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Preventing Recalcitrant Organic Mobile Industrial chemicals for Circular Economy in the soil-sediment-water System

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D6.9 – Market Study Analysis

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Executive Summary

This market study aims to assess the opportunities related to the expectations and needs of the PFAS treatment sector. To provide a comprehensive overview of the market dynamics, an initial literature review was conducted, complemented by 13 interviews with industry professionals from France, Belgium and Luxembourg (public water agencies, technology developers, water management companies).

This work made it possible to establish an exhaustive mapping of the stakeholders in the PFAS value chain, from their production to their management in natural environments. It also identified current regulations and anticipated the directions of future legislation. The analysis highlighted major constraints, notably the gap between the urgency of treatment needs and the scarcity of existing regulatory measures. Indeed, regulations have emerged as the primary market driver, encouraging the funding of treatment solutions and scientific research for their development.

A technological synthesis was conducted across the entire PFAS treatment chain, from detection to end-of-life management. This analysis helps to understand the currently used solutions, the associated operational challenges, and the technological and operational needs of the market. Limitations were identified on all of the three treatment steps:

1. **PFAS Detection:** PFAS detection is complex due to the diversity of compounds involved and the very low detection thresholds required. Developing appropriate methodologies represents a significant investment of time and financial resources, without which large-scale monitoring is impossible. This gap will widen with the emergence of new regulations targeting compounds that cannot be quantified by (more generic) multi-residue methods, such as TFA. For these compounds, more specific methods are required, which significantly increases monitoring costs.
2. **PFAS Treatment:** Existing methods, while effective for specific issues (hot spots, exceedance of regulatory thresholds for the 20 targeted PFAS), are not specifically designed for PFAS treatment. Therefore, they are limited in addressing the global PFAS pollution crisis and unsuitable for future regulatory requirements. Developing new technologies is complex, requiring the consideration of numerous parameters (type of matrix, integration into existing treatment chains, variations in pollutant concentration, etc.).
3. **PFAS Destruction:** Complete PFAS destruction remains a challenge. No mature industrial technology allows total degradation to date, except for incineration. Moreover, the effectiveness of this method is controversial, with no definitive evidence confirming the complete elimination of PFAS or the absence of harmful by-products.

The conclusions of this study, based on the analysis of regulations, recent developments in issues, and the strengths and weaknesses of existing solutions, have enabled the formulation of:

- Strategic recommendations for the development of the PFAS market;
- Key considerations to guide the development of technologies aligned with market needs.

Key points identified include:

- The need for effective solutions for the treatment of very short-chain PFAS, such as TFA;
- The capacity to integrate solutions into existing water treatment infrastructures with significant budgetary implications;

- Greater acceptance of solutions by the market if their overall environmental impact is known (by-product generation, alteration of chemical balances, secondary pollution, need for additional post-treatment);
- Industry stakeholders' preference for solutions with low operating costs and long-term reliability, making comparative cost analysis (OPEX and CAPEX) crucial to offer a tangible comparison to existing alternatives;
- The importance of anticipating future regulations to position technologies as reference solutions in the market.

Since PROMISCES is a Research and Innovation Action (RIA), most targeted technologies were expected to progress from TRL 4 to TRL 6 during the project. This level of technological maturity, although still limited to a comprehensive analysis of opportunities, allowed the evaluation of market receptivity based on three criteria: attractiveness, feasibility, and competitiveness. Finally, the conclusions of this study have led to strategic recommendations regarding ultrasonic cavitation and co-pyrolysis technologies developed within the framework of the PROMISCES project, in compliance with confidentiality requirements.

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List of abbreviations

AOF	Adsorbable Organic Fluorine
AOP	Advanced Oxydation Process
ARP	Advanced Reduction Process
CAPEX	Capital Expenditure
eAOP	Electrochemical Advanced Oxidation Process
EBCT	Electron Beam Computed Tomography
EFSA	European Food Safety Authority
EU	European Union
GAC	Granular Activated Carbon
IARC	International Agency for Research on Cancer
iPM(T)s	Industrial, Persistent, Mobile and potentially Toxic substances
LC	Liquid Chromatography
MO	Metal oxydes
MS	Mass Spectrometry
OJEU	Official Journal of the European Union
NF	Nano Filtration
PAN	Pesticide Action Network
PFAS	Per- and polyfluoroalkyl substances
PFCA	Perfluoroalkyl Carboxylic Acid
PFHxS	Perfluorohexanesulfonic acid
PFNA	Perfluorononanoic acid
PFOA	Perfluorooctanoic acid
PFOS	Perfluorooctanesulfonic acid
PFSA	Perfluorosulfonic Acid
POP	Persistent Organic Pollutant
OPEX	Operational Expenditure
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
RO	Reverse Osmosis
TFA	Trifluoroacetic Acid
TOC	Total Organic Carbon
UC	Ultrasonic Cavitation
WIHC	Water intended for human consumption

The PROMISCES Project is funded by the European Union under the Horizon 2020 Framework Programme to support Europe's Green Deal. It runs from November 2021 to April 2025. PROMISCES aims to increase the circularity of resources by overcoming barriers associated with the presence of industrial Mobile, Persistent and Potentially Toxic chemicals (iPM(T)s) in the soil-sediment-water system.

Understand current practices and existing solutions to assess the competitive landscape and technological state of the art in PFAS treatment.

This market study aims to provide technology developers with the essential market insights needed to gain a comprehensive understanding of the PFAS treatment sector across the entire value chain.

Analyze market dynamics, challenges, and attractiveness to identify key applications and prioritize market opportunities.

By analyzing key market dynamics, expectations, and challenges, the report helps assess business opportunities and strategic directions in the industry.

Assess the perceived value and expectations of key stakeholders, including potential users and partners, to align solutions with industry needs.

To achieve this, the study presents the results of a cross-analysis combining an extensive literature review with interviews conducted with key stakeholders from the PFAS treatment value chain. The objective is to highlight the industry's major concerns and regulatory constraints, as well as to identify trends, innovation needs, and market entry barriers.

Provide strategic recommendations on market positioning, regulatory considerations, and commercialization pathways for innovative PFAS technologies.

The recommendations provided in this report are broad in scope and are specifically designed for stakeholders involved in the development of new PFAS detection and treatment solutions for water. By offering a structured overview of market opportunities and constraints, this study supports the strategic positioning and commercialization of innovative technologies in the PFAS treatment sector.

The PROMISCES Project, funded under the Horizon 2020 Framework, aims to tackle the challenges posed by persistent, mobile, and toxic industrial chemicals (iPM(T)s) in soil, sediment, and water systems. Among these, per- and polyfluoroalkyl substances (PFAS) represent a major environmental and health concern due to their extreme persistence, bioaccumulative potential, and widespread contamination.

This market study provides technology developers, policymakers, and industry stakeholders with key insights into the PFAS treatment sector, analyzing market dynamics, regulatory frameworks, emerging trends, and technological advancements. It serves as a strategic guide for the development and commercialization of innovative PFAS treatment solutions.

All the components of the PFAS treatment value chain, as well as the associated market ecosystem, have been reconstructed and analyzed to identify their strengths and weaknesses. This in-depth analysis has enabled the formulation of strategic conclusions and recommendations aimed at guiding the development of effective and targeted PFAS remediation solutions.

01.

CONTEXT ANALYSIS

Current knowledge of per- and polyfluorinated compounds and the issues involved.

02.

COMPARATIVE ANALYSIS

Interviews with relevant market players to enhance information

03.

SYNTHESIS

Assessing the opportunities and perceived values of PROMISCES technologies

Methods: Bibliographical research and direct interviews with players in the value chain

- Understand the origins, characteristics and impact of PFAS on its environment.
- Analyze and summaries the regulatory framework and current developments.
- Analyze and summaries the methods and technical solutions for characterizing/measuring, treating and eliminating PFAS in relation to the water matrix.
- Focus on the most mature and developing technologies and processes for treating PFAS in water and characterization (for which PFAS, water, sizing, limits, etc.).

- Identifying and interviewing key players in the treatment industry.
- Conducting interviews to understand the real dynamics involved in implementing detection, treatment and elimination solutions.
- Putting bibliographical data into perspective with the results of the context analysis to establish a concrete representation of the resources implemented.

- To analyze all the results of the study and draw up a summary of the overall dynamics and opportunities.
- Assess the perceived potential of PROMISCES solutions in the PFAS treatment market.

To supplement the bibliographical information gathered from reference works, scientific publications, specialist websites, magazines, etc., interviews were conducted with professionals in the PFAS treatment value chain. These interviews enriched the understanding and market analysis explained throughout this document.

