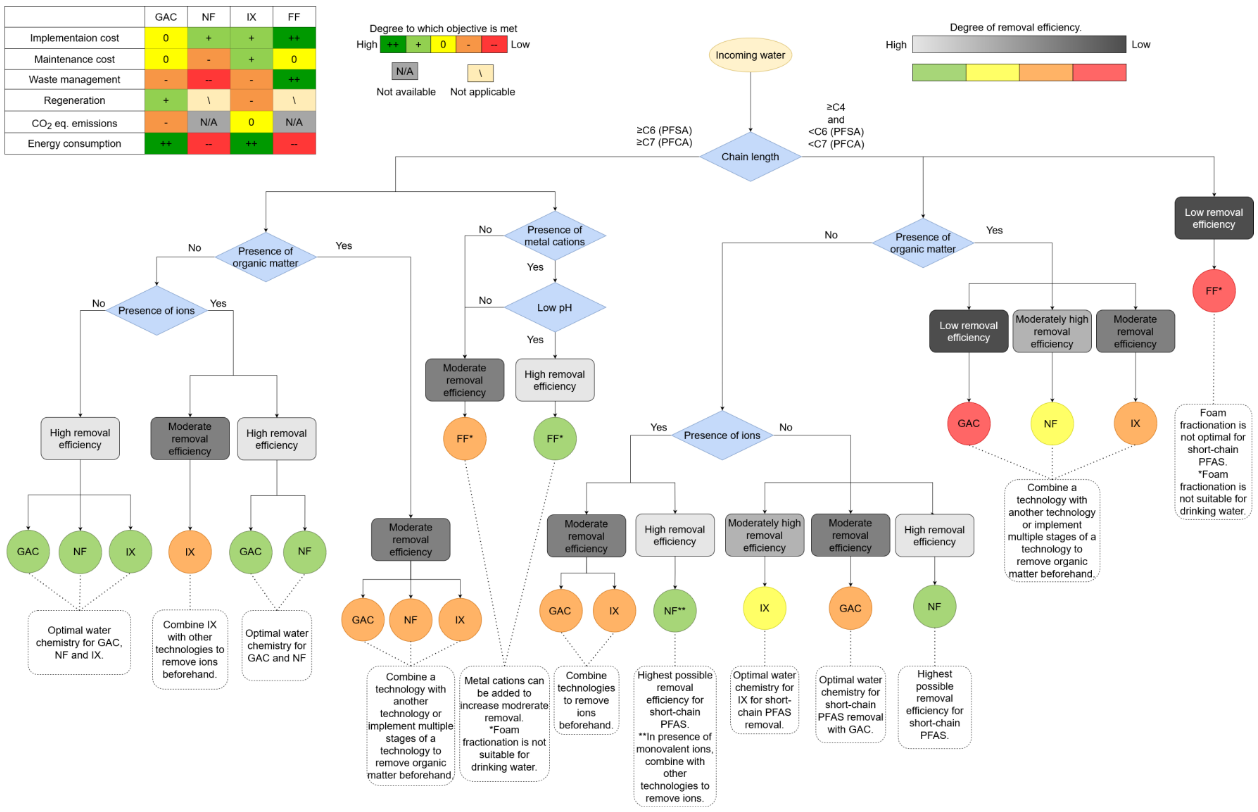

Technology Selection for Removal of PFAS from Raw Water for Drinking Water Purposes

Master's thesis in the master's Programme Infrastructure and Environmental Engineering

FRIDA HANSSON
LISA WU

DEPARTMENT OF ARCHITECHTURE AND CIVIL ENGINEERING
DIVISION OF GEOLOGY AND GEOTECHNICS

CHALMERS UNIVERSITY OF TECHNOLOGY
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MASTER’S THESIS ACEX30

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Chalmers tekniska högskola, 2024

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Cover:
Schematic decision support flowchart depicting how the technologies are affected by water chemistry with support from sustainability performance analysis.

Department of Architecture and Civil Engineering
Göteborg, Sweden, 2024

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ABSTRACT

Per- and polyfluoroalkyl substances (PFAS) are a synthetic group of chemicals that can be harmful for humans and the environment. The use of PFAS has caused the presence of it in drinking water. Two thirds of the groundwater sources in Sweden have found to be contaminated with PFAS. To limit PFAS in drinking water, the European Food Safety Authority, EFSA, has introduced a guideline of 4 ng/L for PFAS 4 and 100 ng/L for PFAS 21 which will be implemented 2026. This study investigates technical and sustainability performance of the technologies Granular Activated Carbon (GAC), Nanofiltration (NF), Ion Exchange (IX) and Foam Fractionation (FF). The study has been performed through a literature study with help from databases such as Web of Science using search strings. The results were presented in a flowchart and a table with results from the sustainability performance analysis. Granular activated carbon and IX alone or in combination with each other or other technologies were to be suggested in the majority of the cases. Nanofiltration showed to have high performance in many aspects, including for short-chained PFAS, with a disadvantage of highly concentrated waste stream that needs further treatment. Foam fractionation needs specific conditions for proper performance but is not suitable for drinking water treatment purposes.

Key words: PFAS, nanofiltration, granular activated carbon, foam fractionation, ion exchange, operation and maintenance cost, decision-support, drinking water, water treatment.

Val av reningsteknik för borttagning av PFAS från råvatten för dricksvattenproduktion

Examensarbete inom mastersprogrammet infrastruktur och miljöteknik

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SAMMANFATTNING

Per- och polyfluoralkylämnen (PFAS) är en syntetisk grupp av kemikalier som kan vara skadliga för människor och miljön. Användningen av PFAS har orsakat att det finns i dricksvatten. Två tredjedelar av grundvattenkällorna i Sverige har visat sig vara förorenade med PFAS. För att begränsa PFAS i dricksvatten har Europeiska myndigheten för livsmedelssäkerhet, EFSA, infört en riktlinje på 4 ng/L för PFAS 4 och 100 ng/L för PFAS 21, som kommer att implementeras 2026. Denna studie undersöker teknisk prestanda, såväl som ekologisk och ekonomisk hållbarhet för teknologierna granulärt aktivt kol (GAC), nanofiltrering (NF), jonbytare (IX) och skumfraktionering (FF). Studien har utförts genom en litteraturstudie med hjälp av databaser som Web of Science där söksträngar har använts. Resultaten presenterades i ett flödesschema och en tabell med resultat från hållbarhetsprestandaanalysen. Granulärt aktivt kol och IX, ensamma eller i kombination med varandra eller andra teknologier, föreslogs i majoriteten av fallen. Nanofiltrering visade hög prestanda i många aspekter, inklusive för kortkedjiga PFAS, med en nackdel av en högkoncentrerad avfallsström som behöver ytterligare behandling. Skumfraktionering behöver specifika förhållanden för att fungera korrekt, men är inte lämplig för dricksvattenreningsändamål.

Nyckelord: PFAS, nanofiltrering, granulärt aktivt kol, skumfraktionering, jonbytare, underhållskostander, beslutsstöd, dricksvatten, vattenrening.

Contents

Preface

In this report, a literature study was conducted through January 2024 and June 2024. The project has been conducted at the Department of Architecture and Civil Engineering, Engineering Geology, at Chalmers University of Technology, Sweden in collaboration with Norconsult AB.

The project has been carried out with Jenny Norrman as supervisor and Andreas Lindhe as examiner from Chalmers University of Technology, and Stephan Köhler as supervisor from Norconsult AB.

We would like to thank Stephan Köhler for his expertise, encouragement and enthusiasm towards the work and the field, Jenny Norrman for an exceptional guidance throughout the thesis and together with Andreas Lindhe for the advice we have received. We would also like to thank Emma Johansson from Laholmsbuktens AB and Ludwig Hedberg from Norconsult AB for providing us with much needed information in the field. At last, we would like to thank Chalmers University of Technology and Norconsult AB for making it possible for us to carry out this thesis.

Göteborg, June 2024

Frida Hansson & Lisa Wu

Abbreviations

GAC – Granular Activated Carbon
NF – Nanofiltration
IE – Ion Exchange
FF – Foam Fractionation
PFAS - Per- and polyfluoroalkyl substances
PFCA - perfluoroalkyl carboxylic acids
PFSA - perfluoroalkane sulphonic acids
PFOS - Perfluorooctanesulphonic acid
PFOA - Perfluorooctanoic acid
PFHxS - Perfluorohexanesulphonic acid
PFNA - Perfluorononanoic acid
PFDA - Perfluorodecanoic acid
PFUnDA - Perfluoroundecanoic acid
PFDoDA - Perfluorododecanoic acid
PFTrDA - Perfluorotridecanoic acid
6:2 FTS - 6:2-fluorotelomersulfonic acid
PFBS - Perfluorobutanesulphonic acid
PFBA - Perfluorobutanoic acid
PFPeS - Perfluoropentanesulphonic acid
PFPeA - Perfluoropentanoic acid
PFHxA - Perfluorohexanoic acid
PFHpA - Perfluoroheptanoic acid
PFHpS - Perfluoroheptanesulphonic acid
PFNS - perfluorononane sulphonic acid
PFDS - perfluorodecane sulphonic acid
PFUnDS - perfluoroundecane sulphonic acid
PFDoDS - perfluorododecane sulphonic acid
PFTrDS - perfluorotridecane sulphonic acid
TOC - Total organic carbon
DOC – Dissolved organic carbon
NOM – Natural organic matter
DOM – Dissolved organic matter
AFFF – Aqueous Film Forming Foam

1 Introduction

In this chapter an introduction to the subject will be presented followed by the aims and objectives with this thesis. Lastly, limitations of the study will be discussed.

1.1 Background

Per- and polyfluoroalkyl substances, PFAS, are chemicals that have been used since the 1930s and are still commonly used today [1]. PFAS consists of a large and complex group of fluorinated substances that are often used in coatings for products made to resist water, heat, and oil [2]. The substances are synthetic chemicals that can be harmful to both humans and the environment as they accumulate over time. Additionally, PFAS do not break down in the environment and are readily bound to soils and can eventually reach groundwater sources. Due to its persistence in nature, occurrence of bioaccumulation in fish and wildlife is also a possibility.

PFAS are PBT substances (Persistent, Bioaccumulative and Toxic). Due to PFAS being used in various products and being a PBT substance, most people have PFAS in their bodies [3]. High levels of PFAS can be found in food as well as drinking water and indoor environments. When it comes to PFAS in drinking water, the water has +most likely originated from groundwater with high contamination levels. Two thirds of the groundwater resources in Sweden have been found to be contaminated with PFAS at various levels, both high and low [4]. The health effects of PFAS are uncertain but studies have shown that PFAS could have a negative impact on human health [5]. Possible risks include decreased fertility in women, increased risks of prostate cancer and kidney cancer, interference with the body's natural hormones as well as increased risk of obesity and increased cholesterol levels among others [6]. To limit PFAS in drinking water, the European Food Safety Authority, EFSA, has introduced new, stricter guideline values (4 ng/L for PFAS 4 and 100 ng/L PFAS 21) which will be implemented in 2026 [7]. As the guidelines have been introduced there is a need for adapting and improving the drinking water treatment process.

Today, there are various technologies available for removing PFAS substances from raw water. These include Granular Activated Carbon (GAC), Ion Exchange (IX), membrane treatment using nanofiltration (NF) and foam fractionation (FF). There are several factors that could influence the choice of the optimal treatment, e.g. the chemical composition of the raw water, technology performance and limitations, energy requirements as well as waste stream management.

Granular activated carbon has long been used to eliminate unwanted substances in raw water. This process is easy to implement and well-known. Ion exchange is a treatment that has been used for many years within industrial applications and is based on removing unwanted ions from the water [8]. For GAC and IX, water chemistry affects how long the treatment operates before the material needs replacement. Nanofiltration is a membrane treatment using pressure to separate soluble ions from the water [9]. For NF, the removal of PFAS substances is affected by the size of the membrane pores, which in turn impacts the necessary pressure and thus the energy required. Foam fractionation can also be utilized to separate PFAS where water is subjected to air bubbles that bind PFAS, and thus separated from the water phase [10]. Foam fractionation is very compact, but has a high energy demand. For PFAS substances with lower molecular weight, all the above technologies have a lower performance.

Knowledge regarding the limitations of different technologies is not readily available for water treatment plants and choosing an optimal treatment process can be difficult. At the same time, the water sector has been urged to develop and implement more sustainable treatment processes and many new technologies and developments are emerging. Therefore, there is a need for easily accessed information regarding the performance of a technology and its sustainability. When evaluating potential solutions, it is important to review multiple aspects of sustainability, such as technical, environmental, social, and economic, to gain extensive knowledge regarding the long-term sustainability of a certain treatment process.

1.2 Aim and Objectives

The overall aim of this study was to develop a decision support tool for selection of the optimal PFAS-treatment technology for drinking water. The literature search results were limited to two main results: a flowchart suggesting which water treatment process is the most suitable considering the raw water chemistry and the results from the sustainability analysis showing the performance of the four water treatment processes according to the economic and environmental aspects. The flowchart and the sustainability performance analysis together build a decision support for development and building of future as well as retrofitting of existing water treatment plants.

The specific objectives were to:

- Collect information regarding the performance of the technologies based on water chemistry.
- Compare performance and disruptions during drinking water treatment and rank the various processes for removing PFAS from different raw water types.
- Compile and present the collected information in a flowchart.
- Quantify energy consumption, costs and environmental impact of the PFAS removal technologies.
- Collect of information regarding carbon footprints for the treatment technologies currently used for PFAS removal.
- Compile and present the sustainability performance of the processes for removing PFAS using a sustainability performance analysis.

1.3 Limitations

The project was limited to four water treatment processes: granular active carbon (GAC), ion exchange (IX), nanofiltration (NF) and foam fractionation (FF). Limitations were set to focus on pilot-scale or full-scale studies and laboratory scale experiments that use small-scale setups were excluded. The research did not include results with simulated samples such as spiking the water with excessive PFAS content. During unavailability of information from larger scale experiments, smaller scales were considered. Furthermore, the research focuses on studies with experiments conducted during longer time periods when available. These limitations were set to ensure that the research was as true to reality as possible with sufficient volumes, flows and time to resemble what potential implementations of the technologies in a treatment process would imply.

Limitations of the study included the time frame of the research. During the study, many articles had to be excluded from the research due to the time limit. There was also a limitation of data, where the different technologies rarely had the same water characteristics to create a fair comparison of the technology performances. Another limitation of data was for environmental impact, as no data of could be for nanofiltration and limited data could be found for ion exchange. During contact with external contacts, there had been no calculations on the carbon footprint for the two technologies in question. Another limitation was the inability to have performed the experiments in full-scale for all technologies.

2 Theory

This chapter includes theoretical information regarding PFAS compounds, PFAS in Swedish water sources, descriptions of drinking water treatment plants and basic knowledge about the four technologies.

2.1 PFAS Compounds

There are thousands of different PFAS compounds [2]. A PFAS compound consists of a fluorinated carbon chain. Where a regular carbon chain would include hydrogen atoms, a fluorinated carbon chain includes fluorine [3]. The compounds can in turn be either perfluorinated compounds or polyfluorinated compounds. Perfluorinated compounds are fully fluorinated carbon chains while polyfluorinated carbon chains are partially fluorinated.

The many different PFAS compounds can be divided into two groups, which are polymers or non-polymers [11]. The difference between polymeric and non-polymeric PFAS is that the non-polymeric PFAS are smaller than the polymeric PFAS and therefore more readily adsorbed by humans, animals and in the environment [12]. Polymeric PFAS can therefore be considered safer than non-polymeric PFAS, with some exceptions. Polymeric PFAS can break down and be degraded in the environment or in manufacturing processes which releases non-polymeric PFAS.

The polymeric and non-polymeric PFAS are in turn divided into more groups. Polymers include fluoropolymers, side-chain fluorinated polymers and perfluoropolyethers [11]. Non-polymers include perfluoroalkyl acids (PFAA), perfluoroalkane sulphonyl fluorides, fluorotelomers and per- and polyfluoroalkyl ethers. The non-polymeric group PFAA includes, among others, perfluoroalkyl carboxylic acids (PFCA) and perfluoroalkane sulphonic acids (PFSA). A general classification of the PFAS compounds can be seen in Figure 2.1.

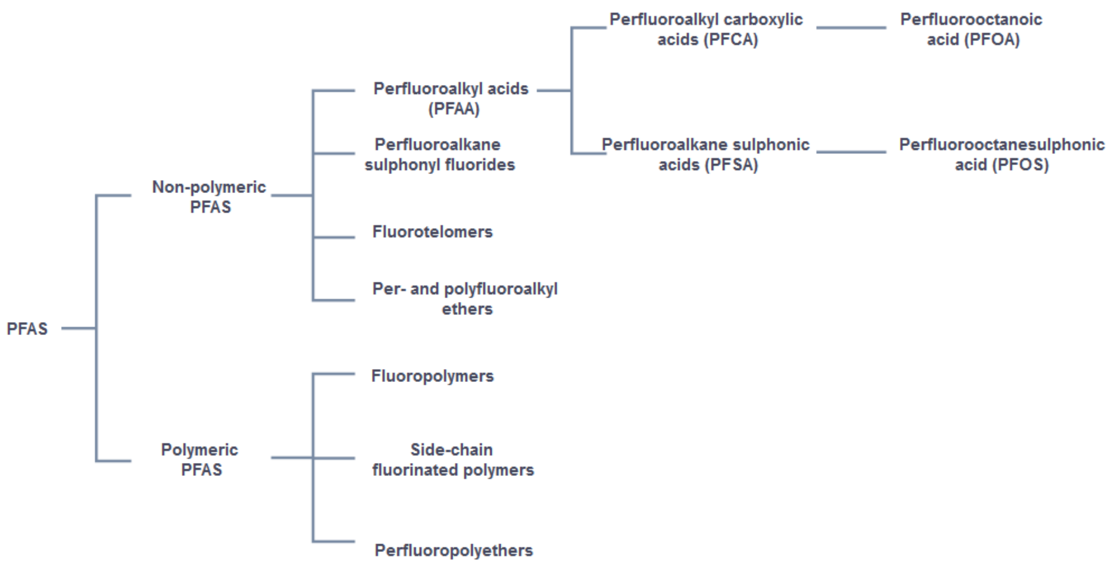


Figure 2.1: A general classification of PFAS.

The compounds of PFCA and PFSA contain functional groups that are bound at the end of the carbon chain [3]. These functional groups can further alter the characteristics of the PFAS compound. The PFCA and PFSA compounds contain a functional group at the end of the carbon chain. In the case of PFCA they contain carboxylic acid as a functional group while PFSA contain sulphonic acid as a functional group. These two groups contain the most common PFAS compounds which are PFOA, with a carboxylic acid functional group, and PFOS, with a sulphonic acid functional group [13]. Other than PFOA and PFOS there are plenty PFAS compounds which are of concern in the various divisions of PFAS compounds.

The compounds can be classified based on the priority to remove them from the environment [14]. The group PFAS 4 consists of the four most toxic and bioavailable compounds and are the most prioritised to remove from the drinking water. Furthermore, there are groups for PFAS 11 and PFAS 21 which consist of the 11 and 21 most prioritised compounds respectively. The 21 PFAS compounds and their respective groups and properties can be seen in Table 2.1: The PFAS compounds included in PFAS 4, PFAS 11 and PFAS 21 and their respective molecular formula, weight, and functional group [16]. PFAS 4 is also included in PFAS 11 and PFAS 21. PFAS 11 is also included in PFAS The new guideline values that will be implemented in 2026 limits discharge of PFAS 4 to 4 ng/L for and 100 ng/L for PFAS 21 [7]. Further recommendations made by the Swedish Food Agency limits PFAS 11 to 90 ng/L [15].

