment process will occur gradually. Water quality focus will include a better separation to minimise microbial contaminants, such as viruses, bacteria, and parasites. One researched area for improving the process is implementing membrane technology and coagulation (Norrvatten, 2021). Coagulation & flocculation are used in various industries, and it is both widespread and an essential alternative to drinking water treatment. Coagulation is especially common for drinking water purification sourced from surface water such as Mälaren (Binnie et al., 2018).

At the Görväln plant, several experiments have previously been performed on a bench-scale pilot plant. The investigation of membranes, especially ultrafiltration (UF), has focused on critical parameters and how they are best adjusted for optimal separation and operation. In addition, they have included experiments using a hybrid coagulation and membrane filtration technique. In previous projects, considerable attention has been put on feed water, dosing, and pH adjustment (Köhler & Sekizovic, 2021; Nikzad, 2021). It has also been decided that the UF unit will be placed after the carbon filter in the process. In this project, experiments are performed as continuous work from previous investigations. The research will be used to complement those works and give a more wholesome picture of how a UF membrane unit can be implemented in the process at the Görväln plant.

## 1.1 Purpose

This project aims to optimise an integrated process of a coagulation and UF unit. The parameters investigated for optimisation are tested for two types of feed water used: carbon filtrate (KF) and sand filtrate (SF). These feed waters are used to compare and assess if the placement of the UF unit after the carbon filter results in as effective treatment as after the sand filter.

## 1.2 Research objectives

- Compare correlations between the indicators fDOM, $UV_{254}$, TOC and DOC to determine their reliability in measuring the removal efficiency of NOM.

- Evaluate the removal efficiency of the ultrafiltration with varying coagulant dosages.

- Evaluate the removal efficiency of the ultrafiltration by adjusting the pH and alkalinity.

- Evaluate the effect of different retention times on the UF membrane.

- Optimise the configuration of mixing in the coagulation step.

- Investigate if the experiments have a notable effect on irreversible fouling.

## 1.3 Delimitations

The experiments are performed disregarding changes in water quality during the testing period between February and March. The water used is  KF and SF:

- KF is sampled at the carbon filter pilot plant at the Görnväln plant. The plant has a packed column, 1 m in height, with a 5 L packed volume of activated carbon (Norit GAC 1240).

- SF is sampled at a faucet after the sand filter at the Görväln plant.

# 2  Background

This chapter presents the treatment process of drinking water at Norrvatten, the background of drinking water, and how the quality is measured. An overview of the investigated methods used in the experiments is also given. The separation techniques used are coagulation & flocculation and membrane filtration.

## 2.1  The treatment process at the Görväln plant

The water treatment at the Görväln plant is performed in several steps to attain high-quality drinking water. The purification is divided into eleven steps, as shown in Figure 1 (Norrvatten, n. d.b).

1.  In the first step, the raw water is collected from the Görväln bay at two different inlet depths.
2.  The water is then filtered in a screening step to separate larger objects like fish and algae.
3.  Then, the water flow is adjusted to suit the treatment process better.
4.  The water is then taken through a slide where aluminium sulphate (ALG) is mixed with the stream.
5.  After that, the water is treated in a flocculation step. The ALG binds to humic substances and other particles to form flocks. Sodium metasilicate is also added to the water to increase the size of the flocks.
6.  The flocks are then separated from the water in a settling tank.
7.  The water enters a sand filter bed to remove residual flocks.
8.  Next, the water is treated in a carbon filter to remove any organic particles that may cause any displeasing taste or smell.
9.  A UV reactor then disinfects the water from harmful microorganisms.
10. Lastly, monochloramine and lime (caustic alkaline substance consisting of calcium oxides) are added to the water to increase pH and avoid bacterial growth. The increase also prevents corrosion and clogging in the drinking water supply system.
11. The water is then sent out in the water supply system.
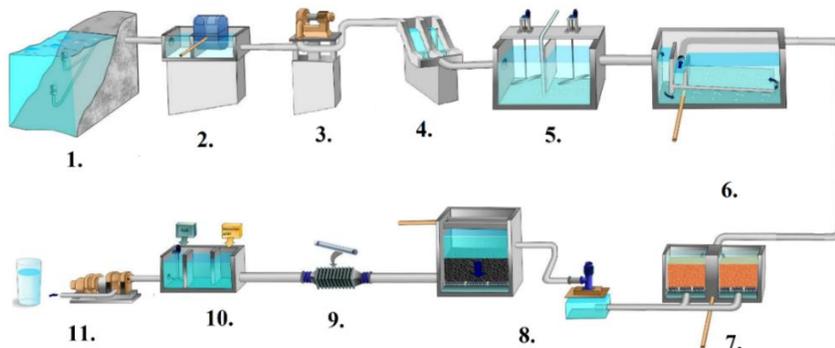


*Figure 1. Drinking water treatment process at the Görväln plant (Norrvatten, n. d.b).*

## 2.2  Drinking quality water

Drinking water in Sweden is accessible to everyone. There is a high supply of raw water, both groundwater and surface water. The quality standard is set so high that the water is safe to drink straight from the faucet. This accessibility is the result of high water quality requirements. Approximately half of the drinking water comes from surface water, taken from lakes, streams, and other watercourses. Surface water needs much more purification than groundwater before it is drinkable. The typical treatment steps included are filtration, flocculation, settling, and disinfection (SvensktVatten, 2016).

Several natural substances in freshwater affect its quality and make it hazardous to drink. These substances include solid matter such as colloids and suspended particles, inorganic ions, organic matter, and biological matter like bacteria and viruses. Such contaminants frequently affect the physical characteristics of water and give it unwanted colour, taste, and odour, which need to be removed (SvensktVatten, 2016). Solid matter is always present as particulates in surface water and can be unwanted contaminants. An exact definition of a particle can be diffuse. Still, it can comprise small solids larger than molecules but are generally not visible to the human eye. Particles can be classified in several ways, such as size, shape, and source. Inorganic matter in surface water, specifically dissolved inorganic matter, comes in the form of ions. The most common substances are alkaline minerals, chlorine, sulphate and nitrate. It also occurs in trace amounts of iron, lead, copper, arsenic, and manganese. These compounds are not dangerous if they do not exceed the standard limits, except for lead and arsenic (Crittenden et al., 2012).

Organic matter is undesired in drinking water and is commonly defined by its chemical properties, which entail a compound consisting of carbon, hydrogen, nitrogen, or oxygen. It comes in various sizes and can be found in 16 to $10^6$ g/mol. Organic compounds come from living organisms; some organic substances have proven to be toxic and even carcinogenic. Even so, it is uncertain to what extent organic matter in drinking water affects health. Nevertheless, organic matter can give an unpleasant smell, taste, and colour. Therefore, this makes it undesirable for consumption and needs to be removed. Often, a foul smell occurs due to plants' degradation; in other cases, the problem can be traced back to human activities. Organic compounds can be divided into four main groups based on their sources (Crittenden et al., 2012).

1. Natural organic matter (NOM)
2. Anthropogenic organic matter
3. Organic matter formed during disinfection
4. Organic matter created or added during treatment and transmission

NOM is a complex mixture of compounds in all naturally occurring freshwater environments found in soils and sediments. It is defined by various organic substances derived from plant life and by-products from bacteria and algae. Consequently, its physical and chemical characteristics can vary greatly, as well as its size and molecular weight – often found between 500 to 3000 Da. The chemical charge also varies, but the majority is negatively charged due to its complex composition. Typical functional groups of NOM include esters, phenols, carboxylic acids, amino acids, and nitrous acids (Sillanpää, 2014).

NOM can be divided into humic substances or non-humic substances. It consists of humic and fulvic acids in aquatic environments from decomposed biological matter. The main difference between them is their solubility. Humic acid is soluble in alkaline solutions and precipitates in acidic solutions, whereas fulvic acid is soluble independent of pH. The charge of these acids is significant to colloidal stability and affects which particles bind to NOM (AWWA, 2011).

It is crucial to characterise and quantify NOM as it significantly affects drinking water quality, and seasonal changes in NOM affect the treatment process. For instance, biofilm build-up on different unit operations in the treatment process is a common problem when removing NOM. It can also carry unwanted metals and hydrophobic organic material. Furthermore, during disinfection, the formation of disinfection by-products (DBP) arises from NOM and has been linked to harmful health effects. Therefore, it is vital to remove organic matter, specifically NOM. Conventional methods for NOM removal include coagulation & flocculation. It is treated further by sedimentation, flotation, or filtration (AWWA, 2011; Sillanpää, 2014).

Besides NOM, other organic compounds included as organic compounds are anthropogenic organic matter traced to human activities. The compounds can come from industries, agriculture, and municipal effluents. These activities give rise to point source pollutants and affect groundwater more often; surface water can rarely be connected to a specific contaminant source (Crittenden et al., 2012).

## 2.3 Water quality indicators

Many different indicators complement each other to ensure a high drinking water quality. For example, the presence of organic matter in the water is an often-measured parameter. Other common indicators include measuring pH, alkalinity, and turbidity.

### 2.3.1 Organic matter

Observing several different parameters can measure the concentration of organic matter in water. These parameters include biological oxygen demand, chemical oxygen demand, total organic carbon (TOC), dissolved organic carbon (DOC), $UV_{254}$, and dissolved organic matter (DOM), either as coloured or fluorescent (Thomas & Burgess, 2017).

TOC is the most crucial indicator of organic contaminants in water. It is a surrogate measure and gives a good indication of the amount of NOM in the water. The NOM is usually twice the amount of TOC. An additional measure of organic matter is DOC, making a fraction of the TOC. It measures the dissolved organic content of up to 80-90 % of TOC (Thomas & Burgess, 2017; Crittenden et al., 2012).

Another effective indicator for organic matter is ultraviolet absorbance ($UV_{254}$) which measures absorbance at 254 nm. Specific compounds in NOM, called chromophores, absorb UV light and correlate $UV_{254}$ and NOM. It is essential to mention that chromophores' compositions in NOM vary, mainly depending on seasons, and affect the signal of $UV_{254}$ (Crittenden et al., 2012).

DOM is a part of NOM and consists of a complex mixture of large biomolecules and smaller substances. An indicator of DOM is to determine the fluorescent DOM (fDOM), which is a fraction of coloured DOM (cDOM). cDOM has a strong absorbance in the ultraviolet spectrum and strongly correlates with TOC (Thomas & Burgess, 2017; YSI, n. a.).

### 2.3.2 pH

pH measures hydrogen ions in water and is expressed as a negative logarithm. The pH is related to the alkalinity and usually positively correlates to it. The optimum interval of drinking water lies between 6.5 and 8.5. Natural freshwater bodies typically have pH values between 6 and 9. Therefore, a pH adjustment may be necessary. Surface water with low pH is often caused by carbon dioxide and acetic acid. Furthermore, excessively high or low pH has a corrosive effect on pipes (Water Quality, 2020).

### 2.3.3 Alkalinity

Alkalinity is the capacity of water to resist acidification. It indicates the number of alkaline compounds, such as carbonate and bicarbonate. The total alkalinity is measured by adding acid to a water sample until all alkaline substances are used. Typical alkalinity levels in natural freshwater

are approximately 50 mg/L but can vary depending on the surrounding environment and the state of the soil. Carbon dioxide in water increases the dissolved minerals surrounding natural waters and alkalinity. In general, groundwater has higher alkalinity than surface water. In drinking water purification, carbonates are added to increase the pH and alkalinity. Adding carbonates improves the water's buffer against acidic pollution (Boyd, 2020).

### 2.3.4  Turbidity

Turbidity measures discolouring and the number of suspended particles in water. It is caused by organic matter and colloids that make the water cloudy. Excessive turbidity is rarely toxic, but it has an unwanted characteristic as coloured water is unpleasant for consumption, and fewer particles make it aesthetically more pleasant to drink (Boyd, 2020).

## 2.4 Coagulation & flocculation

Coagulation & flocculation have advanced significantly since the 90s. Removing dangerous compounds such as pathogens and DBP together with reducing operational costs have long been incentives to develop coagulation & flocculation. However, for optimal treatment conditions, a few parameters are critical. These parameters include feed water characteristics, type of coagulant, dosage, pH adjustment, retention time, mixing, and temperature (Binnie et al., 2018).

### 2.4.1 Principle

Coagulation & flocculation are the processes in which coagulant chemicals are added to a stream to change the properties of particles and make them floc together. A sequential step separates the flocs, usually done with settling, flotation, or filtration. Coagulation & flocculation are related terms within separation processes. Incorrectly, they have been used synonymously used with each other, and definitions have varied considerably. Coagulation is when colloid particles, predominantly hydrophobic, are destabilised. The purpose of coagulation is to disrupt the stability of a system. On the other hand, flocculation happens when the destabilised matter is gathered in flocks and forms larger clusters of particles (Bratby, 2016). There are four types of mechanisms that can achieve colloid destabilisation, namely: (1) Double-layer compression - which forms destabilisation by positively charged ions; (2) Charge neutralisation - formed by cations; (3) Enmeshment in precipitate - hydroxide or carbonate flocks are formed; (4) Particle bridging - coagulate colloids from long cationic molecules. (Binnie et al., 2018)

In raw water, typical particles removed are minerals, organic material, and microorganisms. However, it can also help remove other trace contaminants (AWWA, 2012). Besides removing colloid matter, NOM reduction has become an important goal with coagulation. The necessity to remove NOM is connected to the need to reduce DBS formation. The coagulant dose strongly affects the coagulation mechanism responsible for removing NOM. It is mainly done through precipitate surfaces or direct precipitation for NOM with high molecular weight. (AWWA, 2012)

### 2.4.2 Type of coagulant

There are a few types of chemicals commonly used for coagulation. They are most often divided between polymer and metal coagulants. Among the metal kinds, they are either aluminium-based or iron-based. These coagulants are effective, available, and cheap options. Aluminium and ferric salts are effective because they can achieve several destabilisation mechanisms. Both double layer compression, charge neutralisation and enmeshment in the precipitate are present. Also, metal salts are robust as they can coagulate colloids with changing characteristics in the feed water. This is done by altering the coagulant dose or adjusting the pH value (Binnie et al., 2018).

One disadvantage of metal coagulants is that they consume alkalinity. With lower buffer capacity, the pH value may decrease to a level where the coagulant's efficiency is affected. This decrease may need to be countered by adding chemicals (Bratby, 2016).

It is vital to control mixing and pH when using aluminium or ferric salts. These salts give rise to intermediate complexes that are good for double-layer compression and charge neutralisation. These complexes are short-lived and need good mixing for high efficiency. The salts form flocks as enmeshment in the precipitate, a significant part of the coagulation step. However, feed water with low buffer capacity will likely decrease the pH value when the coagulant is added, which depends on the metal salts' high acidity. A lowered pH may result in an inferior enmeshment mechanism and decreased coagulation. Controlling water pH can be complex, and chemicals may need to be added to increase its buffer capacity (Binnie et al., 2018). Another type of coagulant is polymeric aluminium salt, such as Polyaluminium chloride (PAC) and Polyaluminium silicate sulphate. They are generally more expensive but active at lower temperatures and form faster flocks, decreasing the required coagulant dosage. They also have a lesser effect on pH, reducing the need for buffering chemicals. The use of PAC can mitigate or even, in some cases, eliminate the need to add base chemicals (Binnie et al., 2018; AWWA, 2012).

