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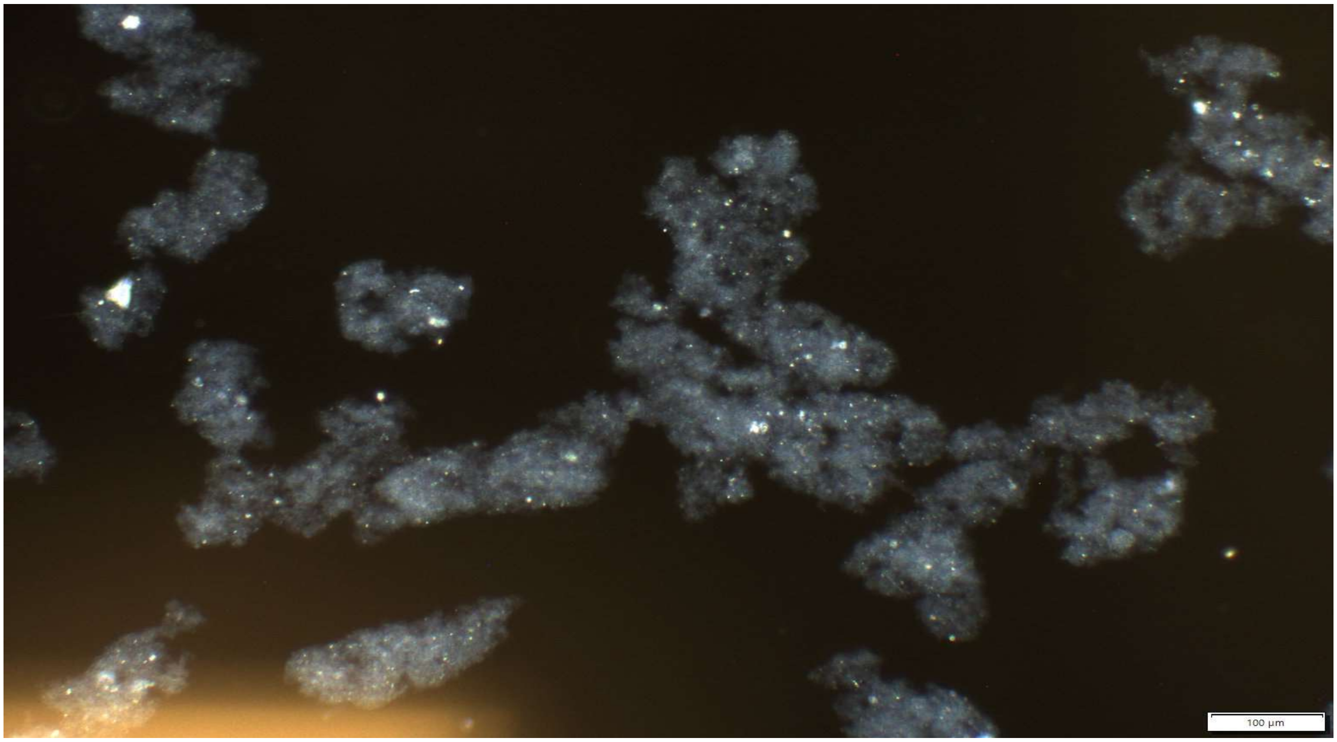

Effects of backwash water recirculation in drinking water treatment

A case study on coagulation, flocculation, and sedimentation performance in Sweden

Master's thesis in Infrastructure and Environmental Engineering

GIACOMO MANNINI

DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING
DIVISION OF WATER ENVIRONMENT TECHNOLOGY

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Department of Architecture and Civil Engineering
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Cover:
Microscopic image of a floc formed during laboratory work for the sample containing spent filter backwash water.
Department of Architecture and Civil Engineering
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ABSTRACT

The purpose of this thesis was to investigate the impact of recycling spent filter backwash water (SFBW) in coagulation, flocculation and sedimentation processes in a Swedish drinking water treatment plant. The study focused on interpreting these effects based on dissolved organic carbon (DOC), turbidity reduction, and visual floc characteristics. These values were measured through laboratory experiments, in which raw water was blended with SFBW. Results showed that by blending raw water and 5% – 40% SFBW, the DOC removal efficiency remained unchanged across all samples. However, the final DOC concentrations decreased, as the level of organics in SFBW was lower compared to raw water, suggesting a dilution effect. Turbidity measurements showed low values across all samples (0-3 FNU). Moreover, the addition of SFBW to the samples led to an increase in floc density. Due to variations in SFBW quality and flow, the implementation of an equalization tank was suggested as a useful intermediate step to improve water quality and allow potential emergency discharges to the sewer. This study is especially relevant for surface water treatment plants with SUVA values around 2.5 and a filtrate backwash system operating filtrate water with a pH of around 6. These findings suggest that the SFBW is feasible for optimal recycling process, though further research is recommended including pilot-scale testing.

Key words: Spent Filter Backwash Water, NOM removal, Backwash, Recirculation, Coagulation, Sedimentation, Flocs

Contents

Preface

This thesis was written as part of my double master's degree in Environmental Engineering – Urban Water and Water Resources Engineering – at Chalmers University of Technology and at the Norwegian University of Science and Technology (NTNU). The project was written in collaboration with a Swedish utility company, and with the supervision of Professor Kathleen Murphy and PhD student Ali Esmaeeli.

Working on this project has been an exciting experience. Being involved in a real-world case and collaborating with a utility company helped me getting a better insight on the topic and becoming highly motivated in delivering useful results.

I would like to thank the employees at treatment plant for their great contribution and interest in showing me around the plant and supervising my work. Furthermore, I would like to thank Kathleen and Ali for excellent supervision and support throughout the project. I also would like to thank all colleagues that have been working at the WET Laboratory, in particular Amir, for their help and encouragement.

Göteborg June 2025

Giacomo Mannini

Notations

$DOC_{initial}$	Initial DOC concentration
DOC_{final}	Final DOC concentration
g	Gravitational force
μ	Water viscosity
ρ_w	Water density
v_s	Settling velocity of a particle
ρ_p	Particle density
d	Particle diameter
pKa	Measure of the acid strength of a substance

1 Introduction

Drinking water is a fundamental human need, which has increasingly become a more constrained resource. While many countries around the world face challenges of water shortage and quality, similar impacts have not been experienced in Sweden yet, although precautionary measurements and appropriate water resource management plans must still be accomplished (WSP Sverige AB, 2021).

In fact, in coming years, extreme natural events such as floodings and water shortages will affect communities (European Parliament and Council, 2020; WSP Sverige AB, 2021). Some of the UN Sustainable Development Goals (SDGs) are currently providing guidelines to find solutions for many global challenges, requiring major infrastructure investments. Within the water sector in Sweden, minimizing water losses and improving water resource management could potentially have great impact on reducing water consumption and improving quality of surrounding water bodies. The need of preventive measures for water reuse and more sustainable approaches with the water sector has been strongly emphasized in the 2020/741 EU Regulation (European Parliament and Council, 2020).

Drinking water treatment plants (DWTPs) regularly produce wastewater formed during cleaning of the filters, also called backwash water (BW) or spent filter backwash water (SFBW). Most often this waste is discharged into the sewer and transported to a wastewater treatment plant (WWTP). However, this is a potential loss of treatable water as well as an unsustainable method (USEPA, 2001). Moreover, WWTPs do not get any major advantages of receiving backwash water, due to its low nutrient content for an improved treatment efficiency (Gottfried et al., 2008).

Recirculation of backwash water into the treatment line has become a valid solution with multiple studies focusing on the main factors improving the efficiency of the treatment process and ensuring no impact on the final water quality sent to the consumers. The EU has published regulations concerning reclaiming wastewater, although only for non-potable purposes, such as agricultural irrigation (European Parliament and Council, 2020). However, the Filter Backwash Recycling Rule (FBRR) by the U.S. Environmental Protection Agency is a valuable regulatory for the understanding of the main requirements for the establishment of a recirculation process.

This thesis investigates the impact of reintroducing backwash water into the treatment line at a DWTP located in Sweden, with a particular focus on the conventional treatment step.

1.1 Objectives

This thesis aims to evaluate the technical, operational and environmental feasibility of recirculating the backwash water used to flush GAC filters to the beginning of the treatment line (prior to coagulation). The primary focus is to assess the impact on the coagulation step, by studying the effect on DOC removal efficiency, change in floc characteristics and turbidity measurements.

1.2 Limitations

While this study provides insight into the effects of recirculating backwash water in a drinking water treatment plant, the following limitations should be noted:

- Microbiological conditions: The microbial content in raw water and backwash water was not monitored or assessed in detail. Although general contamination levels were known, this thesis did not evaluate the risk of microbial buildup throughout the treatment line when returning SFBW.
- Other contaminants: This thesis focused on DOC removal, and parameters such as SUVA and turbidity. No assessment of other contaminants was included in this study, although crucial to determine the impact of backwash recirculation.
- Seasonal variability: Raw water was collected in different months of the year and the quality varied accordingly. Therefore, experiments from different samplings gave different results which could potentially not be compared to each other.
- Laboratory scale: All experiments were carried out in the laboratory. It is expected that upscaling the experiments may show differences in treatment efficiencies, not aligning with what was observed in the laboratory.
- Sludge removal management: Although an estimate of sludge production due to SFBW return was included, no analysis of its composition, management, and reuse was conducted.
- Treatment step for the recycling stream: This study did not provide any clear assessment on the need of pre-treatment for the backwash water recirculation. Although a suggestion to improve the quality of the recycling stream was included, further research is required to fully comprehend the need of any treatment step.

2 Literature review

2.1 Water Treatment

2.1.1 Surface water quality

The water chemistry varies according to the raw water source used for the production of drinking water. Surface water from freshwater bodies such as lakes and rivers provide a direct and easy access to the abstraction and supply of water to the plant. The main constituents in surface water are the following:

- Colloidal constituents: these include clay, silt, organic matter and pathogenic organisms
- Dissolved substances
- Particulates
- Particulate organic matter

The physio-chemical characteristics vary greatly according to the surroundings with most of the water bodies having a pH between 6 to 8.5, while the alkalinity usually is lower than in groundwater given the direct contact with the atmosphere which contains carbon dioxide. Moreover, the mineral levels in surface water are often lower compared to groundwater, especially when considering iron and manganese concentrations. (Crittenden et al., 2012; Karlsen et al., 2014)
The two main natural contaminants often observed in surface water is the presence of Natural Organic Matter (NOM), varying in concentration, and microbes (Crittenden et al., 2012).

Although its clear advantage in terms of easy access and monitoring of the water body's capacity and quality, surface water chemistry is highly dependent on the weather conditions and seasonal change – temperature fluctuations, rainfall, biological activity – affecting treatment plant operations. Moreover, water sources close to urban areas often experience high contamination levels given by human activities in the surrounding. These are mostly related with heavy metals, microplastics (Li et al., 2023) and nutrients from wastewater discharges (Crittenden et al., 2012).

For most surface water sources for drinking water purposes, the most common parameters to be addressed in water treatment are:

- Natural organic matter (NOM)
- Alkalinity and hardness
- Microbial content
- Odor and taste

2.1.2 Natural Organic Matter (NOM)

Natural organic matter in surface waters originates from the degradation of organic material like plants, algae and microbes in the environment, resulting in a complex compound matrix (Matilainen et al., 2010). Although NOM is not directly harmful, it plays a critical role in water treatment processes affecting the coagulant dose and subsequently pH adjustments, disinfection by-products (DBPs) formation caused by the reaction between the organics with certain disinfectants applied in water treatment, fouling membranes, adsorption filters, and providing microbial regrowth in distribution systems (Crittenden et al., 2012). Moreover, the immediate consequence of high NOM levels in waters are seen based on colour, taste and odour. The importance of monitoring and treating NOM in Nordic countries has increased in the past decades due to the increased temperature and precipitations caused by climate change events (Bjørnar Eikebrokk et al., 2018).

NOM is identified by hydrophobicity and molar mass. Hydrophobicity is the measurement of a particle's ability to repel water. Humic substances are a fraction of organic matter which is hydrophobic, while aliphatic carbon and nitrogenous compounds are hydrophilic. Furthermore, humic substances have usually higher molar mass, providing better chance of removal. To determine NOM, a spectrophotometer can be used to measure absorbance. The wavelength to detect organic matter may vary from 220 to 280 nm according to its composition. The specific UV absorbance (SUVA) can be used to evaluate the type of NOM present in the water. SUVA is calculated as the UV absorbance measured at 254 nm wavelength divided by the total organic carbon concentration (TOC). Table 2.1 shows how according to SUVA, the coagulation performance and DOC removal can be estimated. (Crittenden et al., 2012; Matilainen et al., 2010)

Table 2.1: NOM composition and dependance on coagulation and DOC removal. (Tobiason and Edzwald, 1999)

SUVA	Composition	Coagulation	DOC removal
> 4	Mostly aquatic humics, high hydrophobicity, high MW	NOM controls, good DOC removals	> 50 % for alum, little greater for ferric
2 – 4	Mixture of aquatic humics and other NOM, mixture of hydrophobic and hydrophilic, mixture of MWs	NOM influences, DOC removals should be fair to good	25-50 % for alum, little greater for ferric
< 2	Mostly non-humics, low hydrophobicity, low MW	NOM has little influence, poor DOC removals	< 25 % for alum, little greater for ferric

If the concentration of NOM exceeds the limit value of 30 mg/L at the consumer's tap, the treatment plant is required to remove up to an acceptable concentration (Livsmedelsverket, 2022), which can be challenging given the intramolecular forces present in the water. The colloids that float in the water are negatively charged at pH value observed in surface water ($2,5 < pKa < 4,5$), causing the carboxyl group in the compound matrix to dissociate into COO^-. This results in the formation of a double layer of ions surrounding the colloid, creating repulsive forces between colloids, halting any form of aggregation to occur. Figure 2.1 shows the forces acting on the colloids prior any treatment.

