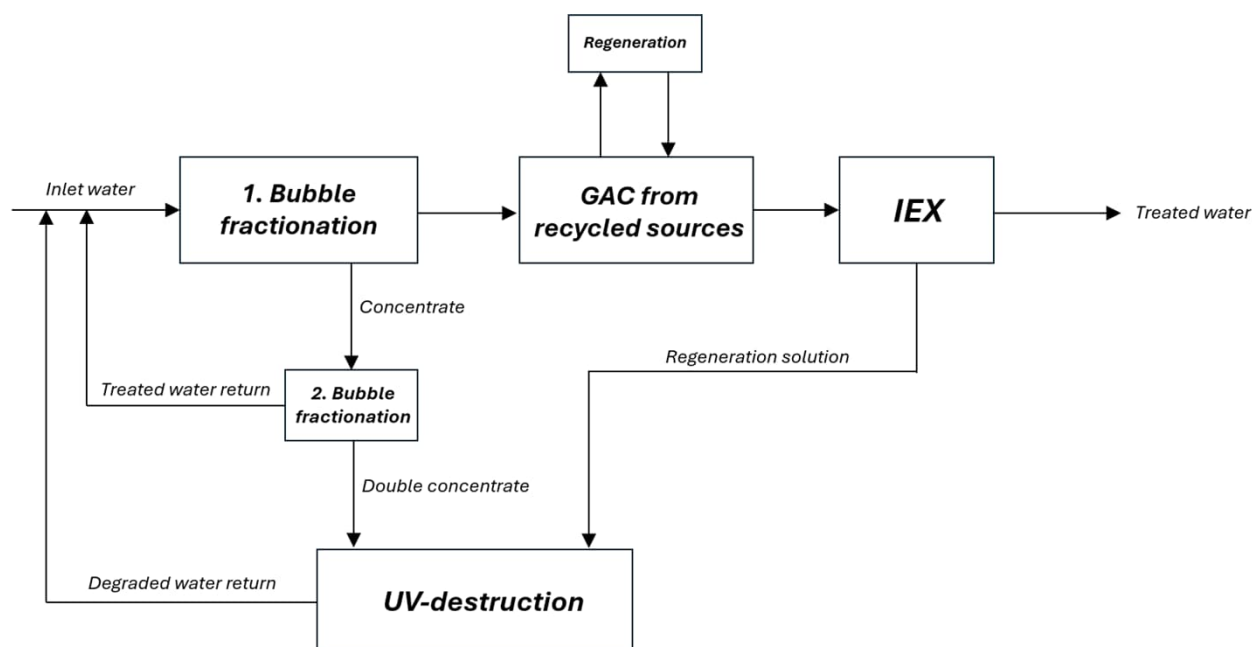




Concept Guideline for PFAS removal

**From Separation to Destruction: A Cost-Effective
Treatment Train for PFAS Contaminated Water**
September 2026

LIMIT

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From Separation to Destruction: A Cost-Effective Treatment Train for PFAS Contaminated Water

This guideline is intended as a practical decision-support document for water managers, engineers, and authorities facing PFAS contamination from point sources. It sets out the principles for structuring a treatment train appropriate to a given site, water matrix, and regulatory context, and presents the technologies available for each step based on experience from the LIMIT project. LIMIT is co-funded by the European Union through the Interreg South Baltic Programme 2021–2027.

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1 Introduction

Per- and polyfluoroalkyl substances (PFAS) are a group of synthetic chemicals that have accumulated in the environment over decades of use. Their exceptional chemical stability, which made them valuable in industrial and consumer applications, also makes them highly resistant to natural degradation. Contamination of groundwater, surface water, and leachate from fire training sites, landfills, harbors, and airports poses a serious challenge to water managers across the South Baltic region and beyond. Current regulatory thresholds demand treatment solutions that are both effective and economically viable at scale.

Existing treatment approaches often focus on a single technology step: adsorption onto granular activated carbon (GAC) or ion exchange resins, membrane filtration, or direct application of destructive processes to the raw contaminated water. While effective in isolation, these approaches do not make efficient use of resources when applied to large volumes of dilute PFAS-contaminated water. Destruction technologies are energy-intensive: the C-F bond is one of the strongest bonds in organic chemistry and breaking it at concentrations of nanograms per liter across thousands of cubic meters of water requires disproportionate amounts of energy.

1.1 The treatment train concept

The central principle of this guideline is that PFAS should be captured and concentrated before any destructive treatment is applied. Destruction then targets only the small-volume stream or material in which PFAS has been accumulated, rather than the full water volume. This principle applies regardless of how the concentration step is implemented.