These professionals provided direct feedback on their areas of expertise, as set out below:

Regulatory entities/ water companies

Interviews conducted : 6

Expertise :

- Insight into the reality of the market and the solutions implemented in water treatment plants
- Knowledge on treatment strategies
- Regulations
- Close contacts with stakeholders

Technology providers

Interviews conducted : 2

Expertise :

- Detailed operation of existing solutions
- Assessing the relevance of new solutions
- Development roadmap orientation
- Certification and regulatory constraints

Engineering and design

Interviews conducted : 4

Expertise

- Integrating technology into a complex environment
- Understanding and reporting on customers' problems encountered and the associated technical limitations
- Knowledge about implementing treatment solutions

End-users

Interviews conducted : 2

Expertise

- Direct feedback on customers' expectations
- Assessment of the benefits of the solution in light of the technical and financial resources available

Analysis of global PFAS market trends and dynamics

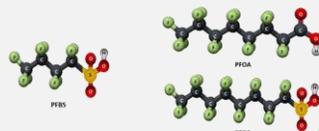


Per- and polyfluoroalkylated substances, or PFASs, represent a vast family of thousands of chemical compounds that have become a significant health and safety challenge for humanity

PFAS classification

The exact number of PFAS is not known: 256 are thought to be produced industrially, but there could be between 4,000 and 14,000 (including legacy, emerging, unknown and byproduct compounds). The fact that they have not all been identified and listed poses difficulties, in improving health monitoring or drawing up pollution inventories. They fall into two broad categories depending on the number of carbon atoms in the CF chain (except functional groups):

- long-chain PFASs containing at least 6 carbon atoms;
- short-chain PFASs containing less than 6 carbon atoms for PFCA and 8 for PFSA.



Multiple sources of exposure

Sources of PFAS are extremely broad due to the many technical properties offered by these chemical species. According to EFSA (2020) and based on current monitoring, seafood, eggs and meat are the foods that contribute most to exposure to PFOS and PFOA. Water intended for human consumption (WIHC) can also be a source of exposure, as can indoor and outdoor air, dust, groundwaters and contaminated soil.

Occupational exposure to PFAS can occur in several industrial sectors, including the chemical industry, textile processing, electronics manufacturing and firefighting. The highest levels of impregnation are found in workers at PFAS manufacturing sites (ECHA, 2023).

80 years ago,
scientists didn't know
how to make PFAS.
Today, we can't get rid
of them.

Persistent substances in the environment...

These substances all contain carbon-fluorine bonds, which are among the most stable chemical bonds in organic chemistry. The wide and varied use of these chemical compounds, combined with their very persistent nature, leads to pollution of all environments: water, air, soil and sediment. Some accumulate in living organisms, plants and animals, and find their way into the food chain. Others, which are more mobile, are transported over very long distances by water or air and can end up in the oceans, even over long distances.

... with unwanted effects

- Bio-accumulation in the human body, animals and plants : the substances do not break down after use and dispersion in the environment.
- Harmful effects on human health: increased cholesterol levels, cancers, effects on fertility and foetal development, on the liver, on the kidneys, etc. They are also suspected of interfering with the endocrine (thyroid) and immune systems. In December 2023, the International Agency for Research on Cancer (IARC) classified PFOA as 'carcinogenic to humans' (Group 1) and PFOS as 'possibly carcinogenic to humans' (Group 2B).

Where to find PFAS ?

These substances have been widely used since the 1950s in a variety of industrial applications for their non-stick, waterproofing and heat-resistant properties.

There are many industries linked to the use of PFAS...

PFAS are distinguished by their exceptional properties given by their molecular structure (CF chain). Hydrophobic and oleophobic, they repel water and grease, making them ideal for textiles, stain-resistant coatings, and food packaging. Their thermal and chemical resistance makes them essential in extreme environments such as aerospace, electronics, and industry. They also act as surfactants in firefighting foams and exhibit exceptional durability, resisting degradation. Finally, their low friction coefficient and insulating properties make them highly versatile materials.

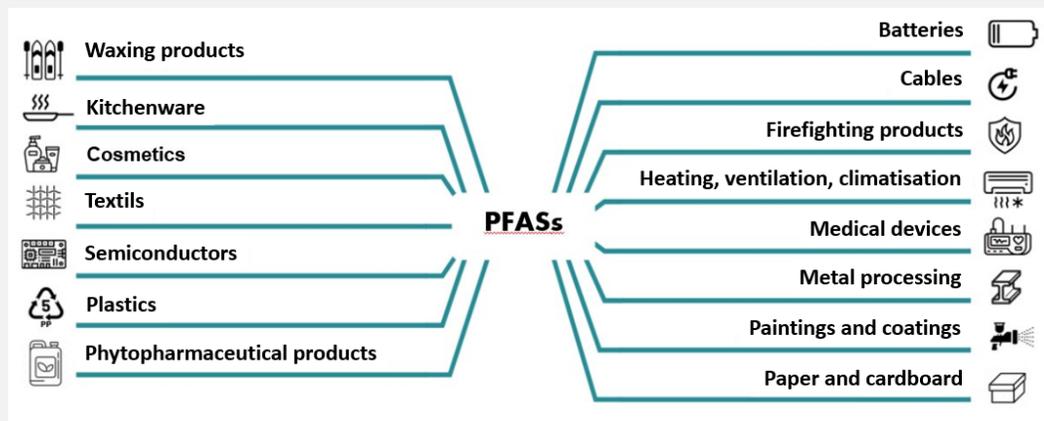
...but only a dozen responsible for their production

The exact number of companies producing PFAS globally is difficult to determine due to proprietary information, trade secrets, and varying levels of regulatory disclosure. However, **a few dozen multinational corporations dominate global PFAS production** with a concentration of major manufacturers in the United States, Europe, China, and Japan. These companies include chemical giants such as 3M, Chemours, Arkema, and DuPont.

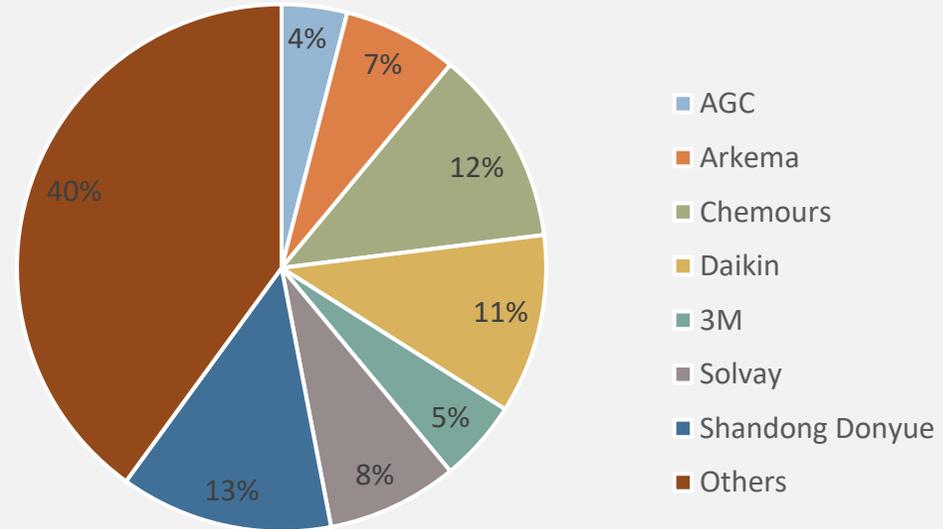
These companies face lawsuits for environmental contamination and public health damages, with settlement costs reaching billions of dollars. Additionally, they must invest in research and development to create more sustainable and less harmful alternatives while meeting the growing demands of consumers and governments for safer chemicals.

The total number of companies involved in manufacturing or using PFAS could be hundreds when considering smaller producers, formulators, and suppliers worldwide.

The market represented by the commercialization of PFAS is negligible compared to the costs associated with their remediation, health consequences, and other impacts, which amount to nearly \$16 trillion annually.



Fluoro-polymer market share



<https://chemsec.org/reports/the-top-12-pfas-producers-in-the-world-and-the-staggering-societal-costs-of-pfas-pollution/>
<https://www.medicities.fr/breve/lyon/2024/06/18/pfas-le-pollueur-daikin-de-nouveau-devant-la-justice/>



Regulatory and certification bodies / Research institutes and universities / Trade associations and environmental organisations

With growing concerns about the toxicity and persistence of PFAS in the environment, various players are having an impact across the value chain

- Overseeing, controlling and limiting their use
- Developing methods to replace, detect and eliminates PFASs
- Informing the public, putting pressure on regulators and encouraging research into alternatives to PFASs

A market at the heart of today's events and multiple tensions

This market is led by the following drivers, which are subject to numerous fluctuations because of the associated challenges and tensions

Public health request

Public health concerns over PFAS are rising as research reveals the health risks these chemicals pose. Communities exposed to contaminated water, air, and soil are calling for urgent action, demanding stricter regulations on PFAS production and faster cleanups. Advocacy groups are also pushing for stronger accountability from industries and governments.