Table 2.1: The PFAS compounds included in PFAS 4, PFAS 11 and PFAS 21 and their respective molecular formula, weight, and functional group [16]. *PFAS 4 is also included in PFAS 11 and PFAS 21. PFAS 11 is also included in PFAS 21.*

<table>
<tr><th>Compound</th><th>Molecular formula</th><th>Molecular weight [g/mol]</th><th>Functional group</th><th colspan="3">Classification</th></tr>
<tr><td>**PFOS**</td><td>$C_8HF_{17}O_3S$</td><td>500.13</td><td>PFSA</td><td rowspan="4">PFAS 4</td><td rowspan="11">PFAS 11</td><td rowspan="21">PFAS 21</td></tr>
<tr><td>**PFOA**</td><td>$C_8HF_{15}O_2$</td><td>414.07</td><td>PFCA</td></tr>
<tr><td>**PFNA**</td><td>$C_9HF_{17}O_2$</td><td>464.08</td><td>PFCA</td></tr>
<tr><td>**PFHxS**</td><td>$C_6HF_{13}O_3S$</td><td>400.11</td><td>PFSA</td></tr>
<tr><td>**PFBS**</td><td>$C_4HF_9O_3S$</td><td>300.10</td><td>PFSA</td><td rowspan="17"></td></tr>
<tr><td>**PFHxA**</td><td>$C_6HF_{11}O_2$</td><td>314.054</td><td>PFCA</td></tr>
<tr><td>**PFPeA**</td><td>$C_5HF_9O_2$</td><td>264.05</td><td>PFCA</td></tr>
<tr><td>**PFHpA**</td><td>$C_7HF_{13}O_2$</td><td>364.06</td><td>PFCA</td></tr>
<tr><td>**PFDA**</td><td>$C_{10}HF_{19}O_2$</td><td>514.086</td><td>PFCA</td></tr>
<tr><td>**6:2 FTS**</td><td>$C_8H_5F_{13}O_3S$</td><td>428.16</td><td>PFSA</td></tr>
<tr><td>**PFBA**</td><td>$C_4HF_7O_2$</td><td>214.039</td><td>PFCA</td></tr>
<tr><td>**PFUnDA**</td><td>$C_{11}HF_{21}O_2$</td><td>564.09</td><td>PFCA</td><td rowspan="10"></td></tr>
<tr><td>**PFDoDA**</td><td>$C_{12}HF_{23}O_2$</td><td>614.10</td><td>PFCA</td></tr>
<tr><td>**PFTrDA**</td><td>$C_{13}HF_{25}O_2$</td><td>664.10</td><td>PFCA</td></tr>
<tr><td>**PFPS**</td><td>$C_5HF_{11}O_3S$</td><td>350.11</td><td>PFSA</td></tr>
<tr><td>**PFHpS**</td><td>$C_7HF_{15}O_3S$</td><td>450.12</td><td>PFSA</td></tr>
<tr><td>**PFNS**</td><td>$C_9HF_{19}O_3S$</td><td>550.14</td><td>PFSA</td></tr>
<tr><td>**PFDS**</td><td>$C_{10}HF_{21}O_3S$</td><td>600.15</td><td>PFSA</td></tr>
<tr><td>**PFUnDS**</td><td>$C_{11}HF_{23}O_3S$</td><td>650.15</td><td>PFSA</td></tr>
<tr><td>**PFDoDS**</td><td>$C_{12}HF_{25}O_3S$</td><td>699.15</td><td>PFSA</td></tr>
<tr><td>**PFTrDS**</td><td>$C_{13}HF_{27}O_3S$</td><td>750.17</td><td>PFSA</td></tr>
</table>

2.2 PFAS in Swedish Water Resources

As PFAS are not degraded naturally, and they can persist for a very long time in the environment [2]. The PFAS compounds are readily bound to soils. Long-chain PFAS, tends to remain bound to the soil for longer than short-chain PFAS as shorter chains have a higher water solubility and are therefore more prone to transportation to various groundwater or water bodies. Compound bound to soils can eventually leach out of the soils and reach groundwater.

About 250 groundwater resources in Sweden are at risk of being contaminated with PFAS [4]. When the municipal groundwater resources were investigated in 2016-2017, PFAS was found in two thirds of the groundwater resources [4]. However, the average level of contamination was low, with certain places having higher levels. These high levels of PFAS can mostly be found near sites where firefighting training has occurred. The sites are mostly civil and military airports where they have reported using Aqueous Film Forming Foam (AFFF) containing PFOS as firefighting foam [17]. Furthermore, most sites were reportedly often situated where the ground largely consisted of gravel, and as gravel is a highly permeable material, the foam was likely transported further into the soil and eventually leaching into the groundwater. It has also been shown that there is a correlation between PFAS contamination found in groundwater and landfill sites located near the groundwater resource [4].

There are various municipalities or drinking water producers in Sweden where PFAS has at some point been detected in the raw water source. According to the Swedish Food Agency, 48 municipalities had at some point detected PFAS levels >10 ng/L [1]. Furthermore, 108 municipalities had at some point detected PFAS levels <10 ng/L. In the raw water while 82 municipalities had not detected any PFAS contamination. There are also several municipalities or drinking water producers where the PFAS contamination detected in the drinking water after treatment had at some point been higher than 10 ng/L. 15 municipalities detected PFAS levels >10 ng/L in their drinking water at some point [1]. 59 municipalities had detected PFAS levels <10 ng/L in their drinking water while 80 municipalities had not detected any PFAS in their drinking water. As mentioned earlier, the new guideline values of 4 ng/L for PFAS 4 and 100 ng/L for PFAS 21 limits the allowed PFAS discharge from the drinking water treatment plants and leads to a need for further treatment in many treatment plants. As can be seen in the cases above, there are various instances where removal of PFAS could be needed, depending on what PFAS compounds are present in the waters, as the PFAS levels in both raw waters and drinking waters have been measured to be over the impending 4 ng/L guideline value for PFAS 4.

Uppsala is a city where the PFAS levels in the raw water that is used to produce drinking water have been found to be high. The high levels have been caused by firefighting foams used at an airport belonging to the Swedish Armed Forces which was located upstream of the groundwater source used for drinking water in Uppsala [18]. The drinking water in Uppsala is currently being treated to remove PFAS with GAC and reduces PFAS from around 150 ng/L to 5-10 ng/L [19]. Uppsala Vatten has sued the Swedish Armed Forces and has asked that they take responsibility of the costs of removing the PFAS contamination in the drinking water as they were the ones who caused the contamination. The legal case is still ongoing, with the latest occurrence being that the Land and Environment Court of Appeal declared the Swedish Armed Forces responsible for the costs to which the Swedish Armed Forces appealed in May 2024 [20].

Another municipality that has been affected by high concentrations of PFAS is Ronneby and more specifically the village of Kallinge where Swedish Armed Forces has used firefighting foam at an airport similarly to the case in Uppsala [19]. However, the PFAS concentrations found in the drinking water in Kallinge were significantly higher, reaching 10 380 ng/L. This led to over 150 people residing in Ronneby suing the municipality for personal injury as the PFAS-levels in their blood were heightened.

In late 2023, 10 years after the high PFAS contamination was discovered, the supreme court declared that the residents would be paid in damages [21]. Shortly after this happened in 2013, the Swedish Food Agency encouraged all municipalities to check their raw water sources for contamination of PFAS [22].

2.3 Drinking Water Treatment

Treatment of raw water for drinking water purposes can consist of many different treatment processes and combinations of technologies. The treatment process depends on the chemistry of the water to be treated. The conventional treatment process includes coagulation and flocculation, sedimentation, filtration, and disinfection [23]. The purpose of this treatment process is to form larger particles of particulate as well as dissolved matter which will be heavy enough to sediment and separate from the water. This is often followed by filtration of smaller organic and inorganic particles and microorganisms. Lastly, disinfection is used to ensure sufficient inactivation of microorganisms such as bacteria or viruses. In some cases, granular activated carbon is used with the purpose of controlling taste and odour [21].

The treatment process can differ depending on the raw water used as a water resource. Surface water contains different types and levels of contaminants than groundwater, and the different water types will generally require different treatment processes to achieve sufficiently clean water. Surface water typically contains higher levels of microbes, organic carbon and suspended solids which will have been removed through natural infiltration for groundwater.

It can be assumed that if a treatment step for removal of PFAS were to be implemented at a drinking water treatment plant, a sufficiently functioning treatment process based on current guideline values is already in place. Adding a treatment step for PFAS removal would be implemented at the end of the treatment process. Lackarebäck's drinking water treatment plant can be used as an example of a how a typical process train in a drinking water treatment plant without PFAS treatment looks. Lackarebäck's drinking water treatment plant provides the municipality of Gothenburg with drinking water. At Lackarebäck surface water from Göta Älv is used as raw water source [24]. The treatment steps at Lackarebäck are flocculation with aluminum salts which creates flocs of organic matter, other particles, and microorganisms. This is followed by sedimentation where the flocs sink to the bottom of the tanks and are separated from the water through scraping the tank floor. The next step at Lackarebäck is granular activated carbon, with an approximate EBCT of 15-20 minutes, which removes smaller particles as well as taste and odour [25]. Lastly the water is disinfected by ultrafiltration where microorganisms are removed from the water. This treatment process provides safe drinking water for the population of Gothenburg where the PFAS 4 levels are low and are expected to stay below the limit of 4 ng/L once the limitation is implemented in 2026 [26].

2.4 Technologies for PFAS Removal

The following section presents the background for the four PFAS removal technologies: Granular Activated Carbon (GAC), Nanofiltration (NF), Ion Exchange (IE), and Foam Fractionation (FF).

2.4.1 Granular Activated Carbon

Granular activated carbon (GAC) can be made from various materials, such as coconut shell, bituminous coal, petroleum coke, wood, and peat [27]. It has the ability to adsorb organic compounds as well as undesirable tastes and odours among others [28]. This is due to the porosity of the GAC[29]. The pores of the GAC make it possible to have a large surface area, which increases the surface area where the carbon can absorb particles [30]. The pores have the capability to adsorb different molecules as well as PFAS from the water during water treatment. The mechanism of the sorption of PFAS by GAC is mainly caused by the hydrophobic interactions between the PFAS compound and the surface of the activated carbon [31]. Granular activated carbon has the capability of absorbing non-water-soluble organic substances.

Granular activated carbon is most commonly designed using a fixed-bed set up [31]. The filters of GAC typically consist of configuration with multiple filters where the first filter removes the bulk of the PFAS and the second filter is used for refining. When reaching breakthrough, the filters are moved so that the second filter becomes the first and a new layer with GAC is added for the refinement.

There are several aspects that need to be taken into consideration in the design of a GAC system. These include the pre-treatment, such as sandfilters, where hydrophobic compounds otherwise can directly interfere with the PFAS sorption [31]. Other aspects include the empty bed contact time (EBCT) and bed lifetime.

When it comes to waste, GAC can be incinerated or regenerated. The regeneration can happen through multiple ways, where it is mostly done through thermal reactivation [32]. This is done through heating the activated carbon, causing 75-90% of the absorbed content to be volatilized. A steam is thereafter injected and reactivates the carbon through removing the remaining volatiles. The exhaust steam needs to be cleaned from hydrofluoric acid to avoid environmental problems in the surroundings [25]. The regeneration of activated carbon commonly causes a loss of up to 10% that needs to be replaced with new activated carbon to reach the same efficiency. Only certain types of GAC have the capability of being regenerated, but by reactivating GAC, the efficiency is of similar level as a virgin GAC while reducing the carbon footprint that normally is generated during production [31].

A simplified figure of granular activated carbon is presented in Figure 2.2. The necessary contact time (EBCT) for removal of PFAS lies between 10-20 minutes [25]. Sometimes a series of two columns is used where the first (“LEAD”) removes the majority of the PFAS and the latter (“LAG”) assures polishing of PFAS.

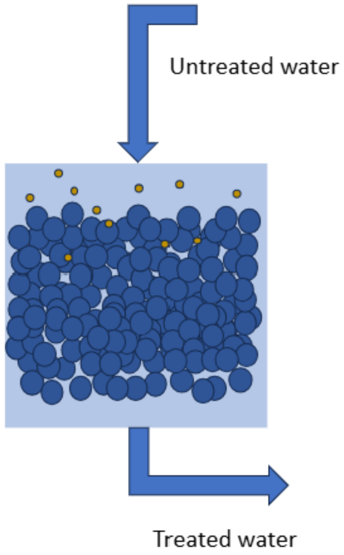


Figure 2.2: Simplified figure of granular activated carbon.

2.4.2 Nanofiltration

Nanofiltration (NF) is a membrane process driven by pressure [33]. The membranes have the capability to reject multivalent inorganic salts as well as small organic molecules. There are variations of membranes, with dense membranes allowing molecules of the sizes 0.5-1 nm, and less dense typically 1-10 nm [33],[34]. The PFAS rejection can differ depending on membrane characteristics.

The membranes of nanofilters are slightly charged when in contact with an aqueous solution. This is due to the dissociation of surface functional groups or adsorption of charge solute [35]. Nanofiltration is considered to have properties in in between ultrafiltration and reverse osmosis [33]. What differs nanofiltration from reverse osmosis, apart from the pore size, is that NF membranes have a low rejection of monovalent ions. Meanwhile the rejection of divalent ions is higher, as well as a higher flux, which is defined by the amount of liquid going through the membrane over time [31], [36].

The process occurring during NF is complex. Within the pores and on the membrane, there are micro-hydrodynamic and interfacial events [36]. The membrane obtains a charge that is dependent on the dissociation of ionizable groups. This can be influenced by specific pH-levels. There is also electrostatic repulsion or attraction that varies dependent on the ion valence, although the concept is not very well understood. Tight nanofiltration membranes separate ions by diffusion gradients while more open membranes also separate larger molecules by size exclusion [25].

What is important to note with nanofiltration is that there is a large waste stream from the separation, with a large amount of water with a high concentration of unwanted particles. This water requires further treatment before going to the wastewater treatment as the level of contaminants are too concentrated [31].

The NF-system typically consists of a feed pump, feeding water to the membrane units, where pre-treatment may be needed to remove particles that may compete with PFAS [31]. Figure 2.3 shows a simplified version of nanofiltration, where permeate water enters the nanofiltration process. The technology separates unwanted particles that together with a large amount of water from the treated water that can move forward in the process.

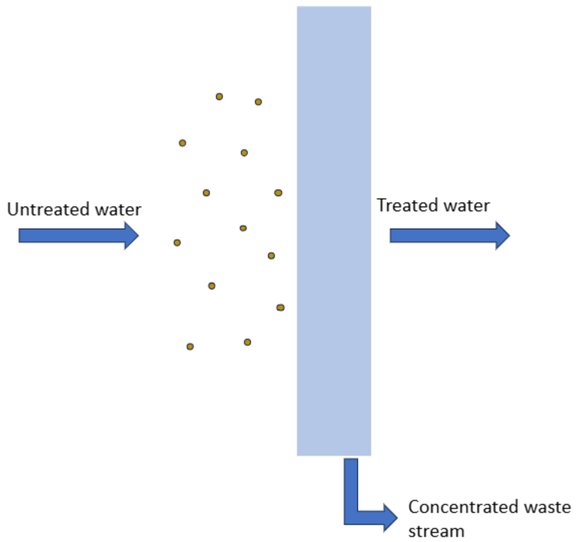


Figure 2.3: Simplified figure of nanofiltration.

2.4.3 Ion Exchange

Ion exchange is a sorption technology where ions of the same charge are exchanged to remove PFAS from the water [37]. Depending on the type of PFAS targeted, the exchange of molecules typically occurs between either the hydrophobic end of the PFAS molecule (the fluorinated carbon chain), or the hydrophilic end of the PFAS molecule (the functional group), and an ion that is less harmful which is released into the water to adsorb to the PFAS molecule. Due to this, different types of PFAS can behave differently during the Ion Exchange, with the hydrophobic end adsorbing to the resins with hydrophobic and van der Waals interactions, and the functional group absorbs to the resins through electrostatic ionic bonds [38].

Ion exchange consists of solid resin beads that are suspended in the water where the positively charged functional groups in the resin beads bind to the negatively charged PFAS in the water [37]. Ionic bonds are formed between the two different media which leads to sorption of the PFAS onto the resin beads. The reaction that occurs in ion exchange can be written as [39]:

$$2RNa + Ca^{2+} \rightarrow R_2Ca + 2Na^{+}$$

What is not shown on the reaction is the presence of SO_3^- which are fixed in the resin. The R represents the resin. To adapt the reaction to PFAS adsorption, Na^+ can be replaced with Cl^-, Ca^{2+} can be replaced with any PFAS compound and SO_3^- can be replaced with NH_4^+ as terminal groups in the resin matrix R [25]. The resin contains Cl^- which reacts with the PFAS coming in contact with the resin and the resin releasing 2 Cl^- for each PFAS [39]. The PFAS then binds to the resin and the fixed NH_4^+. After replacing the compounds, the reaction would look like this:

$$2RCl + PFAS^{2-} \rightarrow R_2PFAS + 2Cl^{-}$$

The resin can be either single-use or it can be regenerated and used multiple times [37]. For removal of PFAS it is most common to use single-use resins as the removal efficiency is high and they are easy to use and do not require any further treatment for regeneration. Studies have also shown that the efficiency of regeneration of the resins have achieved mixed results with some challenges to achieve sufficient regeneration [38]. However, in Europe, regeneration of the resin is not allowed for usage in drinking water treatment as certain chemicals are used which are unfit in drinking water production [25]. This appears to make regenerated resins unsuitable and single-use resins the more feasible option [40].

There are studies on how different resin properties affect the PFAS removal, however, they are not readily available or in early stages [38]. But studies comparing different resins tend to show that there can be a difference in how the resins perform for some aspects and that certain types resin work perform better than others [41].

Overall, ion exchange has been shown to be efficient for a broad interval of PFAS concentrations, both low and high [37].

The necessary contact time (EBCT) for removal of PFAS lies between 2.5-4 minutes [25]. As for GAC, two columns can be couples in series where the first (“LEAD”) removes the majority of the PFAS and the latter (“LAG”) assures polishing of PFAS.

A simplified figure of how the process of ion exchange works is shown in Figure 2.4.

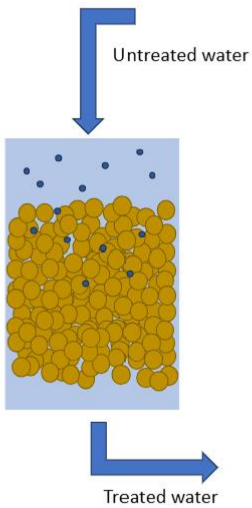


Figure 2.4: Simplified figure of ion exchange.

2.4.4 Foam Fractionation

Foam Fractionation is a process that utilizes physical separation of contaminants from the water [37]. Gas and turbulence are introduced into the water which leads to production of bubbles which will rise to the surface and create a foam. The contaminant is adsorbed onto the bubbles which then rises to the surface [42]. The foam is then separated from the surface of the water, removing the contaminants with it. Foam fractionation typically removes dissolved and soluble surface-active compounds [43]. As PFAS compounds are soluble surface-active compounds, foam fractionation could be used to remove PFAS from water.

PFAS are surface-active compounds as they are amphiphilic, with both hydrophilic and hydrophobic ends [43]. This allows the PFAS compounds to adsorb to the bubble’s air-liquid interface as the hydrophobic end repels water and is situated inside the bubble and the hydrophilic end attracts water and is situated outside the bubble. Once the bubbles have risen and created foam, the foam is separated from the water and foamate is created. Foamate is the foam turned into liquid form which occurs after allowing the foam to collapse.

It is possible to add co-surfactants into the process which can increase the adsorption of PFAS and in particular short-chain PFAS [37]. However, it is not allowed to add co-surfactants for drinking water production [25].

Previous studies regarding foam fractionation have mainly focused on removing various contaminants from wastewater [43], [44]. Progress has also been made in recent years regarding removal of PFAS from groundwater and leachate using foam fractionation. Foam fractionation generally requires high concentrations of PFAS to be efficiently reducing the PFAS contamination.