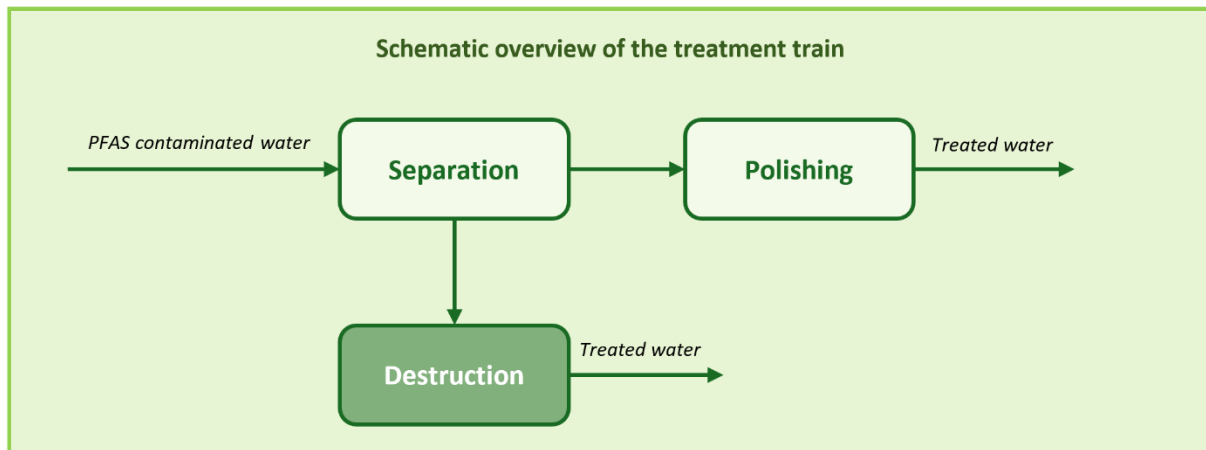
In aqueous-phase separation, technologies such as bubble fractionation, ion exchange, or reverse osmosis transfer PFAS from the bulk water into a concentrated reject stream, which is then routed to a destructive process.

In solid-phase capture, technologies such as GAC adsorb PFAS onto a solid matrix. The spent carbon can be subjected to pyrolysis or superheated/supercritical water oxidation, which destroys adsorbed PFAS directly in the solid phase. In both cases, the volume or mass requiring destructive treatment is orders of magnitude smaller than the original water volume.

This approach delivers three concrete benefits:

- **Resource efficiency.** Concentrating PFAS before destruction reduces both energy consumption and waste volume by orders of magnitude compared to treating the full water volume directly.
- **Treatment efficacy.** Destruction technologies perform better at higher PFAS concentrations, giving more complete mineralization and less interference from background water chemistry.
- **Flexibility.** Separation and destruction technologies can be selected and combined based on the specific water matrix, contamination level, and available infrastructure at each site.

After treatment, the concentration of PFAS should be near or below regulatory limits. Where residual concentrations still exceed the required threshold for discharge or reuse, a polishing step can be inserted after separation.



2 Separation and Polishing Technologies

2.1 Bubble Fractionation

Role in treatment train	Separation and up-concentration for waste reduction
Water matrices investigated	Drainage water and runoff water from firefighting training site
Technology status	Large scale pilot test at firefighting training site in Korsør, Denmark
LIMIT Partner	Ultraaqua A/S

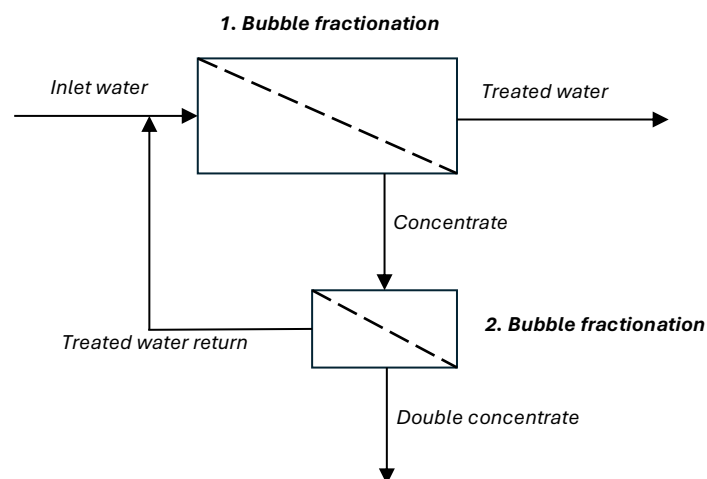
Principle

Bubble fractionation removes PFAS by introducing fine air bubbles into contaminated water. PFAS are attracted to the air-water interface of the bubbles and are transported to the water surface, where a PFAS-enriched concentrate is collected. If further volume reduction is required, the concentrate can be treated in a second bubble fractionation step.

Pilot scale results

In Korsør, bubble fractionation has been demonstrated in a large-scale pilot setup for the treatment of drainage water and surface runoff. The inlet concentration of PFAS4 was 16,000–26,000 ng/L at a flow of 0.5–2 m³/h.

The first bubble fractionation step removed PFAS4 to below 2 ng/L and reduced the volume of PFAS-contaminated water 500 times. The second bubble fractionation step removed 99.9% of PFAS4 from the concentrate and reduced the volume of concentrate to a final flow of 0.1 L/h.