### 2.4.3  pH adjustment

The charge of particles in the stream is affected by the pH, and higher pH results in particles with a more negatively charged surface. Therefore, charge neutralisation can be achieved with pH control. pH adjustment helps control the precipitation of metal hydroxides. The desired pH is at the level where the solubility of the metal hydroxide is at its minimum. Aluminium has a lower solubility limit around approximately pH 7. Changes in feed water are common; generally, if the water is soft, it has lower levels of minerals. These changes in feed water might affect the pH value significantly and, therefore, need to be compensated with chemicals (Binnie et al., 2018). Typical chemicals used to increase pH are lime ($Ca(OH)_2$) and soda (NaOH). Also, soda ash can be used as a base supplement and is commonly added (AWWA, 2012).

### 2.4.4  Mixing and retention time

The mixing is vital to achieving the destabilisation of particles in the stream. The energy input in coagulation & flocculation is essential because it affects the process's effectiveness. Stirring creates energy input and is proportional to the mixer's velocity gradient. The velocity gradient in $s^{-1}$ represents the intensity of the mixing (AWWA, 2012). Coagulation needs high-intensity, so-called rapid mixing, and flocculation requires low-intensity mixing. Why flocculation needs less intensity in its mixing depends on the need for energy input decreases as flocks increase in size and break up if the energy input gets too high. It is also important to consider temperature when adjusting the

mixing intensity. The mixing is affected by the feed water's viscosity, and increased temperatures lower the viscosity (Bratby, 2016).

Another vital parameter under coagulation & flocculation is retention time. The retention is composed of the volume of the feed water in the mixing section divided by the flow. The retention time is not as significant for the coagulation mixing as it occurs in a very short time. On the contrary, it is a more critical parameter for the flocculation, which needs time to agglomerate a cluster (Bratby, 2016). The coagulation step occurs in 0,01 to 1 s, and retention times for rapid mixing may not be improved after more than 5 s. Thereof, the optimal retention time is related to the velocity gradient and the coagulant dosage (AWWA, 2012).

Rapid mixers for coagulation come in many forms, such as flumes/weirs, propeller mixers, and in-line mixers. Types of flocculation mixers include baffled channels, paddle flocculation, or sludge-blanket flocculators (AWWA, 2012). In-line pipe mixing is most common for drinking water, with design options including empty pipe, tee mixer, or static mixer. The static mixer is ideal for coagulant blending in drinking water treatment, called in-line coagulation. The inside of the static mixer is filled with elements or baffles formed in different ways to improve the mixing. Two common elements are: twisted ribbon elements (KMS) and corrugated plate elements (SMV), see Figure 2. They are some of the best design options for mixing coagulants in drinking water purification (Kresta et al., 2016).
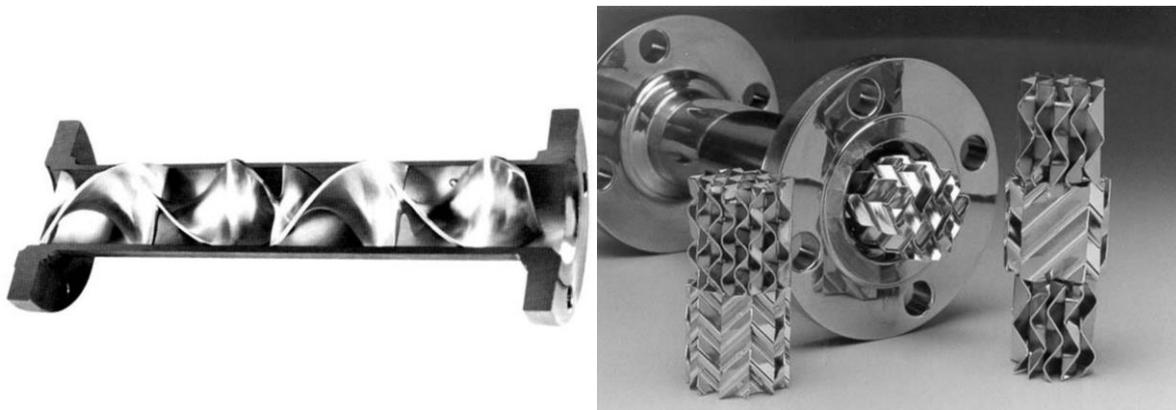


*Figure 2. To the left: a static mixer with KMS. To the right: a static mixer with SMV (Kresta et al., 2016).*

In-line coagulation mixing can often be an economically preferable option. It can be superior when rapid mixing or a short retention time is needed. It is most advantageous when the feed concentration is stable and the process is continuous. When having in-line coagulation, it is essential to regard the viscosity of the mixing fluids to choose the appropriate mixer for the operation. In-line mixers, including static mixers in both pipes and channels, do not have a fixed velocity gradient but should have a given mixing intensity from the manufacturer (Atiemo-Obeng et al., 2004; Bratby, 2016).

## 2.5 Membrane treatment

Membrane technology is well-studied and has long been used for various separation processes. A membrane consists of a semi-permeable barrier interface between two or more homogenous compounds that can selectively separate them by allowing parts of them to passage through. The ingoing stream is called feed, the compound that passes through the membrane is called permeate, and the rejected substances are called retentate. Membrane separation is a common technique (Singh & Hankins, 2016). They are an excellent choice to implement in water treatment as they are easy to operate, have low energy demand, and can be integrated with several other processes (Basile & Charcosset, 2015). Most membranes are used to separate liquids, and almost all types of membranes are pressure-driven. These characteristics make them practical for increasing concentrations and purification purposes (Singh, 2015).

### 2.5.1 Membrane flux

The membrane flux (J) measures the performance and, more precisely, the flow over the membrane area. It is a critical variable for efficient separation. The flux is the cross-flow over a membrane's porous surface, called permeate flow. The flux in a steady state is determined by the permeability (k) of the membrane and a specific driving force (X) (Singh, 2015).

$$J = k * X$$

The permeate flow through the membrane is proportional to the driving force with the permeability as a constant. The permeability is affected by the properties of the membrane. The driving force is often connected to pressure, concentration, or electrical potential (Singh, 2015). For UF membranes, the flux correlation is directly proportional to the transmembrane pressure (TMP) and inversely proportional to the absolute viscosity of the stream. The flux can be derived from Darcy's law, which describes the flow over a porous media. (AWWA, 2016)

$$J = \frac{Q_{total}}{A} = \frac{\Delta P}{\mu R_m}$$

Where $Q_{total}$ is the total flow, A is the membrane surface area of the membrane, $\Delta P$ is the difference in pressure or TMP, $\mu$ is the absolute viscosity of the feed, and $R_m$ is the hydraulic resistance.

For hydraulic resistance, the most critical factor is the pore size. The size is most influential because it is mathematically expressed as a fourth denominator to the resistance. Therefore, small pore size increases can significantly lower the resistance and increase the flux. TMP can be calculated as the mean value of the inlet ($P_i$) and outlet ($P_o$) pressure and then subtracted by permeate pressure ($P_p$) (AWWA, 2016).

$$TMP = \frac{P_i + P_o}{2} - P_p$$

Efficient membrane separation depends on several parameters besides the flux. The performance is often connected to selectivity, feed characteristics, membrane integrity, and fouling. It is vital to notice that there is no optimal membrane for all types of feed, but each membrane is designed and customised for a particular stream. Hence, there is a vast number of membrane types (Singh & Hankins, 2016).

### 2.5.2  Membrane classification

The most used membrane processes are microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), reverse osmosis (RO), and electrodialysis. The first four are classified after pore size, where MF has pores between 100-10,000 nm, UF has between 1-500 nm, NF has between 0.5-5 nm, and RO has between 0.1-1 nm. It is essential to point out that membrane filtration as a transport mechanism is specific for MF and UF, not for NF and RO. Although they all use pressure as a driving force, MF and UF use sieving as transport mechanisms, while NF and RO have sorption-capillary transport mechanisms. Other types include ion mitigation and solution diffusion (Singh, 2015). UF and MF are more flexible and widespread compared to NF and RO. They also have higher flux and lower energy costs, making them more economically viable. Furthermore, the UF membrane can remove bacteria and viruses in potable water. It is known to remove all suspended particles, colloid particles, and larger organisms (AWWA, 2016; Basile et al., 2015).

The material of membranes is either polymeric or ceramic. The structure of polymeric membrane can additionally be divided into symmetric or asymmetric. The most considerable focus on development has been on polymeric alternatives. They are most economically valid but face challenges with improving flux and selectivity and reducing fouling. Fouling is the flux reduction due to the deposition of matter in the membrane pores or on the membrane surface. It is a widespread problem in membrane separation. Therefore, treatment and cleaning are needed (Basile et al., 2015).

There are many different sorts of materials used, but the most common include Polysulphone (PS), Cellulose acetate, Polyether sulphone (PES), and Polyvinylidene fluoride (PVDF). The cellulose-based membranes have the advantage of higher flux and are less susceptible to fouling. Contrary, non-cellulosic membranes have better stability (Singh & Hankins, 2016).

Different modules of membranes are used when treating water. Four configurations are typically used: plate-and-frame, tubular, spiral-wound, and hollow fibre (HF) (Singh & Hankins, 2016). The most popular modules used for drinking water include tubular, SW, and HF. One advantage of HF is that its structure allows the membrane to be backwashed and thereby more easily cleaned. HF

structure has a cylindrical compartment with several hundreds of fibres inside it. Each fibre has pores where the stream passes through its surface. The most common flow is a cross-flow from the outside of the fibres, leaving a permeate on the inside. One advantage of HF is that it takes little space, with a high surface area to volume ratio. HF also has low TMP, somewhere between 0.2 and 1 bar (AWWA, 2016).

### 2.5.3 Mode and operation

Two modes are standard for membrane operation: dead-end and cross-flow. For dead-end membranes, the feed stream flows perpendicular to the membrane surface, while cross-flow membranes have a feed stream that flows parallel to the surface of the membrane. A difference with the dead-end membranes is that they do not have a retentate stream. Dead-end MF/UF has proven effective for treating surface water (Singh & Hankins, 2016). UF membranes operate around a pressure (TMP) at 0.5-10 bar. Besides the pore size, what separates UF from MF is a much denser filtration layer (due to smaller pores), which gives it higher hydrodynamic resistance (Basile et al., 2015).

The feed temperature is vital for the operation. It indirectly affects the permeate flux as it correlates to the water's viscosity, see Table 1. Lower temperatures have higher viscosities, lowering the flux and the flow pumped through the pipes. Therefore, temperature changes may need to be corrected by changing the driving force and the pumping speed (AWWA, 2016).

*Table 1. Various aqueous viscosities with temperatures at atmospheric pressure (AWWA, 2016).*

| Temperature [°C] | Viscosity [cP] |
|---|---|
| 5 | 1.5 |
| 10 | 1.3 |
| 15 | 1.1 |

### 2.5.4 Fouling and cleaning

Fouling is the gradual reduction in the filtrate water flow rate at constant pressure caused by adsorption or deposition of suspended matter within membrane pores or on the membrane surface. The fouling can decline the permeate flux significantly and the quality of treatment. Its porosity decreases when a membrane is fouled and becomes less effective (AWWA, 2016). It is generally categorised as either pore adsorption, pore-blocking, or cake formation. It can further be divided after its content as organic fouling, inorganic fouling, and biofouling. Other ways to categorise it are physically/hydraulically reversible or irreversible fouling. Reversible fouling includes the type

that is removable with physical or hydraulic cleaning. Irreversible fouling is the type that is impossible to remove with ordinary backwashing (Kimura & Kume, 2020).

Most fouling is hydrophobic and negatively charged, particularly for organic fouling and biofouling. The fouling accumulates a gel-layer biofilm on the membrane surface, which can be especially hard to remove when adsorbed to hydrophobic membranes. In addition, organic fouling is high in TOC and DOC, increasing microbial growth on the membrane (Singh, 2015). Therefore, pretreatment might be necessary to reduce the number of hydrophobic compounds and organic matter in the feed water. It might help mitigate the build-up of a biofilm and bacterial growth (AWWA, 2016).

Proper operation control and cleaning are crucial for mitigating fouling. The cleaning is most performed by backwashing. The backwashing is done in cycles and differs depending on the scale of operation. It is often done with a cross-flow from inside-outside. The pressure during backwashing can be seen between 0.5 to 2 bar and can also be performed in a pulsing manner. The pulsing helps to dislodge the layer of fouling accumulated in the membrane. More than physical cleaning, membranes need chemical cleaning to remove irreversible fouling. With suitable chemical cleaning, partial or complete flux recovery is achievable. Sufficient chemical cleaning is dependent on cleaning frequency, duration and chemicals used. Commercially used chemicals that are especially good at removing biofouling are chlorine. To improve the efficiency of chlorine treatment, increasing the temperature or using chlorine together with soda can be beneficial (AWWA, 2016).

In a study, MF and UF were compared on fouling mitigation for treating surface water with coagulation/filtration. The coagulation used was PAC, and the membrane was a PVDF hollow fibre module. Fouling on the UF was less severe than for the MF, and NOM was responsible for the irreversible fouling on the MF. The result concluded that irreversible fouling was less critical for UF than MF. The leading cause of irreversible fouling was biopolymers. Large biopolymers for MF and small biopolymers for UF. The irreversible fouling could be mitigated with coagulation pretreatment for UF but not for MF (Kimura & Kume, 2020).

# 3 Methodology

In this chapter, the design of the pilot plant is described. Then, the protocol for operating the plant is presented. The analytical technique that is used to collect relevant data is also included. Finally, a more detailed description of the separate experiments performed with adjusted parameters is defined.

## 3.1 Design of small-scale pilot plant
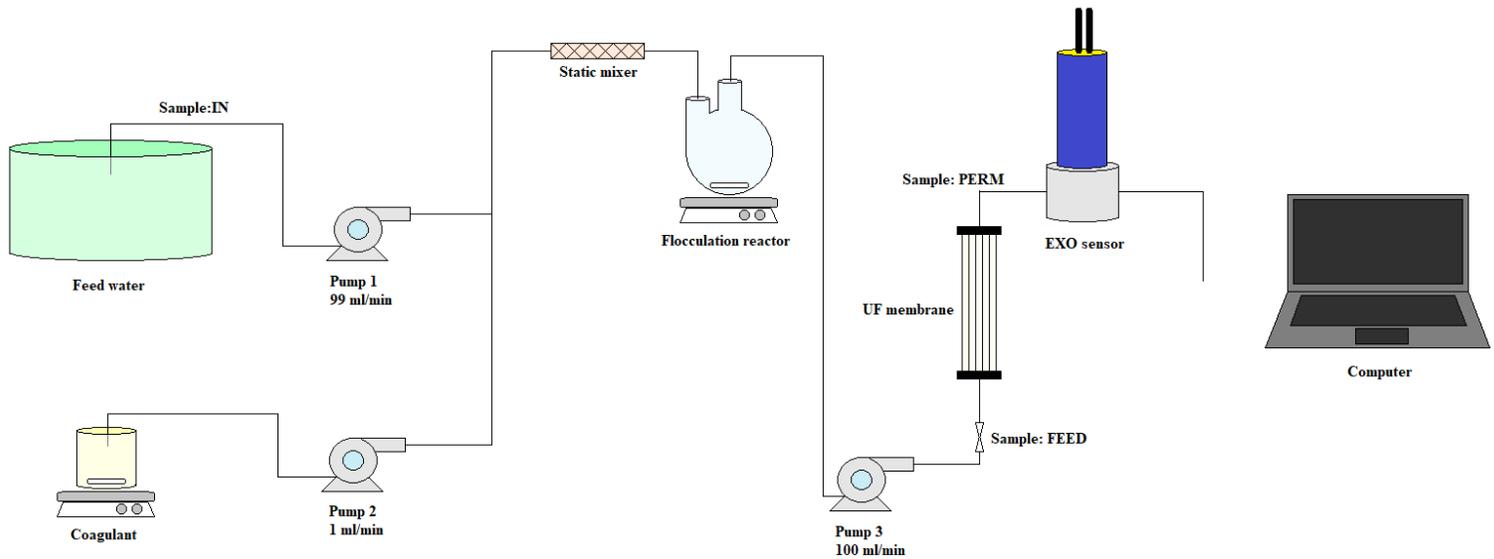


*Figure 3. Schematic design of the bench-scale pilot plant.*

The pilot plant, set up on a bench-scale assembly, is schematically detailed in Figure 3. It consisted of two treatment steps: an initial coagulation & flocculation unit, followed by the following UF unit. Figure 14 in Appendix A shows a picture of the set-up. The duration of each experiment was about one hour.