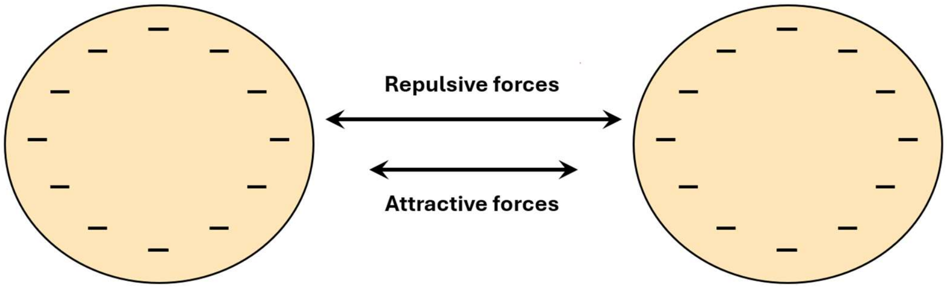

Figure 2.1: Colloidal negatively charged surfaces and forces acting between particles. The surface charge must be destabilized to reduce the repulsive forces present between particles (Crittenden et al., 2012).

The main goal in water treatment is to ensure that the colloids are destabilized by reducing the repulsive forces between particles, while enhancing weak attractive forces causing agglomeration and settling of the organics.

2.1.3 Coagulation

Coagulation is a process providing destabilization and aggregation of particles. It relies on the addition of a coagulant – a chemical compound – that neutralizes the repulsive forces, allowing particle agglomeration, also defined as flocs (Tobiason et al., 2003). Metal and polymer coagulants are the most common coagulant types, acting on the colloids with different processes. For metals, coagulation can occur through charge neutralization or sweep coagulation, according to the dosage and water chemistry. Aluminium and Iron salts are the most common metal coagulants on the market. In this report, only aluminium salts are discussed. (Crittenden et al., 2012)

When adding alum salts in water, the coagulant will first dissociate into free Al^{3+} and then hydrate to form aquometal complexes. According to the final pH in the solution, certain alum species will be present in different ratios as shown in equations 2.1-2.4 and Figure 2.2, where $Al(OH)_{3\ (s)}$ is preferred since it precipitates. (Lawrence K. Wang et al., 2005)

$$Al^{3+} + H_2O \rightleftharpoons AlOH^{2+} + H^+ \tag{2.1}$$

$$Al^{3+} + 2\,H_2O \rightleftharpoons Al(OH)_2^+ + 2\,H^+ \tag{2.2}$$

$$Al^{3+} + 3\,H_2O \rightleftharpoons Al(OH)_{3\,(s)} + 3\,H^+ \tag{2.3}$$

$$Al^{3+} + 4\,H_2O \rightleftharpoons Al(OH)_4^- + 4\,H^+ \tag{2.4}$$

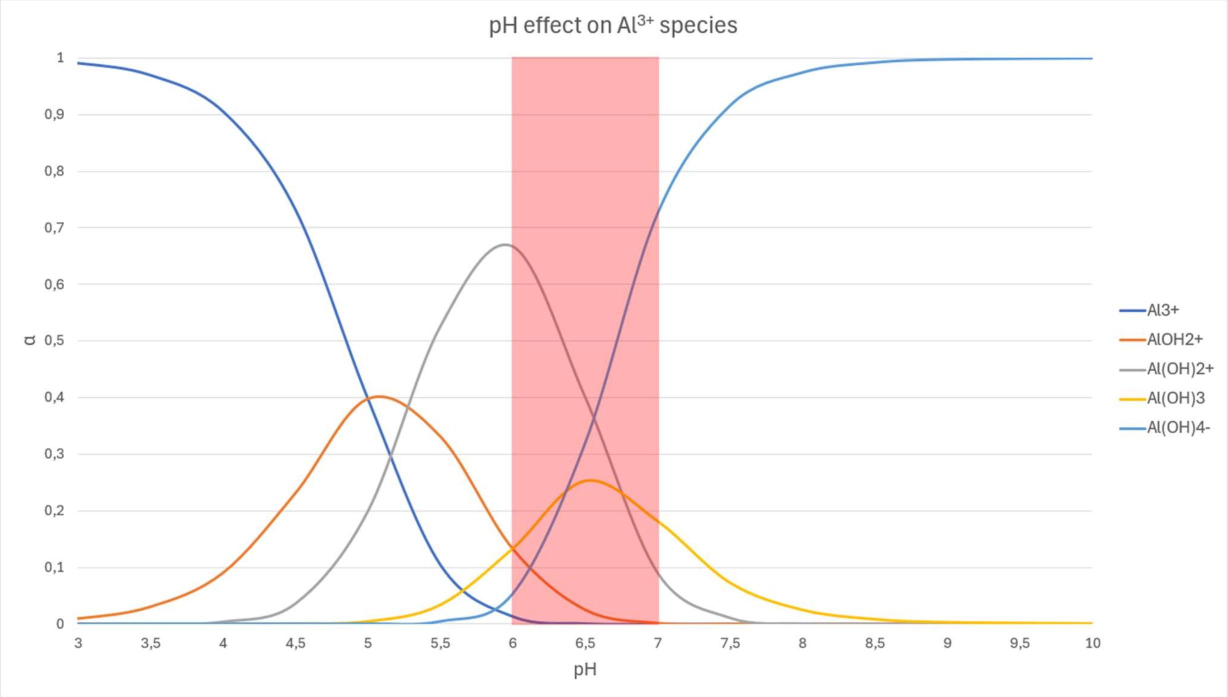

Figure 2.2: Al^{3+} species based on pH change. Al precipitate is seen in pH between 6-7 – marked in red. It should be mentioned that temperature plays a crucial role in the activity of the species (Andrade and Costa Marques, 2012).

With free H^+ in the solution, the alkalinity and equilibrium of the carbonate species will change, shifting the final pH to be more acidic. The optimal coagulation pH from the addition of alum salts is considered way lower than the acceptable pH range in the distribution network, since it would cause corrosion in the pipes and lead to unwanted health risks at the consumer's side (Norsk Vann, 2022). pH adjustments are a common solution to counteract the free H^+ ions, increasing pH and alkalinity (Crittenden et al., 2012; Karlsen et al., 2014; Norsk Vann, 2022).

2.1.4 Flocculation

Flocculation is the process following coagulation, in which previously destabilized particles aggregate to form larger flocs, leading to the particles to be easily removed by sedimentation or filtration (Crittenden et al., 2012).

Figure 2.3 shows the coagulation and flocculation step from stable particles governed by repulsive forces to a floc aggregate.

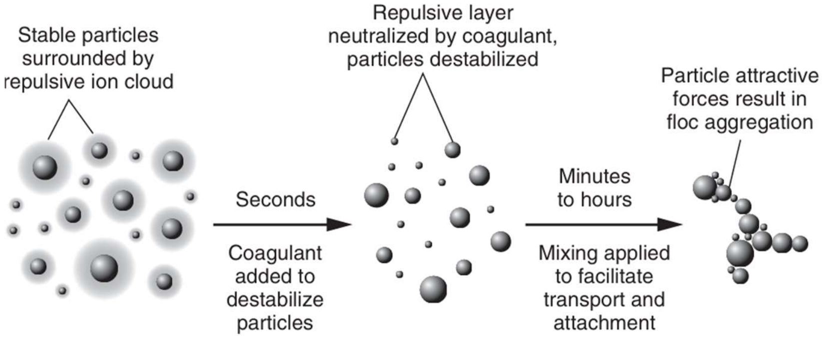

Figure 2.3: Illustration of the particle aggregation process (Crittenden et al., 2012).

Treatment plants perform flocculation through mechanical or hydraulic processes. Mechanical flocculators include the implementation of paddles and impellers, while hydraulic flocculators rely on baffles and channels designed to ensure turbulent conditions and adequate residence time (Crittenden et al., 2012; Karlsen et al., 2014).

2.1.5 Sedimentation

Sedimentation is one of the most common processes follow up in conventional treatment processes. This treatment method relies on gravitational force to remove suspended solids and its efficiency is based on physical characteristics of the particles, water quality and hydraulic behaviour experienced during sedimentation (Crittenden et al., 2012).

Particle settling may occur in different modes, according to the concentration, size, density and shape of the flocs. Bigger particles are expected to settle faster, as well as highly dense floc formation, which has shown improved settling rates. However, excessive presence of flocs, could cause too many collisions between particles and risk to break the formed aggregates.

The settling velocity of a particle is usually based on gravitational, buoyant and drag forces, as shown in Figure 2.4.

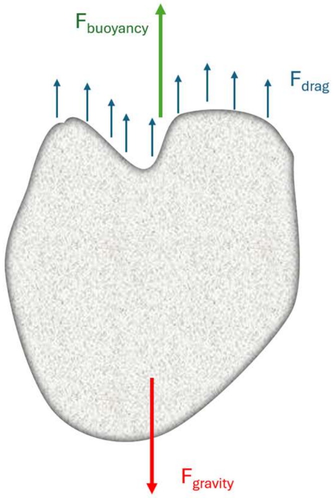

Figure 2.4: Forces acting on a particle settling. To reach effective settling, the gravity force must be larger than the sum of the buoyancy and drag forces.

Moreover, the hydraulic conditions present in the tank would affect the settling velocity too. If the flow regime is estimated to be laminar, then Stokes' law can be utilized to estimate the settling velocity. As shown in equation 2.5, the formula is heavily influenced by the particle size and density, together with the viscosity and density of water, therefore the temperature. However, this equation is not valid for larger particles or different flow regimes.

$$v_s = \frac{g\ (\rho_p - \rho_w)\ d_p^2}{18\ \mu} \tag{2.5}$$

2.1.6 Filtration

Filtration is an important step in drinking water treatment, often used to remove particulate loads of suspended solids, organic matter and even microorganisms by filtering water through a porous medium. In surface water treatment, filtration usually is implemented after conventional treatment steps (coagulation, flocculation and sedimentation). Particle removal in the filtration process occurs through particle entrapment given by the attachment to the grains of the filter media. The attachment of the particles is mainly based on the attachment on the surface of filter media grain. Over time, the impurities trapped in the filter will slowly start forming a coating around the media grains, allowing better particle attachments (Lawrence K. Wang et al., 2005).

One of the filter media increasingly implemented in treatment plants is Granular Activated Carbon medium (GAC). It relies on the adsorption mechanism utilized in removing chemicals linked with taste and odour issues, colour causing compounds, and disinfection by products precursors. Moreover, studies have proven its ability in removing heavy metals and other contaminants which would otherwise not be able to be removed with conventional treatment processes.

2.2 Backwash water and recirculation in water treatment plants

Filter backwashing is an integral part of a drinking water treatment facility, aiming at restoring the performance of granular filter media. As previously mentioned, during filtration, contaminants in the particulate form accumulate in the filter, building up more resistance, hence increasing the head loss. In such conditions, the filter media may end with a decline in effluent water quality, as well as risk of channelling. The backwash process usually involves both air and water flowing in the opposite direction than the normal filtration conditions. Particles that were once trapped in the filter loosen up and are removed from the media, resulting in a waste stream referred to as spent filter backwash water (SFBW). SFBW content varies according to the surface water source and quality, but it is expected to see high turbidity and suspended solids levels. Moreover, organic matter, disinfection by-products, metals and microbes have also been observed (USEPA, 2001).

Backwash frequency depends on several factors, including raw water quality, pretreatment methods and efficiency prior filtration, filtration loading rates, and filter design (Karlsen et al., 2014). With indicators such as turbidity measurements at the outflow or head loss monitoring, the backwash frequency can be determined (USEPA, 2001).

SFBW has traditionally been discharged to wastewater treatment plants or surface water bodies after considerate and regulated treatment steps. The interest in recycling backwash water into the treatment line has received much attention given the many advantages in terms of sustainability and resource recovery goals. However, recycling SFBW has its potential risks and complexities. One of the concerns is the heterogeneity of the water quality throughout time, with high contaminant concentrations seen in the initial stage of the backwash process compared to the end stage (Tobiason et al., 2003; USEPA, 2001).

Previous experimental studies showed the critical role pH plays in recycled backwash water and its influence on coagulation efficiency. At high pH values (8.5-9), DOC in SFBW is negatively charged, requiring a higher coagulant dosage to become destabilized. On the other hand, SFBW at standard pH ($\approx$ 6), particle aggregation occurs more effectively, requiring low or no coagulant demand (Tobiason et al., 2003).

Furthermore, the recirculation of backwash to the treatment line showed positive results when looking into the flocculation and sedimentation process (Tobiason et al., 2003). In fact, the presence of pre-formed flocs and aluminium hydroxide precipitates in SFBW improved floc formation through sweep flocculation, forming bigger aggregates due to increased likelihood in particle collisions. However, it was observed that an excessive amount of particles could negatively affect the settling time due to the increase in inter-particle interactions, hindering settling. Therefore, appropriate recirculation volumes are encouraged (USEPA, 2001; Tobiason et al., 2003).

The U.S. Environmental Protection Agency (USEPA) issued in 2001 a technical manual for recirculation for SFBW, suggesting the implementation of equalization basins to address issues connected with variability in water quality and potential hydraulic surges. Basins would allow an overall better understanding and predictability of water quality and coagulant demand, reducing peak loads the conventional treatment would otherwise risk to experience, affecting filter effluent quality (USEPA, 2001).

According to the type of SFBW, pre-treatment prior to recirculation may be a requirement to comply with regulations and minimum performance requirements (Tobiason et al., 2003; USEPA, 2001).

Moreover, the EPA regulations highlight the need of implementing the recycle stream at the beginning of the treatment line, as discharging SFBW after coagulation could result in microbial breakthrough and performance degradation (USEPA, 2001). Figure 2.7 illustrates a schematic diagram of how recycling could be implemented in a conventional treatment line with an equalization basin.