A simplified figure of how the process of foam fractionation works is shown in Figure 2.5

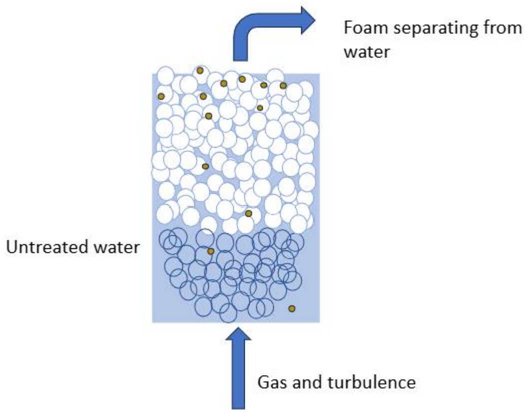


Figure 2.5: Simplified figure of foam fractionation.

3 Methodology

The project has been conducted mainly by collecting information by means of a literature study and receiving data using various tools to generate a general evaluation of the technologies. The tools and methods that have been used are explained below together with a process chart in Figure 3.1.

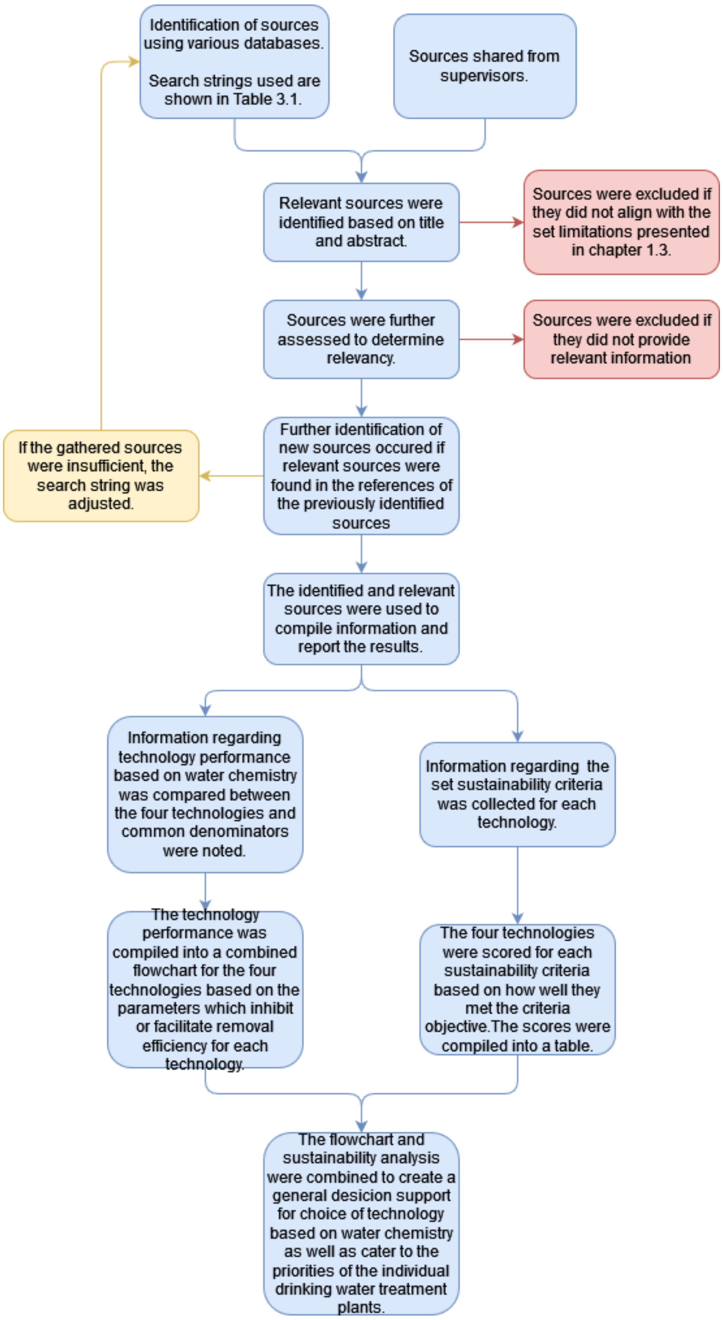


Figure 3.1: Process chart for the working methodology in this study, detailing how the literature research has been conducted and acted as a basis for the results.

A literature study has been conducted to collect information and data regarding the four water treatment processes. The literature has been obtained through various databases with Web of Science as the main database and using various search strings (Table 3.1).

Table 3.1: Search strings used during literature research.

Search Strings Used	Number of Results Web of Science	Number of Relevant Articles Web of Science	Articles used
“GAC” AND PFAS AND “drinking water” AND (“pilot scale” OR “full scale”) (Field: Abstract)	10	4	3
“GAC” AND cost AND “drinking water” AND (“pilot scale” OR “full scale”) (Field: Abstract)	16	2	1
“Granular activated carbon” AND PFAS AND "drinking water" (“pilot scale” OR “full scale”)	35	14	6
nanofiltration AND PFAS* AND “drinking water” AND (“removal efficiency” OR “pilot scale” OR “full scale”)	9	3	2
“nanofiltration” AND “PFAS” AND (“pilot scale” OR “full scale”)	6	3	2
“nanofiltration” AND cost AND "drinking water" AND (“pilot scale” OR “full scale”) (Field: Abstract)	7	2	1
Ion Exchange AND PFAS AND Pilot Scale AND Drinking Water	16	5	3
(Ion Exchange OR Anion Exchange) AND PFAS AND Drinking Water AND (Pilot Scale OR Full Scale)	26	7	3
(Ion Exchange OR Anion Exchange) AND PFAS AND (Pilot Scale OR Full Scale) AND Cost	11	3	1
Foam Fractionation AND PFAS AND Drinking Water AND (Pilot Scale OR Full Scale)	1	1	1
Foam Fractionation AND PFAS AND (Pilot Scale OR Full Scale)	6	4	3

Additional literature has been provided by the supervisors as well as through snowballing when any references in articles have seemed interesting and relevant.

3.1 Collection of Information Regarding Technology Performance

When researching the technology performance, relevant information from the literature, such as water qualities and parameters, as well as removal efficiencies were documented. Through the documented information, a pattern identification has been done for each individual technology. Rough sketches of flowcharts for each technology were made to easily compare the identified patterns of how the PFAS removal was affected by the water chemistry (**Fel! Hittar inte referenskälla.**). These include noting repeated similarities in results as well as known interconnections between water parameters, results, or other conditions. These were later used to create a flowchart and the parameters which have been identified to inhibit or facilitate the removal efficiency for the technologies are included as steps in the flowchart. Parameters which have been relevant are removal efficiency, presence of organic matter, presence of ions, chain-length of the PFAS compound and functional group of the PFAS compound as well as pH-levels. Furthermore, other parameters such as the concentration of PFAS, contact times and breakthrough of sorption media have been some of the important factors identified which have an impact in the performances of the technologies were discussed but not included in the flowchart as they are not part of the water chemistry or for some reason not suitable in the flowchart. The flowchart was created with the purpose of having a schematic decision support for water treatment plants deciding which water treatment process to implement. The final flowchart along with a sustainability analysis is presented in chapter 4.3. The pros and cons for respective treatment process have been discussed according to environmental, and economic sustainability as well as the technical performances.

3.2 Sustainability Analysis

In this project, a sustainability analysis was conducted to get an overview of the overall sustainability of the four water treatment processes. The criteria for the analysis were chosen prior to the collection of information and was chosen according to what was considered relevant and needed for drinking water treatment plants to evaluate the sustainability and feasibility of implementing a treatment technology. Different options for criteria were discussed with supervisors with knowledge in the subject. A tool used for sustainability analysis, in this case WISER, was also used as inspiration for the setup of the criteria. The technical aspect has been discussed in the flowchart and is therefore not included in the sustainability performance analysis, as the purpose of the analysis is to provide additional decision support from other aspects according to sustainability. Criteria were determined and defined with an objective describing each criterion (Table 3.2) and the criteria are implementation cost, maintenance cost, regeneration, CO_2 eq. emissions and energy consumption. Other possible criteria that were discussed were for example space requirement and social aspects. These criteria were ultimately excluded due to time restraints and availability of data.

Scoring for the degree of which a criteria objective was met was determined to five possible score with a range from - - to ++. When there has been no available information regarding a criterion, the score has been set to N/A and when a criterion not applicable for the technology, the score has been marked with a backslash (\). The scores and definitions can be found in Table 3.3.

Table 3.2: Criteria and objectives for the multi-criteria analysis.

Criteria	Objective
Economic	
Implementation cost	Realistic and reasonable implementation cost for a treatment plant
Maintenance cost	Cost for operation and maintenance of the treatment plant, e.g. replacement of media, life span
Environmental	
Regeneration	Possibility of regeneration and its feasibility
CO_2 eq. emissions	Environmental impact of the life cycle of the technology.
Energy	
Energy consumption	Energy consumption due to e.g. aeration and pumping of water

Table 3.3: Scoring for the multi-criteria analysis and the degree to which objective is met for each respective score.

Score	Degree to which objective is met
--	Low
-	Moderately low
0	Neutral
+	Moderately high
++	High
N/A	Not available
\	Not applicable

Information for the analysis was compiled similarly to the flowchart, through a literature study. Information was also obtained from outside sources, such as from Laholmsbuktens VA, and through the Swedish Water and Wastewater Association (Svenskt Vatten). Svenskt Vatten has developed a tool for assessing footprints for different treatment steps. However, this tool is not currently adapted for PFAS treatment, and processes like NF, IX, or FF are not addressed. The tool was further developed by Ludwig Hedberg, which has made it possible to obtain limited information about GAC and NF.

3.3 Compilation of Results for Decision Support

The flowchart and the sustainability analysis were combined into one figure which can act as a decision support for drinking water treatment plants choosing what technology to implement. Recommended technologies were suggested in the last row of the flowchart as suggestions of which removal technology or technologies are the most suitable for the water chemistry. The sustainability analysis was included in the figure to take the treatment's plants priorities into account. Three imaginary examples of drinking water treatment plants, their water chemistry and what sustainability criteria they prioritised when implementing a technology for PFAS removal were created to exemplify the decision support.

4 Results

The literature findings for technology and sustainability performance are presented in chapter 4.1 and 4.2 and the resulting flowchart along with the sustainability analysis is presented in chapter 4.3.

4.1 Technology Performance Based on Water Chemistry

The technology performance for PFAS removal using granular activated carbon, nanofiltration, ion exchange and foam fractionation was assessed based on water chemistry in the incoming water. The findings from the literature search are presented below. Documentations of water chemistry and other relevant parameters can be found in Appendix A. 1 - Appendix A. 15.

4.1.1 Granular Activated Carbon

In a study, full-scale water treatment systems in the US that were studied, where the removal efficiency using GAC was tested [45]. In the study, there were a total of 20 utilities with different water treatment processes, where utility #7 (GAC #7) and utility #20 (GAC #20) are included in this report. In the study, GAC #7 was treated by six granular activated carbon contact adsorbers. The time of which the GAC had been in operation was not specified in the article. The empty bed contact time (EBCT) was 10 min, with adsorbers named Norit GAC30, with surface water as raw water source [45]. GAC #20 used Calgon F600, where EBCT was 13 minutes, and the PFAS concentrations had been monitored for 5 years with groundwater as water source. The system consisted of a series set up with a lead and a lag basin. When comparing the removal efficiencies for PFAS belonging to either PFCA or PFSA, the removal efficiency was shown to be higher for the tested PFSA for this case. For GAC #20 higher removal efficiencies were achieved for PFOA and PFOS.

GAC #20 had an EBCT of 13 min in each contactor. The removal rates in Table 4.1 are based on the average removal over the course of one year for the lag basin [45]. The concentrations of the lag basin had been monitored for 16 months. Concentrations of PFBA, PFPeA, PFHxA, PFOA, PFBS, PFHxS, and PFOS were monitored for nearly five years on the influent and the lead basin effluent.

Table 4.1: Summarised removal efficiencies with consideration to chain length and functional group [45].

PFAS compound	**Chain length**	**Removal efficiency GAC #7** [45]	**Removal efficiency GAC #20** [45]
PFSA			
PFBS	C4 – short	>96%	N/A
PFOS	C8 – long	>89%	>95%
PFHxS	C6 – long	>96%	>41%
PFCA			
PFBA	C4 -short	33%	-17%
PFPeA	C5 - short	74%	>22%
PFHxA	C6 - short	91%	>68%
PFHpA	C7 - long	>89%	N/A
PFOA	C8 - long	>48%	>92%
PFNA	C9 - long	>37%	N/A

*Treatment train for GAC #7: Riverbank Filtration/Aquifer Recharge and Recovery/Softening/Solids Contact Clarifier/UV Photolysis with Advanced Oxidation (Hydrogen Peroxide)/Granular Filtration/Granular Activated Carbon Filtration [45].
** Treatment train for GAC #20: Granular Activated Carbon Filtration/Hypochlorous or Hypochlorite [45].

In another study with a pilot-scale, eight GAC adsorbents were tested from different manufacturers [41]. The absorbers achieved a concentration lower than 2 ng/L PFAS initially. The test showed that GAC reached breakthrough at rates between 2 and 5 months for PFOA for an initial concentration of 17.2 ng/L PFOA. Breakthrough happened earlier for non-/sub-bituminous GAC in comparison to GACs from bituminous carbon sources. This results in bituminous GAC having a longer media life for PFOA. Like the statements from the article above, the study suggests that higher removal efficiencies are obtained for PFOS in comparison to PFOA. The initial breakthrough for PFOS was shown to range between 2 and 8.5 months [41]. The initial breakthrough for PFHxS happened between 4 and 8 months. Short-chained PFAS, <C7 for PFCA and <C6 for PFSA have resulted in in early breakthroughs and poor PFAS removal [46]. Granular activated carbon has been shown to be more effective for long-chained PFAS, such as for PFOS and PFOA [41].

In the test, two short-chain PFAS were consistently detected, with average influent concentrations of 15 ng/L PFBS (C4) and 3 ng/L PFHxA (C6), although reliable results for PFHxA could not be constructed [41]. Initial breakthrough for PFBS ranged from 1 to 4 months. After the test, a total of 16 months, 7 out of 8 GACs had reached 100% exhaustion, and the remaining one (F600) had reached an 85% exhaustion.

In an experiment set-up, not based on a pilot or full-scale GAC, it was discussed how ions can have an influence on GAC by neutralizing the negative charges, which include divalent cations such as Ca^{2+}, Mg^{2+}, Cu^{2+} and Pb^{2+} [46]. What was also been discussed was that the co-existence of inorganic anions can result in a reduction of sorption of PFAS as well as the presence of monovalent and divalent cations. The conclusion of the experiment showed that no sorption change was made for long-chain PFAS with spiked ions, while for short-chained PFAS the salts inhibited the sorption. This needs further investigation and is not based on full-scale or pilot-scale data.

One of the challenges when it comes to GAC as well as drinking water treatment in general is the presence of natural organic matter (NOM) in the water [47]. NOM can be absorbed by GAC, and progressively lead to clogging of the GAC filters. For long-term performance, backwash might therefore be needed. In another article, it has been discussed how dissolved organic matter (DOM) has the capability of limiting the PFAS adsorption due to competition of the pore space [46].

Dissolved organic matter (DOM) has been shown to have overlapping molecular characteristics as PFAS and could therefore interfere with the GAC performance [48]. Results showed that when using GAC with Filtrasorb 400, the removal efficiency was shown to only be influenced by the absence (0 mg L-1) or presence (2-8 mg L-1) of DOM in hydrophilic DOM. Meanwhile a sample from another surface water source with hydrophobic DOM showed a progressive increase in removal efficiency in relation to increase of DOM in the water [48]. For the sample containing hydrophobic DOM, the removal similarly showed a progressive increase for long-chained PFAS in relation with the increased DOM. The removal efficiency was therefore shown to be the highest for long-chained hydrophobic PFAS. The retention of DOM was also shown to be only 10-40% in comparison to 30-70% for IX [48]. The same study showed that the functional groups of PFAS had insignificant influence with the same chain lengths, which was unexpected due to the influence the functional group has on PFAS solubility.

Looking at another study looking at multiple treatment plants for surface water, both with conventional GAC as well as membrane treatment combined with GAC there are a few results that can be found through the study [49]. Filtrasorb 300 was used for the study. There were three different treatment plants with six GAC treatments in total, and each of them was of a different age. The overall results showed that a temperature of 20℃ leads to a higher removal efficiency of PFAS than 4℃ [49]. Using sterilization, in the form of gamma irradiation, resulted in an improvement of removal efficiency. Similarly, an increased EBCT increased the overall efficiency and the treatment using the 1-year-old GAC performed better than the older ones.

When it comes to removal efficiencies, PFSAs are more easily removed due to the higher electrostatic interactions between PFSA and activated carbon in comparison to PFCAs [31]. Long-chained PFAS also tend to be more easily removed because of hydrophobic interactions. Meanwhile short-chained PFAS generally has a low removal efficiency.

4.1.2 Nanofiltration

The membrane characteristics of nanofiltration can have a big impact on the PFAS removal. Among these belong the membrane materials as well as the membrane pore characteristics [31].

Tests have been performed using a pilot-scale membrane system, using a single hollow fibre membrane, named dNF40 manufactured by NX Filtration BV [50]. The research from the study focuses on a pilot-scale operating at approximately 1 m^3/h. The specifications of the membrane are presented in Appendix A. 7 [50]. The water that was used for the test was pretreated surface water, through drum screens, coagulation, rapid sand filtration and granular activated carbon filtration. The other water was the raw water from the surface water source. The water compositions of the different waters can be found in Appendix A. 9. According to the study, the membrane was better at retaining divalent ions over monovalent ions, where there was a Donnan exclusion of the membrane leading to a better retention for negative multivalent ions.

The same study suggests that the reason to why divalent ions are better retained, could be because of its properties of being able to form complexes with NOM when binding to the acidic functional groups, which leads to an increase of the size of the molecule [50]. The monovalent negatively charged ions were not retained due to the charge neutrality as well as the molecule size. In the study, the water contained multiple kinds of PFAS, including PFOS, PFNA, PFOA and PFHxS. The concentrations of the different PFAS compounds can be found in Appendix A. 8 [50]. In this example, both TOC and PFAS compounds were effectively removed (>70%), meaning that PFAS and TOC have the capability of both being effectively removed in the presence of each other [50].

When it comes to fouling, there are multiple parameters and characteristics that can influence fouling, where the raw water quality characteristics are important. NOM is known to be the primary factor for membrane fouling [51]. The presence of NOM has the capability of altering the characteristics of the surface of the membrane which can influence the electrostatic interactions. NOM can also block the pores of the membrane as well as form complexes with ions leading to a filter cake layer.

In another study, pilot-scale field tests with a reject byproduct of 10% and 90% permeate recovery were tested [52]. The NF pilot consisted of NF270 membranes. The groundwater source was monitored for 30 days. The average values of the PFAS compound rejections can be found in Table 4.2 [52]. The study showed a lower rejection of short-chained PFAS during a recovery of >95%, which decreased at a recovery of 97%. The longer-chained PFAS had no significant influence.

In a two-stage NF pilot, PFAS was efficiently removed by 98%, with a permeate water containing approximately 77 ng/L [53]. The removal efficiencies are shown in Table 4.2. The table below shows a high removal rate for PFAS compounds belonging to both PFSA and PFCA with varied chain lengths. The removal efficiency of the two-staged NF pilot plant was using full-scale membranes that were monitored for almost 6 months [53]. The two-stage membrane process had 6 membranes in stage 1 and three membranes in stage 2.

Table 4.2: Summarised removal efficiencies with consideration to chain length, functional groups, and molecular weights. [50], [52], [53].

