ECONOMIC COSTS OF DRINKING WATER TREATMENT

Scientific Report from DCE – Danish Centre for Environment and Energy No. 676 2025

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Julian R. Massenberg

Aarhus University, Department of Environmental Science

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Author: Julian R. Massenberg
Institution: Aarhus University, Department of Environmental Science

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Abstract: This report presents a comprehensive synthesis of treatment technologies for removing per- and polyfluoroalkyl substances (PFAS) and pesticide residues from drinking water, with a specific focus on the Danish groundwater context. Drawing on a systematic review of peer-reviewed literature and expert opinions, the report evaluates available technologies in terms of effectiveness, scalability, costs, sustainability, and technological maturity. The evidence indicates that mainly sorption and separation technologies are proven at full scale, while destructive and emerging processes remain at laboratory or pilot stage. Indicative cost data suggest that granular activated carbon and ion exchange are most cost-effective, whereas hybrid or destructive systems can be substantially costlier. Environmental and waste management considerations, particularly the handling of micropollutant-laden residuals, remain a major issue. For Denmark's highly decentralised water supply sector and strict PFAS threshold, these findings underline both the need for technological adaptation and the limits of existing evidence. The report concludes with recommendations for Danish-specific pilot and full-scale demonstrations and for more holistic assessments integrating removal performance, costs, and environmental impacts.

Keywords: PFAS; pesticides; drinking water; treatment technologies; costs; sustainability

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Preface

The presence of per- and polyfluoroalkyl substances (PFAS) and pesticide residues in drinking water has become an emerging concern across Europe. In Denmark, where drinking water is derived almost exclusively from groundwater, these contaminants pose a particular challenge for ensuring safe and sustainable water supply.

Traditional water treatment approaches were not designed to address these persistent and complex micropollutants and society now faces growing pressure to identify technologies that are both technically effective and economically feasible. This report provides a comprehensive overview of available solutions, their performance, costs as well as sustainability aspects and discusses their applicability in the Danish context.

The main objective of this report is to synthesise existing knowledge on PFAS and pesticide treatment technologies, assess their removal efficiency, costs, and environmental impact and evaluate their technological maturity. By combining evidence from international scientific literature with expert insights from Danish water-sector stakeholders, the report aims to support informed decision-making and identify priorities for future research and implementation.

The work was commissioned by the Danish Ministry of Environment and conducted by Aarhus University, Department of Environmental Science. We hope that the report will serve as a useful resource for policymakers, water utilities, consultants and researchers seeking to develop cost-effective and sustainable solutions to ensure the long-term protection of Denmark's drinking water resources.

Sammenfatning

Denne rapport giver en samlet gennemgang af teknologier til fjernelse af per- og polyfluorerede stoffer (PFAS) og pesticidrester fra drikkevand med fokus på deres anvendelighed, omkostninger og teknologiske modenhed i en dansk grundvandskontekst. Grundvand er den primære – og stort set eneste – kilde til drikkevand i Danmark, og forekomsten af PFAS og pesticider har tydeliggjort behovet for effektive og skalerbare renseløsninger, der kan sikre overholdelse af både europæiske og nationale grænseværdier for mikroforureninger.

Gennemgangen bygger på en systematisk gennemgang af international, fagfællebedømt litteratur kombineret med resultaterne fra en ekspertundersøgelse blandt danske aktører i vandsektoren. Rapporten vurderer hele spektret af tilgængelige teknologier – sorption (f.eks. aktivt kul og ionbytning), separation (f.eks. omvendt osmose og nanofiltrering) og destruktive processer (f.eks. elektrokemisk oxidation, plasma og hydrotermisk behandling) – og belyser deres renseeffektivitet, skønnede omkostninger og bæredygtighedsaspekter.

Resultaterne viser, at det primært er sorptions- og separationsteknologier, der i dag er demonstreret i fuld skala til drikkevandsbehandling. Sorptionssystemer repræsenterer typisk det laveste omkostningsniveau (<1,5 DKK/m^3), mens kombinerede eller nye teknologier, såsom mikrosorberende kulslurryer eller avancerede oxidationsprocesser, kan ligge i intervallet 16–47 DKK/m^3. På trods af stigende forskningsaktivitet er destruktive og biologiske metoder fortsat begrænset til pilot- eller laboratorieniveau, og kun få studier behandler aspekter som omkostninger, affaldshåndtering, energiforbrug og livscyklusvurdering ud over selve renseeffektiviteten.

Rapporten konkluderer, at den høje grad af decentralisering i den danske vandforsyning samt de strenge reguleringskrav stiller krav om både teknologisk tilpasning og et solidt vidensgrundlag for politiske beslutninger. Der er et presserende behov for danske pilot- og fuldskala-demonstrationer, som kan levere pålidelige data om økonomi, ydeevne og bæredygtighed. Fremtidig forskning bør have en helhedsorienteret tilgang, hvor renseeffektivitet kombineres med økonomiske og miljømæssige vurderinger for at understøtte mere informerede beslutninger om bæredygtige løsninger til fremtidens drikkevandsforsyning.

Summary

This report provides a comprehensive review of technologies for removing per- and polyfluoroalkyl substances (PFAS) and pesticide residues from drinking water, focusing on their applicability, costs, and maturity in the Danish groundwater context. Groundwater is principally the sole source of drinking water in Denmark, and occurrence of PFAS and pesticides have underscored the need for effective and scalable treatment solutions that can ensure compliance with European and national micropollutant limits.

The review is based on a systematic synthesis of international peer-reviewed literature combined with input from an expert survey with Danish water-sector stakeholders. The assessment examines the full range of available technologies, sorption (e.g., granular activated carbon and ion exchange), separation (e.g., reverse osmosis and nanofiltration), and destruction processes (e.g., electrochemical oxidation, plasma, and hydrothermal treatment), and evaluates their removal efficiencies, indicative costs, and sustainability implications.

Findings show that mainly sorption and separation technologies are currently technologies demonstrated at full scale for drinking water treatment. Sorption systems typically represent the lowest cost range (<1.5 DKK/m^3), whereas combined or emerging configurations, such as carbon slurry adsorbents or advanced oxidation processes, can reach 16–47 DKK/m^3. Despite growing research, destructive and biological methods were found to remain limited to pilot or laboratory scale, and few studies address cost, waste management, energy use and/or other environmental impacts besides removal efficiencies.

The report concludes that Denmark's highly decentralised water supply and stringent regulations require both technological adaptation and evidence-based policy support. There is an urgent need for Danish-specific pilot and full-scale demonstrations to generate reliable data on costs, performance, and sustainability. Future research should adopt a holistic perspective that integrates treatment efficiency with economic and sustainability dimensions, enabling more informed decisions on feasible and sustainable solutions for long-term drinking water protection.

List of Abbreviations and Acronyms

AlF_3	Aluminium fluoride
AOP	Advanced oxidation processes
BAM	2,6-dichlorobenzamide
BCE	Bubble column evaporator
CaF_2	Calcium fluoride
CGA	Colloidal gas aphron
COF	Covalent organic framework
CRF	Capital recovery factor
DKK	Danish kroner
DMS	N,N-dimethylsulfamid
DPC	Desphenylchloridazon
EO	Electrochemical oxidation
FTS	Fluorotelomer sulfonic acid
GAC	Granular activated carbon
GHG	Greenhouse gas
IX	Ion exchange
LCW	Levelised cost of water treatment
LDH Ca-Fe	Calcium-ferric layered double hydroxide
MCPA	2-methyl-4-chlorophenoxy acetic acid
MCPP	2-methyl-4-chlorophenoxy propionic acid
MOF	Metal–organic framework
NF	Nanofiltration
NH_2	Primary amine group
NTP	Non-thermal plasma
PAC	Powdered activated carbon
PCP	Pentachlorophenol
PFAS	Per- and polyfluoroalkyl substances
PFBA	Perfluorobutanoic acid
PFBS	Perfluorobutane sulfonic acid
PFDA	Perfluorodecanoic acid
PFDoDA	Perfluorododecanoic acid
PFECHS	Perfluoro(4-ethylcyclohexane)sulfonic acid
PFHpA	Perfluoroheptanoic acid
PFHxA	Perfluorohexanoic acid
PFHxS (-lin)	Perfluorohexane sulfonic acid (linear isomer)
PFMOBA	Perfluoro-4-methoxybutanoic acid
PFMOPrA	Perfluoro-3-methoxypropanoic acid
PFNA	Perfluorononanoic acid
PFOA	Perfluorooctanoic acid
PFOS	Perfluorooctane sulfonic acid
PFPeA	Perfluoropentanoic acid
PFPeS	Perfluoropentanesulfonic acid
PFPrS	Perfluoropropanesulfonic acid
RO	Reverse osmosis
TFA	Trifluoroacetic acid
TRL	Technology readiness level
UV	Ultraviolet

1 Introduction

The growth of industrial production and intensification of agriculture has brought a broad spectrum of chemical pollutants into rivers and aquifers, substances that were not considered when conventional drinking water treatment technologies were designed (Amen et al., 2023). These include pesticides, pharmaceuticals, microplastics, and various industrial chemicals, typically present at concentrations from picograms to milligrams per litre (Ateia et al., 2023; Schwarzenbach et al., 2006). These micropollutants can affect aquatic ecosystems and have been linked to severe health effects even at low concentrations (Ateia et al., 2023).

Within this broader category, pesticides and per- and polyfluoroalkyl substances (PFAS) have become two of the most significant challenges for safe drinking water. Both groups are characterised by persistence, toxicity and mobility, which enable them to reach groundwater. In Denmark, where drinking water relies almost entirely on groundwater, the presence of PFAS and pesticide residues, such as 2,6-dichlorobenzamide (BAM), 2-methyl-4-chlorophenoxy acetic acid (MCPA), and 2-methyl-4-chlorophenoxy propionic acid (MCPP), poses a direct risk to the long-term usability of aquifers if advanced treatment is not applied (Ghanbarlou et al., 2020).

PFAS are of particular concern due to their extreme stability making them very resistant to natural degradation (Nafi & Taseidifar, 2024), leading to their reputation as "forever chemicals". PFAS have been used in a variety of industry applications since the mid-20th century and are now found globally in surface waters, groundwater, and humans (Ackerman Grunfeld et al., 2024; Kannan et al., 2004). Even after industry phased out legacy compounds such as Perfluorooctanoic Acid (PFOA) and Perfluorooctane Sulfonic Acid (PFOS) from 2002 onwards, these remain widely detected due to their persistence, while short-chain replacements such as perfluorobutane sulfonic acid (PFBS) and GenX have proven even more mobile and resistant to breakdown (Li et al., 2020).

Both PFAS and pesticides are subject to strict regulation. In the European Union, pesticides in drinking water are limited to 0.1 µg/L per substance and 0.5 µg/L for the total. Also for PFAS, the revised EU Drinking Water Directive sets binding standards of 0.5 µg/L for the total of PFAS and 0.1 µg/L for the sum of 20 PFAS identified as of being of highest concern (European Union Law, 2020). Denmark has even adopted lower national threshold of 2 ng/L for the sum of four PFAS, namely PFOA, PFOS, Perfluorononanoic Acid (PFNA) and Perfluorohexane Sulfonic Acid (PFHxS), reflecting tolerable intake values established by the European Food Safety Authority. In addition, the Danish monitoring framework includes two more PFAS than the 20 listed in the EU Drinking Water Directive, namely perfluorooctane sulfonamide (PFOSA) and 6:2 fluorotelomer sulfonic acid (6:2 FTS) (Danish Environmental Protection Agency, 2024; Sanzana et al., 2025).