The feed water used in the pilot was contained in a 5 L plastic water container. The water was gathered the day before an experiment was performed so it could adjust to the ambient temperature. The water was collected at taps according to what was needed for every specific experiment, i.e., SF or KF. The containers were filled to the top and sealed to avoid bacterial growth. 10 L or two full containers were consumed for each experiment.

Depending on some parameters investigated during the project, Sodium carbonate ($Na_2CO_3$) was added to the feed water to alter the pH value and alkalinity. $Na_2CO_3$ salt was dissolved in Milli-Q (MQ) water and diluted at different doses to the feed water for the experiments that needed pH adjustment.

The coagulant was contained in a 100 mL glass bottle. The coagulant used was a PAC (PAX-XL 60 Uponor). The PAC is a coagulant agent with several multivalent aluminium compounds (Avloppscenter. n. d.). The raw concentration was 98,000 mg Al/L; it needed to be diluted for the operation on the pilot plant. The coagulant was diluted after selected experimental doses, found in Appendix B. The coagulant bottle was placed on a magnetic stirrer to keep the diluted coagulant homogenous.

Tubes were connected from the water and coagulant container and pumped through a peristaltic pump at 99 ml/min and 1 ml. The pump was previously calibrated after pumping 100 mL of liquid. Next, the two streams are joined and mixed in a static in-line mixer. It is in the mixer that the coagulation step occurs. Four kinds of mixers were used in this project (pictures can be seen in Appendix A, Figure 15). The first one is an SMV plastic mixer with 24 elements. The other three are KMS plastic mixers with elements in different amounts (24, 36, and 48 elements) (Esska, n. a.). After the mixing, the water enters a flocculation reactor. The reactor is fully sealed and placed on a magnetic stirrer.

The following UF step is performed with a Hollow fibre UF membrane (X-FLOW RX300, Pentair). The feed flows in at the bottom of the membrane, permeates through the membrane pores, and comes out at the top. The membrane material is a mix of PES and PVP. The hydraulic membrane diameter is 0.83 mm, and the area is 0.08 $m^2$ (Lenntech, 2022). Pressure sensors at the membrane monitor the inlet and outlet pressures during the experiment.

The permeate that flows out from the top of the membrane enters a cell where the permeate resides for a period as a sensor measures different parameters. The sensor is a probe attached to the top of the cell called EXO2 Multiparameter Sonde. It has seven sensor ports and measures conductivity, turbidity, fDOM, temperature, pH, and TDS for every experiment. The sensor is connected via Bluetooth for data collection and storage. (YSI., n. a.b)

Before the inlet of the membrane, a three-way valve was installed to control the inflow of feed water. The valve can be altered to change the water's direction and backwash the membrane. This was done by connecting a secondary pump to the permeate flow tube and connecting it to a secondary pump that backwashes the membrane with cleaning chemicals at the end of each experiment.

### 3.2 Experimental Procedure

The operation of the plant was divided into three main parts, start-up, operation, and maintenance.

#### 3.2.1 Start-up of the plant

1. Water is collected, and relevant solutions are prepared, including coagulant and pH adjusting solutions.
2. The EXO-sensor is washed with ultrapure MQ water and placed in a cell filled with raw water. The sensor is then attached to the cell and strapped to the table's leg.
3. Pumps and mixers are turned on and adjusted to the required speeds. Then, their connected tubes are put into the filtrate feed water container and the coagulant glass container, respectively.
4. The flow is adjusted, and the tubes are inspected for bubbles. This step is done by tapping water from the tube after the coagulation step and filling up a 100 mL graduated cylinder for 1 min. After that, inspect that the collected water equals 100 mL. This procedure is repeated for the suction of the coagulant tube. It is supposed to have displaced 1 mL coagulant during 1 min.
5. The membrane is installed in place, and the valve is directed towards the membrane.
6. The EXO-sensor is connected to the computer, and the experiment starts running.

#### 3.2.2 Operation of plant

While the experiment is running, the tubes are examined for air bubbles. After that, the feed water is connected to the tubes. Four water samples are taken during the experiment at three different sample points, see Figure 3:

- One from the ingoing filtrate (IN) at the start of the experiment.
- One from the permeate (PERM1) 30 minutes after the start-up.
- One water sample (FEED) from the stream between the reactor and the UF membrane 45 minutes after start-up.
- The last sample from the permeate (PERM2) is taken 60 min after the start, at the end of the experiment.

The flow adjustment (Step 4 in the plant start-up) was tested before the permeate samples were taken to ensure a steady flow. The EXO-sensor was running for the 30 first min of the experiment.

#### 3.2.3 Maintenance of the plant

After an experiment is performed, the pilot plant needs to be maintained.

1. The EXO-sensor is washed with MQ water, secured in plastic protection, and stored in a container with MQ water.
2. The UF membrane is backwashed in three steps. First, the permeate stream of the membrane is connected to a separate pump and backwashed with MQ water. Then it is washed with

NaClO solution (6 mL concentrated NaClO for 5 mL MQ water). Lastly, it is rewashed with MQ water to remove any remaining NaClO.

3. The membrane is then stored in a graduated glass filled with MQ water and sealed with parafilm.
4. The EXO-sensor is sporadically wiped clean of data between experiments.

## 3.3 Data gathering and processing

The method of collecting data was performed in two main ways; by monitoring the permeate stream with the help of the EXO-sensor and by taking water samples of the permeate and analysing them in the laboratory. The samples were analysed in a lab and performed analysis were: pH, temperature, alkalinity, TOC, DOC, Chloride concentration, Sulphate concentration, UV-Absorbance, and aluminium dosage. The analyses were performed at the Görväln's lab except for the aluminium dose analysis, which was sent to Eurofins Labs (Stockholm). The uncertainties for each type of analysis method can be seen in Table 7 in Appendix E.

The EXO-sensor is a probe that takes in-line measurements of different parameters. The sensor gathered data every 10 s for 30 min of each experiment. The data from the first minute was used to get values of untreated water on the analysed parameters. Then, permeate water was taken by mean values for treated water 10 min into the experiment until it ended. The analysed parameters were:

- pH
- Temperature (°C)
- Turbidity (NTU)
- fDOM (QSU)

The fDOM was measured by using a fluorescent signal in the EXO-sensor. However, the sensor was sensitive to variations in NOM and temperature. Therefore, the fDOM data gathered needed to be corrected. fDOM was corrected after temperature (T) and turbidity (t) in the equations below (Nikzad, 2021):

$$fDOM_{Tcorr} = fDOM_{QSU} + (fDOM_{QSU} * 0.012 * (T_{feedwater} - 25))$$

$$fDOM_{tcorr} = \frac{fDOM_{Tcorr}}{(0.7225 * e^{(-0.004687*t)}) + (0.3041 * e^{(-0.0003624*t)})}$$

The pressure over the membrane was monitored in by in-line sensors. They were connected to a program (ACurve), which gathered pressure data points throughout the experiment. The difference between the inlet and the outlet pressure was taken to measure the TMP.

### 3.4   Experiments

Five experiments were performed to evaluate the optimum adjustments for the various parameter of the pilot plant. All the experiments performed with different parameters had feed water from the SF and KF. This was done to compare the membrane placement after the sand or carbon filtration step. For a good comparison, the collected water from SF and KF was preferably collected on the same day for more reliable results.

#### 3.4.1   Experiment 1: Coagulation dosage

The coagulant dose was investigated to find if a lower concentration of coagulation dose could achieve equally efficient separation. The added dose of aluminium was prepared with PAX XL60 (See Appendix B). The two coagulant doses of interest were 2.5 and 3.8 mg Al/L.

#### 3.4.2   Experiment 2: pH adjustment

The water quality is highly affected by the pH and the alkalinity. The pH is lowered when added coagulant, negatively affecting the UF separation. This decrease occurs because the destabilisation of colloids is affected by a reduced pH value. An optimum pH range lies between 6.8 and 7.2. The optimum interval is best where the charge is neutral, which occurs closest to a neutral pH at 7.

The addition of sodium carbonate can improve the buffer capacity and the process. Therefore, three doses of sodium carbonate were added to the feed water before the experiment. The doses were: 50, 100 and 150 mL of a 0.01 M $Na_2CO_3$ solution. The preparation of the solution is found in Appendix C.

#### 3.4.3   Experiment 3: Retention time

The process design was altered to investigate how the treatment was affected by differences in retention time. Three retention times were tested at 150 s, 60 s, and 30 s. Various sizes of reaction vessels were used to control the retention time. The flow was constant, adjusted to 100 mL, and reaction vessels of 250 mL, 100 mL, and 50 mL were used to attain the set times. Figure 15 in Appendix A shows the used reactors.

#### 3.4.4   Experiment 4: Mixing

Mixing is essential to achieve effective coagulation. Therefore, different reactor mixing speeds were investigated. Further, mixing with static mixers with different elements was also investigated. The stirring rates of 200, 300, and 400 rpm were tested for the mixer. For the static mixers, the use of 24, 32, and 48 elements were tested. In total, nine tests were performed to evaluate the best configuration of mixing speeds and the types of a static mixer for blending. Figure 15 in Appendix A shows the figures of the used reactors.

### 3.4.5  Experiment 5: Transmembrane pressure

The TMP was investigated both over time and during the operation of the experiment. The pressure helps examine fouling build-up and the extent of irreversible fouling on the membrane.

# 4   Results and discussion

In this chapter, the results are presented and discussed to make conclusions and recommendations for an up-scaled plant. The results are divided into five topics: coagulant dosage, pH & alkalinity, retention time, mixing, and pressure. Coagulant dosage, pH & alkalinity, and retention time are compared for KF and SF. They are described and discussed according to the order they were presented in the methodology. Furthermore, Tables 9-12 in Appendix F present a complete list of all experiments.

First, the different indicators (TOC, DOC, $UV_{254}$, fDOM) investigated for removal efficiency of NOM are compared and examined to determine their suitability.
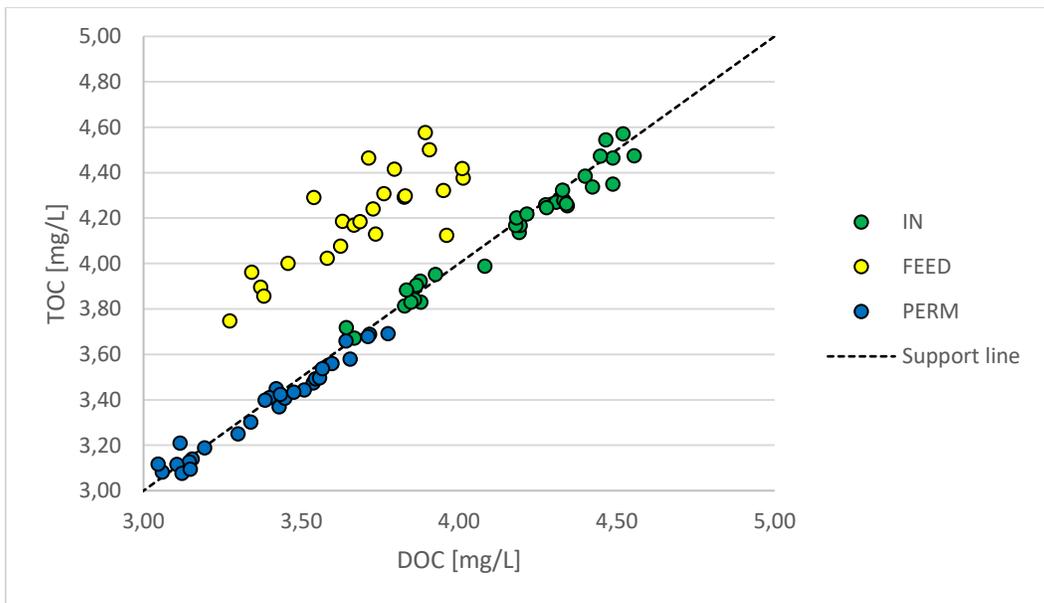


*Figure 4. TOC correlation to DOC for different sampled water in the plant. IN is untreated water, FEED is water sampled before the membrane inlet, and PERM is the water sampled at the membrane outlet. The dashed line is a support line.*

In Figure 4, TOC and DOC were compared to see how much of the organic carbon was in dissolved form. The correlation is strong with both TOC and DOC in the water decreased as the water is treated, suggesting that organic matter is reduced in the process. In most cases, the TOC and DOC are equal for the IN-water and PERM-water. This indicates that the organic matter in the IN and PERM is predominantly dissolved. However, in the FEED, DOC is lower than the TOC due to the coagulant dosage. The coagulant's destabilisation of organic content and flock accumulation produces a higher fraction of particulate than dissolved organic matter, which results in higher TOC than DOC values.

There are also IN and FEED values under the support line, which indicate a higher DOC than TOC. Nevertheless, DOC values cannot be higher than TOC. The most likely reason for these values is that organic matter is almost all DOC, and the analysis's uncertainties are more significant than

their difference. This is not strange as the turbidity of the feed water is low and has been treated in several other process steps before the bench-scale plant.
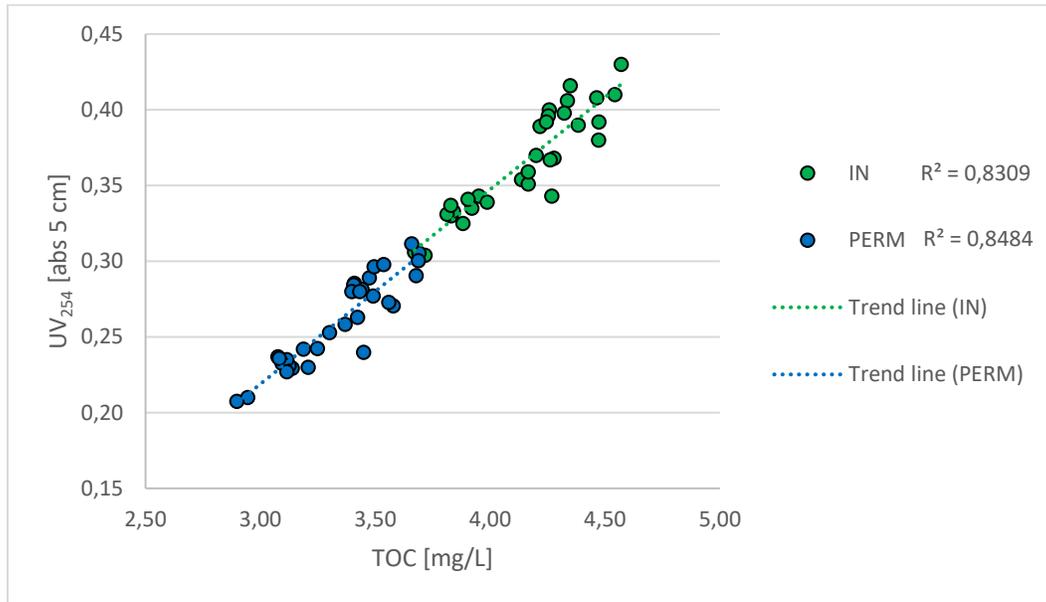


*Figure 5. Correlation between $UV_{254}$ and TOC for untreated water (IN) and the permeate stream (PERM). A trend line is given for the correlation with an $r^2 = 0.83$ and $r^2 = 0.85$.*

Comparing $UV_{254}$ to TOC showed in Figure 5. It has a good correlation with an $R^2$ of approximately 0.84 for both IN and PERM. The correlation is solid, and the connection suggests that $UV_{254}$ is a good indicator of organic matter. The consistency between IN and PERM also makes it more reliable to measure the removal efficiency.