PFAS compound	**Molecular weight (g/mol)**	**Chain length**	**NF90-400 Removal efficiency* [%]** [53]	**NF270 Removal efficiency** [%]** [52]	**dNF40 Removal efficiency*** [%]** [50]
PFSA					
PFPrS	250	C3 - short	N/A	>85	N/A
PFBS	300	C4 – short	96	>90	70
PFPeS	350	C5 - short	97	>95	N/A
PFHxS	400	C6 – long	97	>96	>80
FHxSA	400	C6 - long	N/A	>90	N/A
PFHpS	450	C7 - long	N/A	>96	N/A
PFOS	500	C8 – long	99	>98	>90
PFCA					
PFBA	212	C3/C4 - short	N/A	N/A	70
PFPeA	264	C5 - short	93	>90	N/A
PFHxA	314	C6 - short	97	>95	>80
PFHpA	364	C7 - long	89	>90	>99
PFOA	414	C8 - long	96	>98	>85
PFNA	464	C8/C9 - long	N/A	N/A	>85

*Wellfields, pilot-scale, NF90-400, average for 175 days, 80% recovery
**GW, pilot-scale, NF270, average for 30 days
*** Surface water, dNF40, 11 rounds (cycles) à 7 days

4.1.3 Ion Exchange

Inorganic ions present in the water have been shown to reduce the adsorption of PFAS onto the ion exchange resins [54], [55], [56]. IX has a high selectivity for ions such as sulphate, chloride, nitrate, nitrite among others. That is because these ions compete with the PFAS in adsorption to the IX resins which disturbs the process and reduces the PFAS adsorption and subsequent removal. Additionally, high enough concentrations of ions can replace already adsorbed PFAS and release the PFAS back into the water [25]. In one study, sulphate, bicarbonate, nitrate, and phosphate were increased to 50 mmol/L for 0,5 mmol/L PFHxS [56]. This decreased the adsorption of PFHxS by 10%. Furthermore, increasing the NaCl concentration to 1000 mmol/L decreased PFHxS adsorption by 30%. It can be believed that stronger electrostatic interactions lead to larger reductions of PFAS adsorption and therefore lower removal [54]. Although not as explored, it can also be assumed that the short-chain PFAS will be more affected by the competing ions. The shorter chain will not be as strongly adsorbed onto the resin as long-chain PFAS are which can also lead to short-chain PFAS eventually being re-

released into the water if long enough time passes [25]. This could potentially lead to the effluent short-chain PFAS concentration being higher than the influent.

Like the presence of ions in the water, the presence of organic matter has also been shown to affect the removal of PFAS [54], [55]. The presence of NOM in the water has been shown to reduce PFAS removal due to electrostatic interactions. While the PFAS removal was low in these cases, the removal of DOC was high. What affects the adsorption of organic matter can be the molecular weight of the NOM as well as the carbon content. Furthermore, the resin type could also impact the performance as polyacrylic resins have been shown to be more affected by NOM than polystyrene resins are.

When it comes to dissolved organic matter, it has been suggested that it does not matter what the concentration of DOM the water contained once it was above 0 mg/L [48]. The study showed that for concentrations of 2-8 mg DOC/L the removal of PFSA and PFCA decreased by almost 10 percentage points compared to the concentration of 0 mg/L. The difference between 2, 4 and 8 was not significant when the DOC values were changed, and other parameters remained the same. It was therefore a matter of whether DOM was present in the water or not. Presence of DOM had a slight negative influence on PFAS removal. The PFAS removal was reduced by a maximum of 10% with the presence of DOM at any concentration.

A study regarding the breakthrough of different PFAS found in groundwater used for drinking water in Anaheim, USA, compared ion exchange and GAC [41]. Breakthrough, in this study, is defined as the effluent concentration divided by the influent concentration occurring instantly, the same day. The EBCT used in the study was 2 minutes and the average concentration for the PFAS compounds was 17.3 ng/L for PFOA, 23.0 ng/L for PFOS, 10.7 ng/L for PFHxS, and 29.4 ng/L for PFBS. The results showed a later breakthrough of the IX resins compared to GAC. The study compared four different resins and their removal of the four PFAS compounds detected in the pilot feedwater (Table 4.3).

Table 4.3: The time of breakthrough (months) for four different ion exchange resins and the four detected PFAS types [41]. *No breakthrough means that breakthrough has not occurred when the study ended after 26 months. PFOA, PFOS and PFHxS are all included in PFAS 4, PFBS is included in PFAS 21.*

	PFA694E	**CR2301**	**LC4**	**PSR2+**
PFOA	3.5	3.5	3.5	7
PFOS	No breakthrough	No breakthrough	No breakthrough	No breakthrough
PFHxS	No breakthrough	16	No breakthrough	No breakthrough
PFBS	9	9	9	22

As can be seen Table 4.3, for PFOA, three of the resins had a breakthrough at 3.5 months while one resin had a breakthrough at 7 months [41]. All resins had no breakthrough for removal of PFOS and PFHxS when the study ended after 26 months except for CR2301 for PFHxS which had a breakthrough at 16 months. For PFBS, three resins had a breakthrough at 9 months, and one resin had a breakthrough at 22 months. The only PFAS compound of the four with a carboxylic acid functional group is PFOA, the rest are compounds with sulphonate as functional group. What can be seen is that

PFOA and PFOS, which both have the same chain length of C8, have significantly different times of breakthrough. This suggests that different functional groups have an influence on the removal efficiency.

The study suggests that PFOS is more readily adsorbed compared to PFOA [41]. This has been seen in multiple previous studies which implies that the functional group of the PFAS compound has an influence on the adsorption onto the resins, and particularly suggesting that sulphonates is the group with higher adsorption [41], [57]. While the study states that a clear correlation between chain-length and adsorption could not be confirmed, the results imply that the four IX resins tested remove the long-chain as well as the sulphonic acid PFAS compounds better than both the short-chain and the carboxylic acid PFAS compounds [41]. However, a long-chain PFCA could still be more readily removed than a short-chain PFSA. When it comes to the impact of chain-length, a review of multiple studies suggests that many lengths of PFAS compounds, both long-chain and short-chain, can be removed, except for the absolute shortest chains [58].

Many studies show that pH does not significantly affect IX. Varying results have been noted with different results for different PFAS groups and different resin types, but the studies suggest that pH differences do not have a significant impact on the removal efficiency of ion exchange [54].

4.1.4 Foam Fractionation

Due to the scarcity of available research about foam fractionation used for drinking water purposes, information regarding the technology has been collected based on other limitations compared to the previous technologies mentioned. The studies reviewed for foam fractionation have regarded removal of PFAS from various raw water sources such as leachate water and wastewater. Another article, which was the only one found regarding drinking water, discussed the removal of PFAS from concentrate after nanofiltration, however, the concentrate going through foam fractionation becomes retentate and not drinking water. Due to this, the following review of foam fractionation is not necessarily readily applied to drinking water.

One of the main aspects that affects the efficiency of foam fractionation is that high concentrations of PFAS are generally required to achieve efficient removal [43], [44], [59]. One study looked at the removal of multiple PFAS compounds in landfill leachate water and found that removal of 90% could be reached when the PFAS concentration was above 50 ng/L for every individual compound [60]. Beyond that, a continuous flow experiment was made with the total PFAS concentration ranging from 3200-25 000 ng/L. A removal of above 90% occurred for the tests with 10 000 ng/L and 25 000 ng/L while the concentrations between 3200-5100 ng/L had removal efficiencies around 75-85%.

Further it can be seen that long-chain PFAS has higher removal rates than short-chain PFAS [43], [44], [61]. One study showed a removal efficiency of 67% for long-chain PFAS while short-chain PFAS had a removal efficiency of 10% [59]. Another study reported a removal efficiency of 81-91% for several long-chain PFAS, such as PFOS and PFOA, and below 30% for short-chain PFCA (chain length below six) and PFSA (chain length below seven) [62]. The lower removal of short-chain PFAS is believed to be due to the hydrophobic end having a lower surface activity as the fluorinated carbon chain is shorter [63]. This leads to a weakened adsorption onto the air bubbles. Furthermore, functional groups can also influence removal efficiency of PFAS. It has been shown that sulphonate groups have a lower solubility than carboxylate groups which can increase the hydrophobicity and thus the adsorption of PFAS onto the bubbles [43]. A study made with multiple tests for different PFAS compounds in landfill leachate water, with PFAS concentrations varying between 1100-25 200 ng/L, showed an average removal efficiency of 77% for PFCA and 94% for PFSA [60].

Studies show that a higher concentration of metal cations as well as higher ionic strength in the water increases the removal efficiency [43], [62]. Metal cations that are mono-, di- or tri-valent, such as Na^{+}, K^{+}, Ba^{2+}, Mg^{2+}, Al^{3+}, Fe^{3+}, can be found in groundwater. Studies suggested that the presence of metal cations can increase the removal efficiency and that the efficiency increases further with the charge density of the cation [43], [64]. It has also been observed that higher concentration of ionic salts leads to a lower surface tension of the water allowing faster formation of the foam [64]. It has been suggested that the ionic strength increases removal efficiency due to the solubility of PFAS being reduced as well as the viscosity of the water being increased with increasing ionic strength [42], [43], [60]. However, it was also reported that when the salinity was high, and a co-surfactant (sodium dodecyl sulphate) was used, the removal efficiency decreased as foam formation was decreased.

Depending on what is present in the water, pH can influence the removal efficiency [65]. As previously mentioned, metal cations have been shown to increase the removal efficiency. However, it has been observed that for the metal cations to be efficient, a low pH-level would be favourable. One study showed that when metal cations (Fe^{3+}) were present in the water, PFOS and PFOA were removed with a removal efficiency of around 90% when the pH was relatively low at 2.3. Another study, which was done with a pH-level of 7.8, needed an additional Fe^{3+} amount 20 times higher than the previous study did at a pH-level of 2.3 to reach the same removal efficiency [60]. However, when cationic co-surfactants were present, there was no significant difference and removal remained efficient even at slightly higher pH-levels.

Contact time has also been shown to affect the removal efficiency. Longer contact time leads to higher removal. Studies show that most of the PFAS removal occurs early in the process, but a longer time allows for further removal [59]. Increased gas flow rate increases removal as more bubbles are formed and made available for the contaminants to adsorb onto [43]. However, too high flow rate can break the foam.

Though not very researched, the removal of long-chain PFAS seems to not be affected by temperature while the removal of short-chain PFAS decreases as the temperature increases [43].

4.2 Sustainability Performance

The sustainability of the technologies was evaluated based on the set criteria and scoring (Table 4.4). The scores were set based on the literature search which has been documented in this chapter. An abbreviated summary of the motivation behind the scores can be found in

Appendix B – Summary of Motivations for the Scoring of the Sustainability Analysis

Appendix B. 1.

Table 4.4 Final scoring based on results from the sustainability performance analysis.

	GAC	NF	IX	FF
Implementation cost	**0**	+	+	++
Maintenance cost	**0**	-	+	**0**
Waste management	-	--	-	++
Regeneration	+	\	-	\
CO_2 eq. emissions	-	**N/A**	**0**	**N/A**
Energy consumption	++	--	++	--

4.2.1 Granular Activated Carbon

In a study, multiple PFAS were examined in a full-scale drinking water treatment plant [66]. The study performed an economic analysis for the annual regeneration per Filtrasorb 400 filter. The operational costs were also looked at, defined as annual regeneration costs together with the uniform annual costs of the initial purchase cost of a filter of virgin GAC over 10 years with an interest rate of 5% per year. The annual unit operation cost is defined as the annual operations cost over the annual capacity of treated water. A table of the costs can be found in Appendix A. 10. The drinking water treatment plant is for 7 million m^3 of water per year. The annual operations costs are at approximately 174 000 000 euros to reach the water goal of 85 ng/L PFAS 11.

Another report studied an NF pilot plant used for PFAS removal in drinking water production [67]. The concentrate generated from the NF process was treated with both GAC and ion exchange and all technologies were assessed in the study. The implementation cost of GAC was presented in the supplementary information for the report and was 1142 €/m^3 absorbent of Filtrasorb400 [67]. The operational costs to reach the discharge goal of 4 ng/L was 4.41 €/m^3 concentrate for Filtrasorb 400 and 19.30 €/m^3 concentrate for Norit 1240 W. The operations costs include purchase of virgin GAC, regeneration, transportation to and from the DWTP, pumping energy cost to lift the water 6 meters where no operations personal costs or backwashing costs were included. Table 4.5 shows the costs to reach a discharge of 25 ng/L for the concentrate where a 10-year service life is assumed. The costs consider 10% loss of media from replacing the virgin GAC during regeneration. The energy cost for the calculations is 0.095 €/kWh.a highly concentrated water with FPAS levels. In a calculation based on raw water for GAC, the operation costs are at 0.038 €/m^3 for reaching the goal of 25 ng/L instead of the 0.80 €/m^3 for concentrated water.

Table 4.5: Unit costs and operations costs for GAC [67].

	Filtrasorb 400	Norit 1240 W
Unit costs		
Unit cost of new GAC or AIX [€/m^3 absorbent]	1142	1356
GAC regeneration or AIX incineration cost including transport and GAC handling [€/m^3 absorbent]	714	714
Operations costs		
Annual operations cost new AIX and incineration to meet water goal [€/m^3 concentrate]	0.036	3.12
Pumping energy to lift 6 m with pump efficiency 80% [€/m^3 concentrate]	0.002	0.002
Total operations costs [€/m^3 concentrate]	0.80	3.12

The costs of GAC treatment at one site, according to Laholmbuktens VA AB is presented in Table 4.6. The activated carbon (Brennsorb 1240) is purchased in batches of 2 tonnes when needed and is disposed once exhausted [68]. During the time with the given data, the treatment plant produced 450 000 m^3 water [25]. The total cost of the purchase of carbon together with the waste management was approximately 880 000 SEK leading to an operational cost of 2 SEK/m^3 when only taking the activated carbon into consideration.

Table 4.6: Operations costs for activated carbon based on a treatment plant in south of Sweden [68].

Month	Purchase of Carbon (SEK)	Waste Management (SEK)
2022		
January	79 920	-
March	79 920	-
May	-	109 841
June	74 300	20 734
September	-	-
October	-	67 240
December	74 300	49 415
2023		
March	74 300	-
May	-	67 453
June	74 300	110 966
October	Closed	-

A life cycle assessment was performed for GAC and ion exchange [69]. Regarding GAC, the study included results for single-use GAC with off-site incineration and reactivated GAC with off-site thermal reactivation from pilot-scale studies. The conditions for the GACs can be found in Appendix A. 11. The capital costs for GAC and operation and maintenance costs for GAC with incineration and GAC with reactivation can be found in Appendix A. 12 and

Appendix A. 13. The total capital costs for GAC were $78 445 for both single-use and reactivated GAC and the operation and maintenance cost was $17 589 for GAC with incineration and $16 634 for reactivated GAC [69].

Further results from the same study show that for the GAC systems, the production of activated carbon has the largest impact for all the assessed parameters in the study [69]. The assessed parameters include ozone depletion, global warming, smog, acidification, eutrophication, carcinogenics, non-carcinogenics, respiratory effects, ecotoxicity and fossil fuel depletion. For all parameters, the production of GAC stood for over 40% of the overall environmental impact, and for over 70% for majority of the individual parameters [69]. In total, the production of single-use GAC resulted in >80% of the environmental impact of GAC, and the reactivated GAC had similar results. The second largest impact was caused by the incineration of hazardous waste.

The values for each of the parameters assessed for environmental impact can be found in Appendix A. 14. It can be seen how the reactivated GAC has lower environmental impact in comparison to single-use GAC for all parameters. For single-use GAC the global warming was 0.4407 kg CO_2 eq./m^3 treated water and for GAC with thermal reactivation it was 0.0726 kg CO_2 eq./m^3 treated water [69]. During thermal reactivation approximately 10% of the media goes to losses.

There are multiple variants of GAC filters that can be used that might perform differently sustainability wise. Below follows a short comparison between coal, peat, coconut, wood, and reactivated coal GAC. The overall performance of the different filters was looked at in its original condition, with 20% increase of raw materials, 20% decrease of raw materials, 20% increase of electricity demand as well as 20% decreased energy demand [70]. When it comes to global warming potential, kg CO_2 eq., the direct emissions caused by coal, peat, coconut, and wood were high whereas reactivated coal was the lowest with the main cause being make-up AC production. Looking at the energy consumption for GAC, it is of similar amount as for IX, consuming <0.05 kWh/m^3 [25].

4.2.2 Nanofiltration

A full NF system has been considered to cost 2 to 5 times more than a GAC filter [31]. A cost analysis was performed looking at a pilot-scale NF system fed by a full-scale conventional water treatment plant [71]. The pilot-scale tested both loose nanofiltration (L-NF), with a lower ion rejection capacity, and tight nanofiltration membranes (T-NF). Loose nanofiltration has a molecular weight cut-off (MWCO) of >500 Da and tight nanofiltration has a MWCO <500 Da [72]. The capacity of the pilot-scale NF was 400 000 m^3/d, where the investment cost of L-NF was approximately $104 500 000, which included 47 520 membrane modules, construction, and equipment [71]. For T-NF, the cost was approximately $92 500 000 for 28 800 modules along with remineralization. One unit membrane had a price of $1100.

The cost analysis for the NF-system was performed considering the investment costs of construction cost, mechanical and electrotechnical equipment cost and membrane cost [71]. The operation and maintenance costs included costs of chemicals used for remineralization for post-treatment as the results from the study for the T-NF would otherwise result in corrosion. Other costs for operation and maintenance included membrane replacement, energy, labour as well as maintenance and repair. In the study, electricity consumption for the full-scale NF system was used for calculations to keep margins due to the influence of energy consumption that the size and efficiency of the pumps can cause. The unit cost of electricity was reported as 0.0615 $/kWh in the cost analysis [71]. The chemical costs included costs for chemicals used to prevent membrane clogging and to condition and disinfect the feed water. The lifespan was assumed to be 6.5 years for the average membrane for NF. The final costs from the cost analysis can be found in Table 4.7. For the different membranes, the results showed that the total costs for L-NF and T-NF were just below 29 000 000 $/year [71]. The highest costs per unit could be found in the energy cost of 0.068 $/m^3, the membrane replacement cost of 0.054 $/m^3 for L-NF and 0.033 $/m^3 for T-NF and for the chemical costs that were 0.018 $/m^3 for L-NF and 0.038 $/m^3 for T-NF. The total unit cost was 0.157 $/m^3 for L-NF and 0.156 $/m^3 for T-NF.

The major operational cost for nanofiltration has been shown to be the cost for energy use [31]. The cost is 0.05-0.10 €/m^3 of treated water depending on energy consumption as well as the energy price [31]. According to a study looking at various peer reviewed data on full-scale NF plants, the energy demand is considered to be 0.4 kWh/m^3 [73]. For only pumping energy, another study has reported the value of 0.27 kWh/m^3 permeate [67]. Meanwhile, in a previously mentioned study, the energy consumption for the pilot NF plant was considered to be 1.1 kWh/m^3 [71].

In another pilot-study, where a cost analysis was performed, implementation costs for nanofiltration were reported, which were summarized and are shown in Table 4.8 [67]. The operational costs included energy for feedwater, recirculation, antiscalant dosing pumps, cost of antiscalant, membranes, article filter replacement as well as the cost of the cleaning in place.

When it comes to operational and maintenance costs the pumping of the water and the cleaning of the membrane requires maintenance. Table 4.9 shows the summarized costs [67]. There are also other costs that need to be taken into consideration such as prefilters, antiscalants, and chemicals that could be used for example pH adjustments. This would result in a total operation cost of 0.100 €/m^3 permeate including the purchase of the membrane [67]. Without the membrane the total cost would be 0.085 €/m^3 permeate. The highest costs for nanofiltration are the pumping energy at € 0.026, the antiscalant, to prevent the membrane from scaling or fouling at € 0.036. A summary of all the costs from the two different pilot studies can be found in Table 4.9.

Table 4.9: Implementation, operation and maintenance costs for nanofiltration [67], [71].