Schematic illustration of the two-step bubble fractionation process

Integration in the treatment train

Bubble fractionation is a separation technology that produces a PFAS-enriched concentrate. This concentrate can subsequently be treated using UV-based destruction to fully mineralize the PFAS compounds.

Bubble fractionation is particularly effective for long-chain PFAS compounds. If the water contains a significant fraction of short-chain PFAS, bubble fractionation should be followed by a polishing step, such as anion exchange resins or granular activated carbon, to achieve further removal.

2.2 Ion Exchange Resin

Role in treatment train	Separation and polishing
Water matrices investigated	Surface runoff and drainage water from firefighting training site in Korsør
Technology status	Large scale pilot and laboratory tests
LIMIT Partner	Ultraaqua A/S

Principle

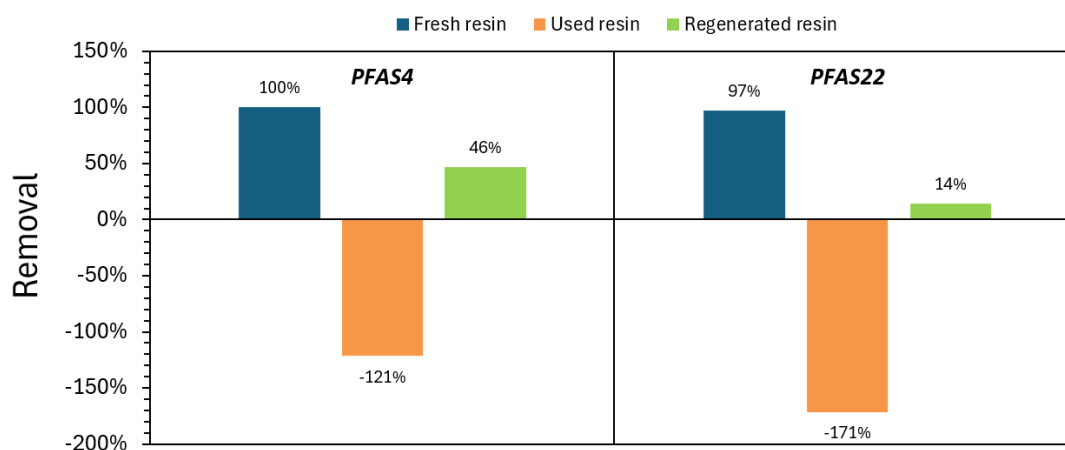
Ion exchange resins (IEX) remove PFAS by binding negatively charged PFAS compounds to positively charged functional groups on the resin, exchanging them with less harmful ions in the water. Regeneration of the resins can increase the lifetime.

Laboratory results

Four resin columns are installed in Korsør for polishing bubble-fractionated water. The resins remove both PFAS and organic compounds, but organics occupy most active sites due to their much higher concentration in the water. Once the active sites are fully occupied, the resin is exhausted and must be replaced with fresh resin unless regeneration is possible.

Regeneration trials showed that PFAS is too strongly bound to be released effectively, whereas organic compounds can be partially removed. Regeneration targeting organic removal can therefore free active sites and partially restore the resin capacity for PFAS polishing.

Fresh resin removed 100% of PFAS4 and 97% of PFAS22. In contrast, used resin from Korsør released previously adsorbed PFAS, resulting in higher PFAS concentrations after treatment than before. After regeneration of the used resin, removal efficiency increased to 46% for PFAS4 and 14% for PFAS22.



Removal of PFAS using fresh, used and regenerated resin

Integration in the treatment train

In clean water matrices, ion exchange resins can be used as stand-alone separation technology, but in complex matrices such as drainage water, competing ions and dissolved organic carbon will cause rapid saturation, and the resin should be used as a polishing step after the primary treatment technology.

2.3 Granular Activated Carbon

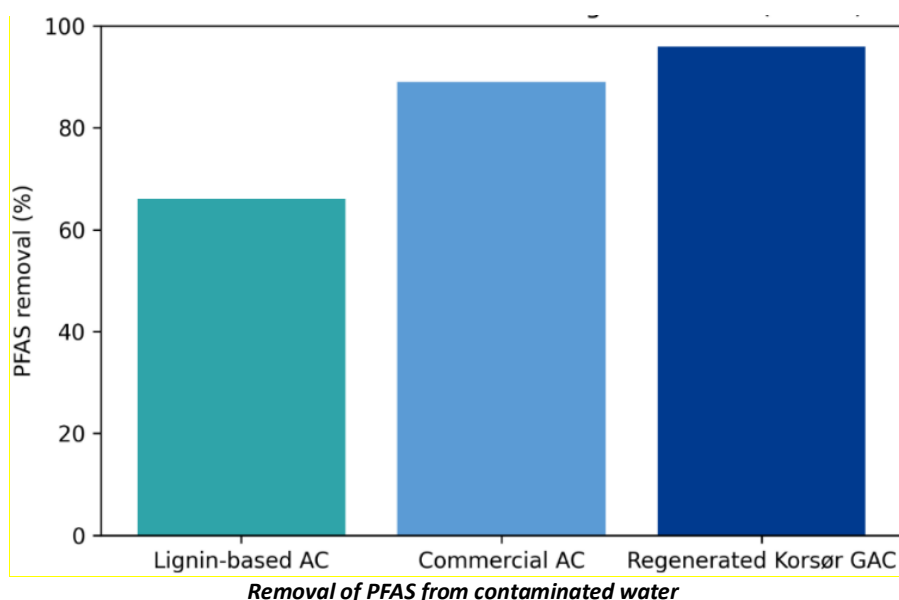
Role in treatment train	Separation and capture of PFAS on solid material
Water matrices investigated	Groundwater from firefighting training site
Technology status	Laboratory scale tests
LIMIT Partner	Lund University