Beyond the technical and environmental challenges, PFAS contamination has wide-ranging health, societal and economic impacts. These impacts and associated costs are long-term, incompletely understood and largely borne by individuals, communities, and public institutions (Cordner et al., 2021; Gold & Wagner, 2020). These externalized costs may include health-care expenses, investments in water-treatment infrastructure, environmental monitoring and remediation, and losses in ecosystem services and property values (Cordner et al., 2021). Goldenman et al. (2019) estimated the annual health-related costs (of inaction) from PFAS exposure range between EUR 2.8–4.6 billion for the Nordic countries and EUR 52–84 billion across the European Economic Area, noting that these figures likely underestimate total impacts since they include only a subset of known health outcomes. Recent legal settlements in the United States with major manufacturers, such as 3M and DuPont, illustrate the growing recognition of producer responsibility, yet they likely cover only a fraction of the total costs, which remain largely borne by society (Mische, 2025).

Denmark is particularly vulnerable to groundwater contamination because its drinking-water supply mainly depends on groundwater, which is typically used without advanced treatment, and due to its highly decentralised national water supply. The country has approximately 2,600 public water suppliers, which together abstracted around 356 million m^3 of groundwater in 2023 (Thorling et al., 2024). Among these, roughly 200 large utilities, each abstracting more than 350,000 m^3 per year, account for around 70% of the annual volume (Miljøstyrelsen, 2024). Alongside the public utilities around 50,000 smaller non-public suppliers that serve fewer than ten properties exist (Thorling et al., 2024). Groundwater in Denmark usually undergoes only simple treatment at the waterworks, such as aeration and sand filtration, without applying advanced treatment technologies to remove contaminants such as PFAS, pesticide residues or nitrate (Schullehner et al., 2017). This reliance on minimally treated groundwater makes the drinking-water supply especially sensitive to even low levels of contamination compared to countries that use surface water and apply more advanced treatment. Meeting such strict standards poses both technical and economic challenges.

In this light, national monitoring data reveals occurrence of both pesticide residues and PFAS in groundwater and supply wells. In 2023, pesticide residues were detected in approximately 51% of Danish water-supply wells, with 12% showing at least one exceedance of the quality criterion of 0.1 µg/L for individual substances (Thorling et al., 2024). The degradation products DMS (N,N-dimethylsulfamid) and DPC (desphenylchloridazon) were the two most frequently detected compounds. Similarly, PFAS were detected in 16% of 1,835 analysed water-supply wells in 2022–2023, and 4.4 % of these exceeded the Danish drinking-water limit for the sum of four PFAS (PFOS, PFOA, PFHxS and PFNA) of 0.002 µg/L (Thorling et al., 2024). Elevated concentrations were particularly observed around Copenhagen but also in regions such as Fanø, Hanstholm and Skagen (Thorling et al., 2024). Although most concentrations remain below the regulatory thresholds, the persistence and mobility of these compounds indicate a long-term risk to groundwater resources and drinking-water safety.

In such a decentralised water supply system, where a few large utilities produce a large share of the drinking water, but numerous small and medium-sized utilities must meet the same quality standards, identifying cost-effective and sustainable solutions is critical to safeguard human health and the long-term safety of groundwater-based drinking water. Thus, Denmark faces an increasingly urgent question: which treatment technologies should be implemented, at what cost and under which circumstances? Beyond technical feasibility, the economic cost of achieving compliance is of central importance for utilities and society. This report therefore synthesises evidence on treatment technologies for PFAS and pesticides, with a specific focus on costs, performance, and sustainability under conditions relevant to Danish drinking water.

2 Brief overview of PFAS and pesticides treatment technologies

Available technologies for PFAS and pesticides removal can be grouped into three broad categories: sorption, separation, and destruction (DiGuiseppi et al., 2024). These categories differ in whether PFAS are captured and stored on a medium, physically separated into a residual stream, or chemically broken down (for a detailed discussion, see, e.g., DiGuiseppi et al., 2024; McLellan et al., 2024). The classification used in this report largely follows DiGuiseppi et al. (2024) but has been extended with additional information from reviews and case studies. The intention is not to provide an exhaustive catalogue of all methods, in particular with respect to those still in experimental stages, but to summarise the technologies currently considered most relevant for implementation in drinking-water treatment, particularly under Danish conditions.

Traditional options such as granular activated carbon (GAC), ion exchange (IX), and high-pressure membranes (reverse osmosis (RO), nanofiltration (NF)) were not originally designed for micropollutant control but are now applied for PFAS and pesticide removal (Amen et al., 2023; Ghanbarlou et al., 2020). In Denmark, some utilities have begun adopting advanced water treatment technologies, for example in Tune and on Fanø IX systems were installed specifically for PFAS removal (Danske Vandværker, 2024), Aalborg Vand is planning a biological treatment facility primarily for nitrate (Aalborg Kommune, 2025), in Stokkemark NF is used to soften the water (SUEZ Water, 2022) and in Greater Copenhagen a pilot combining ion exchange and GAC has been tested for PFAS removal (Tisler et al., 2025). Together, these examples highlight the variety of ongoing technological responses in Denmark and the need to evaluate their performance and scalability.

2.1 Sorption technologies

Sorption methods remove micropollutants by binding them to solid materials.

- GAC and powdered activated carbon (PAC): GAC and PAC are a porous carbon medium with a large surface area that adsorbs organic contaminants through physical and chemical interactions (Appleman et al., 2014; Lei et al., 2023).
- IX resins: IX resins are polymer beads with charged functional groups that exchange ions between the resin and the surrounding water. Anion exchange resins can bind negatively charged PFAS molecules via electrostatic attraction. Resins may be single-use, disposed of when exhausted, or regenerable, in which case PFAS are desorbed using a brine solution (DiGuiseppi et al., 2024; Dixit et al., 2021; Zaggia et al., 2016).
- Biochar: Biochar is a carbon-rich material produced by pyrolysis of organic matter. It has a heterogeneous surface with pores and functional groups that can adsorb organic contaminants, including PFAS. Its properties depend on feedstock and production method (DiGuiseppi et al., 2024).
- Carbon slurry adsorbents: a system using a carbon-based micro-adsorbent suspension to capture PFAS (Quinnan et al., 2023).
- Zeolites and other mineral composites: microporous mineral materials with a defined pore structure that can adsorb PFAS and other micropollutants (Qian et al., 2022).

- Injectable sorbents: Materials such as colloidal activated carbon or polymer adsorbents can be injected directly into contaminated soils or aquifers. These sorbents bind PFAS in situ, immobilising them without pumping groundwater to the surface (DiGuiseppi et al., 2024).

2.2 Separation technologies

Separation processes rely on physical barriers that retain micropollutants while allowing clean water to pass.

- Membrane filtration processes, especially NF and RO: RO is a high-pressure membrane process in which water is forced through a semi-permeable membrane. The membrane allows water molecules to pass but rejects most dissolved ions and organic molecules, including PFAS, thereby separating them into a concentrated residual stream (Ali et al., 2024). NF membranes function similarly to RO but have slightly larger pore sizes and lower operating pressures, they remove pollutants through a combination of size exclusion and electrostatic effects (Ali et al., 2024; DiGuiseppi et al., 2024).
- Foam fractionation: Foam fractionation introduces fine gas bubbles into water, causing PFAS molecules to accumulate at the gas–water interface due to their surfactant properties. As gas bubbles rise, PFAS are concentrated in the foam, which can be separated from the bulk water (DiGuiseppi et al., 2024).
- Colloidal gas aphrons (CGAs): CGAs are microscopic surfactant-coated gas bubbles, produced via high-shear mixing of air, water, and surfactants. PFAS are attracted to and concentrated on these bubbles, which can then be removed from the liquid phase (DiGuiseppi et al., 2024).
- Novel ligands and engineered adsorbents: Research is ongoing into synthetic materials such as graphene oxide (Behroozi et al., 2025), metal–organic frameworks (MOFs) (Amari et al., 2024), and tailored polymers (Rando et al., 2023). These ligands or surface chemistries are designed to bind PFAS selectively and may be incorporated into membranes or sorbents to also decrease the issue of membrane fouling (DiGuiseppi et al., 2024).

2.3 Destructive technologies

Destructive technologies aim to degrade micropollutants, such as PFAS, molecules by breaking the strong carbon–fluorine bonds, rather than concentrating them in a waste stream.

- Advanced oxidation processes (AOPs): AOPs are treatment methods that generate highly reactive radicals that can degrade PFAS molecules (Ghanbarlou et al., 2020; Mojiri et al., 2023). Electrochemical oxidation (EO) is a specific type of AOP that uses electrodes to generate oxidising agents or radicals that can break carbon–fluorine bonds. PFAS are degraded either directly on the electrode surface or indirectly via reactive intermediates (Qiao & Xiong, 2021).
- Non-thermal plasma (NTP): NTP applies electrical discharges to generate a mixture of reactive species (e.g. radicals, ions) in a gas phase that can then interact with PFAS in water, promoting bond cleavage and degradation (Malouchi et al., 2024).
- Ultraviolet (UV) based processes: UV irradiation, often combined with chemical additives (e.g. sulfite), can generate hydrated electrons or radicals that react with PFAS and promote degradation (DiGuiseppi et al., 2024).

- Thermal, hydrothermal and alkaline treatments: Processes such as hydrothermal alkaline treatment or supercritical water oxidation expose PFAS to extreme temperature and pressure conditions, sometimes in the presence of oxidants, to mineralise them into smaller molecules and salts (Krause et al., 2022). Also, conventional thermal methods such as incineration or pyrolysis rely on high temperature and pressure to break down PFAS, e.g. in sorbent media (Gal et al., 2025; Kucharzyk et al., 2017).
- Thermal plasma: Thermal arc plasma generates very high temperatures (several thousand degrees Kelvin) that can completely dissociate PFAS molecules into atomic components (DiGuiseppi et al., 2024; Nzeribe et al., 2019).

PFAS treatment technologies can thus be understood in three functional categories: sorption to solid media such as GAC and IX; separation using membranes such as NF and RO; and destruction by advanced chemical or thermal methods. Each approach has different implications for treatment design, residual management, and costs, which are considered in later sections.

2.4 Technology readiness

DiGuiseppi et al. (2024) assessed the maturity of PFAS liquid treatment technologies using NASA's Technology Readiness Level (TRL) framework (NASA, 2017), which ranges from 1 (basic principle observed) to 9 (proven in real-world operation).[1] According to DiGuiseppi et al. (2024):

- Established for drinking water technologies (TRL 9): GAC, PAC, IX (both single-use and regenerable), RO, and foam fractionation are all demonstrated in full-scale systems.
- Advanced but not fully mainstreamed technologies (TRL 6–9): Several destructive technologies fall into this category, such as EO (TRL 8), non-thermal plasma (TRL 7–9), and hydrothermal alkaline treatment (TRL 6–7), ultraviolet photoreduction (TRL 6-7), and sonolysis (5-7). Also, NF (TRL 7) falls into this category. These have shown promising results in pilot studies or for concentrated waste streams but are not yet established in drinking water treatment. Also, carbon-based micro-adsorbent suspensions, namely the AquaPRS system, have been tested in pilot-scale field demonstrations using a mobile treatment unit but has not yet been deployed at full scale (Quinnan et al., 2023).
- Early-stage concepts (TRL 4–5): Alternative adsorbents such as biochar, zeolites, covalent organic frameworks (COFs), and novel ligands are still at proof-of-concept or bench-scale demonstration. The same applies to colloidal gas aphrons (CGAs).
- Very early-stage technologies (TRL 1–3): For biological approaches (bacteria, enzymes, fungi) only the basic principles have been observed so far (TRL 1).