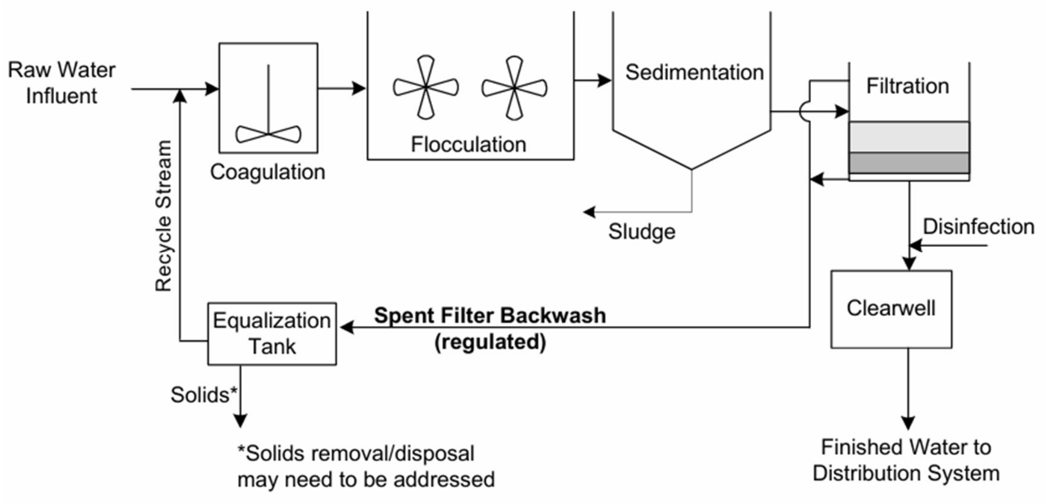

Figure 2.5: Diagram of recirculation of SFBW in a conventional treatment process (USEPA, 2001).

3 Methods

3.1 Site description

The studied drinking water treatment plant is located in Sweden and abstracts surface water. The treatment line consists of a pH adjustment with lime to increase both alkalinity and pH for optimal treatment conditions in the next steps. A conventional treatment step consisting of coagulation, flocculation and sedimentation removes colour and turbidity by forming flocs that are settling throughout the sedimentation tank. The coagulant used by the plant is aluminium sulphate with varying dose according to the raw water quality. The plant operates thereafter with a primary adsorption filtration step consisting of granular activated carbon (TL830), followed by a secondary filtration step, a disinfection step, and final pH adjustments for an optimal water quality.

Only 90% of the treated water is sent to the distribution system, while 10% is utilized for backwash processes alongside with potential maintenance and cleansing of the treatment steps. Focusing on the GAC filtration step, the filter run time between each backwash cycle is expected to be around 80-100 hours, or approximately 15000 m^3. The backwash process for the GAC step is only performed with filtered water with a filtration rate of 30 m/h lasting for around 14 minutes. Backwash is performed with filtered water stored in a separate tank. After the backwash process, around 480 m^3/day of first filtrate post-backwash is discharged to the sewer to ensure acceptable water quality and stable conditions throughout the adsorption filter.

The plant previously performed measurements on the backwash water quality and its potential for returning to the treatment plant, with a special interest in heavy metals, microbes, organics, and suspended solids. Results showed that concentrations of aluminium and coliforms were higher than the drinking water regulations. The possibility of directly discharging the SFBW to a nearby water body was also investigated. However, the regulations for discharge to natural water bodies have stricter limit values compared to the drinking water standards.

3.2 Water sampling

To perform the laboratory experiments, water samples were collected at the water treatment plant (waterworks). The type and number of samples collected reflected the number of experiments that were planned to be conducted. Table 3.1 shows the samples collected during each sampling day for the first set of experiments. Grab samples in ashed amber glass vials were used as reference values to compare the coagulation experiments with the water quality from the waterworks.

Plastic containers were assumed acceptable for water sampling, with low risk of contamination from microplastics or other compounds originating from the container itself. To ensure no cross contamination from previous water samples, the container was thoroughly rinsed with distilled water.

Table 3.1: List of samples collected during each sampling day at the water treatment plant.

Samples	Container type	Type	Location
1	Ashed amber glass vials	Raw water	Sedimentation tank post-lime addition
2	Ashed amber glass vials	Backwash water	GAC filters
3	Ashed amber glass vials	Post-coagulation water	Channel post-sedimentation, pre-filtration
4	Plastic container	Raw water	Sedimentation tank post-lime addition
5	Plastic container	Backwash water	GAC filters

The raw water samples were collected at the stage after lime addition in the treatment line. The addition of lime increases the alkalinity and pH of the raw water, ensuring appropriate pH for optimal coagulation and precipitation (Crittenden et al., 2012). The sampling location was based on the accessibility of collecting the samples without any risks. The samples were collected in the channel where raw water is retained by a baffle before being led into the coagulation step.

The post-coagulation sampling point was selected to provide relevant information about the removal rate of the coagulation process prior the GAC filtration system. The sample was collected in the channel leading to the GAC filters.

Given the heterogeneous quality of backwash (Tobiason et al., 2003; USEPA, 2001), samples were collected at different stages throughout the backwash process. Table 3.2 shows the time when sampling occurred during the 14 minutes backwash process during each sampling campaign. The first sampling collected the sample with most contaminants, the second sampling represented the middle stage, while the last sampling the conclusion of the backwash process. All samples were collected from a mid-life GAC filter prior reactivation. Figure 3.1 shows visually the difference between backwash quality considering the turbidity levels at different time steps.

Table 3.2: Time of backwash sampling during the backwash cycle for each sampling campaign. In the first sampling campaign, only samples from the beginning and the end of the backwash cycle were collected.

Sampling campaign	Filter	Sampling time [min.sec]		
1	KF7	04.00	n.d.	09.00
2	KF7	05.10	07.40	12.00
3	KF1	05.10	07.40	12.00

Figure 3.1: Water collected from the GAC backwash stream at the beginning of the backwash process (left). The water is flowing through a channel that discharges the spent filter backwash water to the sewers. The picture to the right shows a sample being collected during the last phase of the backwash process.

3.3 Laboratory experiments

To assess the impact of recirculating backwash water into the treatment plant, laboratory work was undertaken at the Chalmers WET laboratory at the Department of Architecture and Civil Engineering (ACE) from November 2024 to April 2025.

3.3.1 Coagulation tests

Prior the beginning of the experiments, the vial samples were stored in the fridge while the bigger plastic containers were located in a dark and cool room. The laboratory work consisted of several steps that were followed to produce the most realistic and optimal results.

First, the selected number of experiments were chosen and are shown in Table 3.4. According to the dosage used at the treatment plant and desired conditions during the coagulation step, experiments were carried out to reflect the conditions seen at the plant. The table shows only the samples that underwent the coagulation step. For every sampling day, three reference samples were taken; raw water post-lime addition (1), post-coagulation/pre-GAC filtration (2), and backwash water sample from a specific time step (3).

The coagulant demand was initially selected to correspond a pH in the solution of approximately 6.2-6.3. It was later on established the actual coagulant demand for the laboratory experiments based on the stock solution used at the treatment plant together with the coagulant demand in grams of alum over cubic meters of water $\left[\frac{g\ Alum}{m^3\ H_2O}\right]$. The correct volume of coagulant demand for the laboratory experiments is shown in Table 3.3.

Table 3.3: Coagulant demand at the treatment plant and laboratory for the different sets of experiments. For sets 3-4, the coagulant demand in the laboratory varied according to the experiments carried out.

Coagulant demand			
Sets	1-2	3-4	5
Waterworks coagulant addition [g/m^3]	28	33	29.9
5% Stock solution [g/L]	53	53	53
Coagulant addition during experiments [g/m^3]	18.6	15.9/20.2/26.5	29.9
Dose in laboratory based on WW dosing [µL/L]	528	622	564

The selection of coagulant dose based on pH was decided by pouring 90 mL of raw water in a beaker, testing different doses. The set up is shown in Figure 3.2. The coagulant was added with high mixing and monitoring pH changes through a pH meter.

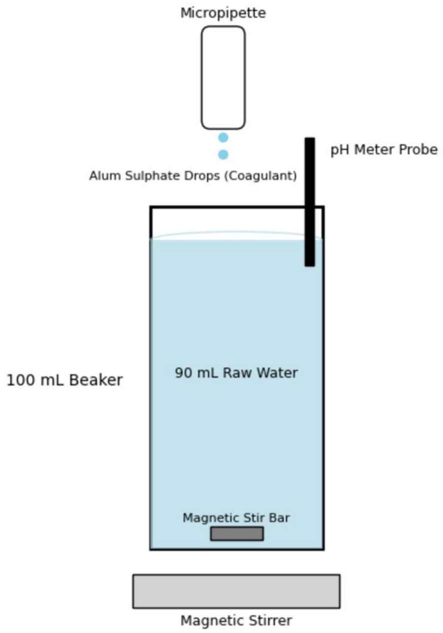

Figure 3.2: Laboratory set up for evaluation of the coagulant demand.

The selected dose for the first experiments was approximately 33% and 39% less than the dose used at the treatment plant. The desired pH during coagulation of 6.2-6.3 was met when underdosing. This discrepancy in coagulant demand might be connected to reactions occurring with the lime addition at the treatment plant. The treatment plant doses lime to increase alkalinity and pH and arrive at an optimal pH for the coagulation process. Since the laboratory experiments could not be performed the same day of sampling, it is possible that the pH was different in the lab experiments than before coagulant dosing at the waterworks due to equilibrium conditions being reached after alkalinity was consumed in other reactions.

Following the first coagulant demand screen, the experiments were scaled up with each sample consisting of 900 mL in a 1000 mL beaker. A FC6S flocculation tester was used to simulate the coagulation-flocculation process with impellers of 7.5 x 2.5 cm in size and with a rotation speed range 0-300 rpm (Figure 3.3).

Following the flocculation and sedimentation process, water samples were collected to measure DOC concentration and absorbance values to estimate the SUVA. To do so, a 60 mL syringe was utilized to collect the water from the surface of the sample in the beaker. The samples were then filtered through a 0.45 µm filter into amber glass vials. To ensure no cross contamination between samples, the equipment was thoroughly rinsed with MilliQ water and with the next sample to not cause any dilution. Filtrating the sample was highly suggested for an optimal measurement of absorbance values and DOC. Figure 3.4 illustrates the equipment used to filter the samples.

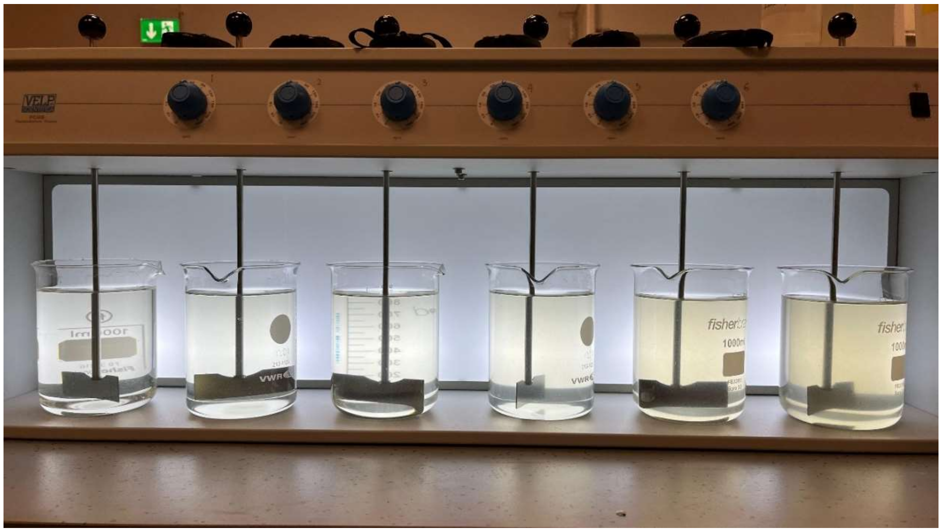

Figure 3.3: Laboratory set up for coagulation experiment.

Figure 3.4: Tools for filtering water samples post-coagulation, and collected them in amber glass vials.

Table 3.4: List of experiments carried out in the laboratory.

Set	Experiment	Sample name	Blending	Raw water	Backwash location	Dosage [μL/L]
1st	1	5%	5%	Post-lime addition	Beginning	350
	2	10%	10%			
	3	15%	15%			
	4	20%	20%			
	5	30%	30%			
	6	40%	40%			
	7	100%	100%			
	8		100%			
	9	0%	0%			
	10		0%			
2nd	1	5%	5%	Post-lime addition	End	350
	2	10%	10%			
	3	15%	15%			
	4	20%	20%			
	5	30%	30%			
	6	40%	40%			
	7	100%	100%			
	8		100%			
	9	0%	0%			
	10		0%			
3rd	1	A1	0%	Post-lime addition	-	300
	2	A2	0%			380
	3	B1	0%			300
	4	B2	0%			380
	5	C1	0%			300
	6	C2	0%			380
4th	1	B3	0%	Post-lime addition	Mixture of beginning, middle and end	500
	2	B3.1	0%			500
	3	B2 - 5%	5%			380
	4		5%			380
	5	B2 - 10%	10%			380
	6		10%			380
	7	B2 - 15%	15%			380
	8		15%			380
5th	1	5%	5%	Post-lime addition	Mixture of beginning, middle and end	564
	2		5%			
	3	10%	10%			
	4		10%			
	5	15%	15%			
	6		15%			
	7	100%	100%			
	8		100%			
	9	0%	0%			
	10		0%			

The mixing conditions and coagulation time were established according to laboratory standards rather than simulate similar conditions operated at the waterworks. However, in the third set of experiments, an investigation of the possible improvements in DOC removal was tested, which resulted in similar mixing conditions as previously operated, although with lower speeds. The selected parameters are shown in Table 3.5.

Table 3.5: List of mixing conditions from the treatment plant and laboratory experiments.