Principle

Granulated activated carbon (GAC) has a large surface area that captures PFAS through adsorption. In water treatment, GAC is typically applied in fixed filters but can also be applied in fluidized beds. The main raw materials for GAC production are fossil coal and biobased carbon sources. During production, the raw material is heated to hundreds of degrees Celsius under an oxygen free atmosphere and activated with a mild oxidant.

Laboratory results

Activated carbon, both from fossil and biobased carbon sources, were evaluated for removal of various PFAS from contaminated water at the cross-collaboration test site. Lignin – a wood residue from the pulp and paper industry – was selected and used for production of biobased activated carbon with nitrogen at 500–700 °C and activated with CO₂ for 15–120 min. Results from these experiments showed that lignin-based activated carbon can remove a broad range of PFAS, including PFOA and PFOS. Although the lignin-based activated carbon did not reach the same adsorption levels as commercial activated carbon, the results demonstrate a clear removal potential and support further optimization of production parameters to improve performance.



Integration in the treatment train

Activated carbon treatments include GAC-filtration and PAC dosing. These treatments are preferably used for polishing or after pre-treatment to reduce the competition for adsorption sites between the dissolved organics and the targeted pollutant.

3 Destruction Technologies

3.1 UV-Advanced Reduction Processes

Role in train	Destruction of PFAS concentrate
Water matrices investigated	Concentrate from bubble fractionation
Technology status	Pilot test at a firefighting training site in Korsør, Denmark
LIMIT Partner	Ultraaqua A/S

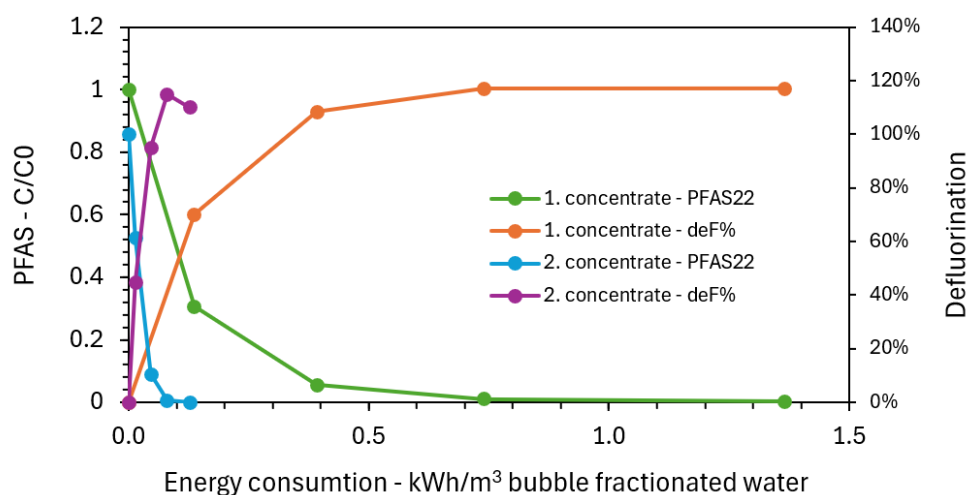
Principle

UV-advanced reduction processes (UV-ARP) destroy PFAS by generating highly reactive radicals called hydrated electrons, e^-_{aq} . The generation of e^-_{aq} occurs when photosensitizers such as water, OH^- or sulfite is irradiated with UV and vacuum UV light. The radicals degrade PFAS and produce harmless compounds such as CO_2 , F^- and water.

Pilot scale results

A pilot scale UV-destruction unit was built in Korsør to test the destruction of aqueous PFAS concentrate from the first and second bubble fractionation process (see section 2.1).

Both tests showed great degradation with more than 99% removal of PFAS22 and a defluorination of more than 100%. UV destruction of the 2. concentrate was 10 times less energy consuming than the 1. concentrate since the volume of concentrate was reduced.