[1] The TRLs as defined by NASA (2017) are: (1) Basic principles observed and reported, (2) Technology concept and/or application formulated, (3) Analytical and experimental critical function and/or characteristic proof of concept, (4) Component and/or breadboard validation in laboratory environment, (5) Component and/or breadboard validation in the relevant environment, (6) System/subsystem model or prototype demonstration in an operational environment, (7) System prototype demonstration in an operational environment, (8) Actual system completed and "flight qualified" through test and demonstration, and (9) Actual system flight proven through successful mission operation.

Importantly, some technologies are assigned broad TRL ranges (e.g. non-thermal plasma, TRL 7–9; PFAS enhanced retention, TRL 1–8). This reflects the fact that individual variants of the same method may be at very different stages of development and/or differences in application context (e.g. pilot tests on concentrated wastes vs. absence of demonstration in drinking water).

3 Methods

This section outlines the methodology used to gather and analyse evidence on treatment technologies for PFAS and pesticide removal from groundwater intended for drinking water. The approach was twofold. First, a systematic literature review was undertaken to identify relevant studies and synthesize existing knowledge on treatment performance, costs, and technological maturity. Second, an expert survey was carried out to capture practice-oriented perspectives on scalability, implementation challenges, and future opportunities. This combination ensures that the analysis reflects both reported evidence from the literature and insights from professionals working in the field.

3.1 Literature review

The literature review formed the core of the evidence base for this report. Its purpose was to identify studies that examined the availability, performance, and effectiveness of technologies for the removal of PFAS and pesticide residues from groundwater intended for drinking water, and to synthesize findings on treatment performance, costs, and technological maturity. To ensure comprehensive coverage, a tailored search strategy was applied in Web of Science. The query was designed to combine terms for pollutants, water matrices, treatment technologies, and evaluation aspects, thereby capturing studies most relevant to drinking-water treatment. The search string is presented in Table 1.

Table 1 Web of Science search string, structured by pollutant terms, water matrix, technology descriptors, and assessment aspects

Focus	Description	Search terms
Pollutants	PFAS and pesticides	PFAS OR PFOS OR perfluoroalkyl OR polyfluoroalkyl OR perfluorocarboxylic OR perfluorooctane OR pesticide*
	AND	
Water matrix	Groundwater and drinking water	"drinking water" OR groundwater
	AND	
Technologies	Treatment processes and systems	"treatment technolog*" OR "treatment technique*" OR "removal technolog*" OR "treatment system*" OR "contaminated water" OR "water treatment"
	AND	
Assessment	Technology evaluation and costs	"technolog* status" OR "technolog* evaluation" OR "technolog* comparison" OR "technolog* assessment" OR "sustainability assessment" OR economic OR "socio-economic" OR cost*

The search identified 143 studies, and an additional 10 studies were retrieved through citation searching, resulting in a total of 153 studies. All records were screened at the title and abstract level before undergoing full-text assessment. Screening was carried out in Covidence, an online platform developed to support systematic reviews which enables the structured screening of abstracts and full texts against predefined criteria and generates transparent flow diagrams of the process. The workflow followed the principles of the PRISMA guidelines (Page et al., 2021) which are widely used to ensure systematic and transparent reporting.

Inclusion criteria required that studies:

- Reported on PFAS and/or pesticide removal from groundwater;
- Addressed technologies applicable to drinking-water treatment (laboratory, pilot, full-scale, or scenario studies);
- Provided extractable data on treatment performance (removal efficiency) and/or costs.

Exclusion criteria included:

- Review papers without primary data;
- Records without extractable or usable data;
- Non-eligible article types (e.g., conference abstracts);
- Studies not focused on groundwater;
- Studies not focused on drinking water;
- Studies not focused on relevant pollutants.

Title and abstract screening resulted in the exclusion of 67 studies, leaving 86 studies for full-text assessment. At this stage, a further 69 studies were excluded for reasons such as being review papers without primary data, lacking extractable information, or not focusing on groundwater, drinking water, or the relevant pollutants. In total, 17 studies met the eligibility criteria and were included in the data extraction phase. The screening process is illustrated in Figure 1. Note that while reviews were excluded from data extraction, they were nonetheless consulted to contextualize findings and inform the synthesis. A full list of included studies and an overview of screening decisions is provided in Table 2 Appendix I.

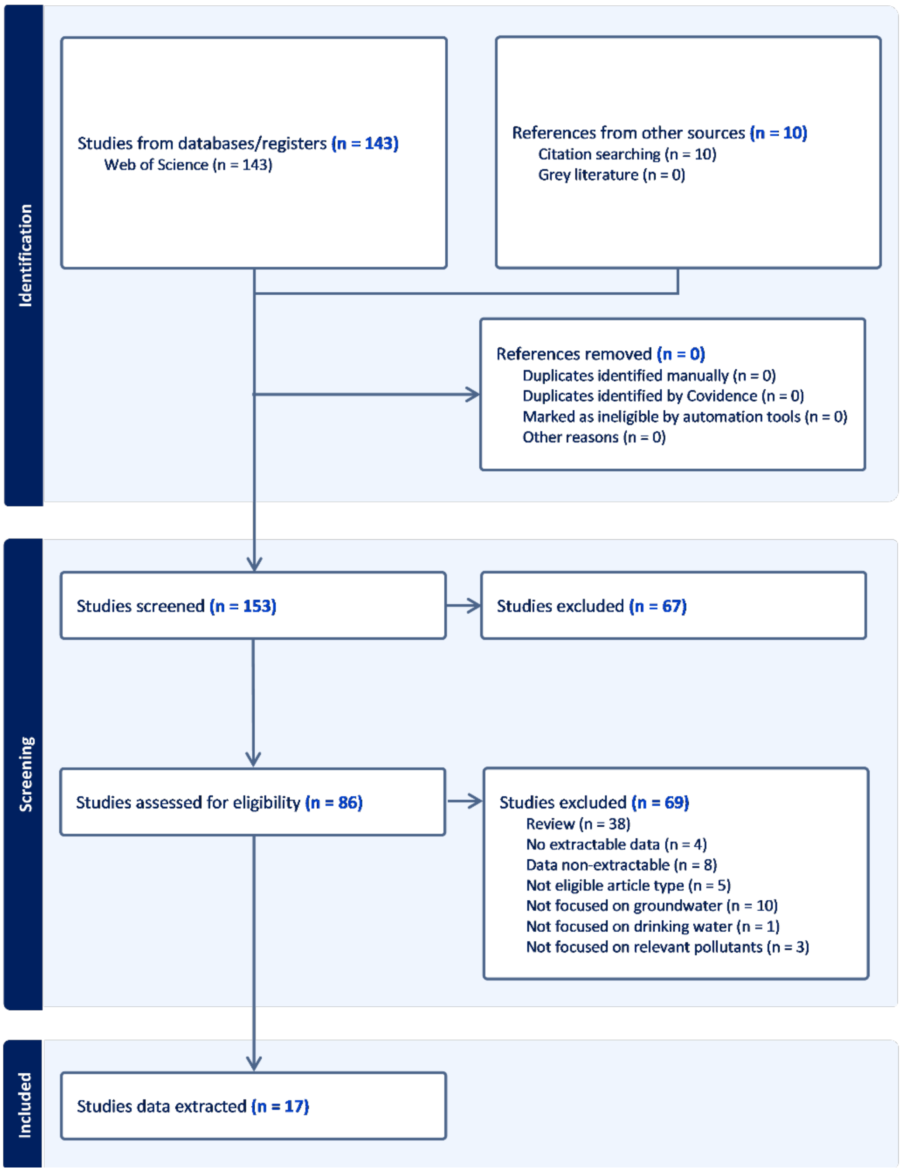

Figure 1 PRISMA flow diagram of study identification, screening and eligibility assessment.

From each included study, data were extracted on bibliographic details, technology type, scale (laboratory, pilot, full-scale, or scenario), pollutants investigated, removal efficiencies, and cost information (capital as well as operation and maintenance cost). Where point estimates were unavailable, midpoint values were calculated from reported ranges. Cost figures were converted to Danish kroner (DKK) and adjusted for inflation (reference year 2024). Where available, information on environmental impacts, technology readiness, and scalability was also recorded.

To enable meaningful comparison across treatment facilities, reported costs were further harmonised into two complementary indicators: capacity-normalised costs and the levelised cost of water treatment (LCW).

Capacity-normalised costs (DKK per m^3/day) were obtained by dividing reported absolute costs by the design capacity of the facility, converted into cubic metres per day (m^3/day). Studies that only reported static volumes (e.g., (m^3) or population served could not be normalised and were excluded from this calculation.

The LCW (DKK per m³ treated) was estimated by annualising capital costs over an assumed 25-year lifetime using a discount rate of 3.5% (as suggested by the Danish Ministry of Finance for periods shorter than 35 years). A capital recovery factor (CRF) was applied in order to calculate annualised capital cost:

$$CRF = \frac{r(1+r)^n}{(1+r)^n - 1} \qquad (1)$$

On this basis, the levelised cost, which expressed the cost per cubic metre of water treated, were calculated as the sum of the annualised cost divided by the annual treatment capacity, resulting in a cost per cubic metre of treated water:

$$LCW = \frac{c_c * CRF + c_{O\&M}}{Capacity\ (m^3/day) * 365} \qquad (2)$$

With c_c representing the capital cost and $c_{O\&M}$ being the cost of operation and maintenance.

Several limitations apply. First, a continuous full-load operation was assumed which may not reflect real conditions. No adjustments were made for load factors, seasonal variation or part-load operation. Second, the financial assumptions (25-year lifetime, 3.5% discount rate) may not match real financing terms. Third, externalities such as energy use or waste disposal were not considered if not reported. These uncertainties mean the results should be interpreted as indicative rather than precise cost estimates.

Because the included studies varied widely in scope, reporting style, and data quality, a descriptive synthesis approach was applied. Although cost and efficiency figures were standardized to comparable units, a formal meta-analysis was not pursued. The dataset contained too few independent studies per technology–pollutant–scale category, and most records did not provide statistical measures of uncertainty (such as confidence intervals or standard deviations) that are required for meta-analysis. In addition, many data points came from the same studies, which would require complex statistical models that are not robust with such a small evidence base. Cost reporting also mixed full-scale case studies with hypothetical scenarios that applied different system boundaries, further increasing heterogeneity. Under these conditions, descriptive synthesis offered the most reliable approach, allowing patterns and trade-offs to be highlighted without overstating the precision of the available evidence.

3.2 Survey

To complement the international literature review, an expert survey was conducted to collect perspectives on the Danish context from practitioners and researchers with direct experience in drinking water treatment. The purpose of the survey was to complement published evidence with practice-based insights into the maturity, costs, scalability and future potential of different treatment technologies for PFAS and pesticide removal from Danish ground- and drinking water sources.

The survey was web-based and implemented using SurveyXact. It was designed as a voluntary and anonymous questionnaire, and invitations were distributed in July–August 2025 via mailing lists to representatives from a broad range of organizations, including water utilities, industry associations and research institutions (reaching approximately 100 persons). Respondents were asked to provide general information about their organizational background and, for utilities, the size of their water production facilities.

The design and formulation of questions were informed by the findings of the literature review. The questionnaire included both closed-ended items (e.g., allocation of points to different technologies across dimensions such as maturity, effectiveness, and environmental impact) and open-ended questions inviting reflections on challenges and outlooks. The questionnaire was structured into five sections:

1. General information – organizational type and facility size.
2. Current challenges – key contaminants of concern, existing treatment practices, and perceived barriers to implementation.
3. Technology evaluation – comparative scoring of different treatment technologies (e.g., GAC, IX, NF, RO, AOPs, foam fractionation, EO, and biological degradation) across dimensions such as maturity, effectiveness for PFAS and pesticides, environmental impacts, cost-efficiency, scalability, and training requirements.
4. Cost considerations – approximate treatment costs per cubic metre, the share attributable to PFAS and pesticide removal, and the distribution of costs across categories such as capital investment, operation, energy, maintenance, and waste disposal.
5. Outlook – open-ended reflections on the most promising technologies or combinations of technologies over the next 5–10 years.