Mixing conditions WTP								
Coagulation	Time	-						minutes
	Speed	Rapid mix						rpm
Flocculation	Time	≈100						minutes
	Speed	4,6-1,3						rpm
Sedimentation	Time	-						minutes
Mixing conditions Laboratory set 1-2								
Coagulation	Time	1						minutes
	Speed	300						rpm
Flocculation	Time	10	15	15				minutes
	Speed	90	60	15				rpm
Sedimentation	Time	60						minutes
Mixing conditions Laboratory set 3								
Mixing group		A		B			C	
Coagulation	Time	1		1			0,5	minutes
	Speed	300		300			300	rpm
Flocculation	Time	10	30	10	15	15	15	minutes
	Speed	15	10	60	30	10	30	rpm
Sedimentation	Time	30		30			30	minutes
Mixing conditions Laboratory set 4-5								
Mixing group		B						
Coagulation	Time	1						minutes
	Speed	300						rpm
Flocculation	Time	10	15	15				minutes
	Speed	60	30	10				rpm
Sedimentation	Time	30						minutes

3.3.1.1 Analytical measurements

To assess the removal efficiency and characterize the type of NOM present in the raw water, the samples were analysed for UV absorbance and DOC.

Absorbance was measured using the UV–1800 spectrophotometer with a 1 cm path length quartz cuvette. Light is transmitted at different wavelengths through the sample. The results were then used to measure the Specific UV Absorbance (SUVA) at 254 nm wavelength.

DOC was measured using a TOC-analyzer. The measured DOC for each sample was then compared with the dissolved organic matter measured in the raw water reference sample to determine the removal efficiency, shown in equation 3.1.

$$Removal\ efficiency\ [\%] = \frac{DOC_{initial} - DOC_{final}}{DOC_{initial}} \tag{3.1}$$

3.3.2 Floc size and settling velocity

Floc characterization was performed to detect changes in floc size which would affect settling velocity and sludge formation. Although it was planned to use image analysis tools to define floc size in different samples, it was unsuccessful to achieve clear, reliable results. Instead, a simpler procedure was selected to determine whether the addition of SFBW would improve the aggregate formation (Tobiason et al., 2003).

Moreover, other experiments were carried out to assess the impact of SFBW on settling. This was done using turbidity measurements and comparisons of the settling velocity.

3.3.2.1 Sample preparation

Since the selected image tools for identifying the floc size rely on high quality images, sample preparation was a crucial part in achieving realistic results. The samples underwent the same experiment settings described for the coagulation process. When the flocculation step concluded, the impellers were removed from the beakers. Quantifying the floc size in the beaker was considered difficult, given the high density of particles formed, with a risk of having the flocs overlap in the picture and the program recognize the overlap as one single big floc. Transferring the water sample into a petri dish to solve this issue was tested, although the flocs would not achieve the same size as seen in the beaker. Figure 3.5 shows an image taken during settling time in the beaker where coagulation and flocculation occurred.

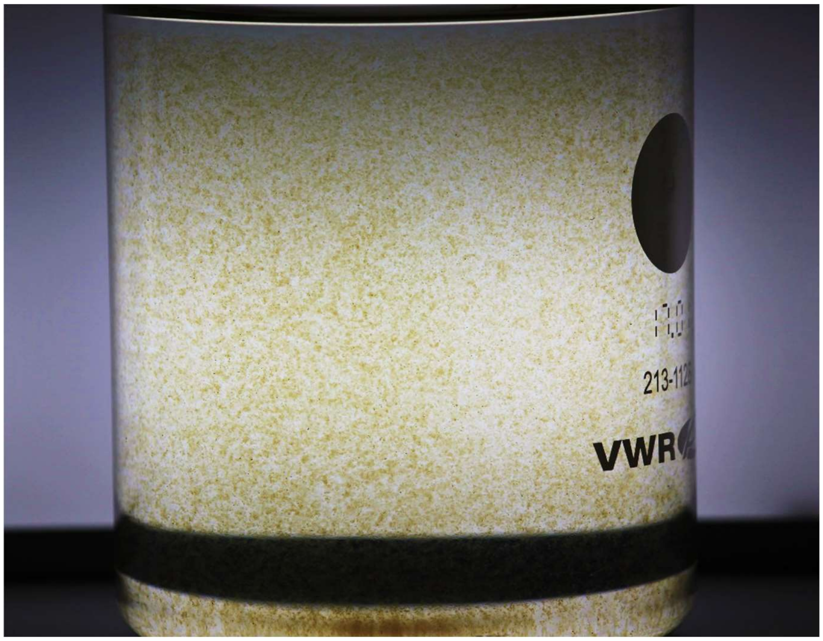

Figure 3.5: Floc formation during sedimentation process for the 15% sample in experiment set 5.

Dilution of the sample with MilliQ water was found to be beneficial, as fewer particles would be seen in the sample with the same volume. However, it was noticed that even with the sample diluted to 50% concentration using MilliQ, the images showed overlap. The risk of further diluting the samples for better image quality conditions would be counterproductive, as the probability of collision of the flocs would diminish, leading to unreliable results.

A visual investigation with normal coagulation conditions was then selected as it was considered valid results to show the increase of the flocs. The pictures of the flocs for each sample were taken with an Iphone 14 Pro Max with enabled macro-lens. Same camera settings and with a constant distance of approximately 13 cm were used for all pictures.

3.3.2.2 Turbidity measurements

Turbidity measurements during the flocculation and sedimentation steps were performed. 15 mL samples from each beaker from experiments in set 5 were taken at time 30 minutes (last flocculation step), 41 minutes (beginning sedimentation step) and 71 minutes (end of sedimentation step). The HACH turbidity meter was utilized and the results shown in FNU units.

3.3.2.3 Mass backwash sludge

A vacuum filtration apparatus was used to measure the TSS present in the backwash water to ultimately determine the potential sludge re-entering the raw water treatment line and possibly sediment prior the GAC filters.

To measure TSS, the standard laboratory procedure was followed. The filter pore size was selected according to the type of sample to be filtered, and a 0.7 µm filter was selected. It should be mentioned that this experiment was solely based on estimating the potential sludge formation if recirculation of backwash would be implemented. The experiment was run with an estimated average backwash sample. Due to the heterogeneous quality of backwash throughout time, it is difficult to precisely calculate the TSS that the waterworks would return to the treatment line and being removed in the GAC filter once again.

3.3.2.4 Estimation of settling velocity

A rough estimate of the settling velocity of the already formed flocs present in the backwash water was carried out. The goal of this experiment was to compare the minimum time necessary to have the flocs settling at the bottom of the beaker in the lab or a tank at the waterworks.

To do so, a first measurement of the settling time for a backwash water sample of homogeneous water quality was carried out by visually monitor the increase in particles settling at the bottom of the beaker. Later, the same experiment was carried out with the same backwash water quality but considering the settling post-coagulation. Therefore, the timer for the second sample was started only after the beginning of the sedimentation step, as it was assumed that the flocs would not settle due to the impeller movement from the flocculator machine.

By assuming that the density of the particles would remain unchanged, the size of the formed particles could be estimated according to Stoke’s law, rewritten in equation 3.2. Although, the flocs would have different sizes, the equation below was used to better showcase the difference in size given by having the sample undergoing the coagulation process.

$$d = \sqrt{\frac{18\,\mu\,v_s}{g\,(\rho_p - \rho_w)}} \tag{3.2}$$

4 Results

In this chapter, all relevant results from the laboratory experiments are shown, as well as considerations regarding possible new treatment design with the recirculating SFBW back in the treatment line.

4.1 Coagulation performance and DOC removal

4.1.1 Impact assessment of backwash on coagulation

The laboratory experiments focused on simulating similar treatment conditions seen at the treatment plant and understanding how mixing SFBW and raw water could affect the DOC removal and coagulation performance.

Figures 4.1 and 4.2 show the first experiments, where a first assessment of mixing the two types of water was studied. The results from the laboratory were compared with the reference values from the water samples collected at the treatment plant. Given the difference in water quality, an understanding of the DOC level in the samples with mixed water was helpful to later assess the actual removal efficiency in each experiment.

The DOC concentrations in the reference raw water during the first sampling day (sets 1-2) were 6.55 and 6.94 mg/L. The 0.4 mg/L difference in DOC measurements was assumed to be due to measurement uncertainty from the TOC analyzer. The post-coagulation DOC level was measured to be 2.94 mg/L. DOC concentration in the backwash was initially 3.31 mg/L at the beginning of the backwash, and 2.50 mg/L at the end, suggesting that SFBW improves its quality throughout time. This could also be visually seen during sampling, as well as documented studies about this phenomenon (Tobiason et al., 2003).

DOC for the samples containing a blend of raw- and backwash water were estimated considering the difference in organic matter measured in raw and SFBW. The final DOC level in all samples have a decreasing trendline with increasing backwash volume. Furthermore, the DOC removal remained somewhat constant in all samples, meaning that the SFBW added seems to dilute the sample rather than improving the DOC removal itself. In fact, the coagulation process in sample "100%" had negligible DOC removal.

It was noticed that the removal efficiency for one of the raw water samples gave a very low organic removal, and low floc formation. It was assumed that the outcome of the experiment might be linked with laboratory errors during the experiment and should not be considered in the overall understanding of the experiments' results. The total removal efficiency seen in the laboratory was considered low compared to what the waterworks experiences, 43% and 55% respectively, which was linked with the underdosage during the experiments as well as possible need of improvement for the selected mixing conditions.

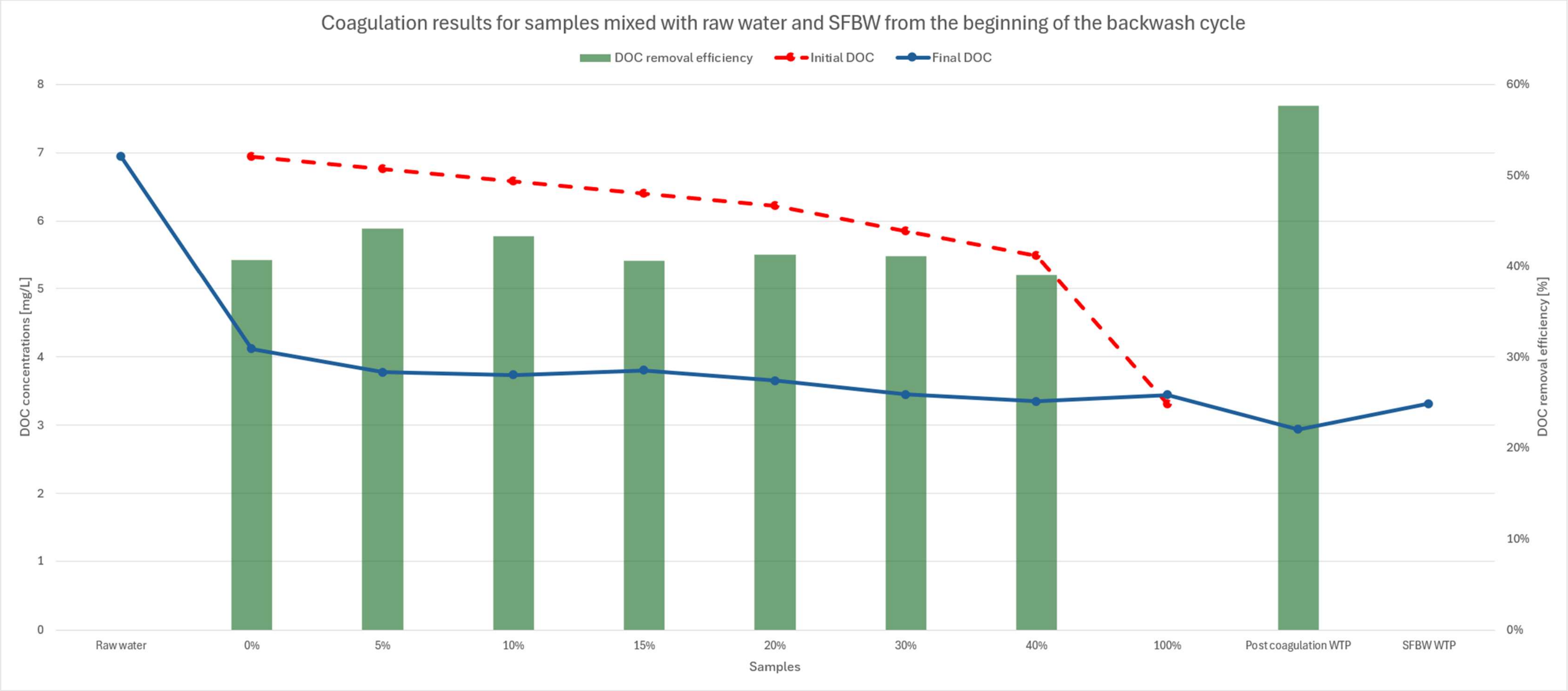

Figure 4.1: Coagulation performance for samples containing varying ratios of raw water (RW) and backwash water (SFBW) taken from the beginning of the backwash cycle. The graph shows DOC content before and after coagulation, as well as the DOC removal efficiency.