Parameter	Description	Two-stage, 6 NF90 & 3 NF270 [67]	L-NF [71]	T-NF [71]
Implementation costs				
NF membrane	Cost of membranes per unit	€ 700 (0.015 €/m^3)	$ 1100 (0.012 $/$m^3$)	$ 1100 (0.012 $/m3)
Construction cost	-	-	0.008 $/$m^3$	0.008 $/$m^3$
Equipment cost	-	-	0.021 $/$m^3$	0.012 $/$m^3$
Remineralization cost	To prevent pipe corrosion (post-treatment)	-	-	0.003 $/$m^3$
Prefilters	Replaced annually	437 €/filter	-	-
Operation and maintenance				
Pumping energy	Feed and recirculation	0.026 €/m^3 (0.095 €/kWh)	0.068 $/$m^3$ (including backflush)	0.068 $/$m^3$ (including backflush)
Chemical cost	All chemicals involved	-	0.018 $/$m^3$	0.038 $/$m^3$
Sodium Hydroxide	pH adjustment from 7.5 - 7.6	0.002 €/m^3	-	-
Labor cost	-	-	0.09 $/$m^3$	0.09 $/$m^3$
Maintenance and repair	-	-	0.09 $/$m^3$	0.09 $/$m^3$
Membrane replacement cost	-	-	0.054 $/$m^3$	0.033 $/$m^3$
Clean in place	Membrane washing acid/chemicals	0.015 €/m^3	-	-

Apart from looking at the numbers above, it is important to note that the final cost is case specific [31]. This can be seen in the varying energy use and price.

Since nanofiltration is a separation process, there will be retentate water as a rest product/waste. The retentate water contains the rejected particles from the feedwater creating a highly concentrated water containing a large amount of PFAS. The high levels of PFAS in the water must be treated before moving to wastewater treatment. The waste stream produced is of significant volume of up to 20% of the original volume [31]. There are many options for treatment of the waste stream where PFAS will be disposed in the end.

In a comparative study, two nanofiltration processes with ultrafiltration as a pre-treatment were tested [74]. The lifespan of the NF membrane was reported to be 10 years. The characteristics of the NF-systems can be found in Appendix A. 15. In the impact assessment, climate change and fossil depletion were discussed. During a nanofiltration installation operationkg CO_2 eq. affects climate change and around 0.1 kg oil eq. affects fossil depletion [74]. What was also looked at for the CO_2 eq. was the NF manufacturing and the NF installation construction where both were at such low values that they were not visible in the graph. It is important to note that the study does not seem to be based on a full or pilot-scale study. Therefore, the given results from the study might not reflect reality. According to Svenskt Vatten the emission factor of one element of NF membrane is 90.4 kg CO_2 eq. for NF from NX filtration and 477 kg CO_2 eq. from N64 Pentair [75], [76]. Other information regarding carbon footprint for NF is not available.

4.2.3 Ion Exchange

The cost of ion exchange is derived from the cost of a new unit, operation and maintenance costs which includes both energy costs and regular costs for new resin, and cost of disposal of the resin once exhausted. A study examined the costs of ion exchange which was used for the concentrate produced after nanofiltration [67]. The costs varied between the sorbent type and brand used and two types (A600 and PFA694) were examined in the study (Table 4.10). The annual operation cost was for reaching the discharge limit of 4 ng/L from an initial PFAS concentration of 583 ng/L. The PFAS concentration is high as the study uses the concentrate produced after nanofiltration which is generally higher than raw water.

Table 4.10: Unit, sorbent, disposal, and annual operation costs for two types of IX [67]. *The annual operation costs are for the discharge concentrations of 4 ng/L with an initial influent concentration of 583 ng/L.*

Component	**A600**	**PFA694**
New unit cost	5000 €/m^3	8500 €/m^3
Disposal cost	510 € m^3	510 €/m^3
Annual operation cost (for a discharge concentration of 4 ng/L)	1.25 €/m^3	1.94 €/m^3

A life cycle assessment investigated the costs of ion exchange on a basis of a 30-year life cycle and with an assumption of a flow of 6000 L/h, or 144 m^3/day. [69]. Single-use ion exchange resin was compared to regenerable ion exchange resin as well as single-use GAC and reactivated GAC. The capital cost was significantly lower for single-use resin compared to the other three. The capital cost for single-use resin was \$44 164 while it was \$77 571 for regenerable resin and \$78 445 for both single-use and reactivated GAC [69]. It was suggested that the shorter EBCT of 2-3 minutes for IX, compared to the EBCT of 10 minutes for GAC, leads to a lower capital cost as IX requires a smaller contactor than GAC does. Additionally, the annual operation cost was also lower than the other three with \$11 246 for single-use resin. Regenerable resin had the annual operation cost of \$14 746, single-use GAC had the cost of \$19 879 while reactivated GAC had the cost of \$16 634 [69].

Table 4.11: Various cost components for ion exchange based on the results of a life cycle assessment of a 30-year life cycle [69].

Component	**Cost**
Capital Infrastructure cost	\$44 164
Sorbent cost	15.70 \$/kg
Annual operation cost	\$11 246
Cost per m^3 of treated water	0.28 \$/m^3

Media changeout have been suggested to occur 1.62 times per year according to the 30-year life cycle assessment [69]. However, the time between changeout depends on the quality of the water as higher presence of ion or organic matter would decrease lead to decreased time until breakthrough as well as decreased PFAS adsorption. The higher organic matter and the subsequent decrease in adsorption of PFAS would increase the costs as it could lead to more frequent exhaustion of the resins and thereby require more frequent exchange of the resin [77]. The waste that is produced during ion exchange is mostly generated from the exhausted resin. The resin contains the adsorbed PFAS and will therefore need to be taken care of. Commonly, the resin is incinerated at another location which entails transportation of the waste from the water treatment plant. The resin could also be transported to a landfill where the resin is disposed.

Regeneration of the resin is possible and available for use. However, it is not suitable for drinking water as the regeneration requires chemicals which are not allowed in drinking water production in the European Union [25]. Furthermore, regeneration requires transportation to another site where the regeneration occurs which leads to increased costs as well as environmental impact [69].

Information regarding CO_2 emissions from ion exchange is limited. The CO_2 emissions was discussed with a company providing ion exchange products, where the conclusion was that they did not have any knowledge to share regarding the emissions of the products. The topic has been explored in various studies, but the data has been inconclusive.

A life cycle assessment was made regarding different technologies for PFAS removal on a time scale of 30 years [69]. Both single-use ion exchange resin and regenerable resin were evaluated and compared to single-use GAC and thermally reactivated GAC. The study evaluated the environmental impact of the technologies for ten different categories which were ozone depletion, global warming, smog, acidification, eutrophication, carcinogenics, non-carcinogenics, respiratory effects, ecotoxicity and fossil fuel depletion. It was shown that the single-use resin had the significantly lowest environmental impact on 9 out of 10 categories with the exception being ozone depletion where it had the highest impact [69]. The overall result was that single-use resin had the lowest impact followed by thermally reactivated GAC, regenerable resin and lastly single-use GAC. It was suggested that the low impact of single-use resin is due to the longer bed volumes until breakthrough compared to GAC. The reason for regenerable resins being higher is suggested to be due to the intense usage of chemicals and solvent solutions for regeneration of the resins which also contributes to hazardous wastes. When it comes to the ozone depletion being highest for single-use resin when compared to the other technologies, it is suggested to be due to the polymer synthesis during production of the resins which releases chemicals that are ozone-depleting [69]. As single-use resins require new resins each time they need to be replaced the impact is higher than for regenerable resin as they are reused and do not require replacement as often as single-use resin does. When looking at what causes most of the environmental impact, the study suggests that most of the impact from single-use resin is caused by the resin production followed by the incineration of exhausted resin while the regenerable resin impact is mostly due to incineration.

Global warming was presented as kg CO_2 eq. released per m^3 treated water. For single-use resin the impact was estimated to be 0.03033 kg CO_2 eq./m^3 [69]. The estimation for regenerable resin, single-use GAC and reactivated GAC was 0.2717 kg CO_2 eq./m^3, 0.4407 kg CO_2 eq./m^3 and 0.07264 kg CO_2 eq./m^3 respectively. The study shows that an estimated 70% of the impact from single-use resin is due to resin production and about 25% is due to incineration of the exhausted resins. The remaining impact comes from infrastructure and transportation.

When it comes to the energy consumption for ion exchange it is relatively low [77]. It has been suggested that the energy consumption is generally <0.05 kWh/m^3 [25].

4.2.4 Foam Fractionation

Implementation costs for FF are not exactly known but it has been stated that they are relatively low [31]. The low cost is due to the simplicity of the process and no need for continuous exchange of media or other materials. Studies have also shown that while the implementation cost is low, it is the biggest cost out of implementation, maintenance, energy, and waste costs [78]. The maintenance costs for FF are mainly driven by the energy consumption from the pumps and aerators providing air into the water to form bubbles, which can be high, causing the maintenance costs to be increased. Furthermore, a higher contact time leads to a larger need for aeration and pumping which raises the energy consumption and the subsequent costs. It has been suggested that the removal efficiency decreases with decreased contact time, and it has been reported that a contact time of at least 20 minutes is preferred [79]. The PFAS removal is suggested to be the most efficient with a contact time of 20-40 min [31], [79].

The process of foam fractionation does not generate high amounts of waste. The foamate that has been separated and collapsed becomes a concentrate with the PFAS. The concentrate is a fraction of the influent water which leaves a small amount of waste to manage. It has been reported that, out of the incoming water, 0.0025% will become waste concentrate [31]. Another study suggested that the waste concentration is <1-10% of the influent water [80]. Additionally, the process does not generally require any additions of chemicals which could also lower the amount of waste generated. The waste needs to be disposed or further treated which can occur in multiple ways such as adsorption onto an adsorptive media, degradation, or destruction of the PFAS [37], [80].

As foam fractionation includes aeration of the water, a mixture of the movement of the water and the air bubbles rising and bursting can lead to spreading of the contaminants due to aerosols being released into the air [80]. Other than that, little information has been found regarding carbon footprint for foam fractionation. However, there is less materials needed for the process compared to other technologies. As the process does not use any media, there is no need for regular transportation and production of media which has been shown to be the largest environmental impacts of GAC and IX [69].

The process of foam fractionation contains pumps and compressors which are responsible for the main energy demand of providing air into the water [31]. Aeration generally has a high energy demand and EPOC enviro's product SAFF (Surface-Active Foam Fractionation) has a power consumption of 0.6-0.8 kWh/m^3 treated water [81]. Additionally, a study reported the energy demand of 2.7 kWh/m^3 for the whole SAFF process, which includes the pre-treatment as well as final polishing [73]. This observation was made after a full-scale operation of 9 months which was conducted by the company. What differentiates foam fractionation from the other technologies is that there is no continuous use and replacement of media in the process since it utilises air bubbles. This means that there is less cost and energy spent on production and transportation of replacement media.

4.3 Decision Support for PFAS Removal Technology Selection

The final flowchart is presented in Figure 4.1. The flowchart includes parameters for chain length, presence of organic matter and presence of ions as these were the most found parameters identified to either inhibit or facilitate the PFAS removal efficiency of the various technologies. Due to the specific conditions needed for FF, presence of metal cations and pH has also been included. Parameters outside of these have been discussed in the separate chapters for each technology but were not included in the flowchart. In Figure 4.1, a chart with the sustainability performances for each of the technologies is presented in a simplified version as additional decision support to the flowchart. It is important to note that the functional group has an influence on the removal efficiencies. Generally, for all technologies, PFSA is more easily removed in comparison to PFCA. Individual flowcharts depicting the identified limitations for each technology can be found in Appendix C. 1-Appendix C. 4.

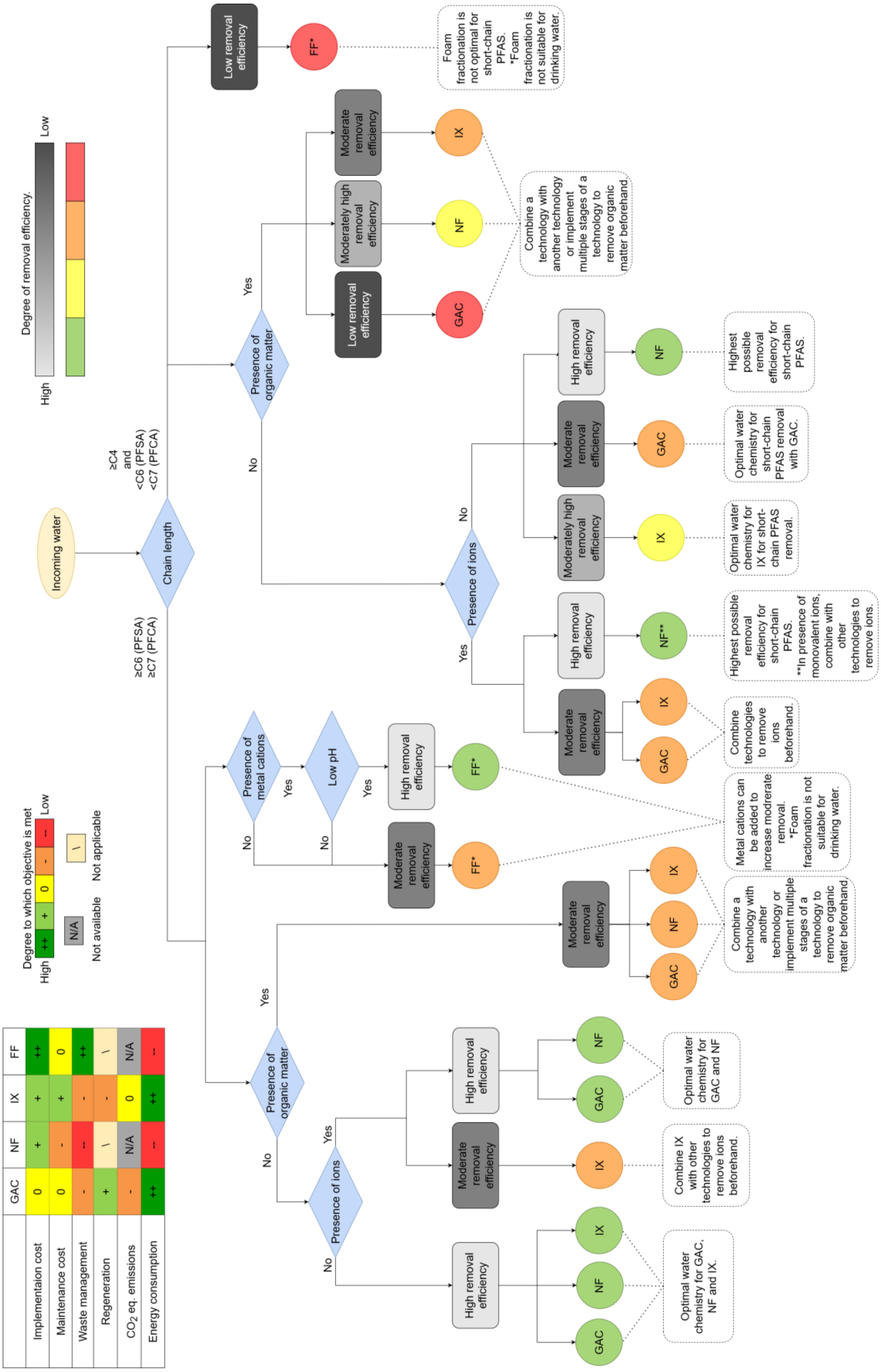


Figure 4.1: *Schematic decision support flowchart depicting how the technologies are affected by water chemistry with support from sustainability performance.*

5 Discussion

Drinking water quality is directly correlated to societal aspects related to the people consuming the water. PFAS has various consequences for human health, and it is therefore important to regulate the levels of PFAS to achieve a safe drinking water. Societal aspects also include the surrounding of, in this case, the water treatment plant. Examples of what could influence the surrounding are noise, smell and size from the water treatment plant that could influence the convenience or comfortability in the surrounding areas. Additionally, logistics regarding the transportation of waste to and from the treatment plants need to be considered.

The ethical aspects need to be considered in the project regarding ethics in humans as well as environmental ethics considering the ecology in the surroundings. One aspect includes the different water treatment processes, how they are maintained, the working environment of those treatment processes as well as the environmental impact those treatment processes might have. It is also important to discuss and weigh different treatments against each other to understand which treatment process might have a higher potential from ethical aspects. Furthermore, economic aspects need to be discussed from an ethical point of view, where questions regarding which stakeholder who will pay for the treatment are important.

Environmental perspectives are taken into account when discussing footprint reduction, reducing transportation and chemicals etc. There are many ecological aspects that can be considered with the drinking water treatment processes of water. Examples of these could be the energy used, the materials needed for the treatment such as chemicals, tanks etc. as well as the transportation needed for the materials, the maintenance needed for the treatment, the waste or byproducts that are created from the process and how that is used or taken care of, the efficiency of the process as well as the direct carbon footprint that is created during the process. Considering the importance of environmental sustainability, it is a critical aspect that has to be taken into account when considering the project.

During this study, the technologies of granular activated carbon, nanofiltration, ion exchange and foam fractionation were investigated. The results are presented as (1) a flowchart based on the technical performances of the technologies and (2) a performance matrix (multi-criteria analysis) showing the sustainability performance. Jointly, these results constitute a decision-making tool for technical and other sustainability aspects of PFAS treatment technologies.

5.1 Technology Performance

Based on the flowchart it can be seen that the final suggestion of technology was in most cases suggested to be GAC and IX, as well as cases of combinations of GAC and IX. Nanofiltration was also suggested for some cases. Regarding FF, there are certain conditions needed for it to work efficiently. Due to the needed conditions, it should be noted that FF is not well suited for drinking water purposes and should therefore be evaluated with this in mind. Despite this, it has been included in the analysis as the knowledge can be useful for future developments. Additionally, it has been shown to be useful for water highly concentrated with PFAS, such as the concentrate waste generated from nanofiltration, which makes it relevant for the evaluation.

In the case of FF, removal of long-chain PFAS is significantly more efficient than removal of short-chain PFAS. However, FF is not as affected by other contaminants, such as organic matter, present in the water compared to the other technologies. The removal efficiency can be increased under certain condition such as when there is presence of metal cations in the water and low pH-levels, which is not suited for drinking water production. Furthermore, it works better at high concentrations of PFAS which is not common in raw water used for drinking water purposes. It can also be seen that short-chain PFAS is not efficiently removed, which is due to the short chains not being able to adhere to the air bubbles as well as long chains.

Ion exchange works well for water where there is low concentration of organic matter and inorganic ions present. That is due to the organic matter and inorganic ions being adsorbed onto the resin instead of PFAS. Otherwise, IX efficiently removes both long- and short-chain PFAS with long-chain PFAS removal being slightly more efficient. As can be seen in the flowchart, the cases where the water contains organic matter, ions, or both, a combination of IX and other technologies has been suggested. The purpose of a combination of technologies would be to remove the contaminants which are preventing removal of PFAS with another technology before removing PFAS with IX. For example, GAC could be used to remove organic matter followed by IX which can then remove PFAS more efficiently. The PFAS compounds will pass through the GAC due to the pores more readily absorbing the organic matter instead of the PFAS compounds.

Nanofiltration is suggested in the case where there was no presence of organic matter as well as for both cases with or without presence of ions. This is due to NF being more efficient in presence of certain ions, such as divalent or multivalent ions of negative charge. However, NF is not optimal in cases where there is a high level of monovalent ions. It can also be discussed how NF compared to other membrane-technologies such as reverse osmosis, can be of advantage due to NF not rejecting certain ions such as minerals which are desirable in drinking water. Compared to other technologies, NF has the capability of filtering out short-chained PFAS with a much higher rejection rate. With presence of organic matter, NF was still suggested, but in combination with other technologies. The reason being that NF risks fouling with high levels of organic matter in the water. By using a pre-treatment for removing the organic matter, it could reduce the maintenance of the NF-plant. It can also be noted that NF creates a large waste stream with a high PFAS concentration. Since this water needs to be treated before moving on to the wastewater treatment plant it is important to look at what the most optimal combination is, as some technologies could be more suited for pre-treatment and others for the treatment of the waste stream in a way that could optimize both the removal efficiency as well as the costs and environmental impacts.