Removal and defluorination of PFAS in concentrate after the first and second bubble fractionation step

Integration in the treatment train

UV destruction of PFAS is an energy-intensive technology and is therefore most viable when combined with a separation process. The separation step reduces the volume of contaminated water and increases the PFAS concentration, making the subsequent UV treatment more efficient.

UV destruction can, in principle, continue until all PFAS compounds are degraded. However, the most energy-efficient approach is often to degrade 95–99% of the PFAS and return the UV-treated water to the separation unit for further processing.

3.2 Electrochemical Oxidation

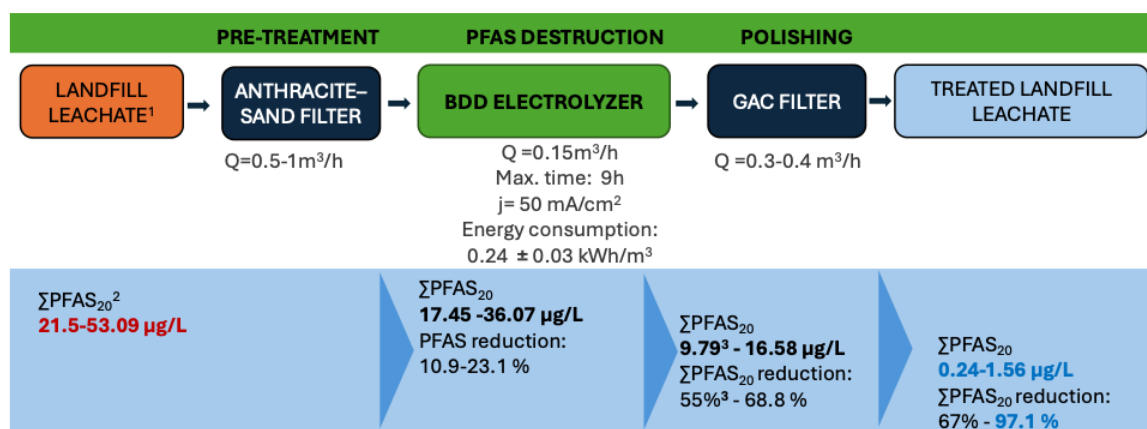
Role in train	Destruction of PFAS
Water matrices investigated	Landfill leachate
Technology status	Pilot test
LIMIT Partner	Gdansk University of Technology

Principle

Electrochemical oxidation (EO) using boron-doped diamond (BDD) electrodes is an advanced destructive treatment technology for PFAS-contaminated water. PFAS molecules reaching the anode undergo destruction through a combination of direct electron transfer at the electrode surface and indirect oxidation by reactive species generated electrochemically e.g. hydroxyl radicals ($\cdot\text{OH}$). The electrochemical degradation proceeds through successive transformation of the perfluoroalkyl chain, including C–C and C–F bond cleavage, shortening of the perfluorinated chain and formation of shorter-chain perfluorocarboxylic acids as intermediates. Continued oxidation can ultimately result in defluorination and mineralization, with carbon being converted to CO_2 and fluorine released predominantly as fluoride ions.

Pilot scale results

The pilot-scale concept developed within LIMIT is intended for treatment of highly contaminated or concentrated PFAS-containing water. The results demonstrate also that PFAS removal should not be evaluated solely from the disappearance of parent compounds. Monitoring short-chain transformation products and fluoride release is important for assessing the degree of actual PFAS destruction. Integration of EO into the pilot scale includes the following flow chart and results:



Legend 1) total tested volume $V = 0.5 \text{ m}^3$; 2) PFAS 20 listed in Deliverable 2.1; 3) after 2h of EO supported by O_3 (10g O_3/h)

Integration in the treatment train

The EO technology combines electrochemical oxidation, PFAS adsorption at the electrode interface, direct electron transfer and progressive defluorination/mineralization. These characteristics make BDD-based EO particularly attractive as a PFAS degradation treatment step for concentrated PFAS streams, treatment residuals, or highly contaminated waters, where conventional separation processes may only transfer PFAS from the aqueous phase to another waste stream. Its integration with separation technologies such as granular activated carbon (GAC) or membrane processes can significantly improve the overall treatment concept.

3.3 Superheated and supercritical Water Oxidation

Role in train	Destruction of PFAS concentrated on GAC
Water matrices investigated	Spiked water; PFAS loaded onto GAC
Technology status	Laboratory-scale proof-of-concept
LIMIT Partner	Kristianstad University

Principle

Superheated and supercritical water oxidation (SHWO/SCWO) uses elevated temperature and pressure to degrade persistent organic compounds. For PFAS, its main potential is as a destruction step following separation and concentration, rather than for direct treatment of large water volumes. Within LIMIT, PFAS were first captured from water onto granular activated carbon (GAC) and the PFAS-loaded carbon subsequently treated by SHWO/SCWO. This combines efficient removal from water with destruction applied to a much smaller, concentrated material stream.