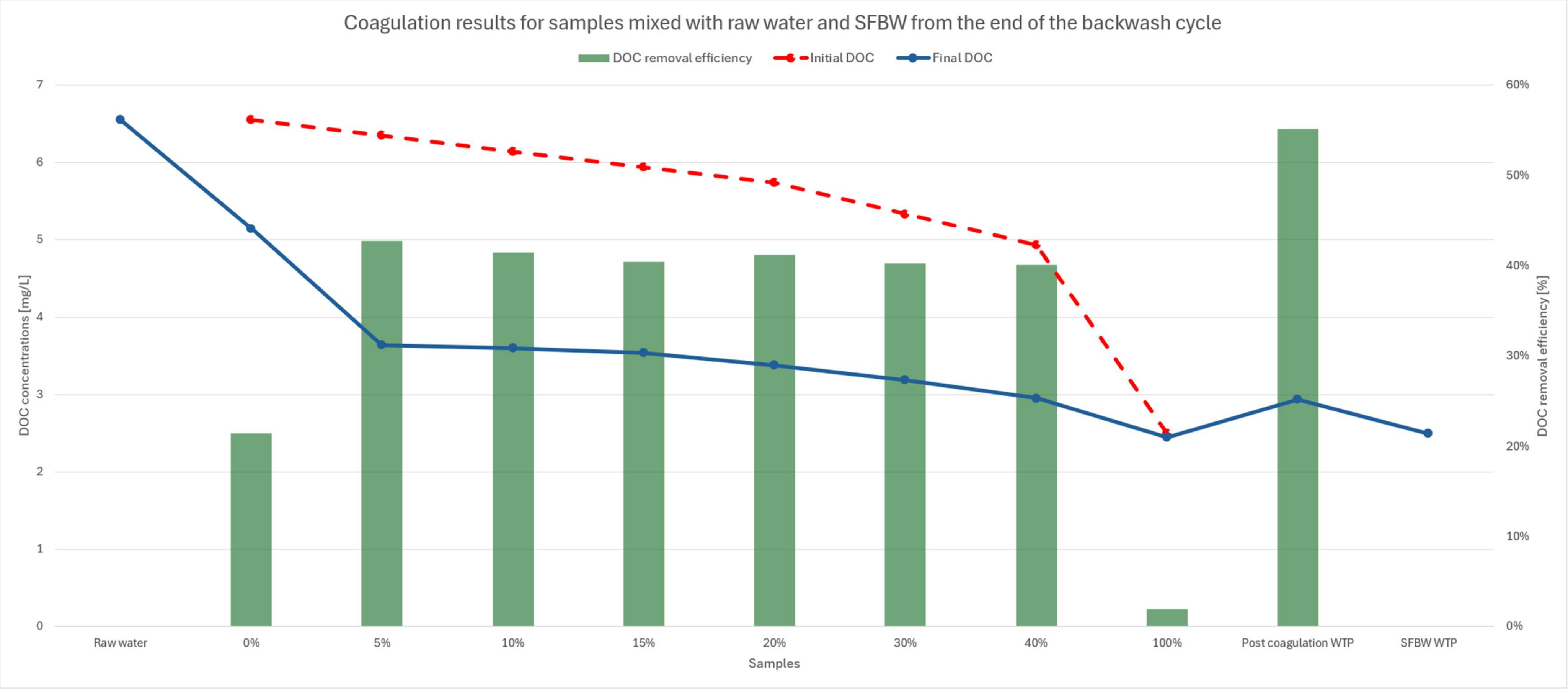

Figure 4.2: Coagulation performance for samples containing varying ratios of raw water (RW) and backwash water (SFBW) taken from the end of the backwash cycle. The graph shows DOC content before and after coagulation, as well as the DOC removal efficiency.

4.1.2 Assessment of varying dosage and mixing conditions

To investigate the effects of different mixing conditions and coagulant dosage, another set of experiments with only raw water samples was performed – set 3-4 – considering different mixing condition and coagulant doses, as shown in the methods section.

The water samples for these experiments were collected during the second sampling campaign, and therefore a slight change in water quality was expected. Figure 4.5 shows the final DOC results, including the measured DOC values for the reference samples collected at the treatment plant. The results show a clear trend in the coagulant demand, suggesting that a higher coagulant dosage reflects better DOC removal, whereas the mixing conditions did not provide any major improvements. However, the mixing conditions "B" was selected for the next experiments. Furthermore, another set of mixed sample experiments were carried out, showing similar outcome to the previous results. Figure 4.6 illustrates the results for the samples with 5, 10, and 15% SFBW. Figures 4.3 and 4.4 illustrate how samples with higher dose formed visible flocs compared to samples with low dosage.

Figure 4.3: End of sedimentation process and floc formation for samples A1, A2 and B1 (labelled left to right). Beaker A2 has the most flocs due to a higher coagulation dose.

Figure 4.4: End of sedimentation process and floc formation for samples B2, C1 and C2 (labelled left to right). Samples with a higher dose showed better floc formation.

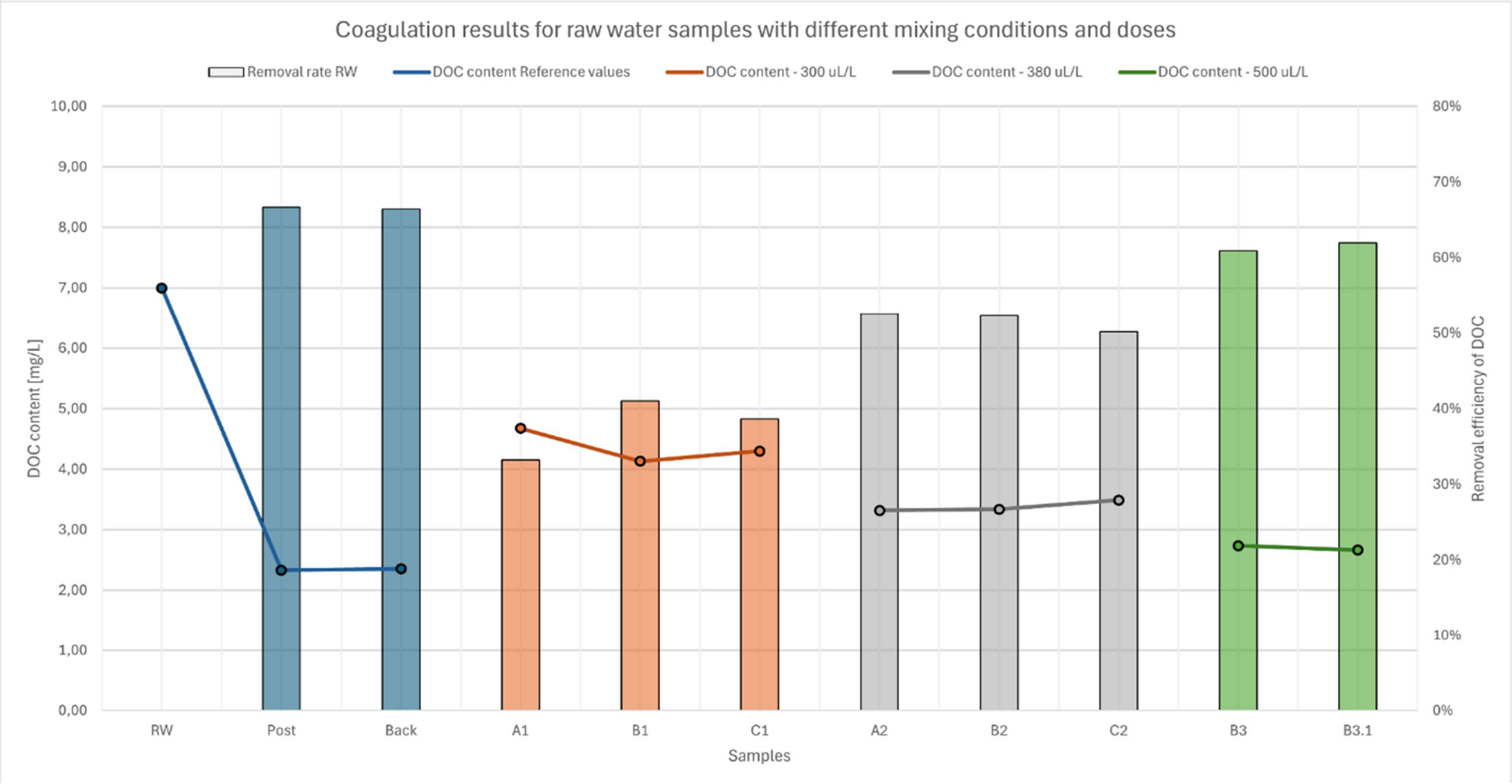

Figure 4.5: DOC content and removal efficiency for raw water samples treated using different coagulation conditions and doses. The bars represent the DOC removal efficiencies for specific mixing conditions and coagulant doses. The blue line corresponds to the DOC content measured at the treatment plant, and is used as a reference to compare with the laboratory experiments. The other lines represent the final DOC content post-coagulation in the laboratory.

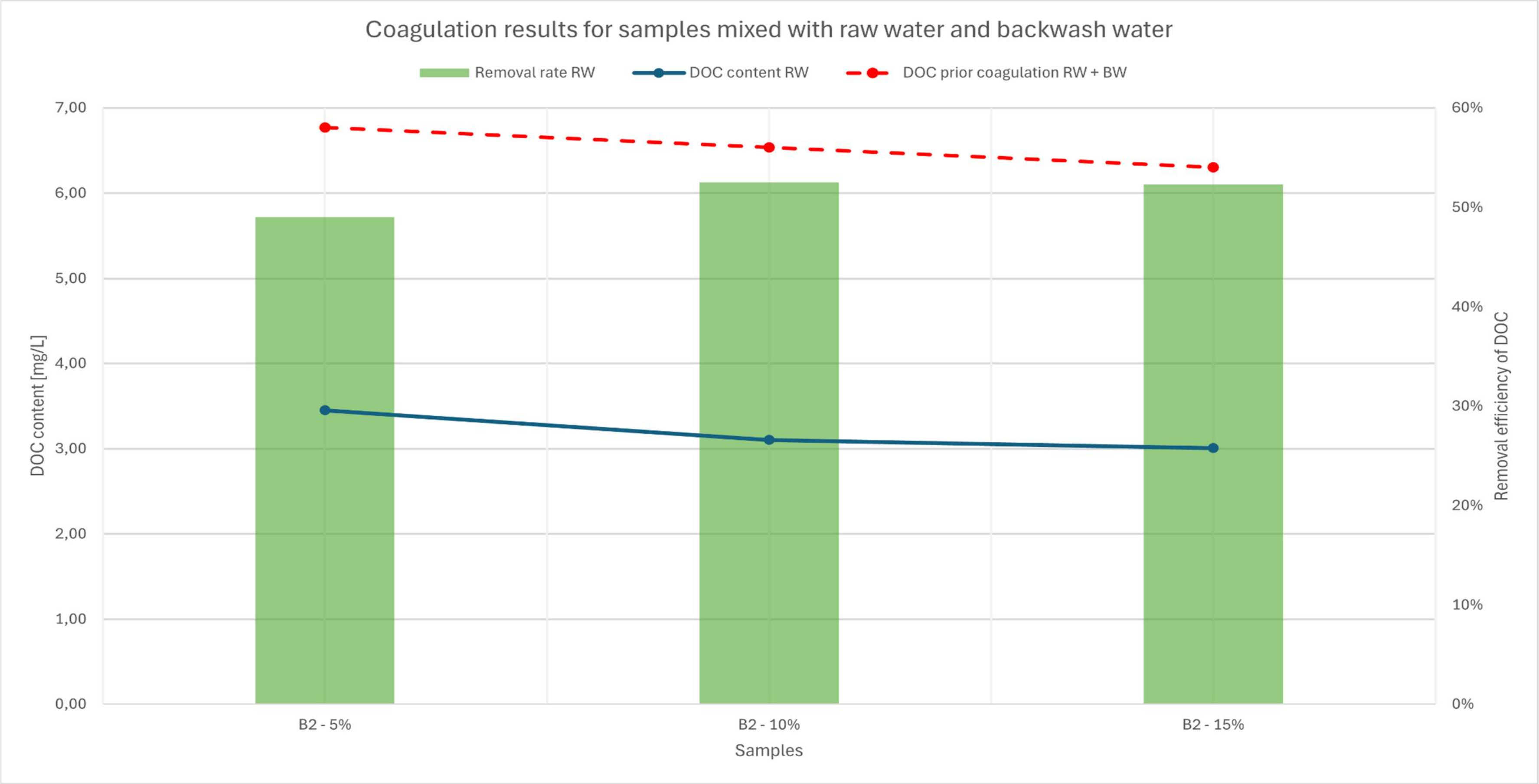

Figure 4.6: Coagulation results for raw water samples mixed with increasing proportions (5%, 10%, and 15%) of backwash water (BW) under B2 mixing conditions. The bars represent the DOC removal efficiency, the dashed red line shows DOC concentration prior to coagulation and the solid blue line indicates post-coagulation DOC concentration.

4.1.3 Final coagulation assessment

In the final set of experiments, the same amount of coagulant was added to each sample as in the treatment plant, i.e., 564 µL/L. Figure 4.9 shows the DOC concentration before and after coagulation and the percent DOC removal.

Compared to previous experiments, the raw water had a lower initial DOC concentration of 5.76 mg/L. At the WTP, DOC removal prior to filtration was around 60%. The samples containing the two water types showed similar trends to previous experiments, even though the 15% backwash sample ended with a higher DOC concentration than the 10% experiment. Moreover, the removal at the treatment plant was measured to be between 5-10% better than what was recorded in the laboratory, which was considered an acceptable outcome due to known difference in treatment rates between jar testing and at the waterworks (Saxena et al., 2020). When comparing the results from the raw water sample (0%) with the other mixed samples (5, 10, 15%) no negative impact was observed, neither in the final DOC removal nor floc formation and settling, suggesting that backwash does not affect negatively the coagulation process. These results align with earlier research (Tobiason et al., 2003; USEPA, 2001). Moreover, the 100% sample with backwash showed a further decrease in DOC, although low, while the high turbidity and colour observed at the beginning resulted in complete settling of the flocs. Further discussion about the turbidity removal is described in section 4.3.2. Figures 4.7 and 4.8 visually illustrates the floc formation following the sedimentation step for this set of experiments.

Figure 4.7: End of sedimentation process and floc formation in samples containing different proportions of backwash (left to right: 5%, 5% and 10%).

Figure 4.8: End of sedimentation process and floc formation for samples 10%, 15% and 15% - from the left.