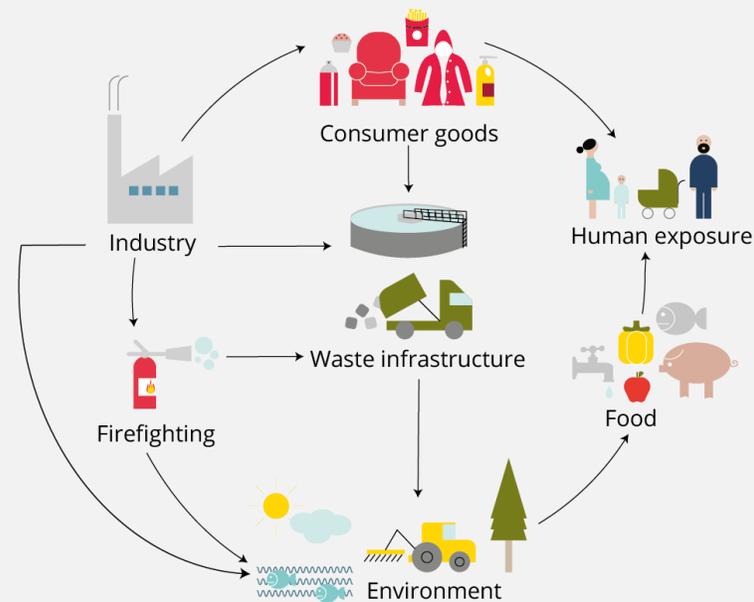
As lawsuits against PFAS manufacturers increase, governments face mounting pressure to enforce stricter limits in drinking water and require full disclosure of PFAS use. Currently, EFSA, the EU's food authority, considers that a maximum of 0.7 nanograms per kilogram of body weight per day is tolerable for health reasons - a threshold that is unfortunately exceeded by significant portions of the European population.

Intensifying monitoring

Monitoring activities are intensifying in Europe, there are almost 21,500 places worldwide where industrial activity is documented as both using and emitting PFAS, and which are presumed to be contaminated. Concurrently, European and worldwide regulators, manufacturers, and various organizations have intensified their monitoring and testing efforts for PFAS in the environment and in human populations.

Market reshaping

Manufacturers reliant on PFAS face mounting financial and operational pressures due to rising costs of regulatory compliance, product reformulation, and legal liabilities. Transitioning away from PFAS involves expensive, time-consuming processes like research, testing, and retooling. Compliance with environmental regulations also demands significant investments in costly treatment technologies to reduce emissions and contamination. Despite the gradual phase-out of long-chain PFAS by major producers and regulations in the U.S., Japan, and Western Europe, new manufacturers, particularly in continental Asia, have started producing long-chain PFAS and their precursors, complicating global efforts.



If no action is taken, around 4.4 million tones of PFAS will be emitted into the European environment over the next thirty years.

European Chemicals Agency, ECHA

Source : Gillam, C., 'A worldwide public health threat', The Guardian, 2022, [link](https://www.rtbef.be/article/polluants-eternels-en-wallonie-et-a-bruxelles-decouvrez-la-carte-inedite-de-la-contamination-par-les-pfas-11281703)
<https://www.rtbef.be/article/polluants-eternels-en-wallonie-et-a-bruxelles-decouvrez-la-carte-inedite-de-la-contamination-par-les-pfas-11281703>

Regulatory context



The international and European context of PFAS-related pollution

Although incomplete, several international guidelines have been put in place worldwide.

- 2002** ● **First publication by the US Environmental Protection Agency** of a risk assessment on PFOA.

 *First evidence of PFOA's potential health effects (liver damage, immune system disruption, etc.), as well as its persistent and bioaccumulative nature.*
- 2009** ● **Registration of PFOS** under the Stockholm Convention

 ⇒ *PFOS is classified as a persistent organic pollutant (POP) by the Stockholm Convention, imposing international restrictions on its use.*
- 2012** ● **Publication of a major study:** “Serum Vaccine Antibody Concentrations in Children Exposed to Perfluorinated Compounds.”

 *Professor Philippe Grandjean, a specialist in environmental medicine, along with several other researchers, found that children exposed to higher levels of PFOA and PFOS had reduced antibody concentrations after being vaccinated against certain diseases.*
- 2012-2013** ● **The results of the largest epidemiological study in the world, conducted on 70,000 people** in West Virginia, have been made available as part of the DuPont Case in the United States.

 *This study, establishes a probable link between prolonged PFOA exposure and several health conditions: kidney cancer, testicular cancer, thyroid disorders, preeclampsia, high cholesterol, and ulcerative colitis. These findings had a major impact on raising awareness of PFAS dangers.*
- June 20, 2013** ● **PFOA was added to the list of Substances of Very High Concern (SVHC)** by the European Chemicals Agency (ECHA). It was classified as persistent, bioaccumulative, and toxic (PBT).


- May 19, 2016** ● **The U.S. health standard for PFOA and PFOS in drinking water came into effect**, applying across the **United States and its overseas military bases**.


- 2020** ● The **European Food Safety Authority (EFSA)** issued a scientific opinion setting a **tolerable weekly intake (TWI)** for humans. The limit was set at **4.4 ng per kilogram of body weight** for the combined exposure to **PFOA, PFOS, PFNA, and PFHxS**.

 ⇒ PFOA has been added to Annex A of the Stockholm Convention, banning its production and use.

⇒ The EU bans PFOA, its salts and its precursors through Regulation (EU) 2019/1021 on persistent organic pollutants.

https://chm.pops.int/Portals/0/sc10/files/a/stockholm_convention_text_f.pdf
<https://www.legifrance.gouv.fr/loda/id/JORFTEXT000000465574/>

The international and European context of PFAS-related pollution

Although incomplete, several international guidelines have been put in place worldwide.

June
2019



Regulation (EC) 850/2004, repealed by Regulation (EU) 2019/1021 of the European Parliament and of the Council of 20 June 2019, on 'POPs' (persistent organic pollutants) resulting from the Stockholm International Convention (2001) bans various compounds such as PFOS and its derivatives since 2009 and PFOA and its salts and related compounds since July 2020. **These provisions supersede the pre-existing provisions restricting them under REACH.**

December
2020



The monitoring of PFAS in drinking water was introduced by European Directive 2020/2184 of 16 December 2020 on the quality of water intended for human consumption (WIHC). To date, **a quality limit of 0.10 µg/L has been set for the sum of 20 PFAS in WIHC.** Another parameter, entitled 'PFAS (total)', has also been introduced, with an associated quality limit of 0.50 µg/L: its purpose is to include all the PFAS that can be measured in water.

⇒The new European standard will come into effect from January 2026

⇒The **EU expands PFAS restrictions**, reinforcing monitoring under the **Water Framework Directive to prevent PFAS contamination of water resources.**

January
2021



The Drinking Water Directive (DWD) aims to protect people and the environment from the harmful effects of contaminated drinking water and to improve access to drinking water. The directive introduces minimum requirements for materials that are in contact with water meant for human consumption throughout the EU.

PFHxS was added on 23 June 2022 to the European regulation on persistent organic pollutants (POPs - Annex IV on waste treatment) and thresholds are modified.

June
2022



⇒A ban on the production and use of PFHxS is expected, following the publication in the OJEU on 27 June 2022 of the EU Decision of 7 April 2022. Une limite de concentration dans les déchets fixée à 1 mg.kg-1 pour le PFHxS et ses sels et à 40 mg.kg-1 pour la somme des composés apparentés au PFHxS.

⇒A concentration limit in waste set at 1 mg.kg-1 for PFOA and its salts and 40 mg.kg-1 for the sum of 'PFOA-related compounds';

The international and European context of PFAS-related pollution

Although incomplete, several international guidelines have been put in place worldwide.

2023



A **Europe-wide PFAS restriction**, proposed by **Sweden, Norway, Denmark, the Netherlands, and Germany** in **January 2023**, is under review by **ECHA**. It seeks to ban **PFAS production and sales** due to their persistence, with **time-limited exemptions** for certain uses.

Since 1 January 2023, **four PFAS have been regulated in certain foodstuffs of animal origin** (fish, molluscs, crustaceans, eggs, meat and offal of slaughter animals, poultry and game) when these foodstuffs are placed on the market (Regulation (EU) 2023/915): in the event of non-compliance, the products may not be offered for sale.

2024



Environmental Protection Agency (EPA) announced legally enforceable **Maximum Contaminant Levels (MCLs) for six PFAS in drinking water** in April. Two common contaminants, PFOA and PFOS, are limited to 4 parts per trillion (ppt), while PFHxS, PFNA, and HFPO-DA are limited to 10 ppt.



Introduction of Regulation 2024/2462 prohibiting the manufacture, placing on the market and use of perfluorohexanoic acid (PFHxA), its salts and related substances was notified on 19 September 2024 with a view to a ban in October 2024.

2025



Regulation (EU) 2025/40 of the European Parliament and of the Council of 19 December 2024 on packaging and packaging waste, amending Regulation (EU) 2019/1020 and Directive (EU) 2019/904, and repealing Directive 94/62/EC

Depending on the level of collective awareness and needs, specific measures tend to appear in several countries



France acts as a pioneer settling regulations. First in 2020 transposing the European Drinking Water Directive of 2020 into national law, setting quality limits for 20 PFAS. Since 2023, the sum of the 20 regulated PFAS must not exceed the quality limit of 0.1 micrograms per liter.