Laboratory results

PFAS were spiked into water, loaded onto GAC in batch, and treated at 150, 250 and 375 °C, followed by ultrasonication to determine residual recoverable PFAS. A strong temperature dependence was observed (see table below). Recovery decreased markedly at 250 and 375 °C, with most PFAS showing very low recoveries compared with 150 °C, indicating substantial destruction and/or transformation during treatment. However, recoveries below 100% already at 150 °C demonstrate that low recovery cannot alone be interpreted as quantitative destruction. Further work is required to establish PFAS and fluorine mass balances and distinguish degradation from incomplete extraction or other losses.

	150 C	250 C	375 C	U-ljud 150 C GAC	U-ljud 250 C GAC	U-ljud 375 C GAC	Totalt	150 C	250 C	375 C
PFPeA	78,6	0,8	3,1	13,5	2,3	1,2	92,0	3,2	4,3	
PFBA	80,0	10,4	16,5	10,5	2,7	2,0	90,5	13,1	18,5	
4:2FTS	45,5	0,3	3,1	23,6	15,1	0,0	69,1	15,4	3,1	
PFHxA	45,3	0,0	2,2	17,3	0,0	0,0	62,6	0,0	2,2	
PFBS	54,5	0,9	2,7	5,2	4,8	1,3	59,7	5,7	4,0	
N-EtFOSAA	2,9	1,4	2,0	53,0	0,6	1,0	55,9	2,0	3,0	
6:2FTS	10,5	0,8	3,2	39,2	17,7	0,6	49,7	18,5	3,8	
PFHpA	22,7	0,2	1,9	22,5	0,0	0,2	45,2	0,2	2,1	
PFOA	13,0	0,2	1,5	27,4	0,0	0,1	40,4	0,2	1,6	
PFDS	0,9	0,3	1,3	39,5	14,5	0,9	40,4	14,8	2,2	
PFPeS	28,5	0,1	2,5	6,1	7,4	0,8	34,6	7,4	3,3	
PFOSA	1,2	0,7	1,0	32,1	0,4	0,7	33,4	1,1	1,7	
8:2FTS	1,9	0,1	0,9	30,4	11,2	0,1	32,3	11,2	0,9	
PFUnA	2,4	0,7	1,9	26,2	0,6	0,6	28,6	1,3	2,5	
PFNA	5,8	0,2	1,0	22,3	0,1	0,2	28,1	0,3	1,1	
N-MeFOSAA	0,9	0,0	0,1	26,2	0,0	0,0	27,1	0,0	0,1	
PFHxS	13,9	0,1	1,9	9,4	8,4	0,4	23,3	8,5	2,3	
PFDA	1,9	0,0	0,4	18,5	0,0	0,0	20,4	0,1	0,4	
PFHpS	4,3	0,1	1,4	9,5	6,3	0,5	13,8	6,4	1,9	
PFNS	0,7	0,1	0,9	13,0	5,7	0,6	13,7	5,8	1,5	
PFOS	2,9	0,1	0,5	10,6	4,9	0,4	13,5	5,0	0,9	

Recovery presented as % of ref

Batch experiment recovery results for spiked PFAS onto GAC followed by SHWO at three different temperatures (150 °C, 250 °C and 375 °C), and ultrasonication. Results are ranked from highest to lowest of the total recovery in the 150 °C GAC experiment (blue column).

Integration in the treatment train

SHWO/SCWO is particularly suited as a destruction step for PFAS concentrated on GAC. Rather than applying an energy-intensive destruction process to the entire water flow, PFAS are first separated and concentrated and then treated in a much smaller material stream. The LIMIT results support the potential of this separation-destruction approach, while further validation of destruction efficiency, energy demand and potential carbon reuse/regeneration is required before full-scale implementation.

3.4 Pyrolysis of Granular Activated Carbon

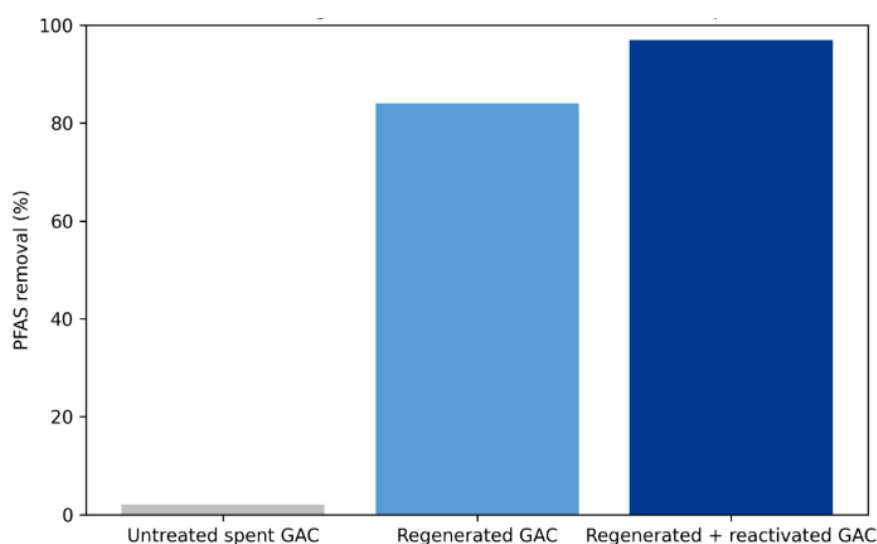
Role in train	Capture and destruction of PFAS on solid material
Water matrices investigated	Concentrate and granulated activated carbon from Korsør Test Site
Technology status	Laboratory scale tests
LIMIT Partner	Lund University