On the contrary, the difference between TOC and DOC measures the particulate organic carbon (POC), assuming that purgeable organic carbon is neglectable. In Figure 16 in Appendix G, POC in the FEED showed a weak correlation with $UV_{254}$ with $R^2$ at 0.12. The correlation specifies how well $UV_{254}$ detect organic content in agglomerated flocs. Compared with Figure 5, $UV_{254}$ better detects DOC, depending on how the fractions of organic carbon in the flocks differ.

fDOM measured with the EXO probe has a low error of only 1 to 2 %, making it an excellent tool for measuring NOM. Unfortunately, due to technical difficulties with the data collection, fDOM data was lost for some experiments, and the removal efficiency could not be calculated. Additionally, several experiments exhibited high turbidity values, which is not likely for this type of feed water. NOM is mainly dissolved and should not have turbidity higher than 5 NTU as it affects fDOM. Therefore, all experiments with turbidity higher than 5 NTU were discarded.

*Table 2. Correlation for fDOM plotted against TOC and UUV$_{254}$ for IN and PERM at different time intervals.*

| fDOM correlation | Type of water | $R^2$ | | |
|---|---|---|---|---|
| | | 02/01-02/16 | 03/01-03/16 | 02/01-03/16 |
| TOC | IN | 0.57 | 0.61 | 0.16 |
| | PERM | 0.75 | 0.81 | 0.63 |
| UV$_{254}$ | IN | 0.71 | 0.59 | 0.37 |
| | PERM | 0.88 | 0.83 | 0.80 |

Table 2 shows that the correlation between fDOM is stronger in UV$_{254}$ than in TOC. It is also more robust in the PERM than IN for each correlation. The $R^2$ for PERM during the total period was 0.63 UV$_{254}$ TOC and 0.80 for UV$_{254}$. However, the inconsistency was high for IN, with $R^2$ 0.16 for TOC and 0.37 for UV$_{254}$. The values are too scattered to be used for reliable removal efficiency. The values could be improved if separately plotted for February and Mars. This suggests that differences in feed water varied in the months and could be the reason for the poor values.

By calculating SUVA for the feed water at different times, an indication of how hard the IN was to coagulate can be given, where SUVA of 1.7 L/mg, m, indicate a normal difficulty of feed water, 1.9 L/mg, m is easily coagulated feed water and 1.5 L/mg, m is hard coagulated feed water.
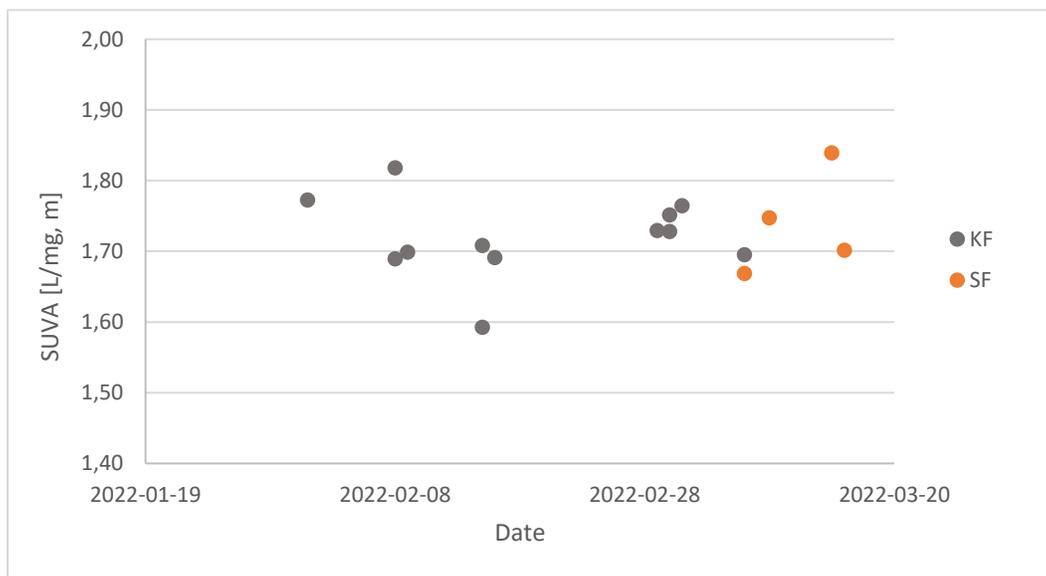


*Figure 6. SUVA for KF and SF throughout the experiment period.*

Figure 6 presents SUVA values for IN between February and Mars. The values range between ca 1.7 to 1.85 L/mg m, suggesting that the feed water used is relatively easy to coagulate. The only deviation is in an experiment with 1.59 L/mg m, which is not too hard to coagulate. The results do not explain the differences between $R^2$ in IN for separate months of experimenting and the overall values. There is no noticeable difference between KF and SF.

Further observing changes in the water quality during the experimenting period shows that the coagulant dosage of ALG in the plant was constant during the period of 45 mg/L. Moreover, changes in Figure 17 in Appendix G show that pH and $UV_{254}$ have no significant water quality changes to contribute to noteworthy differences in NOM in IN water. Consequently, considering SUVA and the raw water quality when evaluating the $R^2$ values in Table 2, the inconsistency in fDOM between IN and PERM is still too significant to measure the removal of NOM.

There are many causes to why the fDOM data showed such scattered values. Previous works using the EXO probe have proven accurate and reliable results. What differed then was that the probe was calibrated at the beginning of the project, which was unfortunately missed. Furthermore, sensors on the probe were recently changed, which only added to the importance of calibrating it. Other explanations can be rooted in the handling of the probe during start-up and operation, which could affect how the data was collected. If the preparation of the probe was not done properly or stored correctly, it could have been affected by fouling, which could have affected the reliability of the EXO probe.

Nevertheless, the previous usage of the EXO sensor has proven to give accurate and reliable results, with $R^2$ for $UVA_{254}$ and fDOM of water (Nikzad, 2021). Figure 18 in Appendix G shows the correlation between fDOM and $UV_{254}$ of SF from the previous year's project compared to this one. The trend line from the previous project shows a better $R^2$ at 0.97 compared to this year at 0.79. The SF comparison shows similar patterns in both years with lower fDOM values of SF experiments 2022. Unfortunately, only three SF experiments were performed in 2021, making it less reliable.

## 4.1 Coagulant dosage

Different coagulant dosages were tested to find the best level used. In addition, TOC and $UV_{254}$ were used to test the removal efficiency at different dosages.
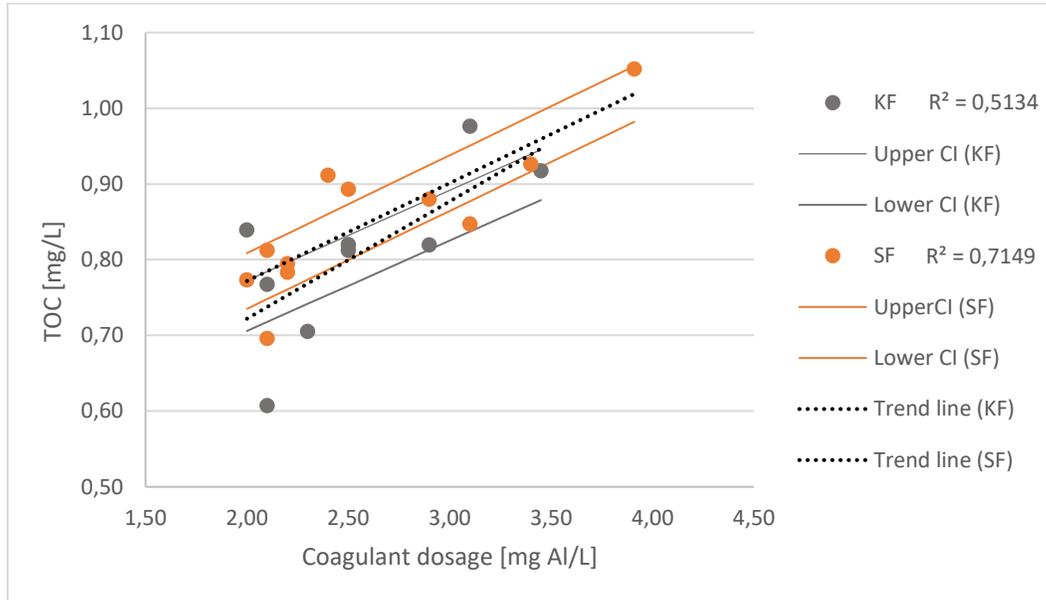


*Figure 7. TOC removal at different coagulation dosages, using different feed waters; SF (orange) and grey KF (grey). The trend lines (black) and confidence intervals (orange for SF and grey for KF trend lines) are presented.*

Figure 7 shows a positive link between coagulant dosage and TOC removal. A higher coagulant dosage improves the TOC removal, with a scattered, ranging between 2.0 and 3.9 mg Al/L. There seems to be no optimum dosage value. The highest removal is achieved at a coagulant dosage of 3.9 mg Al/L, with a 1.05 mg/L removal efficiency. There is a difference between KF and SF when comparing the trend lines. It indicates that SF has an overall higher TOC removal than the KF. Still, the confidence intervals show that their values are too close, where the Upper CI (KF) cross the Lower CI (SF), concluding that the TOC removal for SF is not superior to KF at the given interval. Figure 19 in appendix G displays a similar trend as in Figure 7, where the data is scattered between UV254 and coagulant dosage patterns. The removal of $UV_{254}$ extends from 0.08 to 0.13, and there is no significant difference between KF and SF.

*Table 3. Average TOC and $UV_{254}$ removal efficiency at different coagulation dosages and pH values for KF and SF.*

| Type of water | Coagulant dosage [mg Al/L] | pH | TOC removal [%] | $UV_{254}$ removal [%] |
|---------------|----------------------------|-----|-----------------|------------------------|
| KF | 2.3 | 7.3 | 19.2 | 28.5 |
| | 3.3 | 7.3 | 22.0 | 32.0 |
| SF | 2.3 | 7.1 | 18.5 | 27.0 |
| | 3.5 | 7.0 | 21.5 | 30.1 |

Table 3 shows that the higher coagulant dosages gave a higher removal efficiency. The average removal efficiency is higher for $UV_{254}$ compared to TOC. The highest efficiency for an individual experiment is 23.2 % TOC removal and 32.4 % $UV_{254}$ reduction for a coagulant dosage of 3.9 mg Al/L. The best reduction also had a pH of 7, a favourable pH level for optimum removal. Nevertheless, the comparison of removal efficiency only differs by approximately 3 % for TOC and $UV_{254}$ removal when comparing the average of a higher and lower dosage. Thus, a smaller dosage adjusted at 2.5 mg Al/l may be reasonable. Reducing coagulant chemicals by ca 34 % and only reducing the efficiency by 12 % is the superior option. Furthermore, it is important to consider that these values are averages for all dosages from Figure 7, and the high dispersion of the data makes them less reliable.

By studying the TOC levels of IN water in Appendix F, several of their values are very low for KF. This might explain why many values are scattered since relatively cleaner feed water will be harder to treat. A cause why the feed water is so clean may depend on its coming from a carbon filter pilot plant. Compared with the up-scaled carbon filter, it has a newer carbon packing and a more efficient treatment, making it much cleaner effluent. As a result, flock formation is less effective, which leads to an inferior build-up of a biofilm on the UF membrane. To test how much the correlation between TOC removal and coagulant dosage for KF is affected by the number of TOC values in IN, $R^2$ values were compared. The $R^2$ value increased from 0.26 to 0.53 when TOC levels below 4.1 mg/L were not included. However, the correlation of SF was already strong, with $R^2$ equal to 0.8. So with much cleaner IN the water, the treatment is more challenging. Thus, more trials need to be performed to appreciate an optimal KF coagulant dosage better.

In the coagulation dosage experiment, the dosages were spread mixed between 2 and 4 mg Al/L in Figures 6 and 7, even though the experiment had specific dosages set to 2.5 and 3.8 mg Al/L. It implies that flow control was difficult to achieve and that the flow fluctuated throughout the procedure of the experiments. The temperature could be one parameter responsible for affecting the flow and these variations. As temperatures shifted during operation, the viscosity of the feed water varied and, indirectly, the flow. Therefore, with recirculating feedback, implementing automatic coagulation dosing for a scaled-up plant is recommended to attain a constant coagulation dosage during the plant operation. Other parameters can also be responsible for the scattered values. The retention time was constant throughout the procedure, but the mixing configuration and pH adjustment varied. These differences could have a significant effect on the results.

Lastly, there was no difference between KF and SF effect on removal efficiency for different coagulation dosages. Compared with the sand filter, the placement of a UF unit after the carbon filter will not have an adverse effect based on coagulant dosages.