A total of five experts completed the full survey, representing a mix of organizational backgrounds, including water utilities, research institutions, and regulatory bodies. While the small number of responses limits the representativeness of the findings, the results nonetheless provide valuable indicative insights. Responses were analysed descriptively to identify common themes, points of divergence, and areas where knowledge gaps persist. In this way, the survey serves to complement the literature review by highlighting how technologies are currently viewed in practice, the challenges utilities face in implementation, and which approaches are considered most promising for future adoption in Denmark.

4 Results

4.1 Key findings from the literature review

The literature review identified 17 studies reporting on technologies for the removal of PFAS and pesticide residues from groundwater intended for drinking water. These studies covered a wide range of technologies and scales, including laboratory experiments, pilot studies, full-scale installations, and hypothetical scenarios. The diversity of designs and reporting formats resulted in considerable heterogeneity, but the findings can be organised into three main categories: removal efficiencies, costs, and sustainability aspects.

4.1.1 General overview

A total of 153 records were identified through database and citation searching before screening (143 from Web of Science and 10 through citation searching). This set provides an overview of how research interest in PFAS and pesticide removal technologies has evolved over time. As shown in Figure 2, the publications span from 1991 to 2025, with only sporadic studies appearing before 2010. Research activity increased steadily from 2018 onwards, with high number of publications since 2021. This reflects the growing attention in the scientific community to PFAS and pesticide contamination of drinking water and the technologies available for their treatment.

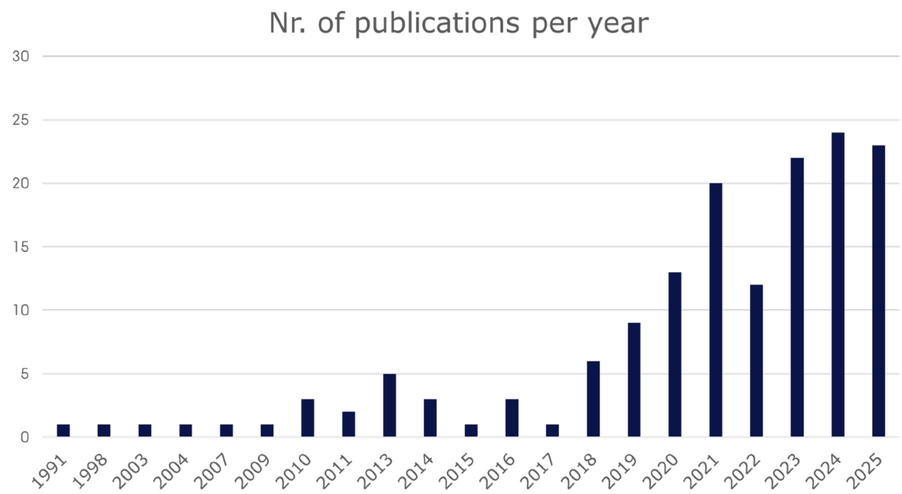

Figure 2 Bar chart showing the distribution of publication years for all 153 studies originally identified through database and citation searching.

From the 17 studies included after full-text screening, a total of 70 individual observations were extracted. In some cases, multiple observations were derived from the same study site because different technologies or scenarios were assessed. Taken together, these observations represent 19 distinct facilities at the full-scale, pilot-scale, and hypothetical levels, in addition to laboratory experiments.

Of these 19 facilities, the vast majority originated from the United States (n = 16), with only two from Germany and one from Denmark (Figure 3). This strong concentration highlights a clear geographical bias in the available evidence, with most data originating from the United States while other regions remain underrepresented. The dominance of U.S. studies in the available literature may reflect earlier regulatory attention to PFAS contamination, more extensive documentation of affected sites and/or greater availability of funding for pilot and full-scale testing. However, this remains speculative based on the literature reviewed.

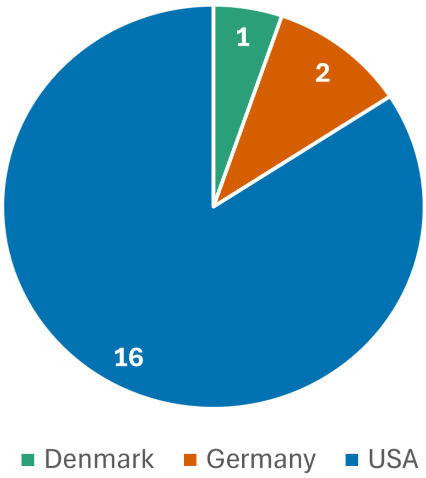

Figure 3 Country of origin for the 19 facilities (full-scale, pilot-scale, and hypothetical up-scaling) represented in the 17 studies included in the review.

The number of technologies analysed per study varied widely (Figure 4). Most studies compared between one and three technologies. Only a smaller number of studies reported a much larger set of observations.

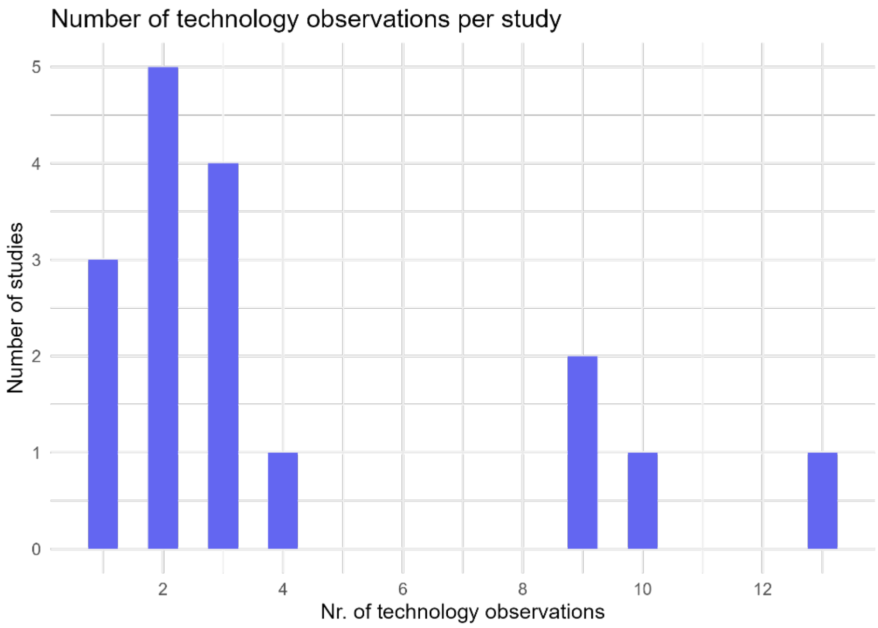

Figure 4 Distribution of the number of observations reported per study.

Most of the included studies examined single treatment technologies (87%), while only a small fraction investigated combined or hybrid approaches (13%). The combined approaches most often paired GAC or IX with additional processes such as advanced oxidation, but the overall evidence base remains dominated by single-technology studies.

The reviewed studies covered a broad range of treatment technologies, but the evidence base was dominated by a few well-established technologies (Figure 5). GAC and IX accounted for the largest share of observations. A smaller number of studies investigated combined systems or emerging approaches such as EO and zeolite-based adsorbents. Other technologies, including biosorbents and catalytic materials, appeared only once, potentially highlighting the experimental or exploratory nature of this part of the evidence base. While Figure 5 provides insight into where the focus of published scientific studies has been, it does not necessarily reflect the full range of technologies currently implemented in practice. Nonetheless, the prominence of GAC, IX, and membrane processes in the literature is consistent with their widespread use as established treatment options. Therefore, the figure should be interpreted primarily as an overview of technologies most frequently examined in this review.

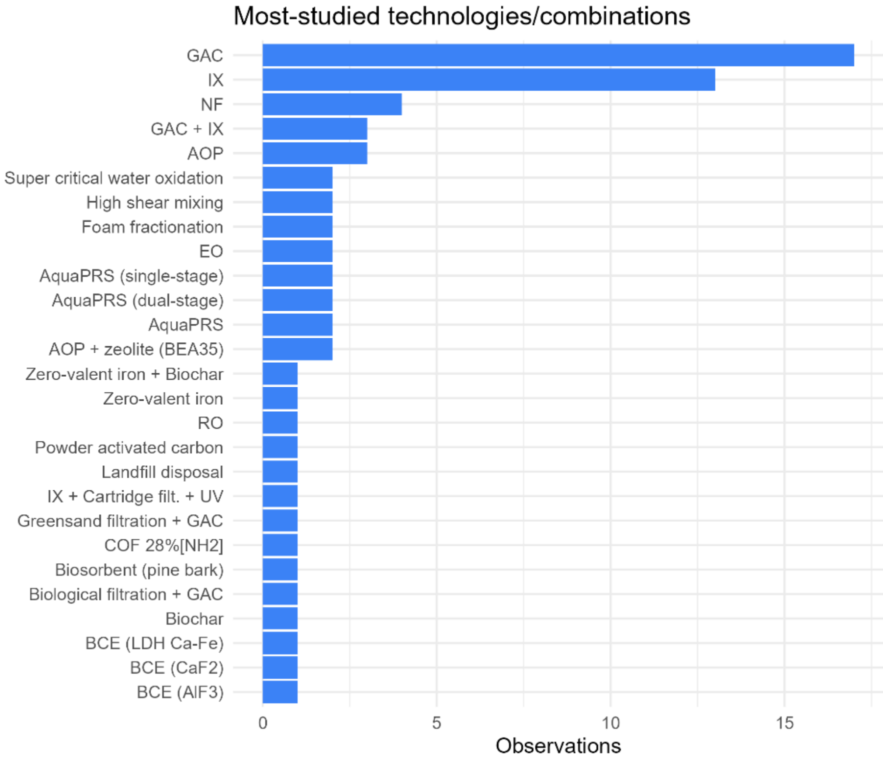

Figure 5 Distribution of treatment technologies investigated across the included studies.

4.1.2 Removal efficiency

Reported removal efficiencies varied considerably across pollutants and technologies (Figure 6). While some compounds and processes achieved consistently high removal, others showed large variation or limited effectiveness.

Several pesticides showed high removal across multiple technologies. For instance, carbofuran removal reached 83% with RO, while aldicarb sulfoxide and aldicarb sulfone were both removed above 90% by RO. Likewise, bentazon and dimethachlor CGA369873 showed high efficiencies with GAC and IX, typically above 85%. Pentachlorophenol (PCP) achieved near-complete removal (98%) by a biosorbent in one study. However, variability was also observed as other pesticides (e.g. BAM, MCPP and MCPA) removal ranged from 55% to 77% depending on the process. Thus, showing rather moderate than nearly complete removal. Nevertheless, overall pesticides tended to be more consistently removed than PFAS, but performance was compound- and technology-specific.

The short-chain PFAS group was the most challenging to remove. Perfluorobutanoic acid (PFBA) removal was extremely poor (5-6%) with GAC or the combination of GAC and IX, while perfluoropentanoic acid (PFPeA) achieved only 37-39% using the same technologies. PFHpA reached higher efficiencies (93% in one case), but data were sparse. Other short-chain compounds such as PFBS showed somewhat better performance (78–98%) depending on technology, but the spread of values indicates a lack of robust, reproducible removal. Also, GenX removal varied a lot from 0% for GAC over 72% for PAC up to 91% for COF. These findings highlight the persistent challenge of treating short-chain PFAS, which are more mobile and less adsorptive than long-chain compounds.