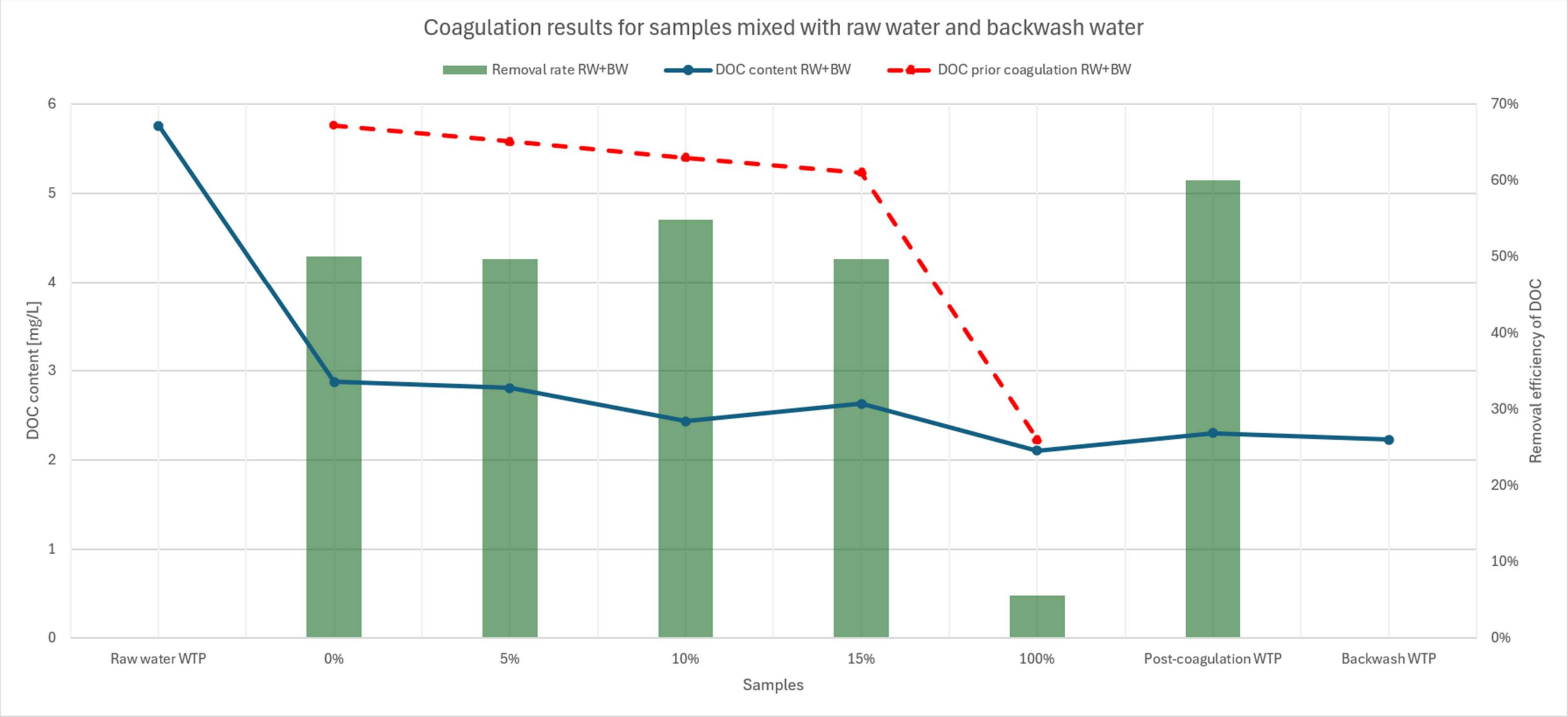

Figure 4.9: Coagulation results for raw water samples mixed with increasing proportions (5%, 10%, and 15%) of backwash water (BW) under B2 mixing conditions. The bars represent the DOC removal efficiency, the solid blue line indicates post-coagulation DOC content, and the dashed red line shows DOC content prior to coagulation.

4.2 NOM quality

The quality of NOM was identified by measuring the UV_{254} absorbance of samples (mixing ratios 5%, 10%, 15%), Raw water, Post-coagulation, and Backwash water. Figure 4.10 shows how the SUVA decreases for the post-coagulation sample and backwash water compared to the raw water. The mixing ratio samples showed a decrease in initial SUVA, as expected.

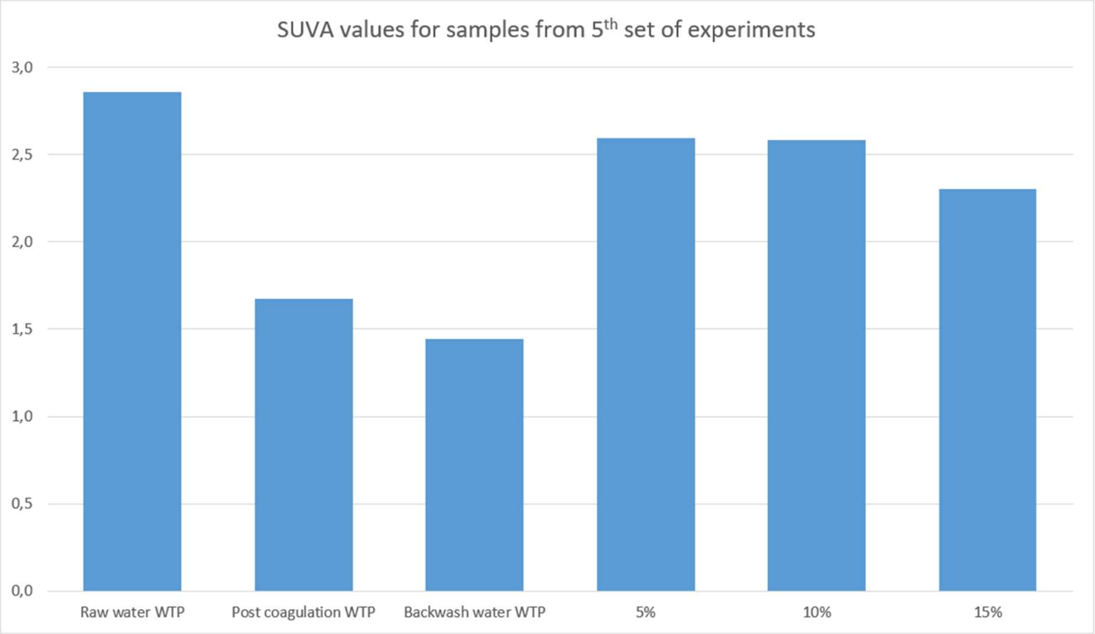

Figure 4.10: Relationship between SUVA and DOC removal for samples (mixing ratios 5%, 10%, 15%), Raw water and Backwash water from experiment set 5.

4.3 Floc characterisation

4.3.1 Floc size analysis

Figure 4.11 shows pictures of 5%, 10%, 15% and RW samples during the sedimentation process – 41 minutes after the coagulant addition. The floc formation across the coagulation-flocculation and sedimentation processes is visually shown in detail in the Appendix (Section 8).

Other than an increase in floc density, the samples containing SFBW appeared to form larger aggregates. This may be a result to the particles in the backwash water already being destabilized according to the neutral pH of water (around 6.3). Even with as little as 5% of backwash water, the formation of larger and denser flocs compared to the raw water sample was visible. Floc size appeared to increase with increasing volume of SFBW.

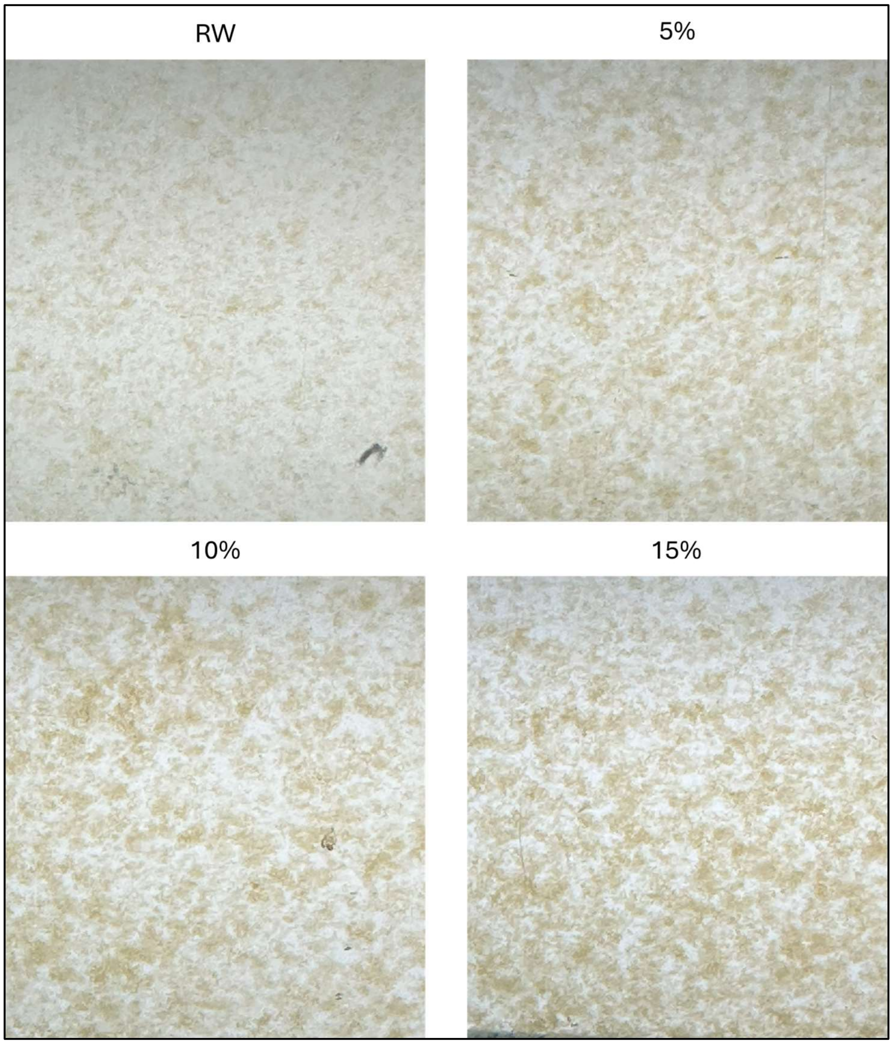

Figure 4.11: Comparison of the floc density and floc size in samples containing different concentrations of SFBW.

4.3.2 Turbidity

Table 4.1 presents the results from the turbidity measurements during the experiments from set 5. During the flocculation process (time 30 minutes), all samples showed similar turbidity values, which decreased at the beginning of the sedimentation process (41 minutes) apart from in the 10%, Raw water and Backwash water samples.

The increase in turbidity at 41 minutes for some of the samples compared to others, may be due to floating flocs on the surface that did not settle given the motion of the impellers during the flocculation process.

By 70 minutes (end of sedimentation), the turbidity levels for all samples decreased significantly, with values below 3 FNU. These final results suggest there was low impact of backwash water on the coagulation process.

Table 4.1: Turbidity measurements during the coagulation, flocculation and sedimentation processes. All values are expressed in FNU units.

Time [min]	5%	10%	15%	Raw water	Backwash water
30	7	9	9	6	7
41	4	14	6	6	17
70	1	1	2	0	3

4.3.3 Mass backwash sludge

To estimate the sludge production due to returning SFBW to the treatment line, a sample containing water from the beginning, middle and ending of the backwash cycle was analysed. This sample was filtered through a 0.7 µm filter paper to capture suspended solids present in the sample. Table 4.2 shows the estimated sludge production, based on the total annual backwash volume reported by the utility company. Figure 4.12 shows the filter containing the particles larger than 0.7 µm.

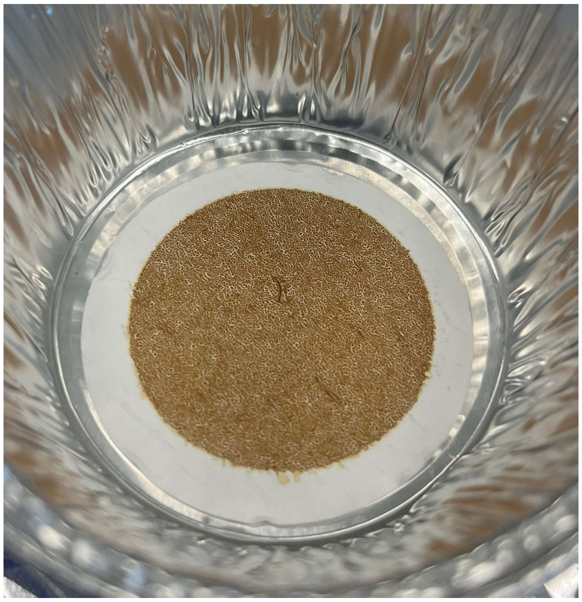

Figure 4.12: Filter paper containing particles larger than 0.7 µm from the SFBW sample.

Table 4.2: Estimated sludge from the backwash process returning to the treatment line. The value for the SFBW volume produced per year was provided by the waterworks.

Parameter	Value	Unit
Mass sludge	9,4	mg
Volume backwash water filtered	200	mL
Sludge density = Mass / Volume	0,047	kg/m^3
Backwash volume produced per year	703777	m^3/year
Mass sludge at the WW	33078	kg/year

4.3.4 Settling velocity

To assess whether suspended particles in SFBW benefited from coagulation, settling tests were conducted by comparing samples with and without coagulation and by measuring the settling time. The results from Table 4.3 show a clear difference between samples, where the non-coagulated sample did not have any visible flocs, although a thin yellow sediment layer appeared at the bottom of the beaker after approximately 90 minutes. The coagulated sample formed instead large flocs that settled within 5 minutes.

Assuming similar floc density and water temperature and applying Stokes' law, the settling time depends only on the floc size. Table 4.3 shows examples of the relationship between the different parameters, where the settling velocity increases with increasing particle diameter. Although the floc size was not measured empirically, the results show the high effectiveness of coagulation even on the SFBW.

Table 4.3: Comparison of settling parameters for SFBW samples with and without coagulation. The settling velocity was calculated from theory assuming a particle diameter and density and water temperature. The settling time was measured in the laboratory.

Parameters	No coagulation	With coagulation	Units
Settling velocity	4,63E-05	8,33E-04	m/s
Highest particle density	1200	1200	kg/m^3
Diameter	23	99	µm
Viscosity of water	0,001307	0,001307	kg/m*s
Water density	997	997	kg/m^3
Gravity	9,81	9,81	m/s^2
Water level	0,25	0,25	m
Settling time	90	5	minutes

5 Discussion

Several results in this study are relevant for determining the impact of the SFBW on the treatment line in case of recirculation. The following subchapters aim at discussing the results, including considerations for the implementation of the recirculation system at the treatment plant.