## 4.2 pH and alkalinity

pH and alkalinity were adjusted for a better treatment process. pH values were taken throughout the operation of the plant. Both with the EXO-sensor and from the samples sent to the lab. From comparing the pH against the alkalinity found in Figure 20 in appendix G, the pH measurements taken with the EXO sensor were very scattered and therefore discarded from being used. The pH values from the lab had a clear correlation with the alkalinity and are reliable.
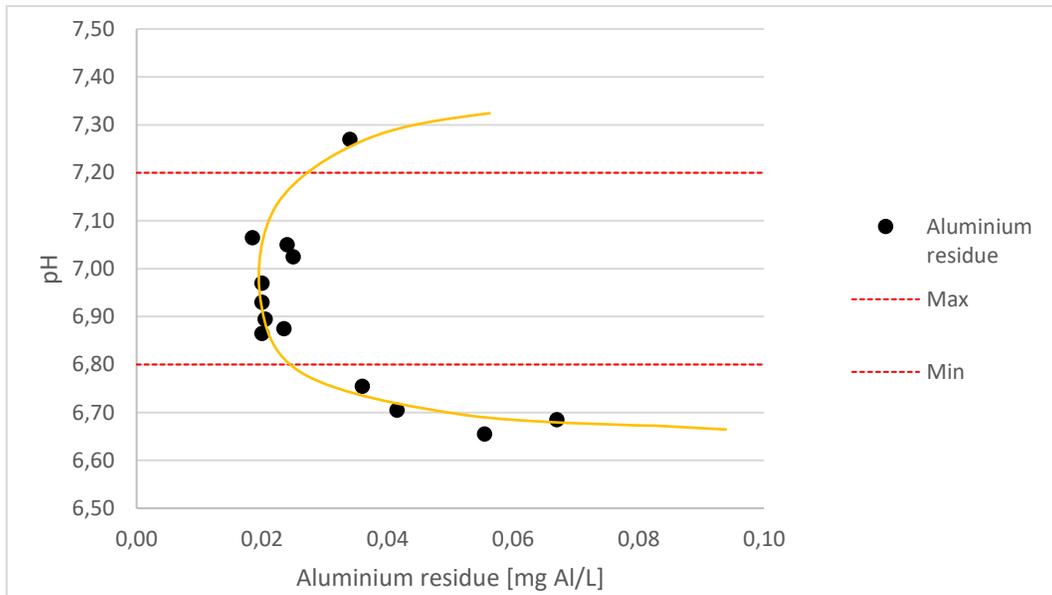


*Figure 8. pH correlation to aluminium residue in the permeate. Dashed lines represent the theoretical optimal pH interval. The orange line follows the values pattern. The data is taken from experiments with a 2.5 mg Al/L coagulant dosage.*

Figure 8 shows the amount of aluminium in the permeate stream at different pH values. The graph shows that aluminium residue in the permeate increases when the pH strays further away from pH 7. This depends on that optimal coagulation occurs within pH intervals 6.8 and 7.2, where charge neutralisation is optimal. Therefore, better coagulation and overall treatment can be achieved by adjusting the feed water's pH. Correct pH value is critical for optimal operation of the plant. The UF step will not be fully utilised if the coagulation & flocculation are appropriately conducted. The flock formation is not as effective outside of pH values of 6.8 and 7.2, and the further away the pH is from 7, the more Aluminium residue passes through the membrane. It indicates that these flocks are too small to be hindered by the membrane and small enough to pass through the pores.
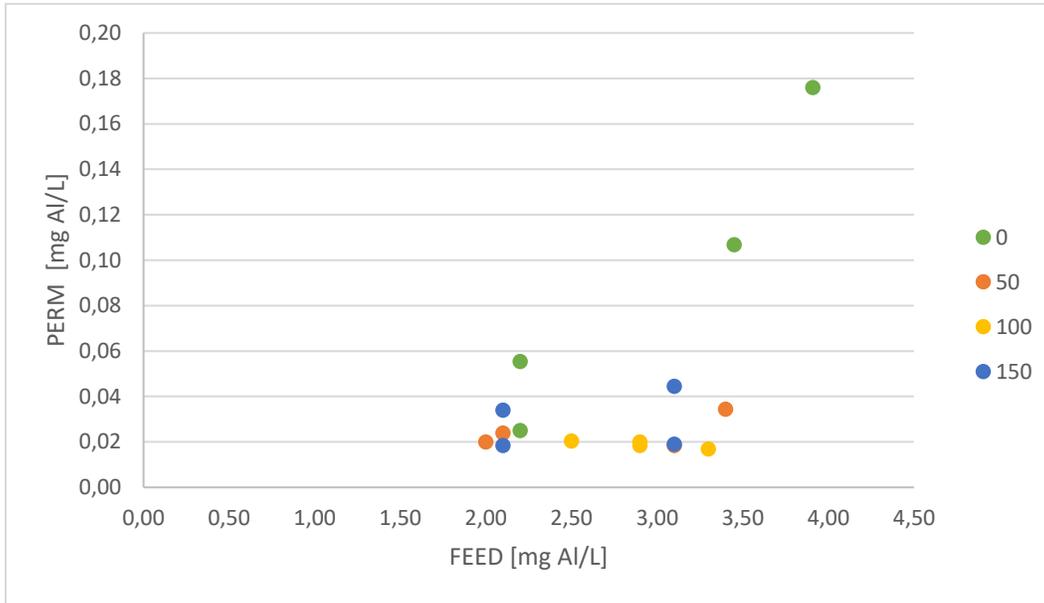
*Figure 9. Comparison between the permeate's aluminium residue (PERM) and the coagulant dosage (FEED). Colours represent the carbonate dosages. The data is taken with a 150 s retention time and the same type of mixing configuration.*

From the results in Figure 9, the aluminium concentration in the permeate shows that the PERM is not adversely affected by the coagulant dosage. In general, the coagulation dosages were 2-4 mg Al/L, while the aluminium residue in the permeate stretched between 0.02 and 0.06 mg Al/L, independent of the coagulant dosage. The exception to the rule is seen in 2 values. The data point with the highest permeate value is 0.107 mg Al/L and 0.176 mg Al/L. Those values were performed without any pH adjustment and, therefore, as is shown in Figure 8, would have a decreased pH (6.6 and 6.5), thus, less efficient coagulation. Besides pH, the causes of the two outliers could depend on the season, as those experiments were performed in December. The coagulation step is less productive during winter due to temperatures, and the feed water characteristic differs slightly.

According to the carbonate dosages in Figure 9, The results without any pH adjustment show the highest amount of aluminium residue in the permeate. Moreover, the aluminium residues in the permeate are not likely caused by differences in the coagulant dosage but are more linked to the absence of a pH adjustment.

28
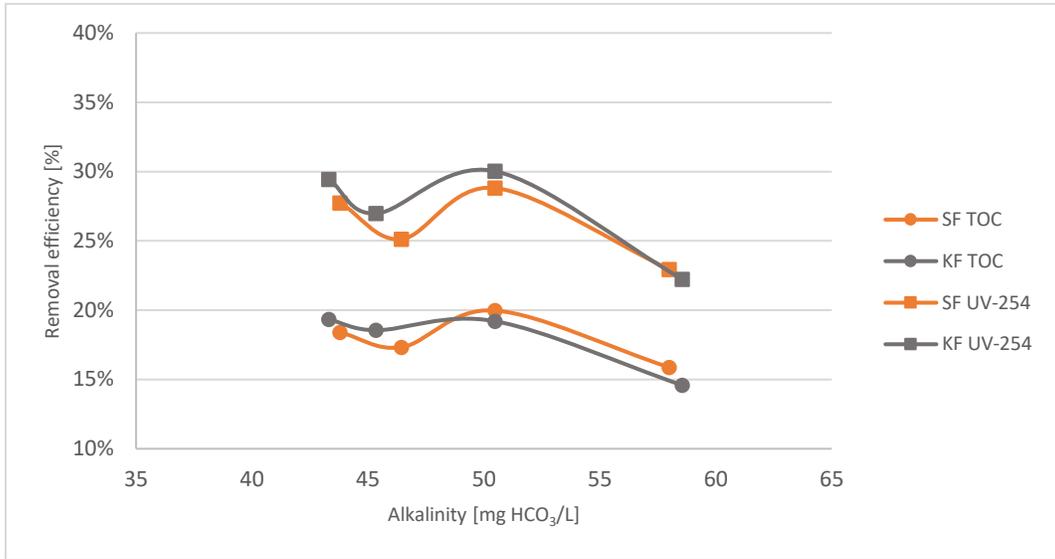
*Figure 10. The efficiency of removal as TOC and UV$_{254}$ at different alkalinities for a 2.5 mg Al/L coagulant dose. Orange is SF, and grey is KF.*
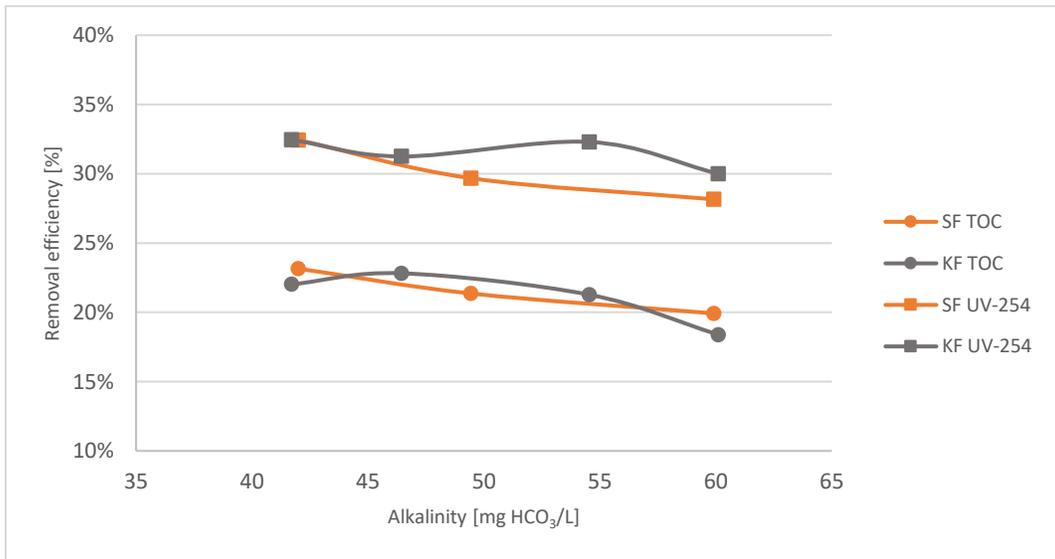


*Figure 11. The efficiency of removal as TOC and UV$_{254}$ at different alkalinities for a 3.8 mg Al/L coagulant dose. Orange is SF, and grey is KF.*

Generally, in Figure 10, removal with 2.5 mg Al/L is lower compared with the results in Figure 11. UV$_{254}$ has an approximately 30 % removal for alkalinity 50.0 and 20 % TOC at the same alkalinity. There is no apparent difference between SF and KF. The optimal alkalinity appears to be between 45 and 50 mg HCO$_3$/L, with minimal differences. Removal efficiencies with alkalinities higher than 50 are lower. In Figure 11, similar trend as in Figure 10. The highest UV$_{254}$ removal at 32 % for 55 mg HCO$_3$/L, and the highest UV$_{254}$ removal at 32 % for 46 mg HCO$_3$/L. There is no apparent difference between SF and KF. The optimal alkalinity appears to be approximately 50 mg HCO$_3$/L. To get ca 50 mg HCO$_3$/L, approximately 50 to 100 carbonate doses are needed, according to Table 4.

Four different $Na_2CO_3$ doses were added to evaluate the removal efficiency for the experiments involving pH adjustment. The $Na_2CO_3$ doses needed to be in the appropriate amount to increase alkalinity and pH without making the water too basic. The doses tested were 0, 50, 100 and 150 mL.

*Table 4. Changes in pH and alkalinity at different carbonate dosages for untreated water. 0.01 M $Na_2CO_3$ carbonate solution.*

| Carbonate dosage [ml] | pH | Alkalinity [mg $HCO_3$/L] |
|---|---|---|
| 0 | $6.95 \pm 0.24$ | $42.71 \pm 0.01$ |
| 50 | $7.30 \pm 0.25$ | $46.92 \pm 0.01$ |
| 100 | $7.52 \pm 0.23$ | $51.83 \pm 0.01$ |
| 150 | $7.72 \pm 0.50$ | $59.14 \pm 0.01$ |

In Table 4, pH and alkalinity show small stable increases for each 50 mL of carbonate added to the water. This means that the added $Na_2CO_3$ was dosed in an appropriate amount. The dosing of carbonate with an increase of 50 mL showed that the alkalinity adjustment is much more precise than the pH. It shows that alkalinity is an easily controlled parameter compared to pH, which is much harder to control. It can be confirmed by comparing the parameters' standard deviation.

## 4.3 Retention time

The retention time was tested at 150, 60, and 30 s to determine its effect on the UF membrane's efficiency. Moreover, each retention time was tested for KF and SF and performed with the same mixing configuration, no pH adjustment, and a 2.5 mg Al/L coagulant dosage.

*Table 5. TOC removal and $UV_{254}$ reduction at different retention times for KF and SF.*

| Type of water | Coagulant dosage [mg Al/L] | Retention time [s] | TOC removal [%] | $UV_{254}$ reduction [%] |
|---|---|---|---|---|
| KF | 2.0 | 150 | 19.7 | 28.3 |
| | 2.3 | 60 | 16.8 | 19.2 |
| | - | 30 | 16.4 | 30.9 |
| | 0.0 | 0 | 3.3 | 5.9 |
| SF | 2.4 | 150 | 19.9 | 27.6 |
| | 2.2 | 60 | 17.8 | 25.9 |
| | 2.1 | 30 | 18.7 | 28.4 |
| | 0.0 | 0 | 1.4 | 5.9 |

Table 5 shows that 20 % TOC removal was possible at 150 s retention time for KF. The removal efficiency was lower for 60 s and 30 s, but not significantly. The trend of removal efficiency between 150, 60 and 30 is not substantial enough to make a clear optimum of the interval. Comparing TOC removal between KF and SF shows no difference in placing the UF unit after the carbon filter is as effective as after the sand filter.

The $UV_{254}$ was reduced between 25 and 30 %, with no overall difference between KF and SF. The best $UV_{254}$ reduction was 31 % for KF at 30 s. The optimal removal efficiency is difficult to determine at a specific interval. Both 30 and 150 s give a better reduction than 60 s. Therefore, a lowered retention time could feasibly be implemented without affecting the treatment immensely based on this results interval. This means that further scaling up of the plant can be implemented with a lower retention time. There are also minor variances in the coagulant dosage that can be the underlying cause of the differences.

The removals were compared with previous data at 0 s retention time (Köhler & Sekizovic, 2021). The TOC removal without coagulation dosage resulted in a 3 % TOC removal for KF and 1 % for SF and a $UV_{254}$ reduction of 6 % for KF and SF. This means that the removal efficiency is critically affected by the retention time. The coagulation step is required to create flocks to utilise the UF membranes at their best capacity.

## 4.4 Mixing

Coagulation & flocculation's effectiveness depends on mixing. Therefore, different mixers and different numbers of elements used (24, 36, and 48) were examined at various mixing speeds in the flocculation reactor (350, 200, 300, 400).

*Table 6. TOC removal and $UV_{254}$ reduction at different mixing speeds and for different types of static mixers.*

| Static mixer | Mixing speed [rpm] | TOC removal [%] | $UV_{254}$ reduction [%] |
|---|---|---|---|
| 24 element SMV | 350 | 19.3 | 29.4 |
| 24 element KMS | 200 | 18.3 | 29.0 |
|  | 300 | 19.4 | 28.0 |
|  | 400 | 19.7 | 29.7 |
| 36 element KMS | 200 | 21.1 | 30.6 |
|  | 300 | 21.1 | 30.8 |
|  | 400 | 19.1 | 28.6 |
| 48 element KMS | 200 | 19.7 | 30.2 |
|  | 300 | 19.8 | 31.4 |
|  | 400 | 22.0 | 31.7 |

Table 6 shows the mixing configuration; the mixer elements were tested at four different mixing speeds in the flocculation reactor. The TOC removal was approximately 20 %, and $UV_{254}$ was reduced by 30 %. The different mixing speeds do not affect the removal efficiency as the differences only differ by 1 or 2 %. The higher number of elements in the mixer gave a higher removal efficiency, but it was not relevant with such a slight increase. Likewise, the difference between KMS and SMV does not affect the removal efficiency differently.