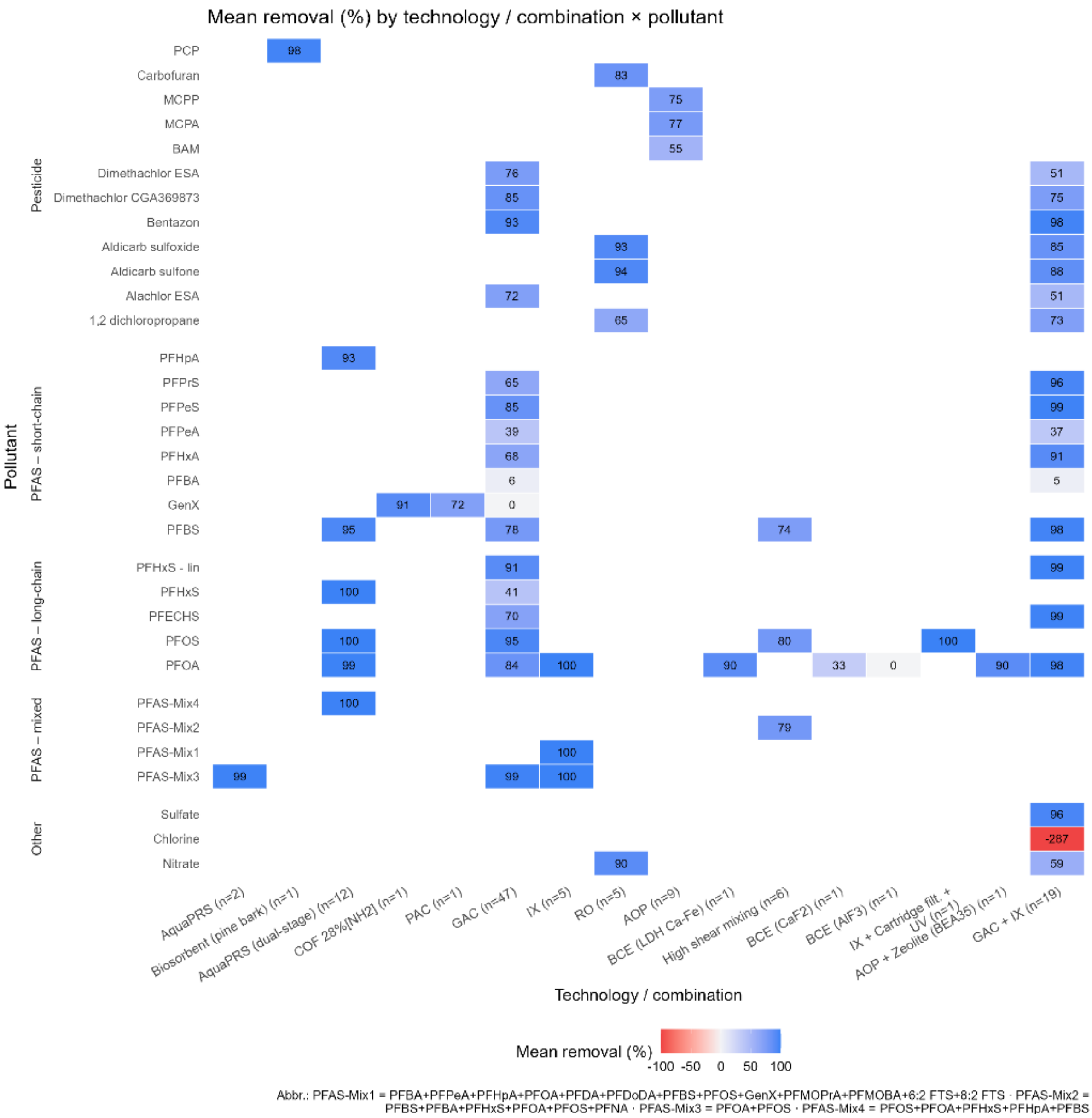

Figure 6 Heatmap of reported removal efficiencies (%) across pollutants and (combinations of) treatment technologies.

Longer-chain PFAS generally showed higher removal, but results were not uniform. PFOA and PFOS were typically removed at very high levels (>90%), e.g. using the combination of GAC and IX, and in some cases 100% removal was reported. However, performance for PFHxS was more variable: while IX achieved 91% in one case, GAC performed poorly (41%), showing that chain length alone does not fully predict treatment outcomes. This variability is important, as reliance on a single treatment process may not guarantee robust removal across all regulated compounds.

A few studies reported results for mixed PFAS groups (PFAS-Mix1, Mix2, Mix3, Mix4). Reported removal was uniformly high (≥99%) with GAC and IX, though the methods of calculation and composition of the mixes varied, making direct comparison difficult.

Some non-PFAS and non-pesticide compounds were also reported. Nitrate was removed at 90% by RO, while sulfate, nitrate and chlorine removal varied widely across GAC combined with IX.

Emerging processes such as biochar sorbents, zeolite composites, and EO were represented only in single studies, often with one or two observations. Reported efficiencies ranged from modest to very high, suggesting potential but insufficient evidence for policy-relevant conclusions.

Overall, the heatmap illustrates a compound-specific and technology-specific pattern of removal. Pesticides and long-chain PFAS tend to be removed more effectively, whereas short-chain PFAS remain difficult to treat. Even within long-chain PFAS, variability exists, as demonstrated by the relatively poor removal of PFHxS with GAC. These findings underline that no single technology offers universal coverage across all pollutants of concern.

4.1.3 Cost of water treatment

Absolute costs

Reported capital and operation and maintenance (O&M) costs varied widely across technologies and study types (Figure 7). For some technologies, such as GAC and IX, including IX and GAC combined with other technologies, the full-scale observations span a very wide range, from tens of millions to well over 150 million DKK in capital costs. In contrast, for technologies like AquaPRS, only few cost observations are available, which limits comparability.

When comparing capital cost and O&M, the capital investments dominate the absolute costs while O&M costs are comparatively modest. IX shows the most substantial O&M costs among the technologies with multiple observations, whereas e.g. AquaPRS appear lower, though evidence is limited.

Much of this variation might reflect differences in scale: large full-scale facilities naturally require much higher absolute investments than small pilot plants, and hypothetical scenario studies often use different system boundaries. As a result, absolute cost ranges should be interpreted primarily in the context of facility size rather than as direct reflections of technological cost-efficiency.

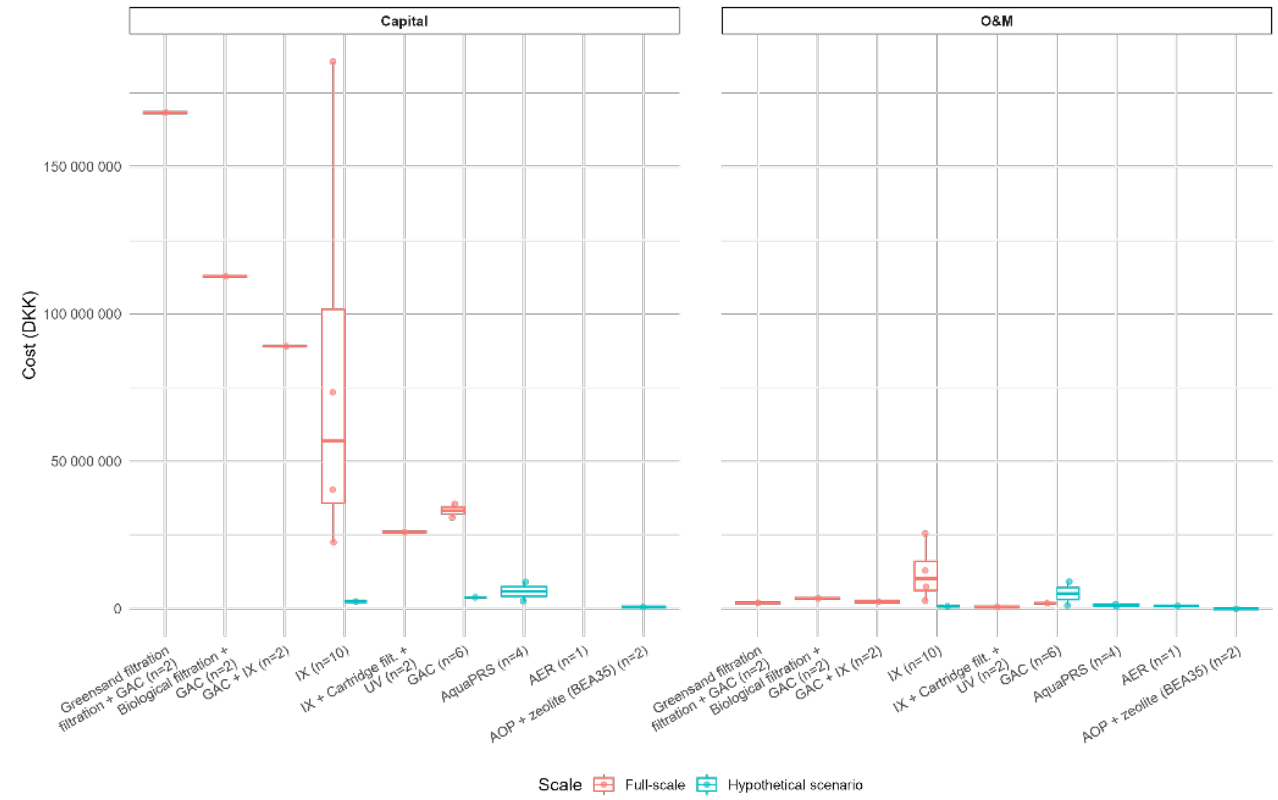

Figure 7 Reported absolute capital and operation and maintenance (O&M) costs for selected treatment technologies, disaggregated by study type (full-scale and hypothetical).

To account for the effect of facility size, costs were normalised by reported design capacity (expressed as flow of water). This measure allows for a more balanced comparison across technologies of different scales (Figure 8).

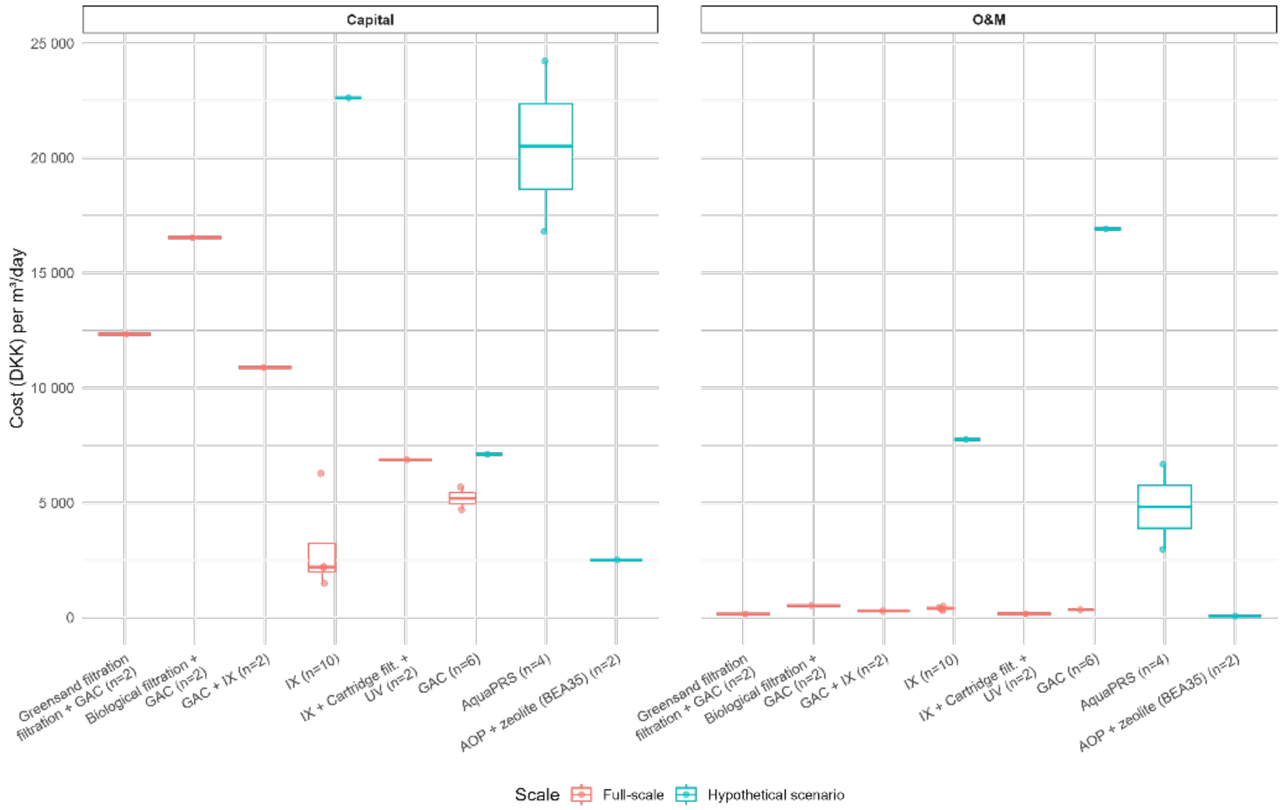

Figure 8 Reported capital and O&M costs normalised by facility design capacity (DKK per m^3/day), disaggregated by study type (full-scale and hypothetical).