In the case of long-chained PFAS with no presence of organic matter or ions, all technologies except for foam fractionation are suggested. With multiple suggestions available, the final decision can be made using the support from the MCA.

Granular activated carbon has been suggested as method of treatment for the case of long-chained PFAS with no presence of organic matter and for cases with and without presence of ions. According to the findings from the literature research, GAC, similarly to NF, has a risk of fouling with high level of organic matters. This is due to the pores absorbing the organic matters instead of other contaminants such as PFAS, as well as causing GAC to reach an earlier breakthrough. The presence of organic matter also causes adsorption of the organic matter which can decrease the adsorption of PFAS compounds. For presence of ions, certain ions have the capability of neutralizing the negative charges in GAC, as well as other ions that have the capability of lowering the absorption of PFAS for GAC. But the presence of ions does not necessarily influence the PFAS absorption negatively.

5.2 Sustainability Performance

Looking at the sustainability analysis it could be seen that foam fractionation had the overall highest score from a sustainability perspective. Foam fractionation was followed by ion exchange, which was in turn followed by granular activated carbon and lastly nanofiltration.

The technology that had the lowest implementation costs and therefore the highest score according to the sustainability performance analysis is FF. Nanofiltration and ion exchange both received moderately high degree in which the objective is met, and GAC received neutral. GAC has an implementation cost where a new unit costs approximately 1000-1500 €/m^3. As seen in the results, the capital costs for GAC are $78 445. It is important to note that the difference in price could be due to firstly, the difference in what is included during calculation of the cost and secondly vary dependent on various factors related to the specific case of the water treatment plant. For the first price, only one unit of GAC was considered, while it for the life cycle assessment had included multiple costs such as the costs for piping and pressure vessels. Comparatively, the cost of a new unit per m^3 is higher for IX than GAC with a cost of 5000-8500 €/m^3 for two different types of resin while the total capital cost is lower than GAC with a cost of $44 164.

Apart from that it is also important to consider the different cases, where the volume, and, the amount of materials for implementation might vary. Looking at the maintenance cost for GAC, there were multiple sources for the annual operation costs, where the annual operation costs including regeneration and initial purchase of virgin GAC gives a total of 174 000 000 €/year. Looking at the values given from Laholmsbuktens VA, the operations costs from activated carbon is 2 SEK/m^3.

Nanofiltration received a moderately high score for the implementation costs, looking at only the membrane varied between 0.010 \$/m^3-0.020 \$/m^3 Similarly to GAC, there might be multiple membranes needed for the same system which varies dependent on the need of the treatment plant. For a capacity of 400 000 m^3/day the investment costs were approximately between $90 000 000 and $105 000 000 which is higher in comparison to the numbers given for IX and GAC. But when taking the capacity into account, the cost is 0.225 \$/m^3 - 2.625 \$/m^3.

When looking at the maintenance costs, GAC needs to consider operation costs, the purchase of carbon, the incineration or regeneration of GAC as well as the needed energy. The maintenance cost of GAC received a neutral degree for which the objective is met. Comparatively, for IX, which also includes media costs, operation, and disposal of exhausted media and energy costs, the maintenance costs are lower, which leads to a higher score than GAC. One study compared the annual operations costs between the two technologies and reported costs around 4-20 €/ m^3 treated water for GAC while IX had costs around 1.25-1.94 €/ m^3 treated water. Foam fractionation received a neutral score for maintenance costs as it does not require regular exchange of media used for the technology but is highly dependent on the energy consumption which can be high due to the large amount of aeration needed.

The absence of media also makes for a low waste production for foam fractionation and the foamate generated leads to a small fraction of the water becoming waste. In comparison, IX and GAC both generate higher amounts of waste from their adsorption media being replaced regularly. The media contains the removed PFAS which needs to be disposed of in a safe manner. The most common way of disposal for both IX and GAC is incineration which requires transportation of the waste to another site leading to higher costs and higher environmental impact. Foam fractionation can also be disposed of through incineration but due to the significantly smaller amount of waste generated, the given score was high. Nanofiltration was given the lowest score out of the four technologies as it generates a retentate of around 20% of the incoming water which is highly concentrated with PFAS. This retentate requires further treatment which, depending on how it is treated, can generate more waste, costs, and energy consumption.

For regeneration, GAC received the highest score, due to its capability of being regenerated, with a loss of only 10%, leading to an overall lower cost as well as less environmental impact. For NF, the membranes need maintenance and can be cleaned to prevent fouling. The membrane is not fully regenerated, due to cleaning being assumed to be a part of the maintenance of the membrane for its normal functioning. There is no data in this study regarding the possibility for a fully regenerated membrane which is why NF received a N/A. Ion exchange was given a low score as regenerable resin exists and works well for other purposes than drinking water production. But regenerable resin is not suitable nor allowed for drinking water production and single-use resin are used instead. Regeneration is not applicable to FF as there is no material to reuse or regenerate used in the process.

Looking at the carbon dioxide emissions, for single-use GAC the impact was approximately 0.5 kg CO_2 eq./m^3 and for regenerated GAC 0.08 kg CO_2 eq./m^3. Limited information is available for NF, however, a small-scale system resulted in CO_2 eq. of approximately 0.5 kg. This information is not reliable, and the score is therefore set to N/A. Ion exchange had a global warming effect of around 0.03 kg CO_2 eq./m^3. Compared to GAC, this is significantly lower even though the impact is mainly due to media production for both technologies. It is possible that this is due to rate of media changeout. The breakthrough, media exhaustion and the subsequent media changeout occurs more often for GAC than it does IX which leads a higher production rate and therefore higher environmental impact. As can be seen for reactivated GAC, which entails less production of new media, the environmental impact is lower than for single-use GAC.

The energy consumption for GAC and IX have been given the highest score, as energy consumption has been reported to be <0.05 kWh/m^3 for both technologies. On the other hand, both NF and FF have received the lowest score due to the high amount of energy needed for pumping in NF and aeration in FF.

5.3 Case Application of Results

To exemplify the usage of the decision support tool, three imaginary examples of cases are given, where a recommendation for each of the cases will be provided.

5.3.1 Case A

In a city, there is currently no drinking water treatment plant. But because of the increased water demand in the area and a growing population, a new drinking water treatment plant (DWTP A) must be built. The information that is given is the following:

- The raw water source is surface water.
- Measurements have shown that the water contains high levels of long-chained PFAS and lower levels of short-chained PFAS.
- The water contains organic matter.
- The water contains multiple ions, including metal ions, multivalent ions and monovalent ions.
- The pH of the water is around 7.4.

The most important aspect according to DWTP A sustainability-wise is a low cost with high removal efficiency of PFAS, without needs of too many pre-treatment or post-treatment steps.

Based on the information regarding the wanted DWTP A, knowing that the water mainly needs to be treated for long-chained PFAS and contains organic matter, one path leads to the alternatives GAC, NF or IX with combination with each other or other technologies. The reason for the moderate removal efficiency is due to the presence of organic matter, meaning that a pre-treatment for removal of the organic matter is needed. Since there is presence of ions, IX will not be as efficient in comparison to GAC and NF unless the ions are removed from the water in the pretreatment steps. When it comes to NF it is important to note that there will be a waste stream from the process that needs to be treated, which should be considered. From the information above, it is stated that the treatment plant does not want too much pre- or post-treatment. Considering that IX might need more pre-treatment due to the presence of ions and NF needs pre-treatment due to the organic matter as well as post-treatment due to the waste stream, GAC might be the most suitable option. But since the pre-treatment method is not set, IX could still be an option due to the need of a pre-treatment for the organic matter despite of the choice. This pre-treatment could potentially remove ions as well as organic matter.

With the known information it is also possible to go the other path, knowing that there is presence of metal ions, but with a close to neutral pH, FF has a moderate removal efficiency. The moderate removal efficiency is due to the high pH in the water. But since lowering the pH is not beneficial for the rest of the water treatment it is not recommended. It is also important to note that high PFAS concentrations are needed for FF to work efficiently.

Since there are multiple options available for treatment, the sustainability performance analysis can act as a support between choosing GAC, NF or IX. It is stated that DWTP A focuses on a low-cost sustainability-wise. Based on the sustainability performance analysis, IX performs better than GAC cost-wise. Furthermore, NF is even more costly as it requires more pre-treatment and energy consumption. Depending on the performance of ion-removal in the pre-treatment either GAC or IX will be recommended in this case, where GAC is recommended if the pre-treatment does not remove ions, while IX is recommended when it does remove ions.

5.3.2 Case B

In another city, there is currently a drinking water treatment plant (DWTP B). The water treatment plant is following the current guidelines of allowed PFAS concentrations in the drinking water. But due to new guidelines being introduced, the treatment plant must lower the concentrations of PFAS in the final treated water. The information given from the treatment plant was the following:

- The raw water source is groundwater.
- Measurements have shown that the water contains high levels of long-chained PFAS and lower levels of short-chained PFAS.
- The influent water has low levels of organic matter, the current treatment plant manages to reach a 95% removal of the organic matter.
- There is presence of ions in the raw water, with 98% being removed by the current treatment, leaving mostly monovalent ions.
- The pH of the water is around 7.9.

For DWTP B it is important to change as little as possible at the existing plant to reach the desired PFAS-limit. All the sustainability aspects are equally important in this case.

Knowing that there is a higher amount of long-chained PFAS, that results in taking the left path in the flowchart, similarly to Case A. Since there is a current treatment plant that manages to remove 95% of the organic matter, it is assumed that this results in the organic matter being insignificantly low. Since the pre-treatment also removes 98% of the ions, this is in this case assumed to be insignificantly low as well, leading to GAC, NF and IX to be the recommended treatment processes. For FF there is no presence of metal cations known of, and the pH is higher than the required pH, and as mentioned in Case A, FF is not suitable for drinking water production.

For DWTP B, all the sustainability aspects are equally important. Based on the sustainability performance analysis it can be seen that IX has the highest scores overall out of the three options. Therefore, assuming insignificant levels of ions, IX is recommended followed by GAC and then NF.

5.3.3 Case C

In a current drinking water treatment plant (DWTP C), the PFAS-levels are exceeding the guidelines with the reason being early breakthrough due to higher levels of organic matter than expected using GAC.

- The raw water source is surface water.
- Measurements have shown that the water contains higher levels of short-chained PFAS in comparison to long-chained PFAS.
- The water contains high levels of organic matter.
- The current pre-treatment retains the unwanted ions from the raw water.
- The pH of the water is around 8.1.

The priority for DWTP C is the removal efficiency of PFAS. They are open to a longer treatment chain where the importance lies in the environmental sustainability.

In this case, there are mainly short-chained PFAS with high organic matter, no ions and high pH. This results in FF not being suitable, due to it not functioning well with short-chain PFAS, and the water does not fulfil the conditions of low pH and presence of metal cations. Due to the high organic matter, all treatment processes have a decreased removal efficiency, with GAC having low removal efficiency, IX having moderate removal efficiency and NF having moderately high removal efficiency. It is recommended to combine the technologies to increase the removal efficiency. Since NF has the highest removal efficiency, implementing NF would be the first recommendation, where the current GAC removes the organic matter and NF removes PFAS. Another alternative is to use IX, but NF has been shown to be more efficient at removing short-chain PFAS.

For DWTP C, the importance is environmental sustainability. According to the sustainability performance analysis, there is no available data for NF. Therefore, IX might be more suitable. What could also be considered is using GAC, since the removal of organic matter from the first GAC could allow an addition of GAC next in the treatment train to result in a high removal efficiency of PFAS. Unlike IX, GAC has the capability of being regenerated, where there are multiple more environmentally friendly options, such as coconut GAC, although only conventional GAC with higher carbon footprint is discussed in this study.

From a technical perspective, IX would be a better choice, but with proper removal of organic matter, GAC could overall, with consideration to regeneration and carbon footprint, result in less environmental impact. Therefore, the recommended treatment process would be GAC when there is no organic matter and secondly IX. If the levels of organic matter are still high after the current treatment, another pre-treatment should be considered.

5.4 The Effects of Subjectivity

During the project, subjectivity has been a part in finalizing the results. For the flowchart, recommendations are based on data found through literature, where the level of efficiency was evaluated with compiled information. It is important to note that limited numbers of articles were involved in the project, which resulted in a generalization. This together with the human factor results in an unpreventable subjectivity considering the time frame of the project. The sustainability performance analysis was of a similar method, where the scores given are based on numbers from the data. But due to the results being presented in a chart, with five possible scores, there is a possibility of subjective interpretations. Therefore, it is important to consider the effects of subjectivity in further work.

The consequence of subjectivity leads to various interpretations of results. The reasoning behind the scores for the sustainability performance analysis has therefore been added in

Appendix B – Summary of Motivations for the Scoring of the Sustainability Analysis

Appendix B. 1 for the reader to be available to access the information behind each of the score, together with the results described in chapter 4. Similarly, the information collected and used as basis for the flowchart is available for reading.

6 Conclusions

The main conclusions based on the presented work are:

- A decision support is currently not readily available for treatment plants.
- A decision support was created and consists of a flowchart detailing the effects water chemistry has on the efficiency of the technologies as well as an evaluation of the sustainability of the technologies.
- All technologies showed varying removal efficiencies for different conditions in the flowchart.
- Both GAC and IX showed promising results in multiple cases, both are affected by presence of organic matter and ions in varying degrees.
- Nanofiltration showed higher removal efficiencies for short-chain PFAS compared to the other technologies.
- Foam fractionation performs well at high PFAS concentrations and long-chain PFAS but is not easily applicable in drinking water production.
- Combining technologies can be beneficial as the interfering contaminant can be removed in a penultimate step before the PFAS removal occurs.
- The overall sustainability of the technologies ranked from highest to lowest based on their given scoring would be FF>IX>GAC>NF.
- It is not purely the performance of the technology that has a significant influence on the final decision of removal technology, but also sustainability aspects.

7 Recommendations for Further Work

Recommendations for further work based on the presented work are:

- Further research on available data for a broader yet more detailed results.
- Further pilot-testing at larger scales for the technologies to reflect real case scenarios, for technology performance as well as sustainability aspects.
- Collect information regarding the sustainability of the technologies, particularly the environmental impact.
- Investigate the value of implementing a technology for PFAS removal in relation the change in consumer cost.
- Explore the discussion of who pays the price of further removal of contaminants in addition to an investigation of whether people are willing to pay an increased price for their drinking water.

References

[1] Swedish Food Agency, E. Lindfeldt, I. Gyllenhammar, S. Strandh, and E. Halldin Ankarberg, “Kartläggning av per-och polyfluorerade alkylsubstanser (PFAS) i Sveriges kommunala rå-och dricksvatten,” Uppsala, 2021. Accessed: May 21, 2024. [Online]. Available: https://www.livsmedelsverket.se/globalassets/publikationsdatabas/rapporter/2021/l-2021-nr-21-kartlaggning-av-per-och-polyfluorerade-alkylsubstanser.pdf

[2] Centers for Disease Control and Prevention, “Per- and Polyfluorinated Substances (PFAS) Factsheet | National Biomonitoring Program | CDC.” Accessed: Feb. 23, 2024. [Online]. Available: https://www.cdc.gov/biomonitoring/PFAS_FactSheet.html

[3] Swedish Chemicals Agency, “PFAS - Kemikalieinspektionen.” Accessed: Feb. 23, 2024. [Online]. Available: https://www.kemi.se/en/chemical-substances-and-materials/pfas

[4] Geological Survey of Sweden (SGU), “PFAS i grundvatten.” Accessed: Apr. 08, 2024. [Online]. Available: https://www.sgu.se/grundvatten/miljoovervakning-av-grundvatten/pfas-i-grundvatten/

[5] Agency for Toxic Substances and Disease Registry, “Potential health effects of PFAS chemicals | ATSDR.” Accessed: Feb. 23, 2024. [Online]. Available: https://www.atsdr.cdc.gov/pfas/health-effects/index.html

[6] United States Environmental Protection Agency, “Our Current Understanding of the Human Health and Environmental Risks of PFAS | US EPA.” Accessed: Feb. 23, 2024. [Online]. Available: https://www.epa.gov/pfas/our-current-understanding-human-health-and-environmental-risks-pfas#:~:text=What%20We%20Know%20about%20Health,blood%20pressure%20in%20pregnant%20women

[7] Swedish Food Agency, “PFAS och andra miljögifter i dricksvatten och livsmedel - kontroll.” Accessed: Feb. 23, 2024. [Online]. Available: https://www.livsmedelsverket.se/foretagande-regler-kontroll/dricksvattenproduktion/kontroll-pfas-miljogifter-dricksvatten-egenfangad-fisk

[8] City Water Purifier, “Ion Exchange Technology: Everything You Need To Know - City Water Purifier.” Accessed: Feb. 23, 2024. [Online]. Available: https://www.citywaterpurifier.com/ion-exchange-technology/

[9] Inc. Pure Aqua, “Nanofiltration NF Systems - Pure Aqua, Inc.” Accessed: Feb. 23, 2024. [Online]. Available: https://pureaqua.com/nanofiltration-nf-systems/

[10] M. Hiraide, “FOAM FRACTIONATION AND FLOTATION,” *Encyclopedia of Analytical Science: Second Edition*, pp. 195–201, 2005, doi: 10.1016/B0-12-369397-7/00174-6.

[11] OECD and UNEP Global PFC Group, “Synthesis Paper on Per- and Polyfuorinated Chemicals (PFCs),” Environment, Health and Safety. Accessed: Apr. 11, 2024. [Online]. Available: https://www.oecd.org/env/ehs/risk-management/PFC_FINAL-Web.pdf

[12] R. Lohmann and R. J. Letcher, “The universe of fluorinated polymers and polymeric substances and potential environmental impacts and concerns,” *Curr Opin Green Sustain Chem*, vol. 41, p. 100795, 2023, doi: 10.1016/J.COGSC.2023.100795.

[13] United States Environmental Protection Agency, “Our Current Understanding of the Human Health and Environmental Risks of PFAS | US EPA.” Accessed: Apr. 11, 2024. [Online]. Available: https://www.epa.gov/pfas/our-current-understanding-human-health-and-environmental-risks-pfas

[14] J. Knulst, “Per- och polyfluorerade ämnen (PFAS) i sjöar och vattendrag i Stockholms län,” Stockholm, Mar. 2022. Accessed: May 22, 2024. [Online]. Available: https://catalog.lansstyrelsen.se/store/39/resource/126

[15] Swedish Food Agency, I. Gyllenhammar, E. Lindfeldt, and E. Halldin Ankarberg, “Vetenskapligt underlag för PFAS i dricksvatten,” Uppsala, 2022. Accessed: May 31, 2024. [Online]. Available: https://www.livsmedelsverket.se/globalassets/publikationsdatabas/pm/2022/pm-2022-vetenskapligt-underlag-for-pfas-i-dricksvatten.pdf

[16] National Center for Biotechnology Information, “National Center for Biotechnology Information.” Accessed: May 31, 2024. [Online]. Available: https://www.ncbi.nlm.nih.gov/

[17] Swedish Chemicals Agency, “Brandskum som möjlig förorenare av dricksvattentäkter,” vol. 5, Dec. 2013.