This result makes deciding on the type of mixer less critical when considering the mixing configuration for scaling up the plant. It gives leeway and assurance that a mixer with 24 elements can have the same efficiency as a mixer with 48 elements. However, it must be remembered that the energy input behaves differently on a larger scale, and the indication given for this plant may differ considerably in a full-sized plant.

The many repetitions of the mixing configuration also gave important information on controlled variables. On average, 20 % TOC removal and 30 % $UV_{254}$ reduction are possible for a plant with a coagulation dosage of 2.5 mg Al/L, 150 s retention time, and no carbonate dosage added.

## 4.1 Pvressure



*Figure 12. TMP average for each experiment over three months. Grey data points represent KF experiments, and yellow data points represent SF.*

Figure 12 shows the average TMP has increased after each performed experiment. No clear difference between SF and KF. Over three months, the average TMP has increased from 0.02 to 0.06 bar. This increase is modest but still reflects the build-up of fouling in the membranes. The fouling affects the membrane's efficiency, as the flux changes when the TMP is altered. Both differences in pressure build-up during operation and over time may indicate the physical condition of the membrane. The increase of TMP over time indicates that the membrane is affected by irreversible fouling; alternatively, the cleaning procedure needs to be seen over physical and chemical backwashing.

The consistency of the increasing TMP confirms that the experiment's procedure has been performed consistently and increases the general reliability of all experiments.

At the end of the experiment's performance, it was always backwashed with MQ water and chlorine solution, conducted in the same manner each time. Because several different experiments were performed, the maintenance might have needed to be individually adjusted. The parameter will be more constant for a full-scale plant, and treatment is better prepared for the flows. Nevertheless, a more comprehensive backwashing routine must be investigated and tested.

*Figure 13. TMP correlation with time in operation. The yellow and blue data points represent the TMP under the first experiment with SF and KF. The orange and green data points represent the TMP under the last experiment with SF and KF.*

Figure 13 shows TMP changes during the performance of an experiment. The TMP was measured for 45 min. The TMP for the first experiment appears to be constant, with minor changes, during operating time. The last experiment had more frequent changes in TMP and seemed to have instead in the end of the operation. No clear difference between SF and KF.

Figures 12 and 13 show that the membrane used for KF and the membrane used for SF behave similarly. This means that from a TMP point of view, the type of water used (KF or SF) is irrelevant, and the membrane should handle a KF stream just as well as an SF stream.

# 5 Conclusions

Adjustments to the investigated parameters influenced the removal efficiency of the bench-scale plant. However, in many experiments, the interval was too small to clearly distinguish the plant's complete optimisation. The verification of the efficiency indicators showed a clear link between TOC and DOC, where the organic content in the water was predominantly dissolved. The correlation between TOC and $UV_{254}$ had a clear connection and strengthened the use of TOC and $UV_{254}$ as indicators of removal efficiency of NOM. The use of fDOM to indicate the amount of NOM was not used as its reliability was very low and did not correlate with $UV_{254}$.

Conclusions on parameters:

- Higher coagulant dosages positively affected the removal efficiency, but with no precise optimum dosage. Dosage set at 3.8 mg Al/L showed an average increase of 2 % TOC removal and 3 % $UV_{254}$ reduction. Because of the slight increase for the set interval, a dosage of 2.5 mg Al/Lis a viable dosage option.
- pH values between 6.8 and 7.2 proved to minimise aluminium residues in the permeate to 0.02 mg Al/L. Still, outside the interval, the residue amount increases exponentially.
- Between 40 and 50 mg $HCO_3$/L, Alkalinities gave the highest removal efficiencies, with higher than 55 $HCO_3$/L decreased efficiency. The carbonate dosage of 50 mL resulted in alkalinity of around 45 mg $HCO_3$/L, an appropriate dosage.
- The retention time did not show a noticeable difference between 150, 60, and 30 s, and a lower retention time than 150 s can be used for the same removal efficiency. However, the removal efficiency without coagulant dosage did dramatically lower the efficiency, with only 1-3 % TOC removal and 6 % $UV_{254}$ reduction.
- There is no noticeable difference between different mixing configurations.

*Table 7. Experiment with the best removal efficiency.*

| Placement | Coagulant dosage [mg Al/L] | Aluminium residue [mg Al/L] | Carbonate dose [mL] | pH | Alkalinity [mg $HCO_3$/L] | TOC [%] | $UV_{254}$ [%] |
|---|---|---|---|---|---|---|---|
| KF | 2.3 | 0.02 | 0 | 7.3 | 41.9 | **22.0** | **31.7** |

The best-performed experiment for a lower coagulant dosage is seen in Table 7. The dosage is 2.3 mg Al/L with a TOC removal of 22 % and $UV_{254}$ reduction of 32 %.

The comparison between SF and KF, based on tests performed at different coagulation dosages, pH adjustments, and retention times, showed that the placement after the carbon filter compared with after the sand filter had no significance to the efficiency.

The membrane is susceptible to fouling, and the long-term TMP shifted from 0.02 to 0.06 bar. The TMP changes are interchangeable for the KF membrane and SF membrane. Additionally, the

pressure during membrane operation fluctuated much more frequently in the last experiment than in the first. The backwashing routine likely needs to be investigated.

## 5.1 Recommendations

The scaling up of the bench-scale plant will have much higher fluxes, and dosing will be much more critical. Therefore it is recommended to implement automatic coagulation dosing with recirculating feedback. This will facilitate and provide more precise dosing of the coagulant. The dosage should be set at 2.5 mg Al/L, and more experiments at a lower dosage need to be performed to verify its removal efficiency. Moreover, pH adjustment should be performed with a carbonate dosage of 5 mL/L untreated water to give better buffer capacity. In addition, less focus can be put on the mixer used in the scaled up pilot and with a lower retention time. Lastly, the cleaning routine must be investigated to avoid irreversible fouling.

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# Appendices

## Appendix A: Pictures of the bench-scale plant
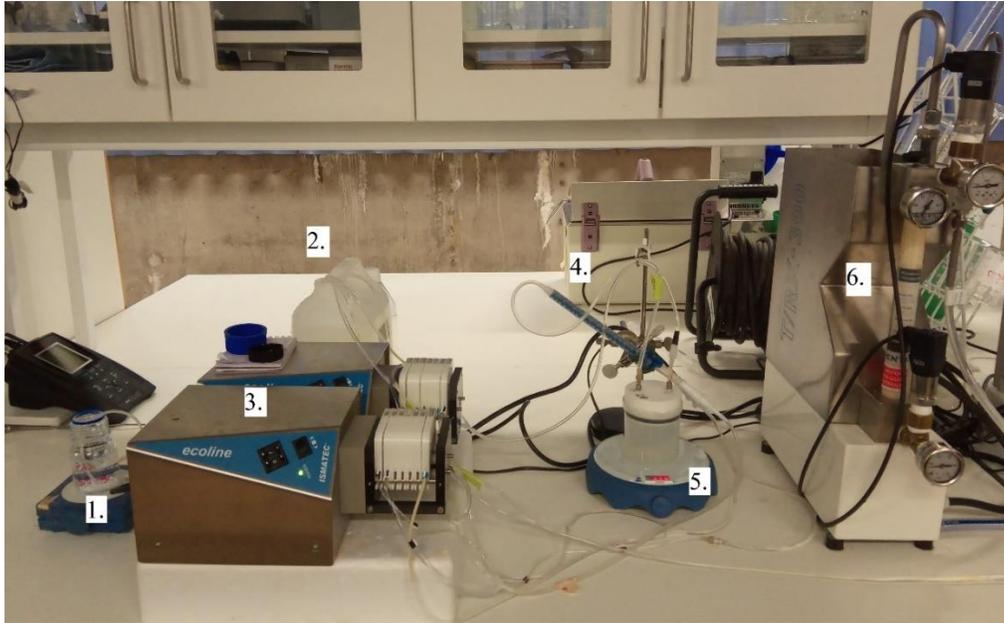


*Figure 14. Set-up of the bench-scale plant. Coagulant dosage (1), feed water dosage (2), pumping (3), static mixer (4), flocculation reactor (5), UF membrane (6).*



*Figure 15. Static mixers (left) and flocculation reactors (right).*

## Appendix B: Preparation of coagulant solution

The raw Polyaluminium chloride had a 98 mg Al/mL concentration and needed to be diluted to the required coagulant doses. Therefore, a new coagulant solution was prepared for 1 L diluted coagulant. The dilution equation was used to calculate the needed volume of raw PAC:

$$C_1 * V_1 = C_2 * V_2$$

$$V_1 = \frac{C_2 * V_2}{C_1}$$

$C_1$ – concentration of raw PAC [mg Al/L]

$V_1$ – Raw PAC volume [mL]

$C_2$ – concentration of diluted coagulant [mg Al/L]

$V_2$ – Diluted coagulant volume [mL]

$$V_1 = \frac{C_2 * V_2}{C_1} = \frac{2.5 \; mg \; Al/mL * 1000 \; mL}{98 \; mg \; Al/mL}$$

$$V_1 = 25.5 \text{ mL}$$

$$V_1 = \frac{C_2 * V_2}{C_1} = \frac{3.8 \; mg \; Al/mL * 1000 \; mL}{98 \; mg \; Al/mL}$$

$$V_1 = 38.9 \text{ mL}$$

First, 100 mL MQ water was added to a measuring flask. Then the volume of raw PAC needed for the wanted dilution was added to the flask, and the flask was stirred. Then the rest of the MQ water was added to the measuring line. Lastly, the flask was shaken 20 times and poured into a glass bottle container.

## Appendix C: Preparing Na$_2$CO$_3$ solution

The sodium carbonate solution was prepared using Na$_2$CO$_3$ salt in MQ water. First, the amount of salt needed to prepare a 0.5 M solution was calculated. Then, the equation of molarity was used to calculate the required mass:

$$Molarity = \frac{Mass\ of\ solute}{Molar\ Mass\ of\ solute} * \frac{1000}{V(mL)}$$

$$Mass\ of\ solute = \frac{Molar\ Mass\ of\ solute}{1} * \frac{Molarity}{1} * \frac{V(mL)}{1000}$$

Mass of solute = X g Na$_2$CO$_3$

Molar Mass of solute = 106 g/mol

Volume = 100 mL

Molarity = 0.5 M

$$Mass\ of\ solute = 106 * 0.5 * \frac{100}{1000}$$

$$Mass\ of\ solute = 5.3\ g\ Na_2CO_3$$

First, the mass of Na$_2$CO$_3$ was measured and poured into a glass bottle. Next, the salt was dissolved with 100 mL MQ water. The bottle was then shaken vigorously.

Secondly, the solution was diluted from 0.5 M to 0.01 M. This was done by pouring 10 mL 0.5 M Na$_2$CO$_3$ solution into a 500 mL measuring flask, and then the flask was filled up to the graduated line with MQ water and inverted 20 times.

**PENTAIR**

**LENNTECH**
WATER TREATMENT SOLUTIONS

## X-FLOW RX300 0.83UFC
## ULTRAFILTRATION MEMBRANE

MEMBRANE ELEMENT DATASHEET

1" RX300 0.83UFC 0.83mm
ARTICLE CODE : 1051BL895A

### GENERAL INFORMATION

RX300 0.83UFC is an ultrafiltration pilot
module, used for production of process and
potable water. Typical applications are the
filtration of surface water, potable water
and WWTP effluent. Mode of operation is
feed-and-bleed with a minor crossflow or
dead-end mode with regular backwash
(permeate only) and chemically enhanced
backwash.

### MEMBRANE CHARACTERISTICS

**Materials of Construction**

| | |
|---|---|
| Housing | PSF |
| Potting | EP resin |
| Membrane | PES/PVP |

### ELEMENT SPECIFICATIONS

| Hydraulic membrane diameter [mm/mil] | Membrane area [m²/ft²] | Element length $L_0$ [mm/Inch] | Element outer diameter [mm/Inch] |
|---|---|---|---|
| 0.83 [32.7] | 0.08 [0.86] | 300 [11.8] | 23.9 [0.94] |
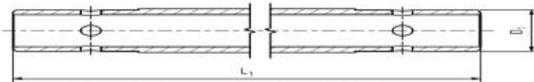
### OPERATING SPECIFICATIONS

| Max. system pressure | Max. trans-membrane pressure | Max. backflush pressure | Max. temp. |
|---|---|---|---|
| [kPa/psi] | [kPa/psi] | [kPa/psi] | [°C/°F] |
| at 20 °C 800 [116] | at 0-30 °C 300 [43] | at 0-30 °C 300 [43] | 60 [140] |
| at 40 °C 600 [86] | at 30-60 °C 200 [29] | at 30-60 °C 150 [21.5] | |
| at 60 °C 400 [58] | | | |

- Final maximum operating limits are determined by the lowest values of the membrane and element pressure and temperature specifications

### PROCESS CHARACTERISTICS (WATER 20 °C)

| Membrane diameter | Flow rate (*) | Pressure-drop across module at 1 m/s | Pressure-drop across module at 2 m/s |
|---|---|---|---|
| [mm/mil] | [m³/h/gpm] | [kPa/psi] | [kPa/psi] |
| 0.83 [32.7] | 0.27 x v [1.19 x v] | 11 [1.6] | 24 [3.5] |

(*) superficial velocity (v) in m/s [ft/s]

- Backwash water should be free of particulates and should be of permeate quality or better
- Backwash pumps should preferably be made of non-corroding materials, e.g., plastic or stainless steel. If compressed air is used to pressurize the backwash water, do not allow a two-phase air/water mixture to enter the element
- To avoid mechanical damage, do not subject the membrane module or element to sudden temperature changes, particularly decreasings. Do not exceed 60 °C process temperature. Bring the module or element back to ambient operating temperature slowly (typical value 1 °C/min). Failure to adhere to this guideline can result in irreparable damage

### ADVANCED FILTRATION

RX300 0.83UFC

# X-FLOW RX300 0.83UFC
## ULTRAFILTRATION MEMBRANE

MEMBRANE ELEMENT DATASHEET

## STORAGE

New membrane modules can be stored as supplied in the original packaging. The membrane elements contain an aqueous preservation solution of glycerine (20wt%) and sodium metabisulfite (1wt%).

Membrane modules should be stored in a dry, normally ventilated place, away from sources of heat, ignition and direct sunlight. Store between 0 and 40 °C.

The membrane modules should not be subjected to any freezing temperatures.

Shelf life is a maximum of 6 months for unused modules in unopened packaging under correct storage conditions after transfer of ownership for X-Flow BV to the Client. After the maximum period of 6 months all warrantees are null and void unless otherwise agreed in writing between the parties.

After use, the UF membrane modules need to be stored wet at all times. To avoid biological growth during shutdowns or storage, wet membranes could be treated with a compatible biocide. The membrane is compatible with many common disinfecting agents or biocidal preservatives.

Typically for short-term shutdowns (1 – 7 days), a daily backwash with UF permeate quality water for 30 seconds at 240 lmh, should be adequate for bacteria control. Before start of the shutdown period, the modules must be cleaned by a standard Chemical Enhanced Backwash (CEB).

In case of long-term storage (> 7 days), membranes should be disinfected. The membranes should be cleaned using a CEB before the disinfection step is carried out. For disinfection, a 0,5% sodium metabisulfite solution can be used. In both short and long term storage situations, the modules should remain filled with storage solution.