In February 2025, France adopted a law to ban cosmetics, clothing, footwear and ski wax containing PFAS starting in 2026. By 2030, all textiles containing PFAS will be banned. Drinking water monitoring, a map of PFAS-emitting sites and a polluter-pays tax are also planned.



In Germany, [Guidelines for PFAS assessment – Recommendations for the uniform nationwide assessment of soil and water contamination and for the disposal of soil material containing PFAS](#) were published in 2022.



Denmark and the Netherlands have banned the use of PFAS in food packaging. Denmark and Norway have also banned PFAS in fire-fighting foams.



The U.S. Environmental Protection Agency's (USEPA) [Drinking Water Treatability Database](#) provides an overview of effective technologies for reducing PFAS in drinking water and includes activated carbon adsorption, ion exchange resins and high-pressure membranes, such as nanofiltration or reverse osmosis.

In April 2024, the EPA issued updated [interim guidance on the destruction and disposal of PFAS-containing materials](#), building on earlier guidance dating from 2020, which adds to Guidance on Destroying and Disposing of PFAS.

9 billion USD in funding has been allocated to address PFAS and other emerging contaminants in drinking water through President Biden's Bipartisan Infrastructure Law.



In 2022, Ramboll prepared [guidelines for the investigation and remediation of contamination by per- and polyfluoroalkyl substances \(PFAS\)](#) on behalf of the Danish regions. The aim of these guidelines is to share knowledge on the challenges associated with PFAS.

Denmark has allocated **54 million euros to a national action plan** to prevent, contain and clean up PFAS contamination throughout the country. In 2024, the Danish Environmental Protection Agency will launch [eight projects to improve understanding of PFAS risks and contamination](#).

<https://eeb.org/wp-content/uploads/2023/10/PFAS-in-drinking-water-briefing-final-1.pdf>
<https://zeropm.eu/regulatory-watch/>

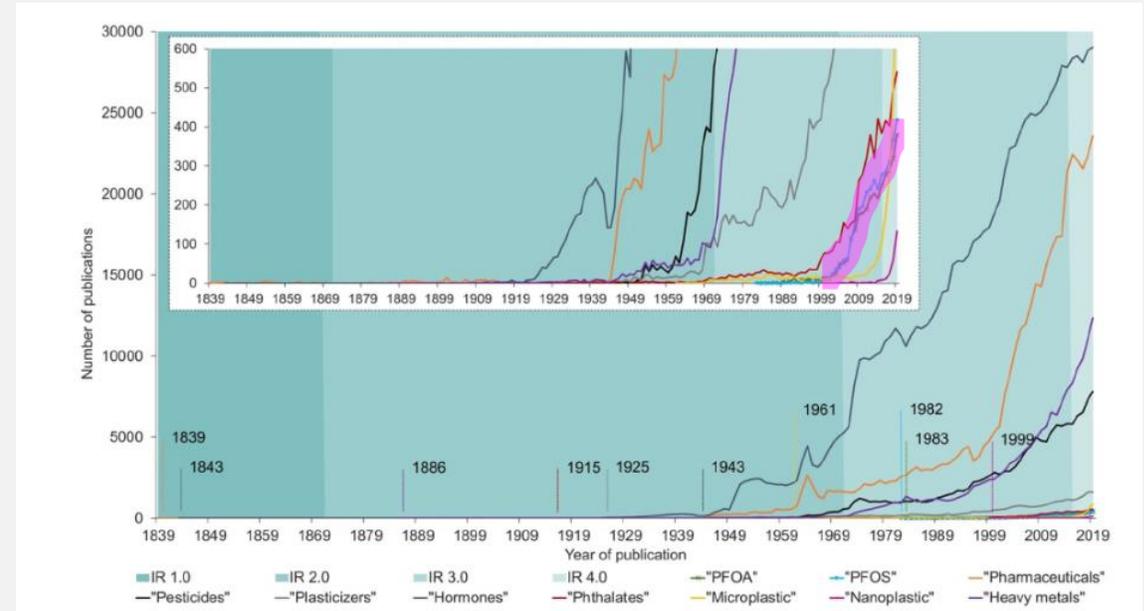
Current standards are still the main driving force behind the treatment of contaminated water

The introduction of regulations on PFAS is the main lever for limiting their emissions and implementing treatments.

Regulations and public pressure act as powerful catalysts for the research and development of solutions aimed at treating PFAS and limiting their impact. These two factors create an environment conducive to innovation by imposing constraints on industries while encouraging collaboration between researchers, governments and companies.

While the regulation of these compounds has encouraged the search for solutions, the opposite effect means that few resources are devoted to the treatment of other PFAS.

It is therefore important to introduce more restrictions on a large number of PFASs as they impose strict standards and high expectations, forcing industrial and scientific players to work together to develop alternative technologies, pollution control processes and long-term sustainable solutions.



Number of studies on various contaminants from 1839 to 2019. Highlighted in pink are the curves for PFOA and PFOS. [Anses](#)



Trifluoroacetic acid (TFA) is a **highly persistent, water-soluble, and mobile PFAS** that does not degrade in nature. It is widely used as a product, byproduct or degradation product of various fluorinated chemicals, including refrigerants, pharmaceuticals, and pesticides. TFA is also a key industrial solvent used in organic synthesis and the production of fluoropolymers.

Findings from the Pesticide Action Network (PAN) Europe Study

Pesticide Action Network (PAN) Europe is a science-based organization who provides analyses, reports and court cases influencing EU policies and helping to protect health and biodiversity. They analyzed several types of water across Europe for the presence of TFA which **showed alarming levels of contamination by the forever chemical TFA (trifluoroacetic acid)**.

A total of 23 surface water samples and 6 groundwater samples were collected and sent to the Water Technology Centre in Karlsruhe for analysis.

- The survey showed that TFA was present in all water samples, with concentrations ranging from 370 ng/l to 3,300 ng/l. The average TFA concentration across all samples was 1,180 ng/l.
- In surface water, the average concentration was slightly higher at 1,220 ng/l compared to groundwater samples, where it was 1,025 ng/l.
- The three most contaminated surface waters among the measurements carried out are the Elbe (DE): 3,3µg/L, Seine (FR): 2,9µg/L and Meuse (BE): 2,5µg/L.

36 tap waters and 19 bottled mineral waters were also tested:

- TFA was detected in 34 of 36 European tap water samples (94 %) from eleven EU countries and in 12 of 19 bottled mineral and spring waters (63 %).
- TFA values in tap water ranged from "undetectable" (corresponding to below the detection limit of 20 ng/L to 4,100 ng/L, with an average of 740 ng/L).
- TFA values in mineral and spring waters ranged from "undetectable" (below the detection limit of 20 ng/L) to 3,200 ng/L, with an average of 278 ng/L.

TFA Dominance Among PFAS

Analysis of 24 additional PFAS in 4 mixed samples confirms that, beyond contamination hotspots, TFA is the dominant (> 98 %) PFAS contamination in the water, indicating its dominance as a PFAS pollutant.