Principle

Granulated activated carbon (GAC) removes PFAS through adsorption onto the carbon surface. With time, the removal of PFAS decreases as the adsorption sites on the carbon surface are saturated by adsorbed PFAS and organics. Thermal regeneration and reactivation through pyrolysis can restore these adsorption sites and enable reuse of the spent GAC.

Laboratory results

Bench-scale thermal regeneration and reactivation experiments were performed at Lund University in Sweden, using spent GAC from the cross-collaboration test site in Denmark. Regeneration with nitrogen at 500–700°C, and 900°C, followed by reactivation with CO₂ at corresponding temperatures. The results from adsorption experiments showed that thermal regeneration alone significantly restored adsorption capacity, achieving more than 80% PFOA removal at a GAC dose of 1 g/L, while 900°C provided limited additional improvement. CO₂ reactivation at 900°C further increased performance, with removal efficiencies higher than 95% and adsorption capacities comparable to, or higher than, fresh commercial GAC. Additional pyrolysis experiments showed that PFOA adsorbed onto GAC was degraded to CO₂ at temperatures >400°C.



Effect of thermal regeneration and reactivation on GAC performance

Integration in the treatment train

Once saturated with PFAS, the GAC must be taken out of the treatment train and treated separately by pyrolysis, enabling regeneration of the carbon and destruction of the adsorbed PFAS.

3.5 Hybrid advanced oxidation and GAC filtration process

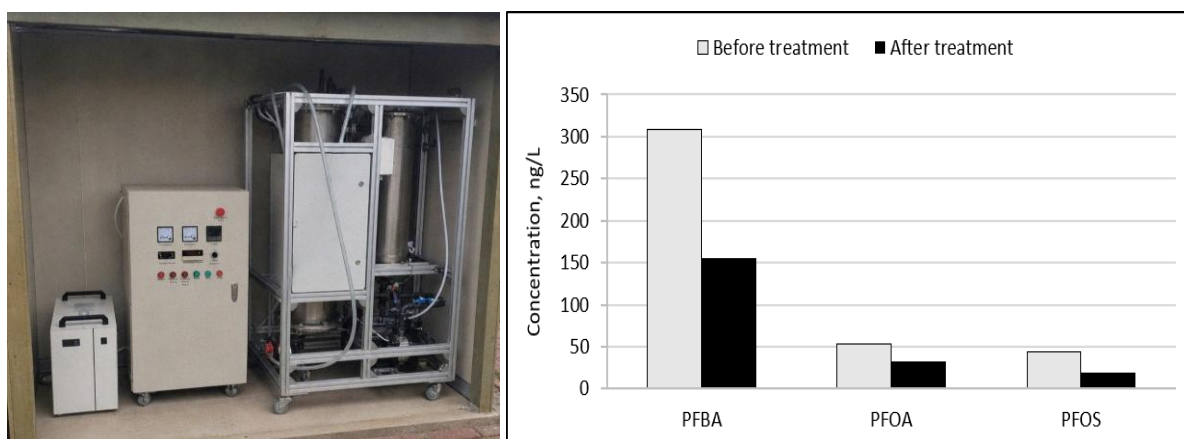
Role in train	Destruction of PFAS in diluted streams
Water matrices investigated	Surface water and secondary effluents
Technology status	Pilot-scale testing
LIMIT Partner	Bioksa

Principle

Combined UV and ozone treatment enhances PFAS degradation through the generation of reactive radicals, mainly hydroxyl radicals ($\bullet\text{OH}$). PFAS are transformed into shorter-chain compounds and partially defluorinated. Residual PFAS and transformation products are subsequently removed by polishing filtration through granular activated carbon (GAC).

Pilot scale results

A pilot-scale hybrid UV/ozonation and GAC unit was built and tested at a plastic products manufacturing plant. UV/ozone treatment achieved 39–55% removal of the investigated PFAS within a treatment time of 30–60 min, while subsequent GAC polishing increased overall PFAS removal to 73–81%. Even higher removal efficiencies, often exceeding 95%, were achieved for pharmaceuticals and plasticizers.



Hybrid ozonation and UV photolysis pilot set-up (left) and PFAS removal results (right).