[18] Uppsala Vatten, “Domstolsförhandling PFAS | Uppsala vatten.” Accessed: Apr. 08, 2024. [Online]. Available: https://www.uppsalavatten.se/hushall/vatten-och-avlopp/dricksvatten/domstolsforhandling-pfas

[19] Uppsala Vatten, “Skillnader mellan Kallinge-fallet och Uppsalas domstolsprocess mot Försvarsmakten.” Accessed: May 31, 2024. [Online]. Available: https://www.uppsalavatten.se/om-oss/nyheter/arkiv/2023-12-08-skillnader-mellan-kallinge-fallet-och-uppsalas-domstolsprocess-mot-forsvarsmakten

[20] M. Holmgren, “Försvarsmakten överklagar Uppsaladomen,” Svenskt Vatten. Accessed: May 31, 2024. [Online]. Available: https://www.svensktvatten.se/om-oss/nyheter-lista/forsvarsmakten-overklagar-uppsaladomen/

[21] The Supreme Court, “The Supreme Court delivers judgment in PFAS case.” Accessed: May 31, 2024. [Online]. Available: https://www.domstol.se/en/supreme-court/news-archive/the-supreme-court-delivers-judgment-in-pfas-case/

[22] Swedish Food Agency, “Nu införs nya gränsvärden för bland annat PFAS i dricksvatten.” Accessed: Jun. 04, 2024. [Online]. Available: https://www.livsmedelsverket.se/om-oss/press/nyheter/pressmeddelanden/nu-infors-nya-gransvarden-for-bland-annat-pfas-i-dricksvatten

[23] Centers for Disease Control and Prevention, “Water Treatment | Public Water Systems | Drinking Water | Healthy Water | CDC.” Accessed: Apr. 11, 2024. [Online]. Available: https://www.cdc.gov/healthywater/drinking/public/water_treatment.html

[24] M. Rubensson, “Lackarebäcks vattenverk, Göteborgs stad.” Accessed: May 31, 2024. [Online]. Available: https://www.lyon.se/html/lackareback_1920.html

[25] S. J. Köhler and (Norconsult AB), “Personal communication thorugh conversation.” 2024.

[26] Göteborgs Stad, “Dricksvattnets kvalitet.” Accessed: May 22, 2024. [Online]. Available: https://goteborg.se/wps/portal/start/bygga-bo-och-leva-hallbart/vatten-och-avlopp/dricksvatten/dricksvattnets-kvalitet

[27] F. Fotouhi and N. Kresic, “Springwater treatment,” in *Groundwater Hydrology of Springs*, N. Kresic and Z. Stevanovic, Eds., Butterworth-Heinemann, 2010, pp. 269–304. doi: 10.1016/B978-1-85617-502-9.00007-4.

[28] V. Yargeau, “Water and wastewater treatment: chemical processes,” in *Metropolitan Sustainability: Understanding and Improving the Urban Environment*, F. Zeman, Ed., Woodhead Publishing, 2012, pp. 390–405. doi: 10.1533/9780857096463.3.390.

[29] United States Environmental Protection Agency, “Overview of Drinking Water Treatment Technologies.” Accessed: May 31, 2024. [Online]. Available: https://www.epa.gov/sdwa/overview-drinking-water-treatment-technologies

[30] CPL Activated Carbons, “What is Granular Activated Carbon?” Accessed: May 31, 2024. [Online]. Available: https://activated-carbon.com/news/granular-activated-carbon/

[31] K. Roest *et al.*, “Performance of Water Treatment Systems For PFAS Removal,” Brussels, Jun. 2021. Accessed: May 08, 2024. [Online]. Available: https://www.concawe.eu/wp-content/uploads/Rpt_21-5.pdf

[32] C. Carlson and A. Ebben, “A Look at Activated Carbon Thermal Regeneration,” FEECO International, Inc. Accessed: May 31, 2024. [Online]. Available: https://feeco.com/a-look-at-activated-carbon-thermal-regeneration/#:~:text=Regeneration%2C%20often%20referred%20to%20as,again%20function%20as%20an%20adsorbent.

[33] E. Nagy, “Nanofiltration,” in *Basic Equations of Mass Transport Through a Membrane Layer*, 2nd ed., Veszprém, Hungary: Elsevier, 2019, pp. 417–428. doi: 10.1016/B978-0-12-813722-2.00015-7.

[34] A. F. Ismail and T. Matsuura, “Nanofiltration,” in *Membrane Separation Processes - Theories, Problems, and Solutions*, Elsevier, 2022, pp. 61–68. doi: 10.1016/B978-0-12-819626-7.00008-9.

[35] N. S. Suhalim *et al.*, “Rejection Mechanism of Ionic Solute Removal by Nanofiltration Membranes: An Overview,” *Nanomaterials*, vol. 12, no. 3, Jan. 2022, doi: 10.3390/NANO12030437/S1.

[36] A. W. Mohammad, Y. H. Teow, W. L. Ang, Y. T. Chung, D. L. Oatley-Radcliffe, and N. Hilal, “Nanofiltration membranes review: Recent advances and future prospects,” *Desalination*, vol. 356, pp. 226–254, Jan. 2015, doi: 10.1016/J.DESAL.2014.10.043.

[37] T. and R. C. Interstate, “PFAS - Per- and Polyfluoroalkyl Substances - 12 Treatment Technologies.”

[38] Y. L. Liu and M. Sun, “Ion exchange removal and resin regeneration to treat per- and polyfluoroalkyl ether acids and other emerging PFAS in drinking water,” *Water Res*, vol. 207, p. 117781, Dec. 2021, doi: 10.1016/J.WATRES.2021.117781.

[39] Rohm and Haas, “Ion Exchange for Dummies - An introduction.” Lenntech, Sep. 2008. Accessed: May 31, 2024. [Online]. Available: https://www.lenntech.com/Data-sheets/Ion-Exchange-for-Dummies-RH.pdf

[40] E. Gagliano, M. Sgroi, P. P. Falciglia, F. G. A. Vagliasindi, and P. Roccaro, “Removal of poly- and perfluoroalkyl substances (PFAS) from water by adsorption: Role of PFAS chain length, effect of organic matter and challenges in adsorbent regeneration,” *Water Res*, vol. 171, p. 115381, Mar. 2020, doi: 10.1016/J.WATRES.2019.115381.

[41] R. Medina, M. W. Pannu, S. A. Grieco, M. Hwang, C. Pham, and M. H. Plumlee, “Pilot-scale comparison of granular activated carbons, ion exchange,

and alternative adsorbents for per- and polyfluoroalkyl substances removal," *AWWA Water Sci*, vol. 4, no. 5, p. e1308, Oct. 2022, doi: 10.1002/AWS2.1308.
[42] T. Buckley, X. Xu, V. Rudolph, M. Firouzi, and P. Shukla, "Review of foam fractionation as a water treatment technology," *Sep Sci Technol*, vol. 57, no. 6, pp. 929–958, Apr. 2022, doi: 10.1080/01496395.2021.1946698.
[43] A. C. E. We, A. Zamyadi, A. D. Stickland, B. O. Clarke, and S. Freguia, "A review of foam fractionation for the removal of per- and polyfluoroalkyl substances (PFAS) from aqueous matrices," *J Hazard Mater*, vol. 465, p. 133182, Mar. 2024, doi: 10.1016/J.JHAZMAT.2023.133182.
[44] P. McCleaf, W. Stefansson, and L. Ahrens, "Drinking water nanofiltration with concentrate foam fractionation—A novel approach for removal of per- and polyfluoroalkyl substances (PFAS)," *Water Res*, vol. 232, p. 119688, Apr. 2023, doi: 10.1016/J.WATRES.2023.119688.
[45] T. D. Appleman *et al.*, "Treatment of poly- and perfluoroalkyl substances in U.S. full-scale water treatment systems," *Water Res*, vol. 51, pp. 246–255, Mar. 2014, doi: 10.1016/J.WATRES.2013.10.067.
[46] Y. Zhang, A. Thomas, O. Apul, and A. K. Venkatesan, "Coexisting ions and long-chain per- and polyfluoroalkyl substances (PFAS) inhibit the adsorption of short-chain PFAS by granular activated carbon," *J Hazard Mater*, vol. 460, p. 132378, Oct. 2023, doi: 10.1016/J.JHAZMAT.2023.132378.
[47] O. Gibert, B. Lefèvre, M. Fernández, X. Bernat, M. Paraira, and M. Pons, "Fractionation and removal of dissolved organic carbon in a full-scale granular activated carbon filter used for drinking water production," *Water Res*, vol. 47, no. 8, pp. 2821–2829, May 2013, doi: 10.1016/J.WATRES.2013.02.028.
[48] D. N. Kothawala, S. J. Köhler, A. Östlund, K. Wiberg, and L. Ahrens, "Influence of dissolved organic matter concentration and composition on the removal efficiency of perfluoroalkyl substances (PFASs) during drinking water treatment," *Water Res*, vol. 121, pp. 320–328, Sep. 2017, doi: 10.1016/J.WATRES.2017.05.047.
[49] J. Yuan, S. Mortazavian, E. Passeport, and R. Hofmann, "Evaluating perfluorooctanoic acid (PFOA) and perfluorooctanesulfonic acid (PFOS) removal across granular activated carbon (GAC) filter-adsorbers in drinking water treatment plants," *Science of The Total Environment*, vol. 838, p. 156406, Sep. 2022, doi: 10.1016/J.SCITOTENV.2022.156406.
[50] M. Ophorst, J. de Grooth, S. G. J. Heijman, E. M. H. Vaudevire, and M. Jafari, "Operation and performance analysis of direct hollow fiber nanofiltration: A pilot study at IJsselmeer," *Sep Purif Technol*, vol. 349, p. 127786, Dec. 2024, doi: 10.1016/J.SEPPUR.2024.127786.
[51] W. Zheng *et al.*, "Research on the factors influencing nanofiltration membrane fouling and the prediction of membrane fouling," *Journal of Water Process Engineering*, vol. 59, p. 104876, Mar. 2024, doi: 10.1016/J.JWPE.2024.104876.
[52] C. J. Liu *et al.*, "Pilot-scale field demonstration of a hybrid nanofiltration and UV-sulfite treatment train for groundwater contaminated by per- and polyfluoroalkyl substances (PFASs)," *Water Res*, vol. 205, p. 117677, Oct. 2021, doi: 10.1016/J.WATRES.2021.117677.
[53] P. McCleaf, W. Stefansson, and L. Ahrens, "Drinking water nanofiltration with concentrate foam fractionation—A novel approach for removal of per- and polyfluoroalkyl substances (PFAS)," *Water Res*, vol. 232, p. 119688, Apr. 2023, doi: 10.1016/J.WATRES.2023.119688.

[54] T. H. Boyer *et al.*, "Anion exchange resin removal of per- and polyfluoroalkyl substances (PFAS) from impacted water: A critical review," *Water Res*, vol. 200, p. 117244, Jul. 2021, doi: 10.1016/J.WATRES.2021.117244.

[55] A. Zaggia, L. Conte, L. Falletti, M. Fant, and A. Chiorboli, "Use of strong anion exchange resins for the removal of perfluoroalkylated substances from contaminated drinking water in batch and continuous pilot plants," *Water Res*, vol. 91, pp. 137–146, Mar. 2016, doi: 10.1016/J.WATRES.2015.12.039.

[56] A. Maimaiti *et al.*, "Competitive adsorption of perfluoroalkyl substances on anion exchange resins in simulated AFFF-impacted groundwater," *Chemical Engineering Journal*, vol. 348, pp. 494–502, Sep. 2018, doi: 10.1016/J.CEJ.2018.05.006.

[57] S. J. Chow *et al.*, "Comparative investigation of PFAS adsorption onto activated carbon and anion exchange resins during long-term operation of a pilot treatment plant," *Water Res*, vol. 226, p. 119198, Nov. 2022, doi: 10.1016/J.WATRES.2022.119198.

[58] I. Ross *et al.*, "A review of emerging technologies for remediation of PFASs," *Remediation*, vol. 28, no. 2, pp. 101–126, Mar. 2018, doi: 10.1002/REM.21553.

[59] A. Krögerström, "Removal of per- and polyfluoroalkyl substances (PFAS) from contaminated leachate using aeration foam fractionation," Swedish University of Agricultural Sciences (SLU), Uppsala, 2021.

[60] P. Mccleaf, Y. Kjellgren, and Lutz Ahrens, "Foam fractionation removal of multiple per-and polyfluoroalkyl substances from landfill leachate," *AWWA Water Sci*, p. e1238, 2021, doi: 10.1002/aws2.1238.

[61] A. Malovanyy, F. Hedman, M. G. Feldtmann, M. Harding, and J. Yang, "Rening av PFAS-förorenat vatten från avfallsanläggningar," Mar. 2021.

[62] S. J. Smith, J. Lewis, K. Wiberg, E. Wall, and L. Ahrens, "Foam fractionation for removal of per- and polyfluoroalkyl substances: Towards closing the mass balance," *Science of The Total Environment*, vol. 871, p. 162050, May 2023, doi: 10.1016/J.SCITOTENV.2023.162050.

[63] P. Meng *et al.*, "Efficient removal of perfluorooctane sulfonate from aqueous film-forming foam solution by aeration-foam collection," *Chemosphere*, vol. 203, pp. 263–270, Jul. 2018, doi: 10.1016/J.CHEMOSPHERE.2018.03.183.

[64] T. Buckley, K. Karanam, X. Xu, P. Shukla, M. Firouzi, and V. Rudolph, "Effect of mono- and di-valent cations on PFAS removal from water using foam fractionation – A modelling and experimental study," *Sep Purif Technol*, vol. 286, p. 120508, Apr. 2022, doi: 10.1016/J.SEPPUR.2022.120508.

[65] D. J. Burns, P. Stevenson, and P. J. C. Murphy, "PFAS removal from groundwaters using Surface-Active Foam Fractionation," *Remediation Journal*, vol. 31, no. 4, pp. 19–33, Aug. 2021, doi: 10.1002/REM.21694.

[66] N. Belkouteb, V. Franke, P. McCleaf, S. Köhler, and L. Ahrens, "Removal of per- and polyfluoroalkyl substances (PFASs) in a full-scale drinking water treatment plant: Long-term performance of granular activated carbon (GAC) and influence of flow-rate," *Water Res*, vol. 182, p. 115913, Sep. 2020, doi: 10.1016/J.WATRES.2020.115913.

[67] V. Franke, M. Ullberg, P. McCleaf, M. Wålinder, S. J. Köhler, and L. Ahrens, "The Price of Really Clean Water: Combining Nanofiltration with Granular Activated Carbon and Anion Exchange Resins for the Removal of Per- And Polyfluoralkyl Substances (PFASs) in Drinking Water Production," *ACS ES*

and T Water, vol. 1, no. 4, pp. 782–795, Jan. 2021, doi: 10.1021/acsestwater.0c00141.
[68] E. Johansson and L. V. (VA-ingenjör, "Personal communication through Email." 2024.
[69] A. C. Ellis, T. H. Boyer, Y. Fang, C. J. Liu, and T. J. Strathmann, "Life cycle assessment and life cycle cost analysis of anion exchange and granular activated carbon systems for remediation of groundwater contaminated by per- and polyfluoroalkyl substances (PFASs)," *Water Res*, vol. 243, p. 120324, Sep. 2023, doi: 10.1016/J.WATRES.2023.120324.
[70] A. Vilén, P. Laurell, and R. Vahala, "Comparative life cycle assessment of activated carbon production from various raw materials," *J Environ Manage*, vol. 324, p. 116356, Dec. 2022, doi: 10.1016/J.JENVMAN.2022.116356.
[71] A. Yuksekdag *et al.*, "Upgrading of conventional water treatment plant by nanofiltration for enhanced organic matter removal," *Sep Purif Technol*, vol. 325, p. 124766, Nov. 2023, doi: 10.1016/J.SEPPUR.2023.124766.
[72] S. Guo, Y. Wan, X. Chen, and J. Luo, "Loose nanofiltration membrane custom-tailored for resource recovery," *Chemical Engineering Journal*, vol. 409, p. 127376, Apr. 2021, doi: 10.1016/J.CEJ.2020.127376.
[73] M. Riegel, S. Egner, and F. Sacher, "Review of water treatment systems for PFAS removal," TZW, Brussels, Aug. 2020. Accessed: May 08, 2024. [Online]. Available: https://www.concawe.eu/wp-content/uploads/Rpt_20-14.pdf
[74] M. Blázquez *et al.*, "Life Cycle Assessment of a Layer by Layer Nanofiltration Membrane - A Case Study of the LbLbrane Project," in *In proceedings of the Avnir conference*, Lille, France, Nov. 2014. Accessed: May 29, 2024. [Online]. Available: https://www.researchgate.net/publication/272684473_LIFE_CYCLE_ASSESSMENT_OF_A_LAYER_BY_LAYER_NANOFILTRATION_MEMBRANE_-_A_CASE_STUDY_OF_THE_LBLBRANE_PROJECT
[75] Svenskt Vatten and K. Westling, "Tillsammans för en klimatneutral VA-bransch." Accessed: May 31, 2024. [Online]. Available: https://www.svensktvatten.se/medlemsservice/klimatneutral-va/
[76] L. Hedberg and (Norconsult AB), "Personal communication through Email." 2024.
[77] X. Huang, S. Guida, B. Jefferson, and A. Soares, "Economic evaluation of ion-exchange processes for nutrient removal and recovery from municipal wastewater," *NPJ Clean Water*, vol. 3, no. 1, pp. 1–10, Mar. 2020, doi: 10.1038/s41545-020-0054-x.
[78] A. Malovanyy *et al.*, "Comparative study of per- and polyfluoroalkyl substances (PFAS) removal from landfill leachate," *J Hazard Mater*, vol. 460, p. 132505, Oct. 2023, doi: 10.1016/J.JHAZMAT.2023.132505.
[79] S. J. Smith, K. Wiberg, P. McCleaf, and L. Ahrens, "Pilot-Scale Continuous Foam Fractionation for the Removal of Per- and Polyfluoroalkyl Substances (PFAS) from Landfill Leachate," *ACS ES&T Water*, vol. 2, no. 5, pp. 841–851, May 2022, doi: 10.1021/ACSESTWATER.2C00032/ASSET/IMAGES/LARGE/EW2C00032_0006.JPEG.
[80] S. J. Smith, "Innovative treatment technologies for PFAS-contaminated water," Swedish University of Agricultural Sciences, Uppsala, 2023. doi: https://doi.org/10.54612/a.6p8i5lbs8l.

[81] EPOC enviro, “SAFF ® 20 & SAFF ® 40 - Technical Datasheet & Specification,” 2021, doi: 10.1002/rem.21694.

Appendices

Appendix A – Water Chemistry and Setup Values of the Studies

Appendix A. 1: Water chemistry and other parameters for [55]

Parameter	Value
EBCT	10.1 min
Surface loading rate	3.0 m/h
pH	7.6
Nitrates	19 mg/L
Sulphates	44 mg/L
Chlorides	24 mg/L
PFBA	212 ng/L
PFPeA	133 ng/L
PFHxA	109 ng/L
PFHpA	24 ng/L
PFOA	430 ng/L
PFNA	<1 ng/L
PFDA	1 ng/L
PFUnA	<1 ng/L
PFDoA	<1 ng/L
PFBS	171 ng/L
PFHxS	13 ng/L
PFOS	27 ng/L

Appendix A. 2: PFAS concentrations for [41].

PFAS Compound	Chain Length	Average Concentration (ng/L)
PFBS	C4	14.6
PFBA	C4	29.4
PFPeA	C5	6.8
PFPeS	C5	2.1
PFHxS	C6	10.7
PFHxA	C6	3.1
PFHpA	C7	2.5
PFOA	C8	17.3
PFOS	C8	23.0
PFNA	C9	2.8
PFDA	C10	3.1

Appendix A. 3: Influent water quality for [41].