5.1 Key findings

5.1.1 Impact of backwash recirculation

The coagulation experiments aimed to evaluate how blending SFBW with raw water could influence the coagulation efficiency.

The SFBW from the treatment plant showed difference in water quality according to the time step the water sample was collected. Samples from the beginning of the backwash cycle showed higher particle concentration, which resulted in faster particle aggregation and settling. On the other hand, samples from the end of the backwash cycle contained fewer visible particles. However, the DOC concentration was similar in both collected samples and was lower compared to the DOC in raw water. This suggested that the particles in the backwash water did not dissolve in the water even under high turbulence conditions.

When SFBW was mixed with raw water, no significant change was observed in DOC removal efficiency compared to the raw water sample. This was unchanged across different dosages. The coagulation process on the SFBW sample alone showed visible floc formation, although the DOC removal was measured to be low (<10%). This outcome can be attributed to the neutral particle surface charge of the flocs in the backwash, due to the neutral pH of the SFBW (Tobiason et al., 2003). Moreover, the SUVA value for the backwash water sample was around 1.45, indicating an organic matter composition that is difficult to remove by conventional treatment processes.

The mixing conditions in the lab were adjusted to verify how much they would affect the final results. Mixing conditions were important; however, the coagulant dosage played a more crucial role in determining the removal efficiency.

5.1.2 Floc dynamic

Investigating the floc dynamic with the addition of SFBW provided insights into the expected impact of recirculated backwash on floc formation and their settling rate. By only adding 5% SFBW, a notable increase in floc density and size was observed. This effect increased with higher SFBW volumes. This may suggest that particles present in the SFBW help forming bigger aggregates, leading to faster settling of the flocs. Turbidity measurements showed that regardless of the SFBW content, turbidity remained low at the end of the sedimentation step, ranging between 0 to 3 FNU.

With 100% return of SFBW into the treatment line, more sludge is expected to settle in the sedimentation and flocculation tanks. To study the impact of returning backwash, homogenous water quality from the backwash cycle was filtered using a 0.7 μm filter paper, estimating the suspended solids that would contribute to sludge accumulation. This value can be used as an initial estimate for tank clean up before knowing empirically how much sludge from the recycling stream would settle and hinder an optimal water quality.

5.2 Operational implications for recirculating SFBW

When considering the implementation of recycling SFBW in the treatment plant, several operational aspects must be accounted for to ensure optimal process efficiency.

Recirculating backwash water into the treatment line would increase the mass of suspended solids re-entering the treatment line, resulting in higher sludge accumulation in the flocculation and sedimentation tank. Minor volumes could be expected to reach the filtration process, which is not desirable. Even though the treatment plant already operates a scheduled sludge removal protocol, the sludge production from the SFBW would require a new planning system. The estimated sludge production from a 100% SFBW scenario presented above serves as a mere guideline. The treatment plant should monitor the sludge build up and implement a new sludge removal protocol. The plant should prevent excessive accumulation, as turbulent flow caused by the mixing process could resuspend the flocs and worsen the final water quality; furthermore, the resuspended flocs trapped in the GAC filter would require more frequent backwash.

The variability in backwash water quality should also be considered when designing a recirculation system. If SFBW would directly be returned to the treatment line, inconsistencies in water quality could affect the coagulant demand and the flocculation efficiency. Moreover, no monitoring step of the backwash water quality would be possible prior to blending it with the raw water. It is therefore desirable to return a more homogenized backwash stream, allowing better control and monitoring of the water quality, hence better estimation of the coagulant demand and analysis of potential presence of unwanted compounds or pathogens in the water.

An effective solution to ensure homogeneous water quality is the implementation of equalization tanks. The U.S. Environmental Protection Agency (EPA) recommends a minimum retention time of 24 hours in the tanks before returning the backwash stream to the treatment line. For the studied treatment plant, a volume of 1928 m^3 would be required to comply with the recommendations by EPA. While the benefits of implementing equalization tanks include improved water quality safety and coagulation predictability, such a solution requires additional space and maintenance. Furthermore, frequent monitoring of the water quality in the tanks would be required.

For operational flexibility, the equalization tank should be designed with a bypass line connected to the sewer system. The by-pass would be active in scenarios where the SFBW quality is not acceptable for returning to the treatment line, maintenance of the equalization tank is required, or the treatment plant would temporarily not have enough capacity to receive SFBW.

The backwash water stream from the equalization tank should be regulated according to the treatment line capacity, backwash- and raw water quality. Laboratory experiments showed that even at high percentages of SFBW, the efficiency of the coagulation process was unchanged. However, higher return rates – above 10-15% - may impact coagulation and flocculation efficiencies due to pH disruption and high concentrations of solids. Moreover, high return rates could potentially lead to highly dense flocs, which would not allow quick settling. A brief review of the literature suggested a maximum return of 10% (Tobiason et al., 2003; USEPA, 2001).

6 Conclusion and recommendations

This thesis evaluated the impact of recirculating spent filter backwash water (SFBW) from a granular activated carbon (GAC) filtration step in a drinking water treatment plant in Sweden. The aim was to assess how backwash affects the conventional treatment processes – coagulation, flocculation and sedimentation processes. The treatment plant receives water from a surface water body, where the removal of natural organic matter (NOM) and microbes is of utmost importance.

Literature review revealed the potential of returning backwash alongside its limitations. Improvements in the formation of larger flocs were observed at pH levels of around 6, as the particles are already destabilized. In contrast, backwash with higher pH requires an increase in coagulant dosing to maintain performance.
In this study, backwash water had a stable pH of 6.2-6.3, therefore ideal conditions for optimal recirculation.

During sampling of the backwash water, it was observed how heterogeneous the water quality was, where the beginning of the backwash cycle contained much higher concentrations of suspended solids compared to the end of the process. Laboratory work was carried out studying the effects of blending SFBW and raw water at different ratios based on DOC removal, turbidity, and floc characterization. SUVA was also calculated to evaluate the treatability of the organics present in the samples.

Results showed that backwash water had lower DOC concentrations and SUVA compared to raw water, indicating that the organics in SFBW would not be easily removed through coagulation. The DOC removal efficiency was consistent for the remaining samples, regardless of the mixing ratios. The backwash was observed to dilute the DOC levels in the samples, rather than improving its removal efficiency. Moreover, turbidity was measured at the end of the sedimentation step, with acceptable levels across all samples.

The flocs formed in the 5%, 10%, 15% SFBW, raw water and backwash water samples were visually compared, showing clear increase in floc density with increasing backwash content.

These results align fully with published literature, indicating the feasibility of implementing a recirculation step at the treatment plant. However, further evaluation is needed to assess the impact on microbial load and potential contaminants that have not been addressed in this thesis.

A pilot scale plant should be implemented to investigate whether the SFBW would benefit from a pre-treatment step prior returning to the treatment line. An equalization tank is recommended as it would not only contribute to achieving a more homogeneous water quality, but would allow the installation of monitoring control systems, as well as the implementation of emergency systems and by-pass lines to the sewer.

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8 Appendix

The following figures illustrate the floc formation and settling for mixed samples (5%, 10%, 15%), raw water (RW), and backwash water (BW) samples throughout the coagulation-flocculation-sedimentation processes.

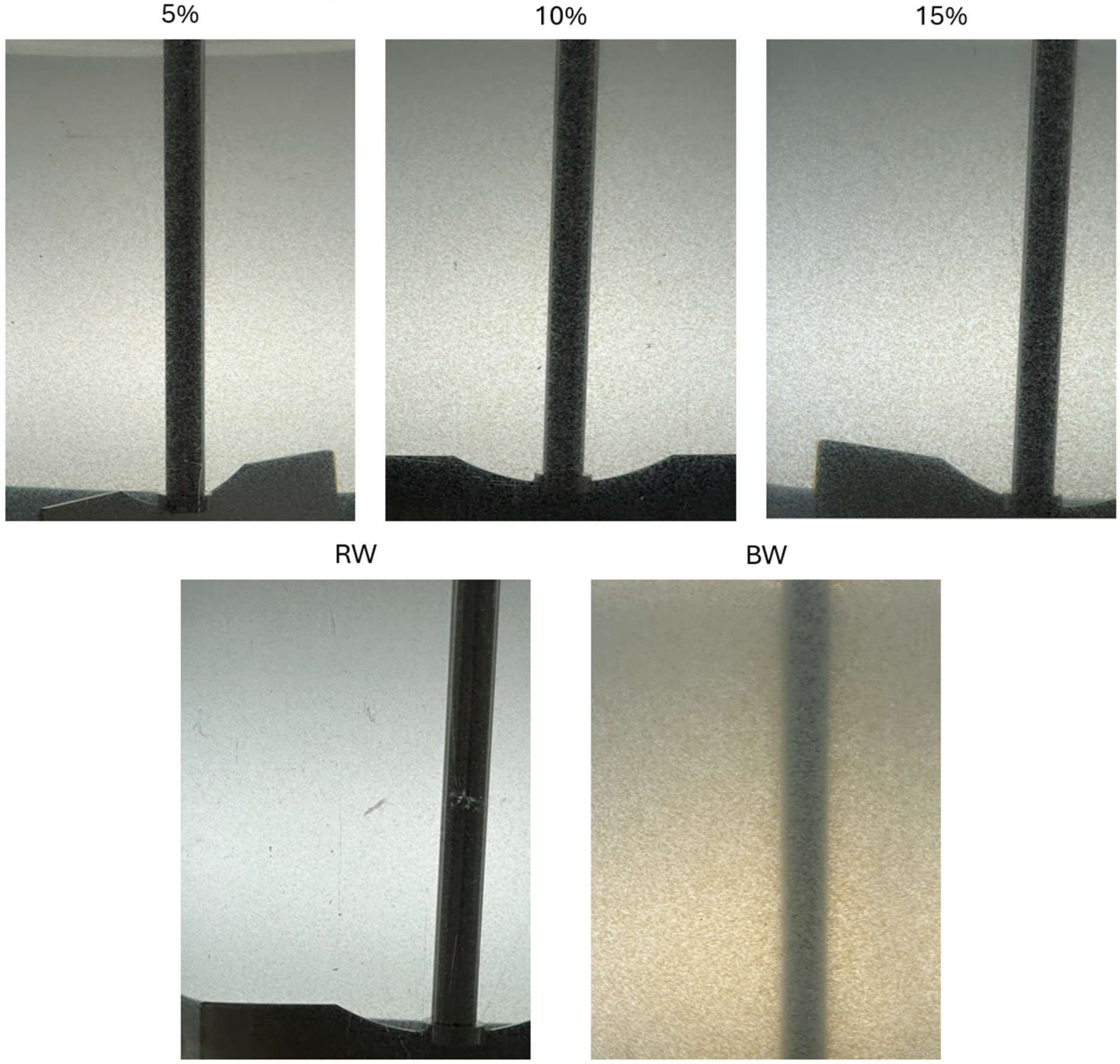


Figure 8.1: Floc formation 9 minutes in the coagulation process.

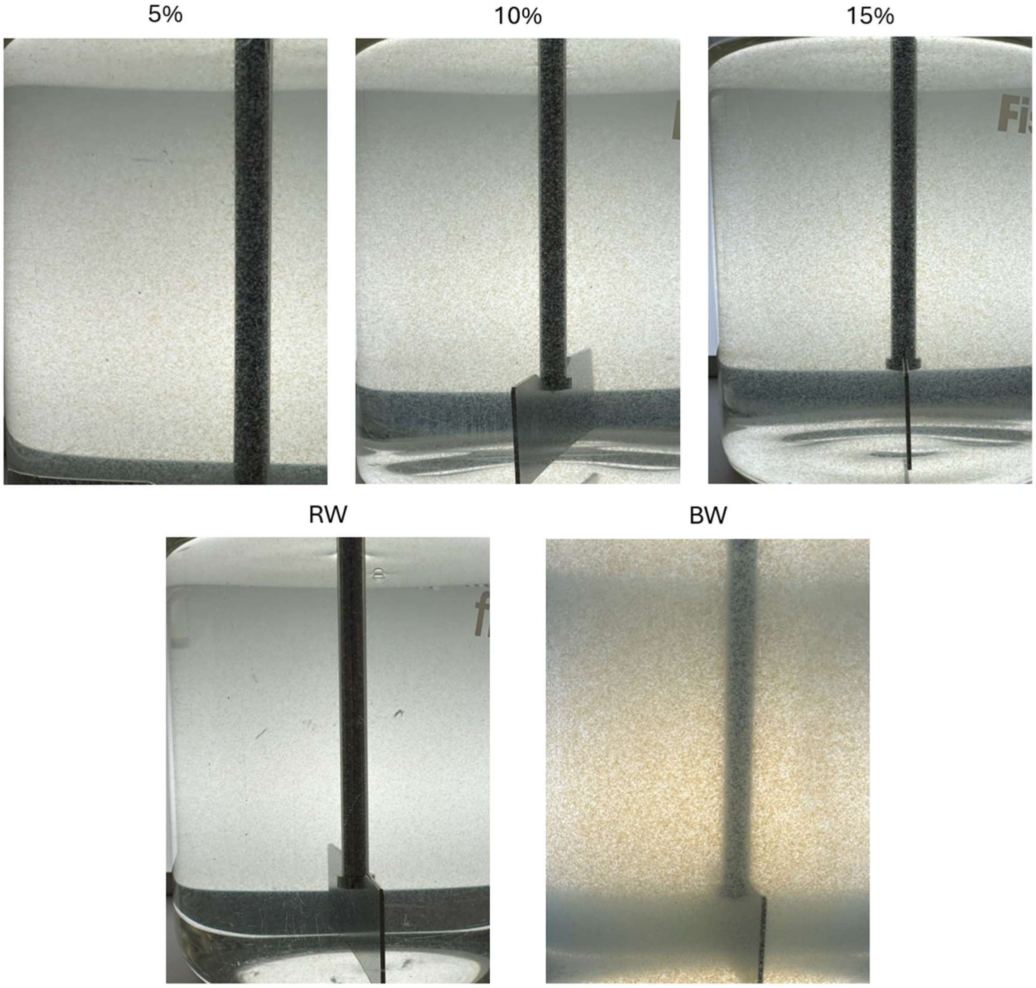


Figure 8.2: Floc formation 14 minutes in the coagulation process.