The results show that while absolute costs for full-scale facilities were often very high, capacity-normalised costs for these systems were typically lower than for pilots. In other words, larger facilities are more expensive overall, but cheaper per unit of installed capacity, reflecting economies of scale. O&M costs followed a similar pattern: full-scale facilities tended to report lower costs per capacity, while pilot plants appeared more costly on a relative basis.

Another aspect is the comparison between single and combined technologies. While data are sparse, combined processes appear to cluster at the higher end of the cost spectrum compared to single-process systems like IX or GAC. This pattern is intuitive, as multi-barrier configurations, i.e., treatment trains combining two or more processes to achieve enhanced removal, require additional infrastructure and operational steps, though more evidence would be needed to confirm this consistently.

The levelised cost of treatment (LCW) expresses the cost per cubic metre of water treated, combining annualised capital expenditures with reported O&M costs relative to treatment capacity. This provides a directly comparable indicator of the cost of water delivered under different treatment configurations (Figure 9).

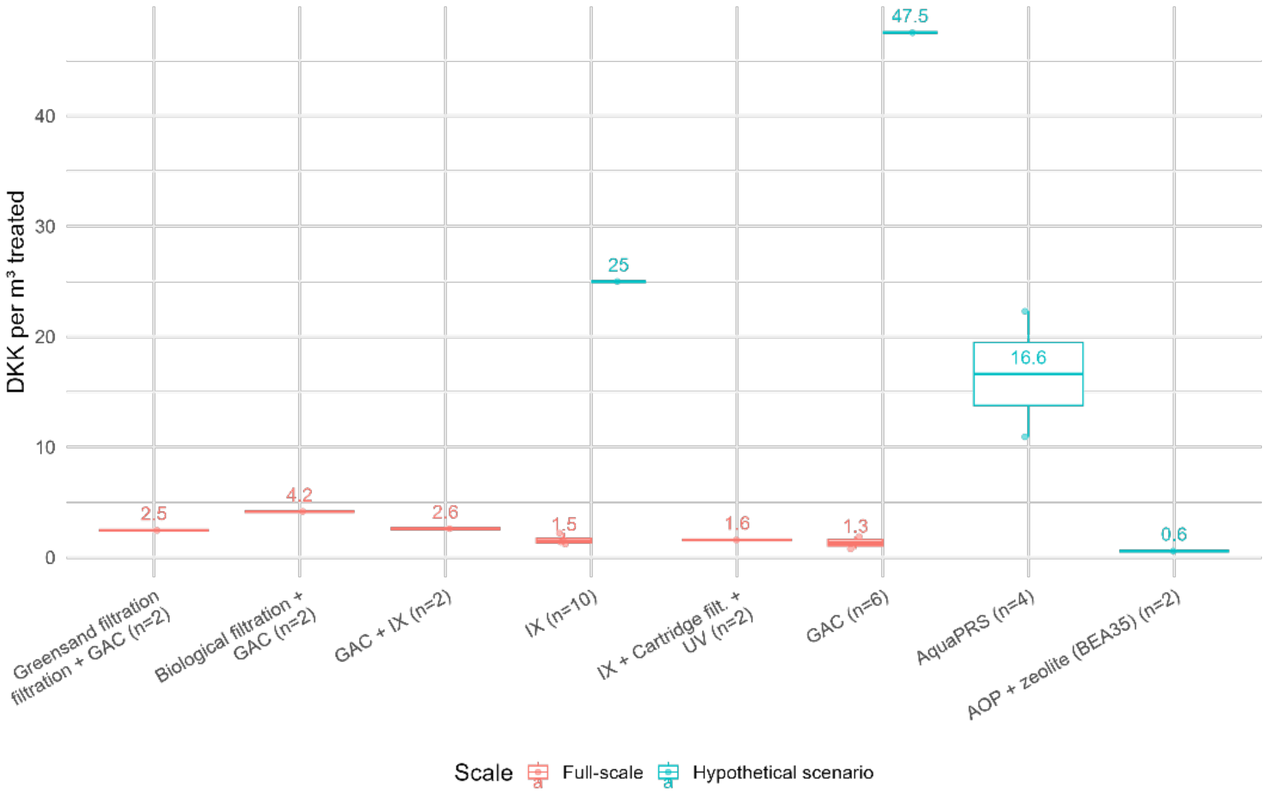

Figure 9 Indicative unit treatment costs for PFAS removal technologies (DKK per m³ treated), disaggregated by study type (full-scale and hypothetical).

Across the reviewed studies, GAC and IX exhibited the lowest levelised costs, generally below 1.5 DKK/m³, with their combination reported at 2.6 DKK/m³. Other combinations of technologies appeared more expensive, e.g. biological filtration and GAC. The combination of AOP and zeolite, however, also appeared at the lower end (0.6 DKK/m³), though this was based on only two observations from a pilot study. By contrast, AquaPRS showed substantially higher values around 16–17 DKK/m³, while individual observations for other technologies (GAC and IX) extended further, with estimates of 25–47 DKK/m³.

These results suggest that conventional adsorption and exchange processes dominate the lower-cost end, while some emerging or experimental systems currently appear more resource-intensive on a per-volume basis. However, some of the highest values were also reported for IX and GAC at pilot scale, illustrating that pilot-derived LCW estimates should be treated with caution. Small-scale pilots, when hypothetically upscaled, may produce inflated unit costs that do not reflect the economics of full-scale plants. This indicates that the LCW approach may be generally more adequate for full-scale implementations than for pilots.

Moreover, as discussed in the method section, several other caveats apply. First, all LCW estimates are based on simplifying assumptions: continuous full-load operation, a 25-year system lifetime, and a uniform discount rate of 3.5%. In practice, plants may operate below capacity, financing terms can vary, and externalities such as energy use and waste disposal were not consistently included. Second, the number of observations per technology is limited, with some systems represented by only a single study. This makes the comparison indicative rather than definitive. Third, costs could also be expressed relative to contaminant removal (e.g., as cost per percentage removed), which would provide a more performance-based comparison. However, such normalisation requires consistent reporting of influent concentrations, removal efficiencies and analytical detection limits. Yet, this information was not available or comparable across many studies. Calculating cost-per-removal metrics could therefore introduce additional uncertainty instead of improving comparability. For this reason, the focus on LCW per treated water volume was considered the most robust and interpretable basis for cross-technology comparison.

Taken together, the reported LCW values should be interpreted as indicative cost ranges suitable for highlighting potential ranges and trade-offs between technologies, but not as precise cost figures.

4.1.4 Sustainability

Environmental impacts were rarely quantified in the reviewed studies. In all reported cases, treatment residues were ultimately disposed of through incineration, except for a single case where landfilling was reported. Only one study (Molzahn et al., 2024) attempted to systematically assess the greenhouse gas (GHG) implications of different treatment processes. Molzahn et al. (2024) modelled GHG emissions for two different scenarios: i) Low-volume, high-concentration water (3.8 m^3 at 50,000 ng/L PFOA + PFOS), and ii) high-volume, low-concentration water (189,000 m^3 at 500 ng/L PFOA + PFOS).

The results (Figure 10) illustrate the strong influence of treatment context on GHG emissions. In the low-volume, high-concentration scenario, average GHG emissions were modest, with most technologies falling below 3 metric tons. The exception was landfilling, at around 8 metric tons. By contrast, in the high-volume, low-concentration scenario, estimated emissions were substantially higher: around 20,000 t for supercritical water oxidation and 13,000 t for EO.

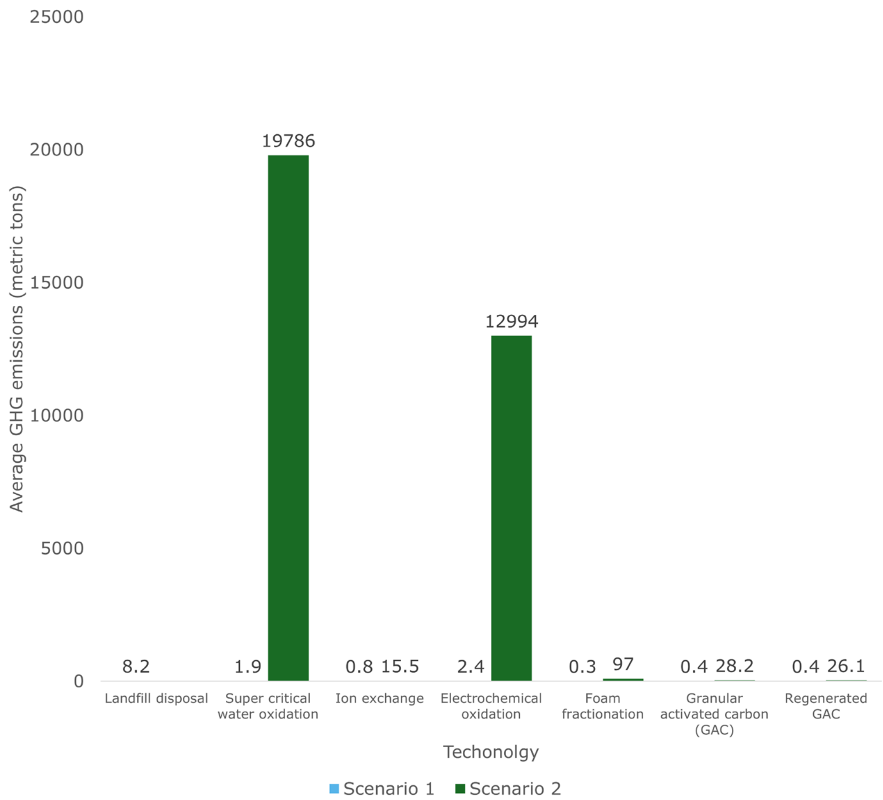

Figure 10 Estimated GHG emissions for different treatment technologies under the two scenarios: Scenario 1 (low volume and high concentration) and Scenario 2 (high volume and low concentration), adapted from Molzahn et al. (2024).

These results highlight three points:

- Scale and concentration matter: emissions increase sharply when technologies are applied to large, dilute flows.
- Technology matters: some options (e.g. IX and GAC) have much lower emissions than destruction processes, irrespective of the scenario.
- Evidence is limited: only one study quantified GHG emissions, and cost figures for waste disposal were rarely reported.