Parameter	Average value	Unit
Operation time	26	months
EBCT	2	min
Hydraulic loading rate – HLR	375	L/(min*m^2)
pH	7.66	
UV absorbance	0.031	1/cm
Alkalinity	195	mg/L
Total dissolved solids – TDS	624	mg/L
Total organic carbon – TOC	1.3	mg/L
Dissolved organic carbon – DOC	1.3	mg/L
Cl^-	130	mg/L
SO_4^{2-}	131	mg/L
NO_3^-	0.3	mg/L
PO_4^{3-}	0.4	mg/L
HCO_3^-	237	mg/L
Ba^{2+}	69.8	ug/L
Ca^{2+}	82.2	mg/L
Cu^{2+}	2.93	ug/L
Fe^{2+}	4.32	ug/L
Mg^{2+}	21.7	mg/L
Mn^{2+}	232	ug/L

Appendix A. 4: Parameter values for [57]

Parameter	Value	Unit
Operation time	15	months
Resins	PFA694E PSR2+	
EBCT	2.7	min
HLR	22	m/hr
Flowrate	1.7	L/min
pH	7.51	
Alkalinity	221.3	mg/L
Conductivity	634	µS/cm
TOC	0.71	mg/L
Total iron	130	µg/L
Total manganese	60	µg/L
$\boldsymbol{Cl^-}$	37.1	mg/L
$\boldsymbol{NO_3^-}$	0.77	mg/L
$\boldsymbol{SO_4^{2-}}$	58.0	mg/L
PFPrA	435.0	ng/L
PFBA	914.6	ng/L
PFPeA	59.1	ng/L
PFHxA	44.3	ng/L
PFHpA	6.0	ng/L
PFOA	14.5	ng/L
PFEtS	24.1	ng/L
PFPrS	95.4	ng/L
PFBS	130.4	ng/L
PFPeS	82.9	ng/L
PFHxS	48.2	ng/L
PFHpS	0.9	ng/L
PFOS	1.5	ng/L
FBSA	3.5	ng/L
FHxSA	0.8	ng/L

Appendix A. 5: Parameter values for [60]

Parameter	Value	Unit
Contact times	5, 10 and 20	min
Water column height	1	m
Air flowrates	3500 and 7000	L/(min*m^2)
Conductivity	5.3-5.4	mS/cm
Temperature	19	℃
pH	7.7	
Tested ΣPFAS	3200-25 000	ng/L
Average removal of ΣPFCA	77	%
Average removal of ΣPFSA	94	%
Average removal of precursors	68	%
Average removal of ΣPFAS	83	%

Appendix A. 6: Parameters for the NF concentrate that was used for the ion exchange in [67].

Parameters	Value (±SD)	Unit
Temperature	8.3	℃
Color	17.9±3.9	mg*Pt/L
Conductivity	221±13.1	mS/m
pH	8±0	mg/L
HCO_3^-	1180±85	mg/L
NH_4^+	<0.003	mg/L
NO_3^-	9.0±0.6	mg/L
F^-	4.7±0.3	mg/L
Cl^-	113±7.6	mg/L
Br^-	462±51	µg/L
SO_4^{2-}	209±20	mg/L
COD (Mn(III))	7.0±0.9	mg/L
Fe^{2+}	<0.01	mg/L
Mn^{2+}	41±16	µg/L
Cu^{2+}	<0.02	mg/L
Na^+	73±4.4	mg/L
K^+	NA	mg/L
Ca^{2+}	376±23	mg/L
Mg^{2+}	69±5.3	mg/L
Al^{3+}	<0.01	mg/L
Hardness	69±4.5	˚dH
Uranium-238	168±13	µg/L
DOC	16.0	mg/L
PFBA	17±4.7	µg/L
PFPeA	16±3.7	µg/L
PFHxA	37±9.2	µg/L
PFHpA	15±7.0	µg/L
PFOA	24±3.3	µg/L
PFBS	44±9.7	µg/L
PFHxS	306±24	µg/L
PFOS	142±24	µg/L
$\Sigma_{11}PFAS$	583±87	µg/L
PFPeS	46±13	µg/L
UV$_{254nm}$	0.26	1/cm
Turbidity	0.14±0.06	FNU

Appendix A. 7. Specifications of dNF40 membrane used in [50].

Parameters	
Membrane parameters	
Module length [mm]	1428
External diameter [mm]	200
Module material (housing-membrane)	PVC-Modified PES
Membrane area [m2]	43
Membrane MWCO	400
Membrane charge	Negative at pH 7
Membrane rejection (MgSO4) [%]	91
Fiber inner diameter	0.7
Membrane operational limits	
Max temperature [deg C]	40
Operating pH	2---12
Cleaning pH	1---13
Crossflow velocity [m/s]	-2
Max TMP [bar]	6
Max backwash pressure [bar]	6
Max active chlorine concentration [ppm]	500 at pH > 10

Appendix A. 8: The concentrations of PFAS compounds in the water for [50].

PFAS compound	**MW [g/mol]**	**Concentration in spike solution [µg/L]**
PFOS	500	0.1
PFNA	464	0.02
PFOA	414	0.1
PFHxS	400	0.1

Appendix A. 9: The water composition for the different waters in [50].

Parameter	**Unit**	**Pre-treated water**	**Raw water**
Ca2+	mg/L	63±3.76	65.9±2.21
Mg2+	mg/L	11.5±0.21	11.9±0.51
SO4 2-	mg/L	61.9±2.13	57.7±2.20
Na+	mg/L	Not measured	50.8±3.64
Cl-	mg/L	138.1±1.55	91.0±5.04
HCO3-	mg/L	149.2±7.48	17.6±2.11
NO3-	mg/L	10.4±0.27	10.1±0.48
TOC	mg/L	3.5±0.28	6.2±0.24

Appendix A. 10: Parameters for [66].

Parameter	**Filtrasorb 400** [66]			
Treated water goal [ng/L ∑PFAS11]	10	25	50	85
Unit regeneration costs [€/m^3 treated]	0.10	0.06	0.03	0.02
Annual regeneration cost at studied DWTP (1000 €/year)	707 000	404 000	206 000	169 000
Annual operations cost at DWTP including regeneration and initial purchase of virgin GAC (1000 €/year)	712 000	409 000	211 000	174 000

Appendix A. 11: Parameters for GAC for [69].

Operating parameter	**GAC (single-use)**	**GAC (Thermal regen.)**
Vessel size	1000	1000
EBCT (min)	10	10
Sorbent Mass (kg)	540	540
Sorbent Density (g/L)	540	540
BVs until breakthrough	13 000	13 000
Media Changeouts per year	4.04	4.04
Sorbent Burn Rate (kg/month)	181.9	181.9
Management of Spent Media	Incineration	Reactivation

Appendix A. 12: Capital costs for GAC for [69].

Category	**GAC capital costs [$]**
Pressure Vessels	35 320
Media	2 774
Storage Tanks	5 800
Piping	764
Valves and fittings	7 354
Pumps	8 020
Instrumentation	9 141
System control	9 272
Total	78 445

Appendix A. 13:Maintenance costs for GAC for [69].

Category	GAC with incineration [$]	GAC with regeneration [$]
Labor	7 552	7 440
Media replacement	6 327	4 727
Off-site disposal	2 111	2 955
Miscellaneous allowances	1 599	1 512
Total annual O&M	17 589	16 634

Appendix A. 14: Environmental impact for GAC for [69].

Impact category	Unit	Single-use GAC	GAC with thermal reactivation
Ozone depletion	kg CFC-11 eq	1.716E-08	3.998E-09
Global warming	kg CO2 eq	4.407E-01	7.264E-02
Smog	kg O3 eq	1.829E-02	4.371E-03
Acidification	kg SO2 eq	2.168E-03	4.027E-04
Eutrophication	kg N eq	1.083E-03	1.670E-04
Carcinogenics	CTUh	2.925E-08	2.853E-09
Non carcinogenics	CTUh	6.315E-08	1.026E-08
Respiratory effects	kg PM2.5 eq	2.063E-04	3.459E-05
Ecotoxicity	CTUe	1.703E+00	2.709E-01
Fossil fuel depletion	MJ surplus	1.827E-01	6.249-02

Appendix A. 15: Parameters for [74].

UF pretreatment	NF treatment
Membrane area 15 m2	Membrane area: 40 m2
Flux: 80 l/m2*h	Flux: 30 l/m*h
Permeate:1.2000 l/h	Permeate: 1.200 l/h
Lifetime of the UF membrane: 10 years	Lifetime of the NF membrane: 10 years
Lifetime of the UF installation: 30 years	Lifetime of the NF installation: 15 years

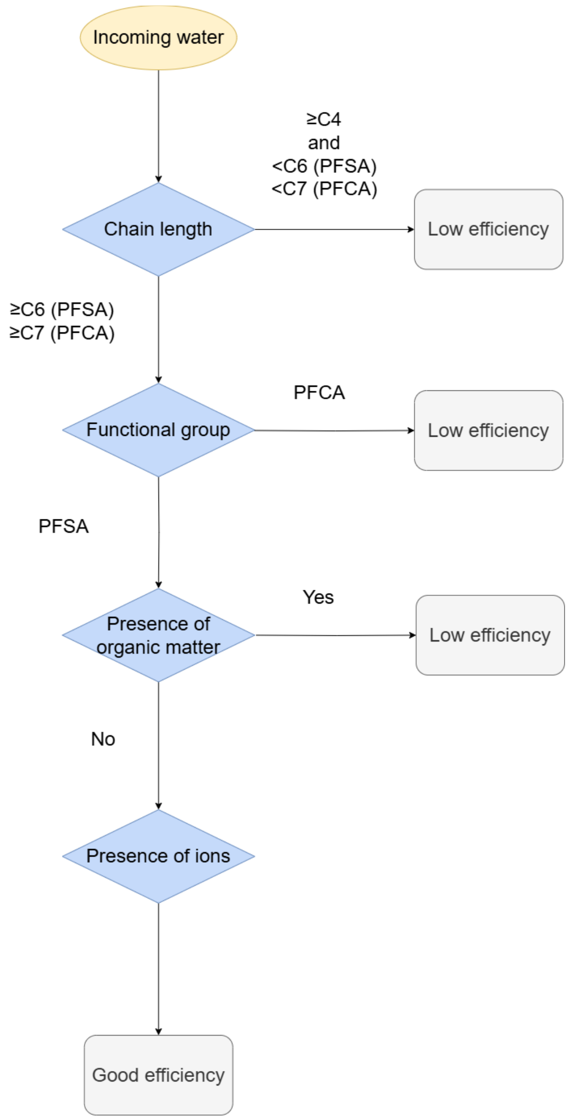
Appendix B – Summary of Motivations for the Scoring of the Sustainability Analysis

Appendix B. 1: Motivations for the scores set for each criterion and technology in the sustainability analysis.

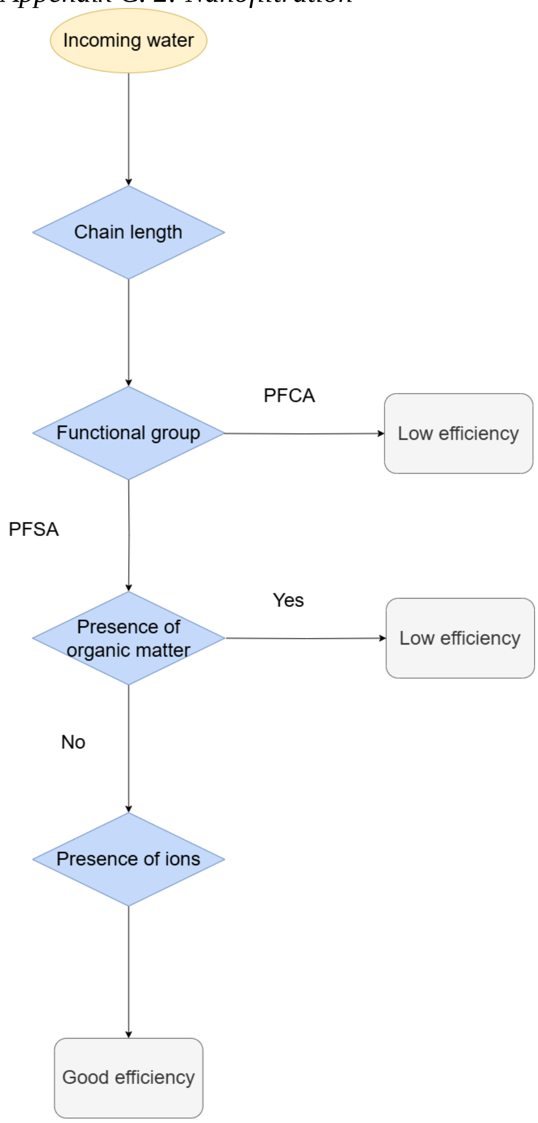
	GAC	NF	IX	FF
Implementation cost	1142 €/m^3 $78 445	700 €/membrane	5000-8500 €/m^3 $44 164	Generally low. Tank and pumps, no media needed.
Maintenance cost	4-20 €/m^3 concentrate. 308 440 SEK annually for new carbon.	0.085 €/m^3	1.25-1.94 €/ m^3 11 246 $/year 0.28 $/$m^3$ 510 €/ m^3	Mainly driven by the energy consumption from pumps and aerators. No regular exchange of media.
Waste management	247 230 SEK annually for combustion of carbon. Incineration or reactivation.	20% of the incoming water becomes waste. Retentate water, needs to be treated, depends on what is chosen.	Incineration (or landfill).	Low waste. Only concentrate 0.0025%-10% of the influent water.
Regeneration	There is possibility, 10% loss, cheaper, less emissions.	The membranes can be cleaned but not fully regenerated. Retentate water??	Possible but requires chemicals for regeneration and lead to more costs, transport, environmental impact etc. Also, not allowed in drinking water production	\
Carbon dioxide emissions	0.4407 kg CO_2 eq./m^3 treated water.	Unknown Installation of NF maybe 0.3500 kg CO2 eq.	0.033 kg CO_2 eq./m^3 treated water. 70% from resin production 25% from incineration	No regeneration or chemicals used leads to low environmental impact.
Energy consumption	<0.05 kWh/m^3	0.3 - 0.5 kWh/m^3	<0.05 kWh/m^3	0.6-0.8 kWh/m^3

Appendix C – Flowcharts for Individual Technologies

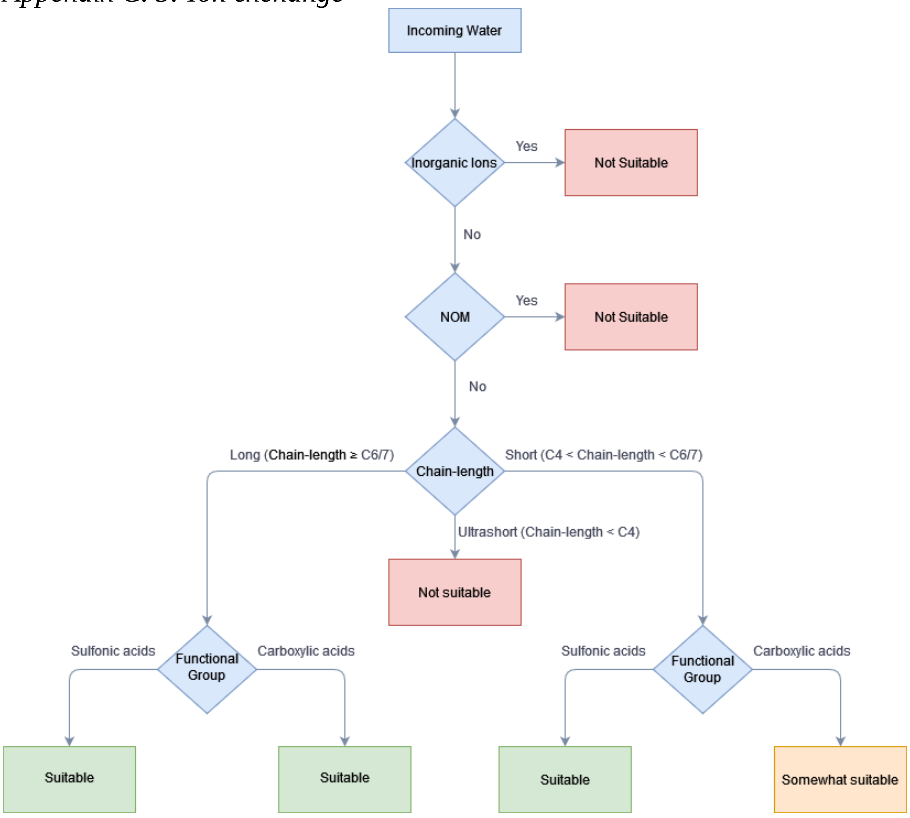
Appendix C. 1: Granular activated carbon



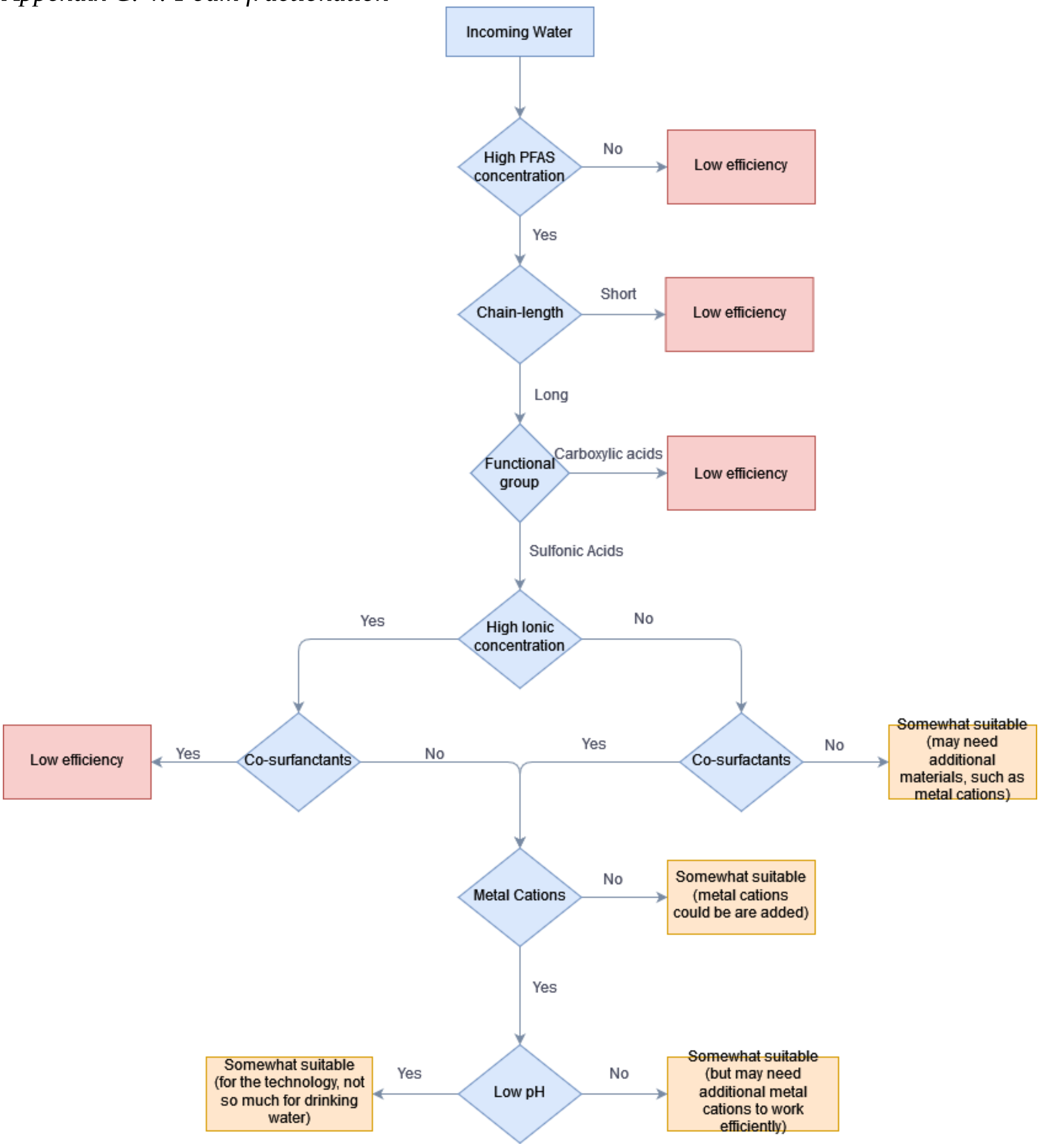
Appendix C. 2: Nanofiltration



Appendix C. 3: Ion exchange



Appendix C. 4: Foam fractionation



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