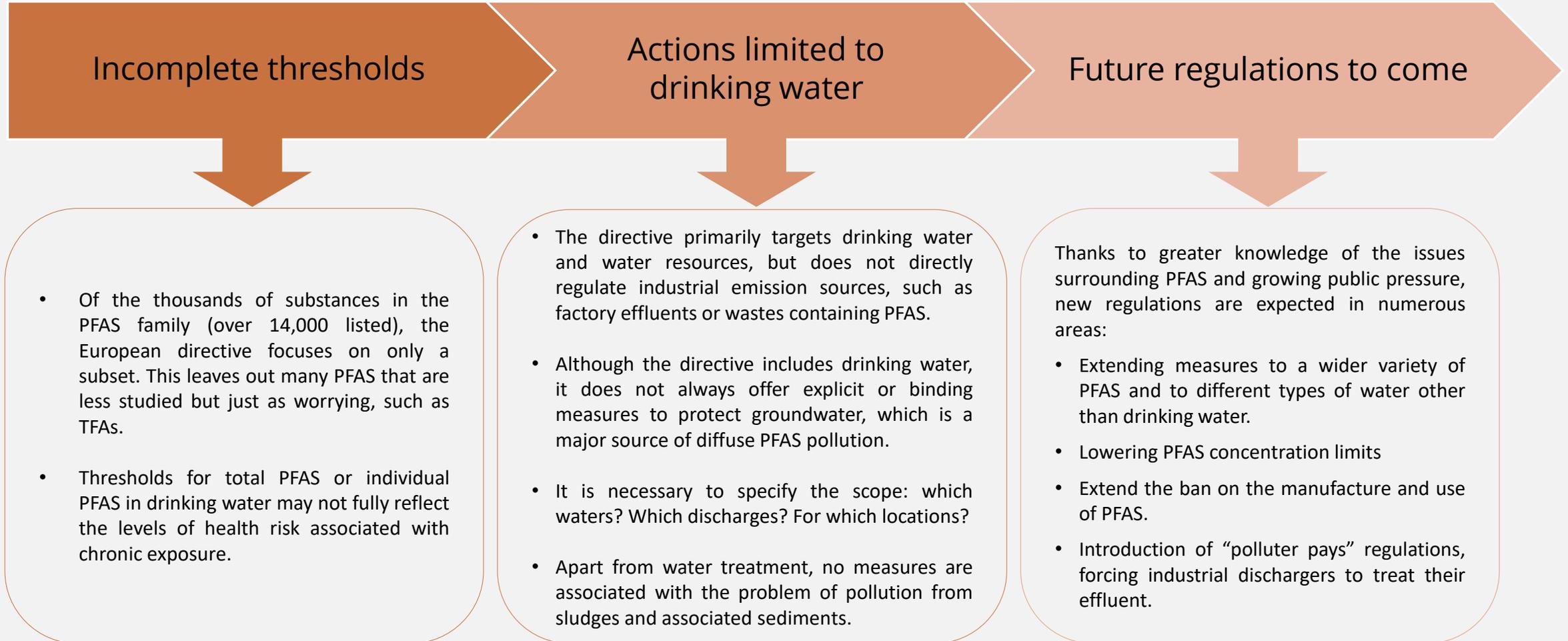
Regulatory Gap & Urgent Need for Action

Despite its widespread presence and persistence, TFA remains unregulated in surface water, groundwater, and drinking water in the EU. Its ability to penetrate deep groundwater reserves raises concerns about long-term water safety and potential health risks. Given the increasing evidence of TFA pollution, urgent regulatory action is needed to establish legal limits and develop efficient removal technologies to protect drinking water sources.

<https://www.pan-europe.info/resources/briefings/2024/12/tfa-%E2%80%98forever-chemical%E2%80%99-european-mineral-waters>

<https://www.generations-futures.fr/wp-content/uploads/2024/05/tfa-mai-2024-v>

Current regulations are still in their early stages but are set to become more stringent in the future.



Methods for analyzing and treating PFAS



The operational processing of PFAS can be separated into 3 stages with complementary purposes:





Overview and key issues of the analysis stage

Currently, **no standardized, universally accepted method for PFAS measurement exists**, leading to **inconsistencies in detection and regulation**. While only few accredited laboratories exist across Europe and internationally, yet they **follow different methodologies**, making cross-comparisons difficult.

⇒ **A standardized approach to PFAS analysis is urgently needed across the EU and globally** to ensure data comparability, regulatory enforcement, and effective cross-border pollution monitoring.

Analytical Limitations and Detection Challenges	Regulatory Gaps: The Missing Link Between Science and Policy	The Financial and Industrial Barriers to Widespread PFAS Monitoring	Linking Measurement Gaps to Treatment and Remediation
<p>PFAS should be monitored even at ultra-low concentrations (ng/L or ppt levels) due to their toxicity but many current detection methods struggle to detect them in particular because of a lack of knowledge of the molecules to be monitored.</p> <p>Thus, conventional targeted analysis, often focus on a restricted list of PFAS, leading to underestimation of contamination.</p>	<p>Current PFAS regulations often focus on the limited number of regulated compounds, ignoring their transformation products. For example, polyfluorinated precursors can degrade into perfluorinated compounds, but many of these end-products remain unregulated.</p> <p>Regulations are evolving slowly, which means that research into new analytical methods is receiving very little support. They therefore remain limited.</p>	<p>Developing highly sensitive and standardized PFAS monitoring methods requires significant investment, and many industries resist stricter monitoring due to cost concerns.</p> <p>Without financial incentives or public-private collaborations, large-scale monitoring remains limited to regulatory purposes and very contaminated hotspots treatment.</p>	<p>PFAS measurement is not just about monitoring pollution, it is critical for guiding treatment technologies.</p> <p>However, current testing methods do not always provide real-time data, making it difficult to assess the efficiency of remediation solutions.</p>

Addressing PFAS pollution requires standardized, high-sensitivity detection methods that are **scientifically** robust, economically viable, and aligned with regulations. Investment in advanced analytical technologies, regulatory integration, and industrial cooperation is essential to build a comprehensive, enforceable PFAS monitoring system.



Existing analysis methods are based on imperfect methods that are not up to the challenge of PFAS issues. These methods can be categorized as screening and targeted ones.

Screening methods: global or indirect approaches that measure the total presence of PFAS or groups of compounds.

- No specific identification of compounds : cannot answer to a “sum of PFAS”
- Sensitivity in the µg/L range
- Hardly compatible with drinking water concentration levels but operational in all other cases

Adsorbable Organic Fluor (AOF)

Combustion (hydropyrolysis) coupled with ion chromatography. Extraction of a large number of molecules adsorbable on activated carbon. Technically mastered, results usable and representative (with exclusion of ultra short chain PFAS) but robustness should be improved for complex matrices

Extractible Organic Fluor (EOF)

Combustion (hydropyrolysis) coupled with ion chromatography. Polymeric extraction with weak anion exchange. Technically mastered method.

Total Fluor (TF)

Combustion (hydropyrolysis) coupled with ion chromatography.
Extraction of all inorganic and organic fluorinated compounds (not just PFAS).

Total Oxidizable Precursors (TOP)

Oxidation of PFAS precursors to perfluorinated carboxylates (PFCA), then analysis by liquid chromatography-mass spectrometry.
Represents the potential of PFAS to form PFCA (the actual substances present are unknown).

Targeted methods

- Sensitivity in ng/L range

Individual PFAS determination

Liquid chromatography/mass spectrometry (LC-MS/MS)

Need for an analytical standard (costly). Some 150 currently in development.

Currently, EN 17892:2024 is the latest European standard regulating PFAS analysis in water using LC-MS/MS.

While other national and international methods exist, this standard aims to harmonize PFAS detection across the EU.



PFAS remediation technologies

Several treatment technologies are available for removing PFAS from contaminated water, but each has limitations and challenges.



ADSORPTIVE TECHNOLOGIES

Adsorption is a **mature and widely used** PFAS remediation method due to its **effectiveness and ease of operation**. It includes **activated carbon** and **ion exchange resins**, which capture and concentrate PFAS. Spent materials require **disposal via landfilling or incineration** but can also be **reactivated for reuse**.

OXYDATION TECHNOLOGIES

Advanced Oxidation Processes (AOPs), such as ozone/hydrogen peroxide, UV/hydrogen peroxide, and Fenton's reagent, produce **highly reactive hydroxyl radicals** that break down PFAS molecules. **Electrochemical oxidation** applies an **electric current** to generate **reactive species** that oxidize PFAS contaminants. These methods offer the **potential for complete PFAS degradation**, converting them into **less harmful substances**. However, they require precise reaction control, are energy-intensive, and involve high operational costs.

SEPARATIVE TECHNOLOGIES

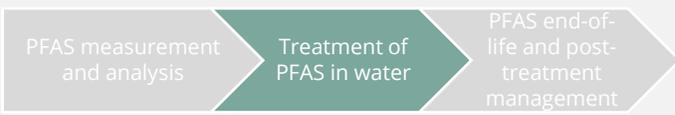
Reverse osmosis (RO), nanofiltration (NF), and ultrafiltration (UF) use **semi-permeable membranes** to physically separate **PFAS from water** based on **size and charge**. These methods are **highly effective** but can be **energy-intensive**, require **regular maintenance** due to **membrane fouling** and imply **complex management of the waste generated**.

EMERGING TECHNOLOGIES

Emerging technologies for PFAS remediation focus on innovative approaches such as **bioremediation**, using microbes or enzymes to break down PFAS, and **photolytic degradation**, where UV or visible light aids in PFAS destruction. Research is also exploring **nanotechnology** and new materials like engineered biochar and catalytic adsorbents that can both capture and degrade PFAS. Though still experimental, these methods offer promising, sustainable solutions to address the challenges of PFAS contamination more effectively.