Finally, the real-world relevance of the two scenarios differs. The high-volume, low-concentration case is much more representative of groundwater treatment, where large flows and relatively low contaminant concentrations dominate. By contrast, the low-volume, high-concentration case is more typical of wastewater streams, including those from IX systems, where small volumes but high contaminant loads occur. This distinction is important when interpreting the emission results in relation to drinking-water treatment.

4.2 Key findings from the survey

Five experts completed the survey, representing a mix of organizational backgrounds: three from research institutions, one from a private water utility, and one from an industry association. While the sample is too small to be representative, it provides complementary perspectives on how treatment technologies are viewed in practice. The responses help illustrate experts' concerns, perceived maturity of technologies, and the challenges faced when considering implementation in Denmark.

4.2.1 Perceived challenges

As illustrated in Figure 11, survey respondents consistently identified PFAS and pesticides as the most pressing groundwater contaminants in Denmark, with all five participants selecting both. Heavy metals and nitrate were also highlighted by three respondents each, while one respondent flagged arsenic as a local concern.

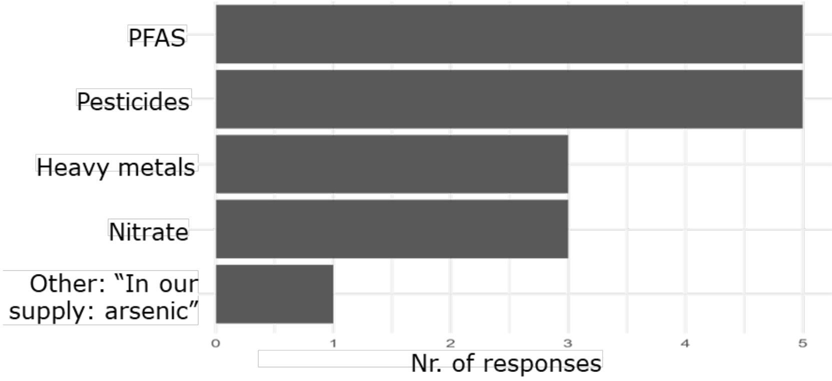

Figure 12 Pollutants considered most important in Danish groundwater by survey respondents. Note: Respondents were asked to select all pollutants they consider most important in their supply area (multiple answers allowed). Responses reflect perceived local priorities, which may not fully align with national occurrence data.

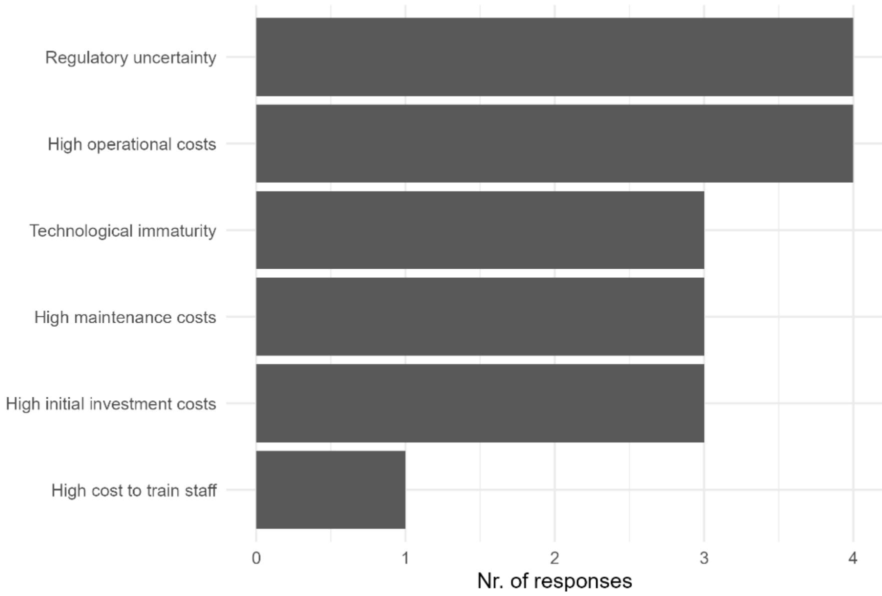

Figure 11 Perceived challenges for implementing water treatment technologies in Denmark, based on survey responses.

Alongside these priorities, respondents pointed to a range of challenges for implementing treatment technologies (Figure 12). The most frequently cited barriers were regulatory uncertainty and high operational costs. Concerns were also raised about the immaturity of certain technologies, casting doubt on their reliability in full-scale operation. In addition, maintenance and investment costs were mentioned as obstacles, and in some cases the need for specialised staff training was emphasised.

Taken together, the responses highlight that concerns are not limited to up-front capital costs, but extend to long-term operation, regulatory clarity, and the practical capacity of utilities to manage new treatment systems. These issues are highly relevant in the Danish context, where many drinking water utilities operate at small to medium scale and therefore face tighter budgetary and staffing constraints. As noted earlier in the report, technologies currently being introduced or piloted in Denmark comprise, among others, IX, GAC, NF and biological treatment, all of which incur ongoing operational and maintenance costs that utilities must consider when selecting treatment technologies.

4.2.2 Perceived technological readiness

Respondents were asked to distribute 100 points across treatment technologies according to how well each performed against six criteria: scalability, cost-efficiency, environmental impact, effectiveness for pesticides, effectiveness for PFAS, and technological maturity. Technologies considered more favourable for a given criterion received higher point allocations.

The results (Figure 13) provide an overview of how experts perceive the relative strengths of different approaches. GAC and RO were rated highly across several dimensions, with GAC scoring particularly strongly on technological maturity and scalability, while RO received high scores for effectiveness against PFAS and pesticides. IX also performed well but somewhat lower than GAC and RO. By contrast, biological treatments and some emerging technologies (e.g. advanced oxidation, EO, foam fractionation) were generally rated lower, reflecting concerns about immaturity and limited demonstrated scalability.

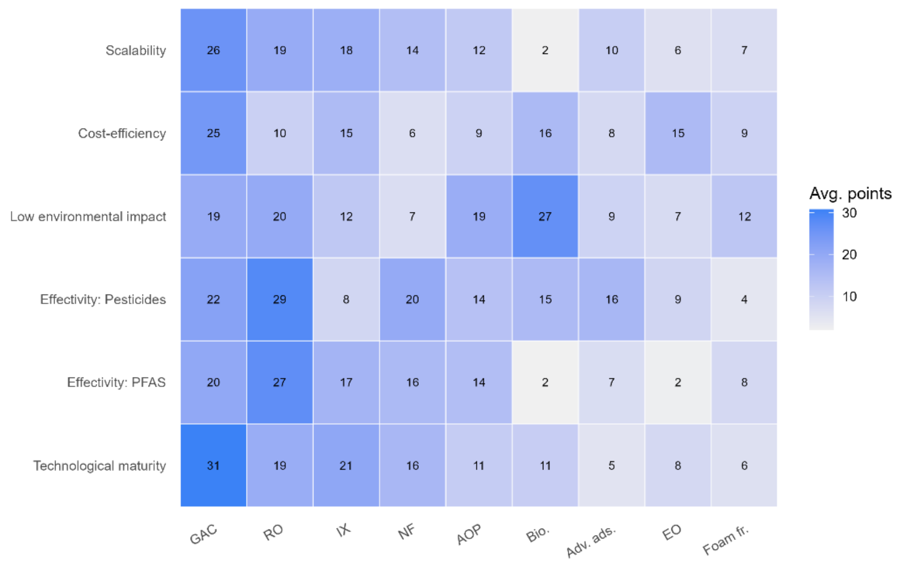

Figure 13 Expert evaluation of treatment technologies by six readiness criteria, expressed as average point allocations.

Overall, the evaluation suggests that while adsorptive and membrane-based technologies are currently seen as the readiest for implementation, experts also recognise trade-offs: RO scores high on effectiveness but lower on cost-efficiency, while GAC is mature and scalable but considered less efficient with respect to PFAS and pesticide removal.

When asked to identify the most promising removal technologies for the next 5–10 years, respondents expressed both cautious and forward-looking views. Some emphasised that utilities, particularly medium-sized suppliers, must rely on proven market-ready technologies rather than experimenting with untested options. Others highlighted innovative approaches, including concentration followed by UV-based photodegradation, the use of recyclable activated carbon produced locally from residual biomass, and combinations of GAC with IX or RO for addressing specific pollutants such as trifluoroacetic acid (TFA).

Taken together, these views indicate a dual perspective: experts expect established technologies to remain the backbone of treatment in the near term but also see scope for emerging solutions to expand the treatment toolbox if cost, scalability, and environmental performance can be demonstrated.

5 Synthesis and discussion

The evidence reviewed here, together with perspectives from Danish stakeholders, highlights a set of recurring insights about treatment options for PFAS and pesticides in groundwater. These insights point to both the opportunities and the constraints of current technologies, and they clarify where knowledge gaps remain most urgent for Denmark.

5.1 No silver bullet

GAC, IX and NF/RO are all documented as mature and viable treatment technologies options across the literature, and all can achieve high removal under some conditions (Appleman et al., 2014; DiGuiseppi et al., 2024; Haupert et al., 2023). Yet each has clear constraints. GAC consistently removes long-chain PFAS, such as PFOS and PFOA, but has poorer affinity for short-chain species (Cantoni et al., 2021; Eschauzier et al., 2012; Ji et al., 2018), especially emerging ones such as GenX or PFBA (see again Figure 6). IX resins in some cases exceed GAC performance for short-chain PFAS (Carter & Farrell, 2010; Zaggia et al., 2016; Zhang et al., 2019) but are vulnerable to fouling and generate wastes that require treatment or disposal (DiGuiseppi et al., 2024; C. J. Liu et al., 2022; Quinnan et al., 2023). Also, NF/RO processes share these two constraints. First, the process produces a concentrated waste stream (retentate) that contains the captured PFAS and must be handled safely. Second, the systems are costly to install and operate, and are prone to fouling, which increases maintenance demands (Ali et al., 2024; DiGuiseppi et al., 2024; Jafarinejad, 2025; C. J. Liu et al., 2022). As discussed above, destructive processes are best suited for concentrated residuals (e.g., IX regenerants, RO/NF brines) rather than direct groundwater treatment (DiGuiseppi et al., 2024; Gal et al., 2025). In a Danish drinking water context, this makes their inclusion in hybrid trains a potential solution, e.g., sorptive or membrane processes as a first step, followed by targeted destruction of residuals (DiGuiseppi et al., 2024; Malouchi et al., 2024). This aligns with the expert survey, where the combination of GAC with IX or RO was similarly as reliable option while also highlighting the potential of hybrid systems, such as combining carbon-based adsorption with UV-based degradation, to enhance removal and manage residuals more sustainably. Yet, Juve et al. (2023) emphasise that despite rapid progress in destructive technologies, complete PFAS mineralisation remains an aspirational goal rather than a demonstrated reality. This underscores that even advanced destruction approaches are unlikely to replace conventional adsorption and separation processes soon but may instead serve as complementary steps within integrated systems.

5.2 Costs and economics of scale

Costs vary systematically with both technology type and plant scale. The indicative cost ranges from this review suggest that full-scale, proven adsorption systems, GAC and IX systems, are currently among the least costly (<1.5 DKK/m^3), while combined or emerging configurations span a much wider range. For example, hybrid systems integrating IX, cartridge filtration, and UV have been reported around 2.6 DKK/m^3, while more complex or novel systems such as AquaPRS or AOP combined with zeolite can reach between 16 and 47 DKK/m^3.

These figures are illustrative rather than definitive, as published cost data remain sparse, assumptions may differ leading to uncertainty and data gaps which prevent robust, generalisable metrics. Still, the general pattern is also found in the literature. They highlight a pattern that single technologies already proven at full scale are at the lower end of the cost range, while newer or combined processes may be substantially more costly.