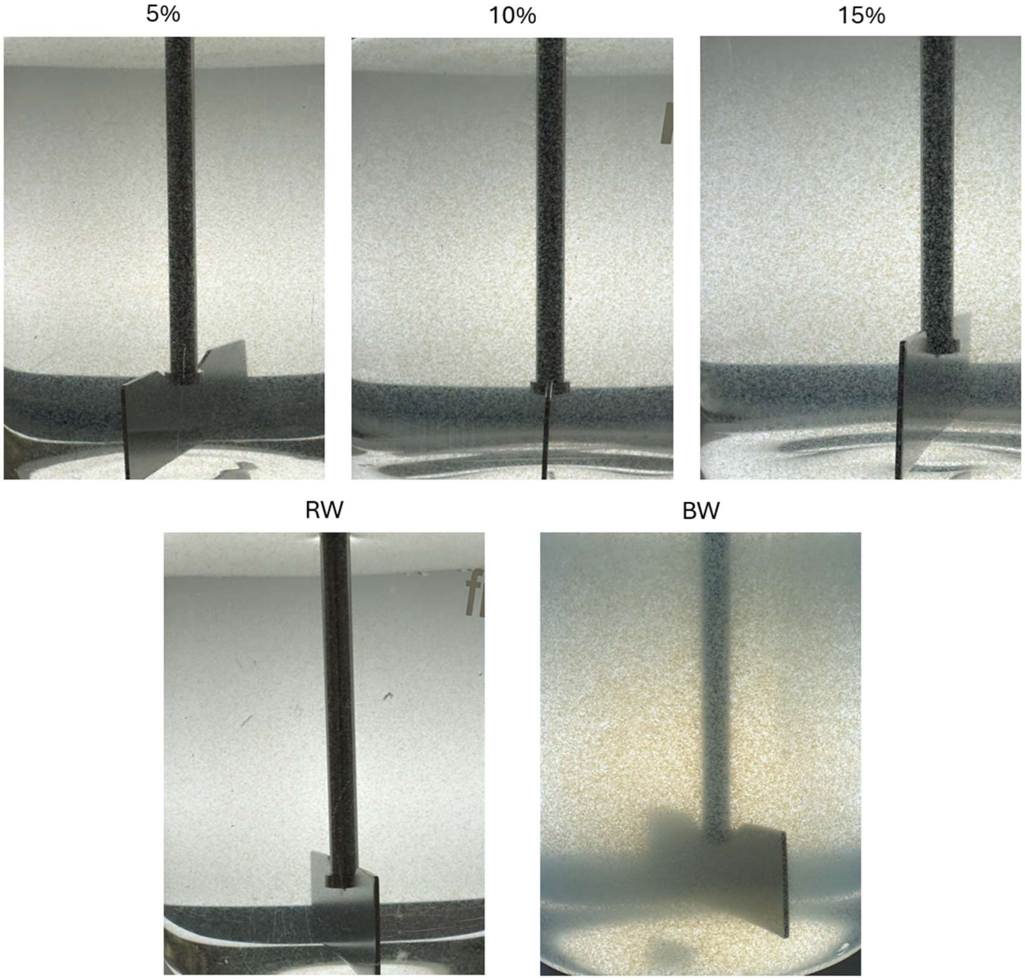


Figure 8.3: Floc formation 21 minutes in the coagulation process.

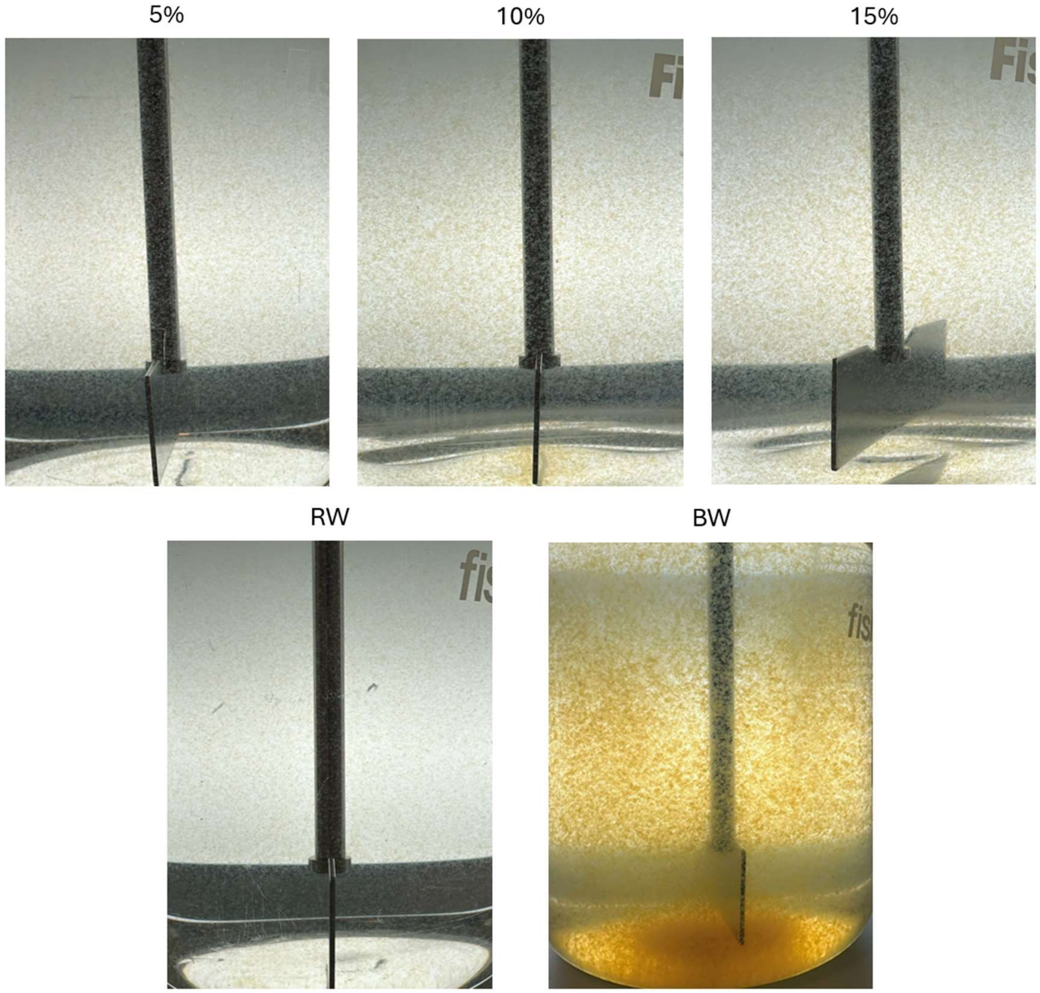


Figure 8.4: Floc formation 26 minutes in the coagulation process.

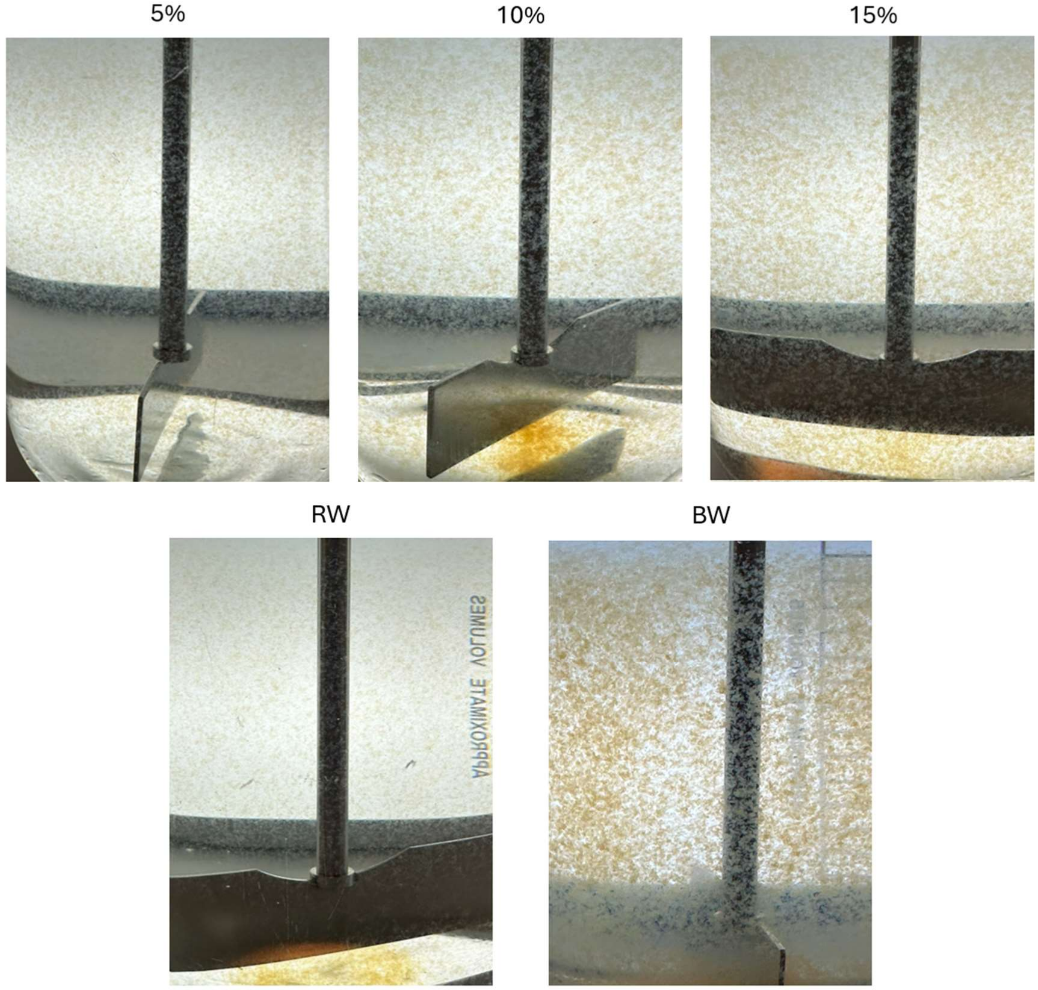
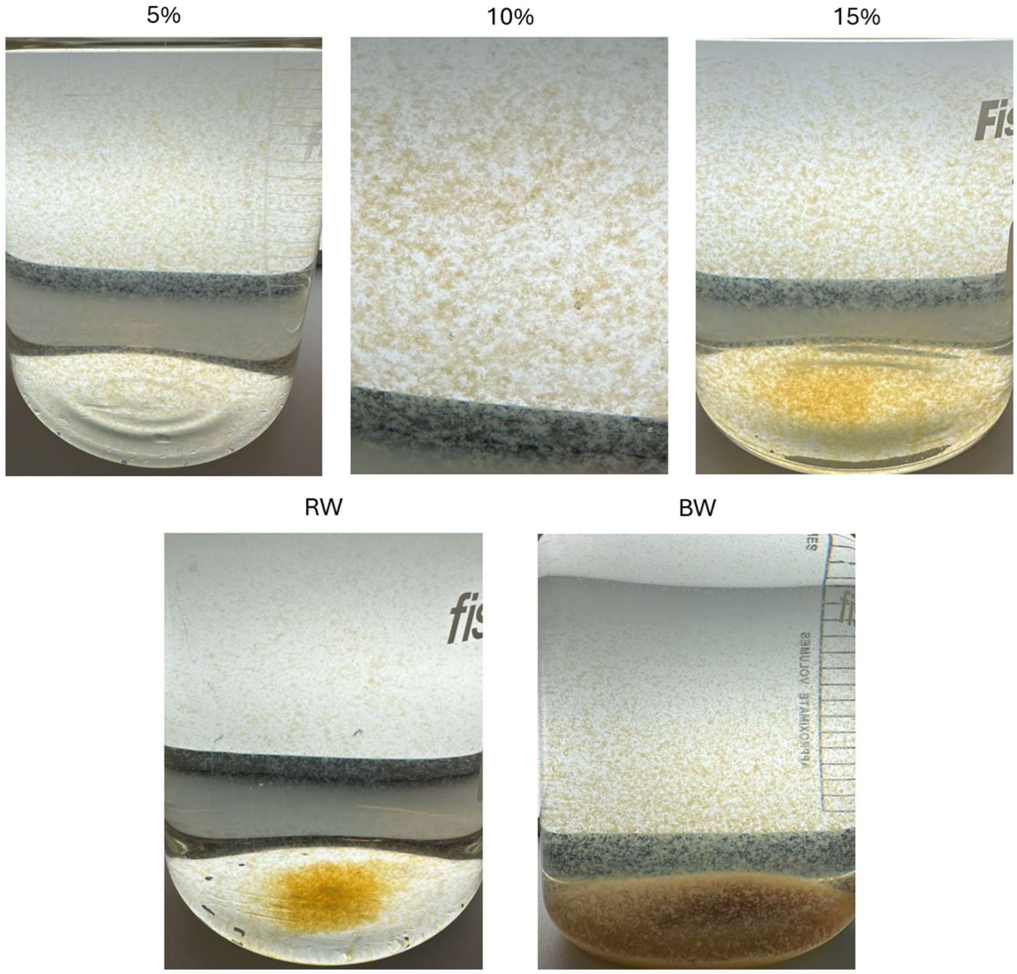


Figure 8.5: Floc settling 30 minutes in the coagulation process.



5% 10% 15%

RW BW

Figure 8.6: Floc settling 41 minutes in the coagulation process. The raw water sample experienced a faster settling rate of flocs. In fact, it was observed that the speed of the impeller – set at 10 rpm – operated at lower rpm compared to the other impellers of the flocculator machine. This allowed the flocs to settle prior other samples.

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