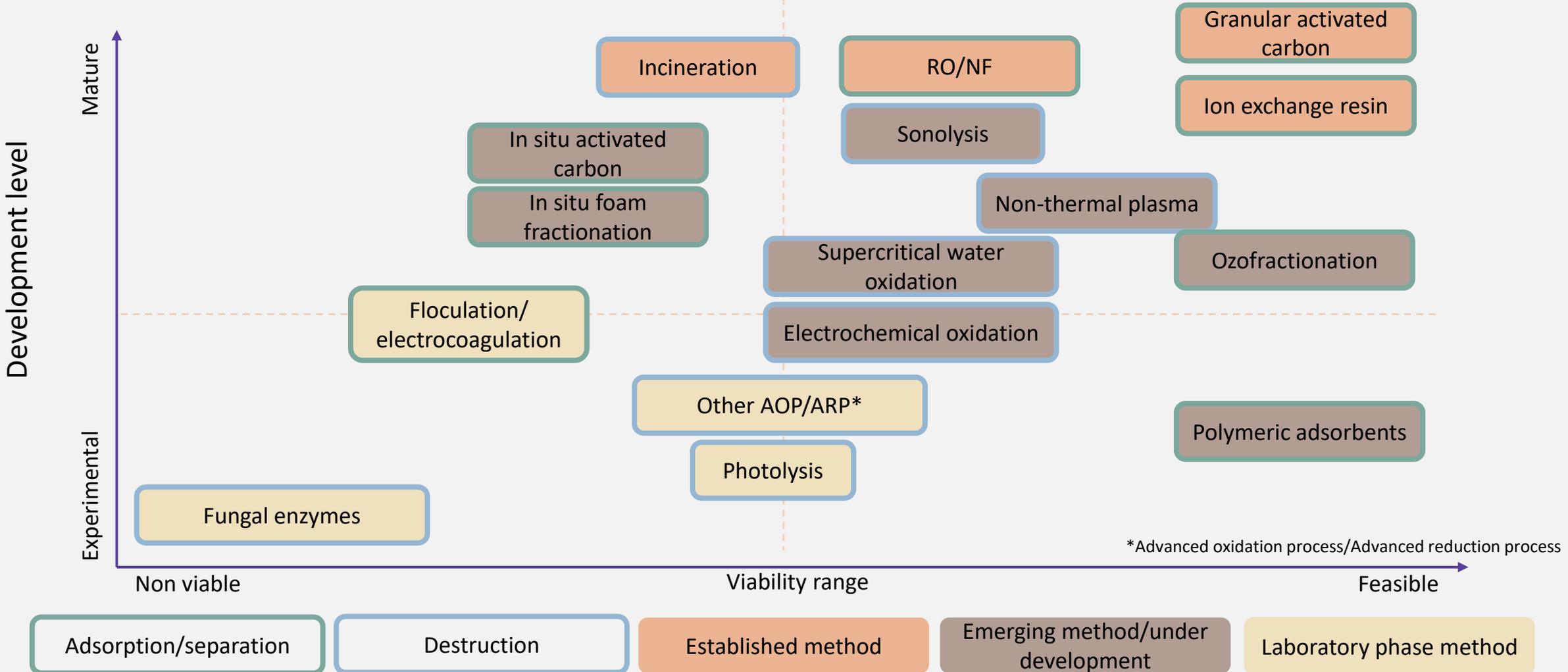
- Current technologies primarily focus on **PFAS removal rather than destruction**, which creates challenges in **managing and disposing of PFAS waste**. **Incineration remains the only mature destruction method**, but concerns persist about potential atmospheric emissions and incomplete PFAS breakdown during combustion.
- Advanced oxidation and emerging technologies show promise for effective PFAS degradation, yet they still require further research, optimization, and large-scale validation.
- A **hybrid approach combining multiple treatment methods** may be necessary to achieve efficient and sustainable PFAS remediation, ensuring both **removal from contaminated water and ultimate destruction** of PFAS compounds.

https://pfas-1.itrcweb.org/wp-content/uploads/2020/10/treatment_tech_508_Aug-2020-Final.pdf
<https://www.actu-environnement.com/ae/news/pfas-detection-elimination-air-eau-icpe-charbons-membranes-45240.php4>



Overview of existing treatment methods

Despite the prevalence of 3 industrialized treatment methods, various other technologies are currently being developed.



Source : Ross, I. et al.(2018). A review of emerging technologies for remediation of PFASs. *Remediation Journal*, 28(2), 101-126

Selecting an appropriate PFAS treatment solution requires a comprehensive assessment of several critical factors to ensure optimal performance and long-term sustainability.

CHARACTERISTICS OF WATER TO BE TREATED

- **Chemical Composition of PFAS:**
 - Identify the **specific PFAS compounds** present, as different types require different treatment approaches.
 - Consider **classification factors**, such as:
 - **Chemical structure** (linear vs. branched PFAS) and **charge** (zwitterionic, cationic, anionic).
 - **Chain length** (short-chain vs. long-chain PFAS, as short-chain compounds are harder to remove).
 - **Solubility and mobility** in water, adsorption on the soil, influencing treatment selection.
- **PFAS Concentration Levels:**
 - Measure **initial PFAS concentration** in water, typically expressed in **nanograms per liter (ng/L) or micrograms per liter (µg/L)**.
 - Higher concentrations may require **more intensive or multi-stage treatment processes**.
- **Overall Water Quality:**
 - Assess **other water parameters** that may impact treatment efficiency, such as:
 - **pH levels**, which influence adsorption and oxidation processes.
 - **Turbidity**, as high particulate levels can reduce treatment effectiveness.
 - **Organic matter concentration and conductivity of water**, which can interfere with adsorption and filtration.
 - **Presence of co-contaminants**, which may require pre-treatment steps.

TREATMENT SYSTEM CAPACITY AND SIZING

- **Flow Rate Requirements:**
 - Define the **volume of water to be treated daily (m³/day)**.
 - High flow rates require **robust and scalable treatment systems**.
- **Existing Infrastructure and Performance:**
 - Evaluate the **current treatment technologies in place** and their effectiveness in removing PFAS.
 - Identify **operational limitations** and whether upgrades or complementary technologies are needed.
- **Treatment Capacity Planning:**
 - Calculate the **facility's current and future capacity** to ensure it meets **regulatory compliance and long-term operational demands**.
 - Plan for **scalability** in response to evolving PFAS regulations and contamination levels.
- **Contact Time Optimization:**
 - Adjust the **contact time between water and treatment media** (e.g., **activated carbon, ion exchange resins**) to **maximize PFAS removal efficiency**.
 - Shorter contact times may reduce efficiency, while longer times may **increase operational costs**.
- **Remediation yield**, depending on it, it's possible to choose primary, secondary or tertiary technologies.

Finding an efficient PFAS treatment solution is complex, requiring a tailored, multi-technology approach to address contamination levels, water composition, and operational constraints, while ensuring long-term effectiveness and regulatory compliance.



PFAS remediation technologies

The 3 main treatment methods are associated with their own specificities, constraints and limitations.

	Granular Activated Carbon (GAC)	Ion exchange resins	Reverse osmosis
Affinity	<ul style="list-style-type: none"> Long-chain PFAS Not very specific (broad spectrum) Less effective on carboxylates than sulfonics 	<ul style="list-style-type: none"> Medium/short chain PFAS Highly specific Very good retention 	<ul style="list-style-type: none"> All types of PFAS covered Very short and non-ionized PFAS might show less than 100 % removal
Water type	<ul style="list-style-type: none"> Treated wastewater, drinking water, groundwater, landfill leachate High/low concentrations 	<ul style="list-style-type: none"> Drinking water, groundwater (or pre-treatment required if wastewater) High/low flows High/low concentrations <p><i>Note: drinking water treatment not yet authorized</i></p>	<ul style="list-style-type: none"> Wastewater, drinking water, groundwater Storage leachates highly contaminated with PFAS High/low flow rates High concentrations
Technical constraints	<ul style="list-style-type: none"> Sizing required for high flow rates Low flow rates (to maximize contact time to EBCT > 20 min) Risk of clogging 	<ul style="list-style-type: none"> Risk of clogging depending on conditions (sensitive to suspended solids, TOC, etc.) 	<ul style="list-style-type: none"> Risk of clogging depending on conditions (sensitive to high levels of fluoride, chloride, salts, suspended solids, etc.). High volume of brine stream
Preferential process step	<ul style="list-style-type: none"> End of process to achieve low concentrations 	<ul style="list-style-type: none"> End of process 	<ul style="list-style-type: none"> End of process
End of life	<ul style="list-style-type: none"> Incineration Regeneration/reactivation if non-POP waste (preliminary desorption) 	<ul style="list-style-type: none"> Regeneration with potential to cause environmental concerns during disposal 	<ul style="list-style-type: none"> Concentrate incineration as hazardous waste Permeate discharge into the natural environment



Risks and main challenges

The 3 main treatment methods are associated with their own risks and challenges

Granular Activated Carbon



Limited effectiveness:

Despite their proven effectiveness on long-chain PFAS, activated carbons are not effective on all short-chain PFAS, particularly TFA.



Infrastructure costs:

- Setting up new production facilities or expanding existing capacity requires heavy investment in infrastructure and equipment, particularly for processes such as thermal activation, which are very energy-intensive.
- The production process involves carbonization and activation, which can emit pollutants. Stricter environmental regulations are forcing producers to invest in cleaner technologies and emission control systems, which can lead to higher operating costs.
- The activation process, particularly thermal activation, consumes a lot of energy. Rising energy costs and the desire to adopt sustainable practices are forcing producers to look for more energy-efficient methods or alternative activation techniques.