## PENTAIR

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## Appendix E: Uncertainties

*Table 8. List of used analytical methods and their errors.*

| PARAMETER | METHOD | RANGE | ERROR Factor=2 |
|---|---|---|---|
| * SAMPLING, Chem. (Anvisning provtagning) | SS028185, utg. 1 ”Vägledning till SLVFS 2001:30” | | |
| ALKALINITY, HCO$_3$ (SOP) | SS-EN ISO 9963-2 Titration | 4-<10 mg/l HCO$_3$ 10-240 mg/l HCO$_3$ | ±40% ±10% |
| ALUMINIUM, Al (SOP) | SS-EN ISO 15586:2004 GFAAS | 0,010-<0,040 mg/l 0,040-0,10 mg/l | ±30% ±20% |
| CHLORIDE, Cl (SOP) | SS-EN ISO 10304-1:2009 IC, ASTN 33/86 | 2,0-20 mg/l | ±10% |
| CONDUCTIVITY (SOP) | SS-EN27888-1 Electrode | 5-1290 mS/m | ±5% |
| *DISSOLVED ORGANIC CONTENT, DOC (SOP) | SS-EN 1484 Combustion | 1-<2 mg/l C 2-10 mg/l C | ±20% ±15% |
| TOTAL ORGANIC CONTENT, TOC (SOP) | SS-EN 1484 Combustion | 1-<2 mg/l C 2-10 mg/l C | ±20% ±15% |
| pH-VALUE (SOP) | SS-EN ISO 10523:2012 Electrode | 3-11 | ±0,2enh. |
| SULPHATE, SO4 (SOP) | SS-EN ISO 10304-1:2009 IC, ASTN 33/86 | 5-50 mg/l | ±10% |
| HARDNESS, Ca | Calculated SS-EN ISO 14911 IC | 5-<20 mg/l 20-100 mg/l | ±15% ±10% |
| TURBIDITY (SOP) | SS-EN ISO 7027-1:2016 Photometry | 0,10-<0,50 FNU 0,50-200 FNU | ±40% ±15% |

# Appendix F: Table of experiments

*Table 9. Experiments were performed at a 2.5 mg Al./L coagulant dosage.*

| Sample | Placement | Na2CO3 dose [mL] | Turbidity [FNU] | fDOM corr. [QSU] | TMP [bar] | pH | Alkalinity [mg HCO3/L] | TOC [mg/L] | DOC [mg/L] | UV-254 [abs 5 cm] | Al. rest [mg Al/L] | fDOM corr. [%] | TOC [%] | DOC [%] | UV-254 [%] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| IN | SF | 0 | 27,40 | 21,58 | | 6,78 | 43,80 | 4,26 | 4,28 | 0,40 | 0,04 | | | | |
| FEED | SF | 0 | | | | 6,65 | 36,63 | 4,29 | 3,83 | 0,47 | 2,20 | | | | |
| PERM | SF | 0 | 27,84 | 16,19 | 0,04 | 6,66 | 36,55 | 3,47 | 3,54 | 0,29 | 0,06 | 25,01 | 18,40 | 17,24 | 27,75 |
| IN | KF | 0 | 0,65 | 19,32 | | 7,30 | 43,32 | 3,95 | 3,93 | 0,34 | 0,02 | | | | |
| FEED | KF | 0 | | | | 6,99 | 36,13 | 4,00 | 3,46 | 0,41 | 2,20 | | | | |
| PERM | KF | 0 | 0,64 | 14,52 | 0,03 | 7,03 | 36,57 | 3,19 | 3,19 | 0,24 | 0,03 | 24,87 | 19,33 | 18,63 | 29,45 |
| IN | SF | 50 | 0,64 | 19,68 | | 7,22 | 46,44 | 4,46 | 4,49 | 0,41 | 0,03 | | | | |
| FEED | SF | 50 | | | | 6,92 | 39,31 | 4,38 | 4,01 | 0,46 | 2,00 | | | | |
| PERM | SF | 50 | 0,61 | 19,48 | 0,04 | 6,93 | 38,87 | 3,69 | 3,78 | 0,31 | 0,02 | 0,99 | 17,32 | 15,87 | 25,12 |
| IN | KF | 50 | 0,74 | 15,08 | | 7,53 | 45,35 | 4,14 | 4,19 | 0,35 | 0,02 | | | | |
| FEED | KF | 50 | | | | 7,07 | 38,62 | 4,08 | 3,62 | 0,41 | 2,10 | | | | |
| PERM | KF | 50 | 0,72 | 13,43 | 0,03 | 7,05 | 37,73 | 3,37 | 3,43 | 0,26 | 0,02 | 10,95 | 18,55 | 18,15 | 26,98 |
| IN | SF | 100 | 1,39 | 20,47 | | 7,25 | 50,48 | 4,47 | 4,45 | 0,38 | 0,04 | | | | |
| FEED | SF | 100 | | | | 6,91 | 39,95 | 4,50 | 3,91 | 0,46 | 2,50 | | | | |
| PERM | SF | 100 | 2,82 | 18,27 | 0,04 | 6,90 | 38,87 | 3,58 | 3,65 | 0,27 | 0,02 | 10,73 | 19,97 | 17,84 | 28,82 |
| IN | KF | 100 | 0,84 | 12,30 | | 7,65 | 50,48 | 4,27 | 4,31 | 0,34 | 0,02 | | | | |
| FEED | KF | 100 | | | | 7,65 | 50,48 | 4,27 | 4,31 | 0,34 | 2,90 | | | | |
| PERM | KF | 100 | 0,68 | 11,34 | 0,05 | 6,97 | 38,88 | 3,45 | 3,42 | 0,24 | 0,02 | 7,84 | 19,20 | 20,59 | 30,03 |
| IN | SF | 150 | 0,82 | 20,60 | | 7,37 | 57,99 | 4,38 | 4,40 | 0,39 | 0,04 | | | | |
| FEED | SF | 150 | | | | 7,09 | 50,84 | 4,32 | 3,95 | 0,44 | 2,10 | | | | |
| PERM | SF | 150 | 0,76 | 19,80 | 0,03 | 7,07 | 50,47 | 3,69 | 3,72 | 0,30 | 0,02 | 3,87 | 15,87 | 15,53 | 22,95 |
| IN | KF | 150 | 11,45 | 17,79 | | 7,82 | 58,56 | 4,17 | 4,19 | 0,35 | 0,02 | | | | |
| FEED | KF | 150 | | | | 7,30 | 51,61 | 4,13 | 3,74 | 0,40 | 2,10 | | | | |
| PERM | KF | 150 | 16,41 | 14,54 | 0,02 | 7,27 | 50,63 | 3,56 | 3,60 | 0,27 | 0,03 | 18,23 | 14,58 | 14,22 | 22,22 |

*Table 10. Experiments were performed at a 3.8 mg Al./L coagulant dosage.*

| Sample | Placement | Na2CO3 dose [mL] | Turbidity [FNU] | fDOM corr. [QSU] | TMP [bar] | pH | Alkalinity [mg HCO3/L] | TOC [mg/L] | DOC [mg/L] | UV-254 [abs 5 cm] | Al. rest [mg Al/L] | fDOM corr. [%] | TOC [%] | DOC [%] | UV-254 [%] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| IN | SF | 0 | - | - | - | 6,84 | 42,00 | 4,54 | 4,47 | 0,41 | 0,03 | | | | |
| FEED | SF | 0 | - | - | - | 6,52 | 29,43 | 4,46 | 3,71 | 0,54 | 3,91 | | | | |
| PERM | SF | 0 | - | - | | 6,54 | 28,45 | 3,49 | 3,54 | 0,28 | 0,18 | - | 23,15 | 20,61 | 32,44 |
| IN | KF | 0 | - | - | - | 6,89 | 41,71 | 4,17 | 4,18 | 0,36 | 0,01 | | | | |
| FEED | KF | 0 | - | - | - | 6,60 | 31,09 | 4,02 | 3,58 | 0,46 | 3,45 | | | | |
| PERM | KF | 0 | - | - | - | 6,61 | 29,66 | 3,25 | 3,30 | 0,24 | 0,11 | - | 22,02 | 21,06 | 32,45 |
| IN | SF | 50 | 2,37 | 25,77 | | 6,99 | 49,44 | 4,34 | 4,42 | 0,41 | 0,04 | | | | |
| FEED | SF | 50 | | | | 6,76 | 39,27 | 4,31 | 3,76 | 0,51 | 3,40 | | | | |
| PERM | SF | 50 | 5,77 | 19,57 | 0,06 | 6,78 | 38,52 | 3,41 | 3,40 | 0,29 | 0,03 | - | 21,36 | 23,13 | 29,68 |
| IN | KF | 50 | 0,71 | 14,24 | | 7,47 | 46,44 | 4,28 | 4,33 | 0,37 | 0,02 | | | | |
| FEED | KF | 50 | | | | 6,89 | 36,15 | 4,29 | 3,54 | 0,45 | 3,10 | | | | |
| PERM | KF | 50 | 0,69 | 13,83 | 0,04 | 6,91 | 35,23 | 3,30 | 3,34 | 0,25 | 0,02 | 2,87 | 22,82 | 22,89 | 31,25 |
| IN | SF | 100 | 1,04 | 22,24 | | 7,29 | 54,91 | 4,32 | 4,33 | 0,40 | 0,03 | | | | |
| FEED | SF | 100 | | | | 6,91 | 43,67 | 4,17 | 3,67 | 0,49 | 2,90 | | | | |
| PERM | SF | 100 | 1,35 | 19,21 | 0,04 | 6,89 | 42,59 | 3,44 | 3,51 | 0,28 | 0,02 | 13,63 | 20,36 | 18,92 | 29,27 |
| IN | KF | 100 | - | - | | 7,65 | 54,54 | 3,99 | 4,08 | 0,34 | 0,02 | | | | |
| FEED | KF | 100 | | | | 7,00 | 43,92 | 3,96 | 3,34 | 0,43 | 3,30 | | | | |
| PERM | KF | 100 | - | - | 0,06 | 7,03 | 43,14 | 3,14 | 3,15 | 0,23 | 0,02 | - | 21,27 | 22,73 | 32,30 |
| IN | SF | 150 | - | - | | 7,30 | 59,91 | 4,25 | 4,34 | 0,40 | 0,03 | | | | |
| FEED | SF | 150 | | | | 6,98 | 48,78 | 4,24 | 3,73 | 0,49 | 3,10 | | | | |
| PERM | SF | 150 | - | - | 0,06 | 6,95 | 47,39 | 3,41 | 3,45 | 0,28 | 0,04 | - | 19,92 | 20,60 | 28,16 |
| IN | KF | 150 | 0,67 | 17,38 | | 8,39 | 60,11 | 3,83 | 3,88 | 0,33 | 0,02 | | | | |
| FEED | KF | 150 | | | | 7,16 | 49,39 | 3,90 | 3,37 | 0,42 | 3,10 | | | | |
| PERM | KF | 150 | 0,62 | 12,46 | 0,05 | 7,16 | 47,95 | 3,13 | 3,15 | 0,23 | 0,02 | 28,30 | 18,39 | 18,91 | 30,00 |

*Table 11. Experiments were performed at different retention times.*

| Sample | Placement | Retention time [s] | Turbidity [FNU] | fDOM corr. [QSU] | TMP [bar] | pH | Alkalinity [mg HCO3/L] | TOC [mg/L] | DOC [mg/L] | UV-254 [abs 5 cm] | Al. rest [mg Al/L] | fDOM corr. [%] | TOC [%] | DOC [%] | UV-254 [%] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| IN | SF | 150 | 8,08 | 27,02 | | 6,94 | 46,04 | 4,57 | 4,52 | 0,43 | 0,04 | | | | |
| FEED | SF | 150 | | | | 6,75 | 38,50 | 4,58 | 3,89 | 0,50 | 2,40 | | | | |
| PERM | SF | 150 | 1,04 | 18,51 | 0,05 | 6,76 | 38,01 | 3,66 | 3,64 | 0,31 | 0,04 | 31,50 | 19,95 | 19,43 | 27,56 |
| IN | KF | 150 | 0,75 | 17,51 | | 7,18 | 39,13 | 4,26 | 4,34 | 0,37 | 0,02 | | | | |
| FEED | KF | 150 | | | | 6,85 | 31,67 | 4,18 | 3,69 | 0,41 | 2,00 | | | | |
| PERM | KF | 150 | 0,69 | 14,22 | 0,05 | 6,87 | 32,13 | 3,42 | 3,43 | 0,26 | 0,02 | 18,78 | 19,69 | 20,89 | 28,34 |
| IN | SF | 60 | 5,83 | 18,26 | | 6,78 | 40,12 | 4,47 | 4,56 | 0,39 | 0,04 | | | | |
| FEED | SF | 60 | | | | 6,67 | 33,31 | 4,42 | 4,01 | 0,49 | 2,20 | | | | |
| PERM | SF | 60 | 15,60 | 16,51 | 0,04 | 6,69 | 33,55 | 3,68 | 3,71 | 0,29 | 0,07 | 9,57 | 17,76 | 18,51 | 25,89 |
| IN | KF | 60 | 16,85 | 14,09 | | 7,05 | 40,71 | 4,20 | 4,18 | 0,37 | 0,02 | | | | |
| FEED | KF | 60 | | | | 6,84 | 33,64 | 4,30 | 3,83 | 0,41 | 2,30 | | | | |
| PERM | KF | 60 | 17,78 | 11,96 | 0,05 | 6,88 | 33,44 | 3,50 | 3,56 | 0,30 | 0,02 | 15,11 | 16,79 | 14,94 | 19,86 |
| IN | SF | 30 | 8,48 | 24,41 | | 6,81 | 44,21 | 4,35 | 4,49 | 0,42 | 0,04 | | | | |
| FEED | SF | 30 | | | | 6,71 | 36,17 | 4,41 | 3,80 | 0,49 | 2,10 | | | | |
| PERM | SF | 30 | 14,00 | 18,34 | 0,05 | 6,71 | 36,36 | 3,54 | 3,57 | 0,30 | 0,04 | 24,89 | 18,68 | 20,52 | 28,37 |
| IN | KF | 30 | 0,63 | 17,30 | | 7,21 | 42,37 | 3,84 | 3,86 | 0,33 | 0,01 | | | | |
| FEED | KF | 30 | | | | 6,97 | 35,46 | 3,09 | 3,25 | 0,23 | 0,02 | | | | |
| PERM | KF | 30 | 0,60 | 12,58 | 0,06 | 6,98 | 35,45 | 3,21 | 3,12 | 0,23 | 0,02 | 27,30 | 16,45 | 19,25 | 30,93 |