Integration in the treatment train

Hybrid UV/ozone treatment followed by GAC polishing provides an energy-efficient option for treating larger volumes of dilute streams while achieving high-quality effluent. The system is relatively flexible and can accommodate variations in wastewater composition; however, lower concentrations of organic carbon and other radical scavengers are favorable, as they improve the overall treatment performance.

4 Recommendations for selecting and combining technologies

No single technology addresses all aspects of PFAS treatment under all site conditions. The treatment train concept is inherently modular: separation, polishing, and destruction steps can be selected independently and combined according to the specific requirements of the site, the water matrix, and the regulatory context.

The choice of separation technology depends primarily on the matrix composition. Adsorption-based approaches such as GAC and ion exchange resins are well suited to relatively clean water matrices at low PFAS concentrations and a high amount of short chain PFAS, but in complex matrices with high dissolved organic carbon or competing ions, they saturate rapidly. For these sources, membrane-based separation or bubble fractionation may be more appropriate, as they are less sensitive to matrix interference. The destruction step is selected based on the volume and composition of the resulting concentrate and the required degree of mineralization.

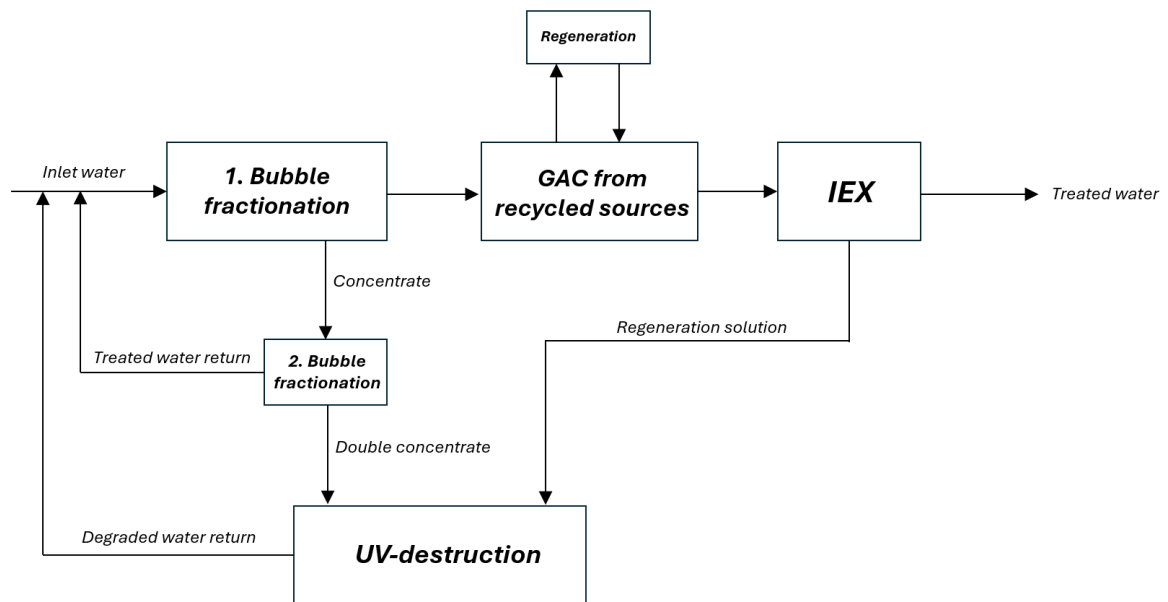
During the LIMIT project, the firefighting training site in Korsør, Denmark has acted as a cross-border collaboration site for all partners to test the different treatment technologies. The site collects PFAS contaminated drainage water from the surrounding fields and surface runoff water from the training facility.

Based on this water matrix, which consists of a high amount of PFAS and other organic compounds, the recommended treatment train consists of a 2-stage bubble fractionation followed by GAC and IEX. Upon saturation, the GAC should be regenerated using appropriate thermal treatment, such as superheated water oxidation (SHWO), supercritical water oxidation (SCWO), or pyrolysis. The IEX resin should be regenerated using a suitable regeneration solution to restore its PFAS adsorption capacity.

The concentrate produced from bubble fractionation and the regeneration solution from the resins should be treated with a destruction process to ensure complete degradation of PFAS to harmless compounds. Due to its technological maturity and high degradation efficiency, a UV-based process has been selected for the Korsør site. However, other destruction technologies, such as electrochemical oxidation, could also be considered.

The inlet water has a concentration of PFAS₄ of 16000 ng/L, which is removed to below the detection limit after treatment with bubble fractionation, GAC and IEX. UV-destruction ensures permanent degradation of the PFAS compounds with approximately 100% documented defluorination within analytical uncertainty.

The energy consumption is 0.5 kWh/m³ and accounts for the energy needed for pumps, aeration during bubble fractionation and UV lamps. This leads to operational costs for electricity, GAC and IEX of around 0.7 euro/m³. The energy consumption for regeneration of the GAC is not included since the technologies have only been investigated in lab scale.



Treatment train recommended for highly PFAS-contaminated water with a high content of other organic compounds