Activated carbon regeneration:

- With increasing demand for sustainable solutions, producers also need to invest in regeneration facilities to extend the life of activated carbon and meet the requirements of a circular economy.
- Most of the virgin activated carbon used in Europe comes from China. This dependence generates risks linked to export regulations, geopolitical tensions and fluctuations in raw material prices. European companies may need to diversify their sources of supply or increase their stocks to mitigate these risks. Shortages of raw materials can already affect the availability of finished products.



Risks and main challenges

The 3 main treatment methods are associated with their own risks and challenges

Ion exchange resins



Limited effectiveness:

While ion exchange resins are highly effective in removing both long-chain and some short-chain PFAS, their efficiency can be compromised in the presence of competing ions, such as sulfate, chloride, or natural organic matter. Additionally, TFA and ultra-short-chain PFAS may not be effectively captured, limiting their application in certain contaminated waters.



Infrastructure costs:

- Establishing new resin production facilities or expanding existing ones requires significant capital investment in infrastructure and equipment.
- The manufacturing process involves complex chemical synthesis, often requiring strict environmental controls due to the use of solvents and reagents.
- Resin production is energy-intensive, particularly for polymeric materials that require controlled polymerization and crosslinking.
- Increasing energy costs and sustainability requirements are driving the industry to explore more energy-efficient production techniques.



Ion Exchange Resin Regeneration and Disposal:

- Used resins containing concentrated PFAS must be properly managed, either through thermal destruction, incineration, or specialized chemical treatments to prevent secondary contamination.
- Regulatory pressure on PFAS waste management is forcing companies to adopt circular economy approaches, but cost-effective regeneration processes are still under development.
- The industry is dependent on specific raw materials, including styrene and divinylbenzene, which are subject to price fluctuations and supply chain disruptions. The European market heavily depends on resin imports, particularly from Asia and North America.



Risks and main challenges

The 3 main treatment methods are associated with their own risks and challenges

Reverse Osmosis (RO)



Limited effectiveness:

While reverse osmosis (RO) is one of the most effective methods for removing PFAS, including short-chain compounds, it does not destroy PFAS—it concentrates them into a reject stream (brine), which requires further treatment or disposal. Managing this PFAS-rich waste is a major challenge and limits the sustainability of the process.



Infrastructure costs:

- Installing RO treatment systems requires significant capital investment, especially for large-scale municipal or industrial applications.
- Upgrading existing water treatment facilities to integrate RO technology can be complex and costly, requiring specialized infrastructure for membrane systems and high-pressure pumps.
- Regulatory requirements for PFAS disposal add to operational costs, particularly for handling brine concentrates that contain high levels of PFAS.
- RO is highly energy-intensive, as it relies on high-pressure pumps to force water through membranes.
- Rising energy costs and increasing sustainability regulations are pushing industries to seek more energy-efficient membrane technologies, but improvements are still limited.
- Membrane fouling and scaling (caused by organic matter, biofilm, and mineral deposits) reduce efficiency and increase maintenance frequency and costs.



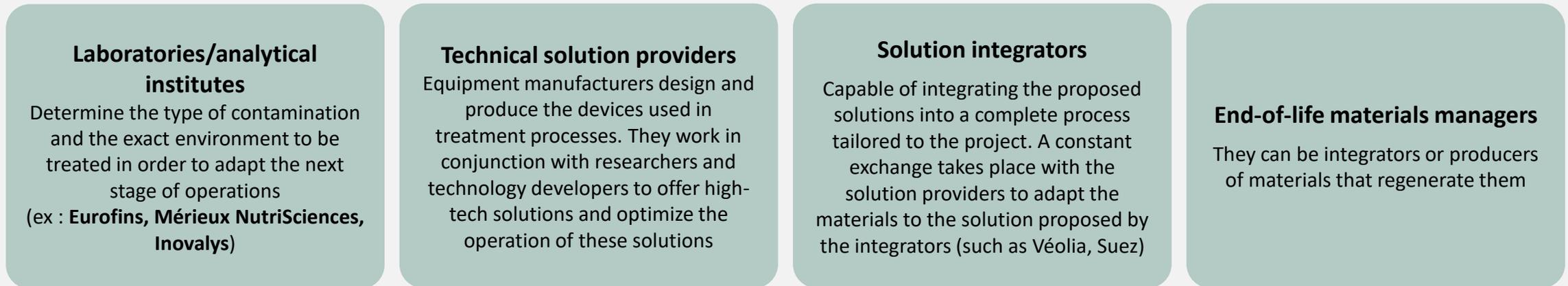
Supply Chain and Material Dependency:

- RO membranes and system components depend on specialized polymeric materials (such as polyamide thin-film composites), which are subject to global supply chain fluctuations.
- Dependence on key manufacturers in Asia and North America makes the sector vulnerable to trade restrictions, raw material shortages, and geopolitical risks.



The operational reality of treatment methods

A process chain organized to provide suitable treatment infrastructures



When a potential project is identified, a preliminary technico-economic feasibility study is carried out: this is a methodological protocol for arriving at the combination best suited to the challenges of the water to be treated. This is carried out by players such as HPC International.

Some stakeholders are exploring **innovative techniques that remain in the research phase or have yet to be widely implemented**. Despite promising technologies, they often remain expensive. These economic constraints combined with a lack of regulations, provide little incentive for industries to invest.

For the treatment stage, one of the biggest challenges is the adsorption/destruction of short-chain PFASs, which are not well treated today, but are found in very high concentrations in the environment. Current industrial solutions are not yet capable of handling them.

Feedback from the interviews has enabled us to draw up a complete operational picture of the reality of the implementation of solutions

Water treatment complexity

- Water treatment is a complex process that requires **action on a variety of parameters and the capacity to handle a large number of inputs**. A treatment solution must therefore be adapted for use on a variety of matrices, but also **in continuity with other technologies** having different functions.
- One technology is not sufficient on its own; it will often be used in combination with others (the combinations are almost infinite depending on the configurations).
- In the case of PFAS, this treatment complexity is also present, with the **need to combine adsorption and destruction technologies**.

Implementation of PFAS treatment solutions

- Interviews with public water agencies have shown that few treatment solutions dedicated to PFAS are currently being implemented in existing treatment chains. Because of important associated costs, **treatment solutions will not be implemented before regulations exist**.
- Except in areas immediately concerned by PFAS management (hotspots, exposed and publicly exposed sites), conventional water treatment management involves using activated carbons or diluting the contaminated water to lower the concentration of toxic compounds. If it is too complex or costly to implement one of these solutions, stopping the operation of certain sources is also a solution.

Limits associated with regulations

- Solutions are still not widely used, mainly because **regulations are only introduced for drinking water**, which is not the most affected water by PFAS contamination.
- In the case of spot checks on wastewater and industrial water, even if PFAS levels are above the legal threshold, **no one is obliged to set up costly treatment processes**, which are costly.
- Future regulations will be problematic because, to date, water treatment solutions are only partially capable of treating PFAS.
- **TFA, which is at the heart of the public debate, is a major source of concern, as none of the treatment solutions can handle it.**



The methods used to treat PFAS are not without impact

The fate of post-treatment waste represents a major health and environmental challenge. These issues are also closely linked to the challenges and objectives to be met by manufacturers.

PFAS TREATED AS FINAL WASTE

Being extremely stable, PFAS are very difficult to degrade. The industrial solutions currently in use will either adsorb or separate PFAS, which means that the adsorbents or concentrates will have to be treated in all cases. **Incineration is currently the only method of destruction used.** The complete destruction of PFAS requires very high temperatures, often between 1000°C and 1400°C as used for other hazardous waste streams.

ISSUES ASSOCIATED WITH INCINERATION

When PFAS are incinerated, there is a **risk of the formation of toxic by-products**, such as inorganic fluorides and fluorinated dioxins, which can be **harmful to human health and the environment**. Moreover, incineration may be associated with TFA emissions to the air.

There is a **need to analyze emissions and consequently to develop methods for measuring PFAS in atmospheric discharges**, which are still emerging.