*Table 12. Experiments were performed with different mixing configurations.*

| Sample | Mixing set up | Turbidity [FNU] | fDOM corr. [QSU] | TMP [bar] | pH | Alkalinitet [mg HCO3/L] | TOC [mg/L] | DOC [mg/L] | UV-254 [abs 5 cm] | Al. rest [mg Al/L] | fDOM corr. [%] | TOC [%] | DOC [%] | UV-254 [%] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| IN | 400+PMS24 | 0,64 | 15,36 | | 7,14 | 41,15 | 3,81 | 3,83 | 0,33 | 0,02 | | | | |
| FEED | 400+PMS24 | | | | 6,88 | 34,30 | 3,75 | 3,27 | 0,27 | 2,10 | | | | |
| PERM | 400+PMS24 | 0,65 | 13,03 | 0,05 | 6,90 | 33,86 | 3,12 | 3,11 | 0,24 | 0,02 | 15,20 | 18,27 | 18,85 | 29,00 |
| IN | 300+PMS24 | 9,51 | 20,22 | | 7,22 | 43,79 | 4,22 | 4,22 | 0,39 | 0,02 | | | | |
| FEED | 300+PMS24 | | | | 7,04 | 36,55 | 4,12 | 3,96 | 0,45 | 2,50 | | | | |
| PERM | 300+PMS24 | 13,07 | 15,09 | 0,06 | 7,10 | 36,49 | 3,40 | 3,39 | 0,28 | 0,03 | 25,35 | 19,44 | 19,67 | 28,02 |
| IN | 200+PMS24 | 0,77 | 15,61 | | 7,13 | 41,14 | 3,83 | 3,85 | 0,34 | 0,03 | | | | |
| FEED | 200+PMS24 | | | | 6,87 | 34,23 | 3,86 | 3,38 | 0,41 | 2,10 | | | | |
| PERM | 200+PMS24 | 0,72 | 12,97 | 0,05 | 6,90 | 34,27 | 3,08 | 3,12 | 0,24 | 0,02 | 16,92 | 19,68 | 18,86 | 29,67 |
| IN | 400+PMS36 | 0,67 | 14,00 | | 7,20 | 39,05 | 3,92 | 3,88 | 0,34 | 0,03 | | | | |
| FEED | 400+PMS36 | | | | 6,87 | 32,10 | 3,89 | 3,48 | 0,38 | 2,10 | | | | |
| PERM | 400+PMS36 | 0,68 | 12,75 | 0,06 | 6,95 | 32,63 | 3,09 | 3,15 | 0,23 | 0,02 | 8,93 | 21,08 | 18,78 | 30,60 |
| IN | 300+PMS36 | 0,63 | 18,69 | | 7,12 | 40,53 | 3,90 | 3,86 | 0,34 | 0,02 | | | | |
| FEED | 300+PMS36 | | | | 6,90 | 33,14 | 3,90 | 3,42 | 0,40 | 2,20 | | | | |
| PERM | 300+PMS36 | 0,62 | 13,40 | 0,05 | 6,91 | 33,23 | 3,08 | 3,06 | 0,24 | 0,02 | 28,31 | 21,05 | 20,84 | 30,79 |
| IN | 200+PMS36 | 1,14 | 16,81 | | 7,33 | 44,80 | 4,24 | 4,28 | 0,39 | 0,02 | | | | |
| FEED | 200+PMS36 | | | | 7,02 | 36,50 | 4,23 | 3,65 | 0,46 | 2,50 | | | | |
| PERM | 200+PMS36 | 0,66 | 17,18 | 0,05 | 7,10 | 37,41 | 3,43 | 3,48 | 0,28 | 0,02 | -2,24 | 19,14 | 18,75 | 28,57 |
| IN | 400+PMS48 | 0,71 | 17,66 | | 7,28 | 39,15 | 3,88 | 3,83 | 0,33 | 0,02 | | | | |
| FEED | 400+PMS48 | | | | 6,91 | 32,22 | 3,90 | 3,34 | 0,38 | 2,50 | | | | |
| PERM | 400+PMS48 | 0,69 | 12,75 | 0,04 | 6,93 | 31,86 | 3,12 | 3,05 | 0,23 | 0,02 | 27,82 | 19,73 | 20,54 | 30,15 |
| IN | 300+PMS48 | 0,89 | 15,49 | | 7,27 | 41,76 | 3,67 | 3,67 | 0,31 | 0,02 | | | | |
| FEED | 300+PMS48 | | | | 6,98 | 34,85 | 3,64 | 3,26 | 0,37 | 2,50 | | | | |
| PERM | 300+PMS48 | 0,86 | 4,66 | 0,06 | 7,00 | 34,87 | 2,94 | 2,97 | 0,21 | 0,02 | 69,91 | 19,78 | 18,93 | 31,37 |
| IN | 200+PMS48 | - | - | | 7,27 | 41,91 | 3,72 | 3,64 | 0,30 | 0,02 | | | | |
| FEED | 200+PMS48 | | | | 6,96 | 34,64 | 3,61 | 3,20 | 0,35 | 2,30 | | | | |
| PERM | 200+PMS48 | - | - | 0,04 | 6,97 | 34,95 | 2,90 | 2,92 | 0,21 | 0,02 | - | 22,04 | 19,77 | 31,74 |

## Appendix G: Verification of indicators
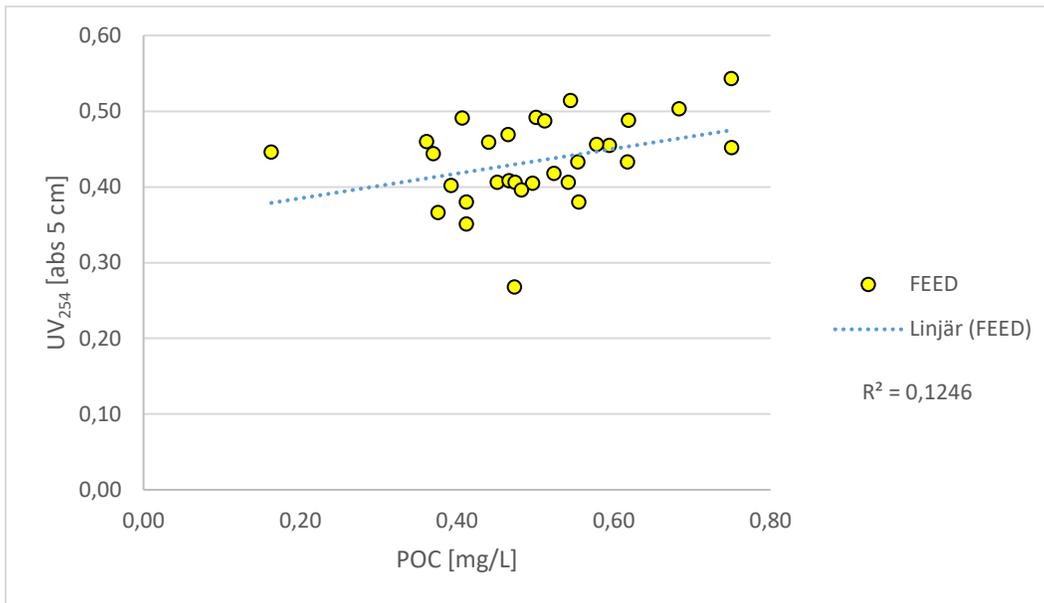


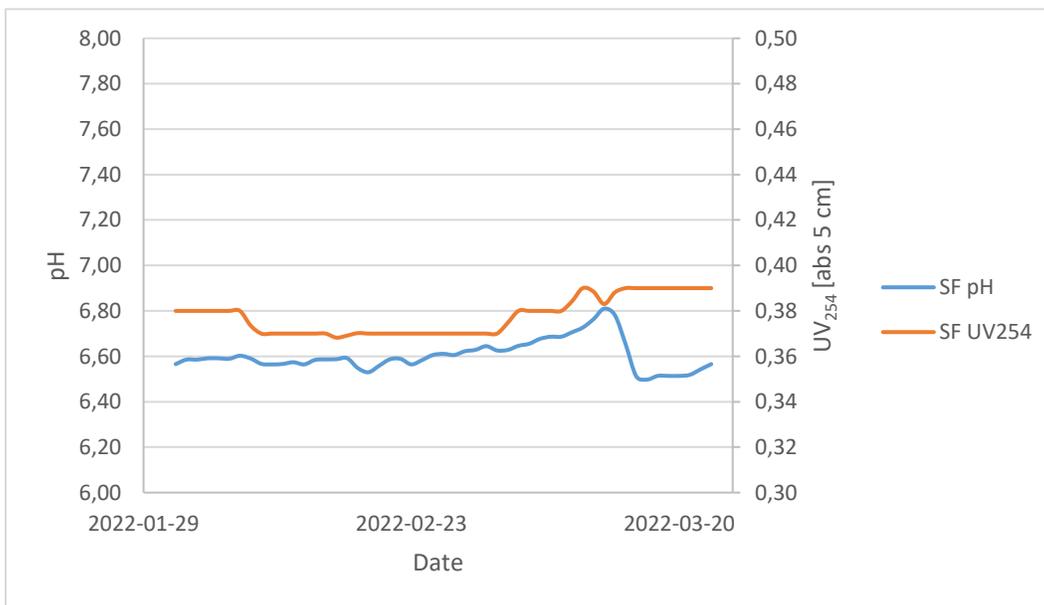*Figure 16. Comparison between UV$_{254}$ and POC for samples from FEED.*



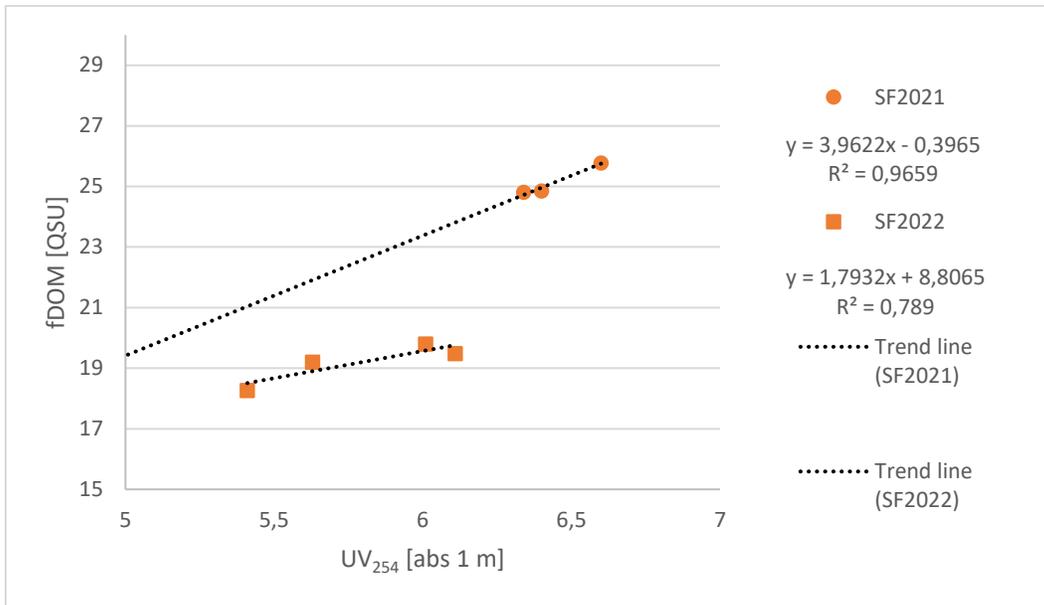*Figure 17. Changes in pH and UV$_{254}$ over time in IN.*

48

*Figure 18. Comparing trends in the correlation of fDOM and UV254 between 2021 and 2022.*
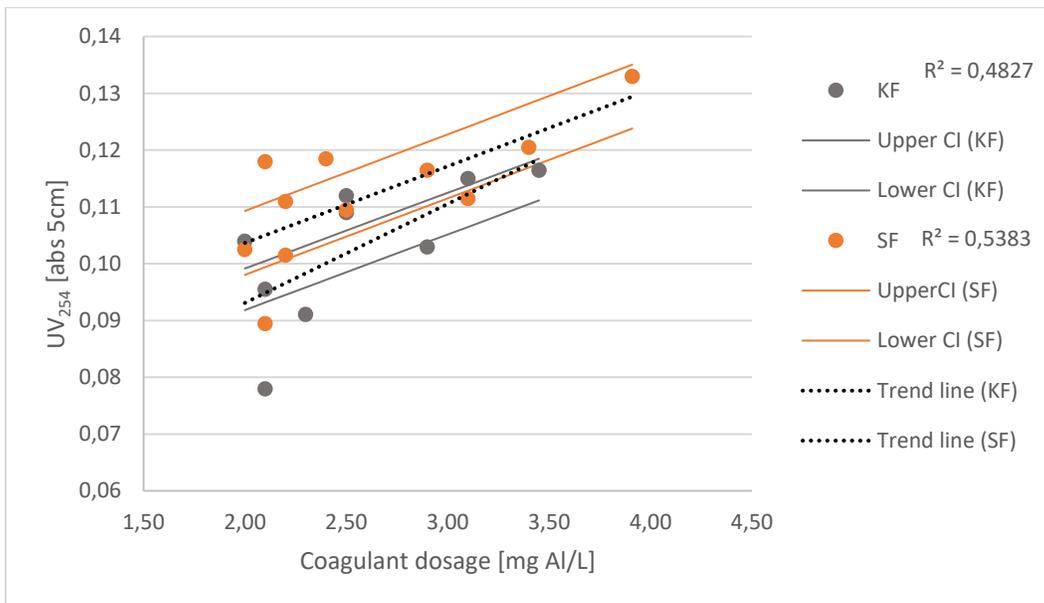


*Figure 19. UV$_{254}$ reduction at different coagulation dosages, using different feed waters; SF (orange) and grey KF (grey). The trend lines (black) and confidence intervals (orange for SF and grey for KF trend lines) are presented.*
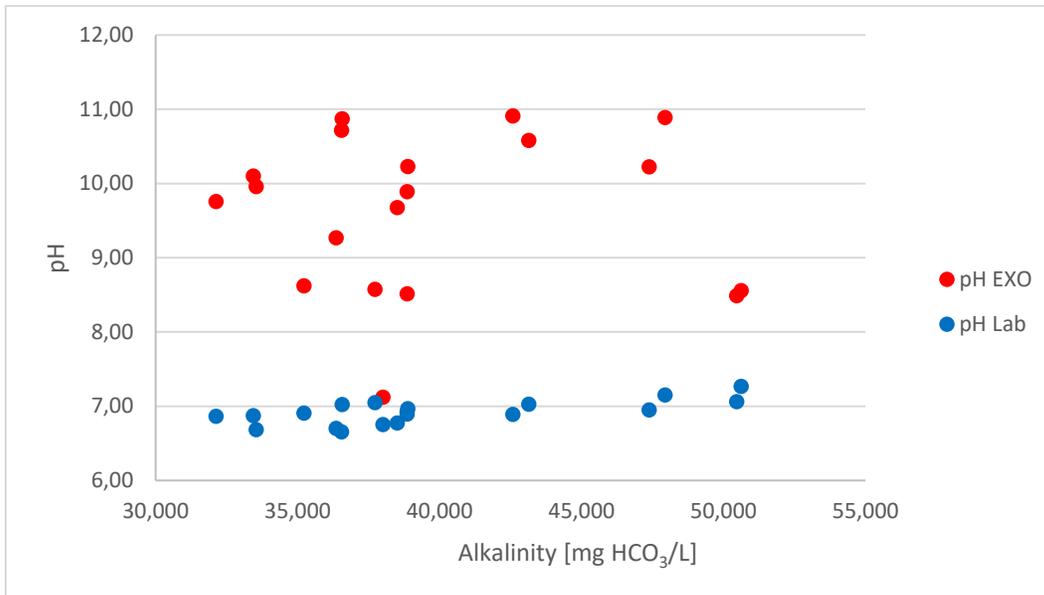
49

*Figure 20. Comparison of pH EXO and pH Lab plotted against alkalinity in the permeate stream.*