For Denmark, where most utilities operate at small to medium scale, IX is likely to be the more cost-effective option. IX is generally cheapest for small–medium plants, while GAC becomes more cost-effective at larger capacities (Gardner et al., 2024). Still, also for IX capital costs may decrease with plant size, while operation and O&M costs scale with maximum capacity (deSilva & Deshmukh, 2025). By contrast, NF/RO are considered a more expensive option across scales (Gardner et al., 2024; Goodrich et al., 1991; Jafarinejad, 2025). Thus, it may also be the case in a Danish context that GAC's relative advantages are only realised at larger plants, while NF/RO might represent the highest-cost option under all size scenarios.

5.3 Context matters

Treatment performance is affected not only by technology choice but also by raw water chemistry. Natural organic matter, iron, and manganese accelerate GAC breakthrough and shorten media life (deSilva & Deshmukh, 2025). IX resins are prone to fouling under the same conditions, often requiring pretreatment (C. J. Liu et al., 2022; McLellan et al., 2024; Quinnan et al., 2023). Membrane processes are similarly vulnerable to fouling and scaling, increasing cleaning frequency and energy demand (Ali et al., 2024; C. Liu et al., 2022; Sanzana et al., 2025). Destructive processes, while effective on residuals, become inefficient and emission-intensive when applied directly to large volumes of dilute groundwater (DiGuiseppi et al., 2024; Gal et al., 2025; Molzahn et al., 2024).

For Denmark, these factors are particularly relevant, as groundwater typically contains iron, manganese, and/or natural organic matter. Under such conditions, GAC is likely to exhaust faster, IX resins to foul unless pretreatment is installed, and NF/RO membranes to experience rapid fouling. Given the Danish PFAS standards for ground- and drinking water, even small performance losses increase compliance risks. A recent Danish study by Tisler et al. (2025) illustrates why assessments need to go beyond single pollutants or single pollutant classes alone. The authors found that both GAC and IX filters removed PFAS effectively, with breakthroughs observed only for PFBA, PFPeA and perfluoro(4-ethylcyclohexane)sulfonic acid (PFECHS). At the same time, important differences emerged: GAC filters also removed over 90% of non-PFAS contaminants, whereas resin filters achieved only about 50% removal. More critically, resin filters released new contaminants into drinking water, among other tributylamine and monobutyl phthalate. These findings underline that treatment studies focusing narrowly on a single contaminant group may overlook broader co-benefits and risks. Ideally, evaluations should examine performance across multiple pollutant classes and potential by-products.

5.4 Waste management and sustainability

Residual handling is a critical blind spot. For solid wastes, incineration is the dominant pathway reported for spent adsorbents, with only isolated references to landfilling. However, cost data for these disposal steps are rarely reported. In addition, neither pathway is without risks. Landfilling can contribute to PFAS contamination in leachate, while incineration may lead to incomplete breakdown and the formation of harmful by-products such as perfluoroalkanes, which can contribute to ozone depletion. Mitigation requires very high combustion temperatures and post-combustion gas treatment. Current regeneration approaches offer potential alternatives but also come with their own uncertainties and costs (Ersan et al., 2023). Also, for NF/RO, retentates are identified as a principal constraint, concentrating PFAS and requiring downstream management (Ali et al., 2024; Sanzana et al., 2025). If such residuals are not destroyed or handled properly, there is a risk of emitting pollutants into the environment again. Molzahn et al. (2024) illustrate that destructive processes applied directly to large volumes of low-concentration water are associated with substantially higher greenhouse gas emissions, whereas concentration-based approaches (e.g., GAC, IX, foam fractionation) have much lower footprints. For Denmark, where drinking water production treats high volumes of low-concentration groundwater, this makes sustainability considerations integral to feasibility assessments. However, disposal costs are still rarely included in cost analyses (Dixit et al., 2021), and life-cycle evaluations remain largely absent (Molzahn et al., 2024; Sanzana et al., 2025).

5.5 Outlook

Taken together, the findings indicate that while several technologies can achieve high removal in some contexts, none might be sufficient on its own to consistently treat PFAS pollution. The most realistic pathway is therefore likely to involve hybrid treatment trains that combine the strength of different technologies based on local conditions and context. In this light, significant uncertainties remain. The reviewed literature shows a lack of independent, comparative full-scale studies (Jafarinejad, 2025; C. J. Liu et al., 2022) and very limited cost and life-cycle assessments (Lei et al., 2023; Li et al., 2020). Moreover, many of the cited full-scale studies on drinking water treatment originate from the United States, where utilities are typically larger, systems more centralised and regulatory thresholds and waste management practices are also generally less stringent than in Europe. Therefore, this evidence gap is particularly problematic for Denmark due its highly decentralised drinking water infrastructure, comprising many small to medium-sized utilities that lack economies of scale, and the regulatory being among the strictest in Europe. These contextual differences limit the direct applicability of U.S. findings to Danish conditions, reinforcing the need for Danish pilot- and full-scale demonstrations.

Future research should therefore prioritise pilot- and full-scale demonstrations under Danish conditions, accompanied by holistic assessments that consider not only removal efficiency but also costs, co-contamination and sustainability aspects such as waste and residuals management and energy use. Only such comprehensive evaluations will provide the robust evidence base needed for informed policy decisions. Despite growing practical implementation, technological development in this field remains rapid. Significant efforts are currently directed toward improving adsorptive materials, enhancing regeneration, developing novel destructive processes and exploring nature-based solutions for source protection or passive remediation. Yet, many of these are still in early demonstration stages. Given this ongoing innovation in drinking water treatment, it will be important to maintain systematic monitoring of technological developments and real-world performance. Establishing processes for regularly updating evidence on costs, effectiveness, and sustainability impacts will help ensure that regulatory and investment decisions remain based on the best available knowledge.

6 Literature

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Appendix I

Table 1 Overview of Studies and Screening Decisions.

Nr.	Study	Screening decision
1	Abbaszadegan, M., Alum, A., Kitajima, M., Fujioka, T., Matsui, Y., Sano, D., & Katayama, H. (2025). Water Reuse-Retrospective Study on Sustainable Future Prospects. *Water*, *17*(6), Article 789. https://doi.org/10.3390/w17060789	Abstract
2	Abdullahi, M., Stead, I., Bennett, S., Orozco, R., Abdallah, M. A., Jabbari, S., Macaskie, L. E., Tzella, A., Krause, S., Al -Duri, B., Lee, R. G., Herbert, B., Thompson, P., Schalkwyk, M., Getahun, S., Dearn, K. D., & Orsini, L. (2023). Harnessing water fleas for water reclamation: A nature-based tertiary wastewater treatment technology. *Science of The Total Environment*, *905*, Article 167224. https://doi.org/10.1016/j.scitotenv.2023.167224	Abstract
3	Abdulrahman, H. H., Sdiq, A. F. H., Ismail, H. K., Omer, R. A., Alesary, H. F., Kareem, A. A., & Barton, S. (2025). Polymer Nanocomposite Adsorbents for the Removal of Pharmaceutical Formulations the Aquatic Environment: A Review. *WATER AIR AND SOIL POLLUTION*, *236*(9), Article 584. https://doi.org/10.1007/s11270-025-08240-3	Abstract
4	Abogabal, A., Khodeif, K., Bakr, M. B. M., & Souya, E. (2020). The efficiency of bank filtration to remove chemical pollutants in Egypt: field and batch studies. *Egyptian Journal of Chemistry*, *63*(12), 4695-4701. https://doi.org/10.21608/EJCHEM.2020.17965.2093	Abstract
5	Al Sharabati, M., Abokwiek, R., Al-Othman, A., Tawalbeh, M., Karaman, C., Orooji, Y., & Karimi, F. (2021). Biodegradable polymers and their nano-composites for the removal of endocrine-disrupting chemicals (EDCs) from wastewater: A review. *Environmental Research*, *202*, Article 111694. https://doi.org/10.1016/j.envres.2021.111694	Abstract
6	Ali, S., Wang, R. N., Huang, H. O., Yin, S. D., & Feng, X. S. (2024). Per- and polyfluoroalkyl substance separation by NF and RO membranes: a critical evaluation of advances and future perspectives. *Environmental Science-Water Research & Technology*, *10*(9), 1994-2012. https://doi.org/10.1039/d4ew00066h	Full-text
7	Almeida-Naranjo, C. E., Tejedor, J., Villamar-Ayala, C. A., & Vizuete, G. (2025). Transforming waste into solutions: Raw and modified bioadsorbents for emerging contaminant removal. *Journal of Environmental Chemical Engineering*, *13*(3), Article 116720. https://doi.org/10.1016/j.jece.2025.116720	Full-text
8	Al-Nuaim, M. A., Alwasiti, A. A., & Shnain, Z. Y. (2023). The photocatalytic process in the treatment of polluted water. *Chemical Papers*, *77*(2), 677-701. https://doi.org/10.1007/s11696-022-02468-7	Abstract
9	Altieri, V. G., Sanctis, M. D., Barca, E., & Iaconi, C. D. (2023). SBBGR technology for reducing waste sludge production during plastic recycling process: Assessment of potential increase in sludge hazardousness. *Science of The Total Environment*, *880*, Article 163388. https://doi.org/10.1016/j.scitotenv.2023.163388	Abstract
10	Altowayti, W. A. H., Othman, N., Shahir, S., Alshalif, A. F., Al-Gheethi, A. A., Al-Towayti, F. A. H., Saleh, Z. M., & Haris, S. A. (2022). Removal of arsenic from wastewater by using different technologies and adsorbents: a review. *International Journal of Environmental Science and Technology*, *19*(9), 9243-9266. https://doi.org/10.1007/s13762-021-03660-0	Abstract

11	Alyasi, H., Wahib, S., Gomez, T. A., Rasool, K., & Mahmoud, K. A. (2024). The power of MXene-based materials for emerging contaminant removal from water- A review. *DESALINATION*, *586*, Article 117913. https://doi.org/10.1016/j.desal.2024.117913	Full-text
12	Amari, A., Saber, A. I., Osman, H., Spalevic, V., & Dudic, B. (2024). Development of laboratory-cooked, water-resistant, and high-performance Cu-MOF: an economic analysis of Cu-MOF for PFOS pollution management and remediation. *Applied Water Science*, *14*(9), Article 200. https://doi.org/10.1007/s13201-024-02269-1	Full-text
13	Amen, R., Ibrahim, A., Shafqat, W., & Hassan, E. (2023). A Critical Review on PFAS Removal from Water: Removal Mechanism and Future Challenges. *Sustainability*, *15*(23), Article 16173. https://doi.org/10.3390/su152316173	Full-text
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Note: Screening decision refers to the stage at which the study was excluded or included: “Abstract” = excluded at title/abstract stage, “Full-text” = excluded at full-text stage, “Extracted” = included for data extraction.

ECONOMIC COSTS OF DRINKING WATER TREATMENT

This report presents a comprehensive synthesis of treatment technologies for removing per- and polyfluoroalkyl substances (PFAS) and pesticide residues from drinking water, with a specific focus on the Danish groundwater context. Drawing on a systematic review of peer-reviewed literature and expert opinions, the report evaluates available technologies in terms of effectiveness, scalability, costs, sustainability, and technological maturity. The evidence indicates that mainly sorption and separation technologies are proven at full scale, while destructive and emerging processes remain at laboratory or pilot stage. Indicative cost data suggest that granular activated carbon and ion exchange are most cost-effective, whereas hybrid or destructive systems can be substantially costlier. Environmental and waste management considerations, particularly the handling of micropollutant-laden residuals, remain a major issue. For Denmark's highly decentralised water supply sector and strict PFAS threshold, these findings underline both the need for technological adaptation and the limits of existing evidence. The report concludes with recommendations for Danish-specific pilot and full-scale demonstrations and for more holistic assessments integrating removal performance, costs, and environmental impacts.

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