REGENERATIVE SOLUTIONS IN STUDY

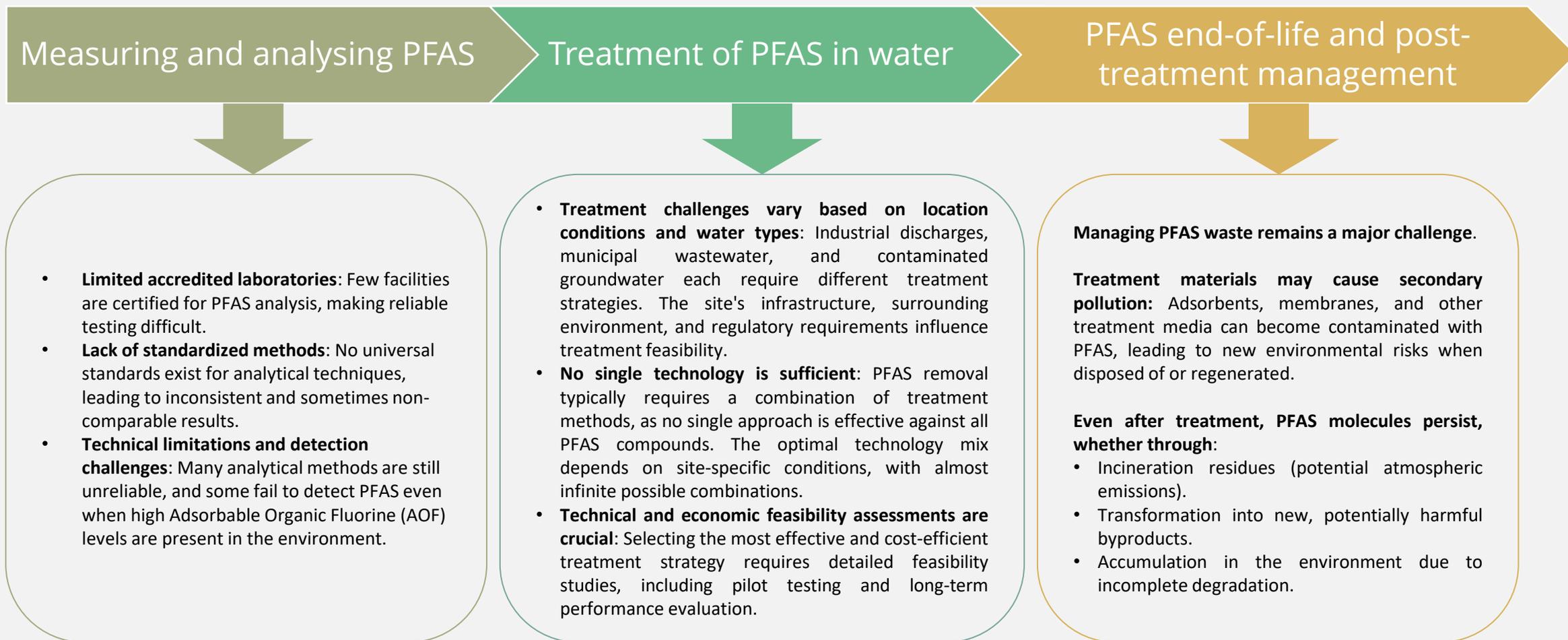
There are circularity issues associated with adsorbent materials. Some players are seeking to develop new solutions to enable their sorbents to be regenerated.

However, this approach remains complex and is not always adapted to the different sorbents. In the case of activated carbon, **POP regulations** hinder its recovery, since **above a certain PFAS content, it can no longer be regenerated.**



Key points regarding analyzing and treatment methods

Challenges exist at every stage of the PFAS value chain, influencing the choice of treatment solutions and their effectiveness.



Synthesis



What are the dynamics influencing demand for PFAS treatment technologies?

MARKET DRIVERS

- ✓ **Increasing Regulatory Pressure:** Stricter environmental regulations worldwide are major drivers. Governments are setting limits for PFAS concentrations in waters and soils, pushing industries to adopt effective treatment technologies to comply with these rules.
- ✓ **Rising Awareness of PFAS Health Risks:** Public health concerns about PFAS exposure, linked to diseases like cancer, immune system issues, and developmental problems, are driving the demand for remediation technologies. As communities push for cleaner environments, both public and private sectors face growing pressure to address contamination.
- ✓ **Litigation and Legal Liabilities:** The increase in lawsuits related to PFAS contamination, where companies are held responsible for environmental damage and public health risks, is forcing industries to adopt remediation technologies to mitigate potential legal costs and environmental and individual damages.

MARKET OPPORTUNITIES

- ✓ **Market expansion:** The growing number of locations significant market expansion opportunity for remediation and water treatment technologies.
- ✓ **Collaborations and partnerships:** collaborations between technology providers, research institutes and government agencies can accelerate the development and adoption of effective PFAS remediation solutions.
- ✓ **Innovation in Destructive Technologies:** Technologies that not only capture but destroy PFAS are becoming a significant area of opportunity, more sustainable in the long term.
- ✓ **Growing Demand in Emerging Markets:** Regions like Asia-Pacific, Latin America, and parts of Africa are becoming more aware of PFAS contamination, presenting a growing market for remediation solutions.

MARKET CONSTRAINTS

- ✓ **High costs:** The cost of PFAS remediation technologies can be significant, slowing down their adoption, particularly for small businesses or municipalities.
- ✓ **Limited standardization:** the lack of standardized regulations and guidelines for cleaning up PFAS can create uncertainty and hamper market growth.
- ✓ **Responsibility:** difficulty in identifying who is responsible for site pollution and therefore who should pay for remediation.
- ✓ **Waste Management After Capture:** Non-destructive technologies like adsorption or filtration merely capture PFAS, leaving the problem of safely disposing of or further treating the concentrated waste.
- ✓ **Ensuring the Safe and Effective Destruction of PFAS:** Even for emerging technologies capable of destroying PFAS, it will be essential to assess potential risks and ensure their effectiveness to prevent the formation of new PFAS compounds that could be even more hazardous.

USA:
The largest market for PFAS remediation, driven by stringent regulations and high awareness of PFAS contamination.

North America
The North American market is dominated by filtration technologies such as activated carbon and reverse osmosis, but demand for destructive solutions is soaring due to regulatory pressure.

South America
Few PFAS regulations implemented but is beginning to feel the impact of PFAS pollution in some industries. Brazil and Mexico are gradually recognizing the need to treat industrial wastewater, with some pilot projects underway.

Europe:
Key market, driven by EU's REACH regulation, strictly limits PFAS use and production. European governments actively fund research on PFAS destruction technologies while pushing for broader bans in consumer products, driving demand for sustainable alternatives in water and soil treatment.

Japan-South Korea :
strict regulations and actively invest in PFAS treatment technologies, similar to those in the U.S. and Europe.

China :
One of the largest PFAS producers, regulations are newer and less strict, though environmental awareness is growing. As both a major producer and user of PFAS, China has a rising demand for treatment technologies while continuing to supply global markets.

Africa :
Efforts remain limited, but initiatives are beginning to emerge, particularly in urban areas where wastewater management is a growing challenge.



How Much Will It Cost to Remove PFAS from Contaminated Sites Before They Reach Drinking Water, Food, and Ultimately, Our Bodies?

It is estimated that **in Europe alone, the cost of PFAS decontamination could range from €95 billion to over €2,000 billion over 20 years**, depending on the scenario. This translates to €100 billion per year "in perpetuity" in the worst-case scenario.

Scenario 1: The Lower Estimate ("Legacy Scenario")

If **all PFAS emissions into the environment stopped tomorrow**, without any changes to **current regulations**, it would still cost **approximately €95 billion over two decades** to clean up existing PFAS contamination in Europe.

Important note: This scenario only considers the **remediation of historical PFAS contamination**, specifically **long-chain PFAS (6 to 12 carbon atoms)** such as **PFOS and PFOA**. These compounds, now **banned in Europe** (with some exceptions), have been **extensively studied**, allowing for the establishment of **country-specific threshold values** for cleanup.

Scenario 2: The Higher Estimate

This second scenario **not only includes the cost of cleaning up historical PFAS contamination** but also accounts for the **remediation of "emerging" PFAS**—short-chain and ultra-short-chain compounds developed by **industry to bypass evolving regulations**.

In this scenario, the **total cost skyrockets to €2,000 billion over 20 years** to remediate all PFAS pollution.

To **reduce this cost**, a **progressive phase-out of these emerging PFAS**—which are **much harder to remove from the environment**—would be necessary. Otherwise, the **remediation costs could exceed €100 billion per year indefinitely**.

An Unprecedented Cost Assessment

These estimates were calculated by **RTBF and 29 partners from the Forever Pollution Project**, in collaboration with researchers **Hans Peter Arp** (Norwegian University of Science and Technology) and **Ali Ling** (University of St. Thomas, Minnesota, USA).

This **groundbreaking study** combines the **limited scientific and economic data available** with insights from **local PFAS remediation initiatives**, providing one of the most **comprehensive assessments of PFAS cleanup costs to date**.

“There is not enough money on earth to remedy environmental pollution, given current levels of PFAS production and emissions”

Ali Ling, civil engineering researcher

The PFAS treatment market is an emerging and topical one, to which few solutions have been found.

The problem of treating PFAS is a complex, with limitations in terms of knowledge, technological and financial resources arising for each identified problem.

Pollutant emissions

PFASs continue to be produced, integrated into many industries and used every day by billions of human beings, leading to new discharge into the environment in significant quantities. Despite the introduction of regulations on the use of certain long-chain PFASs, their substitution by short-chain PFASs by industry is even leading to the emergence of new problems, including the presence in natural environments of compounds that cannot be treated (such as TFA).

Partial solutions or under development

The treatment solutions currently in place for water treatment are not technologies that have been specifically designed to treat PFAS. These technologies are used in emergency situations because they have an effect on contaminants, but their spectrum of action does not cover all PFAS and none of them can destroy them.

Limited knowledge of compounds

Scientific knowledge on the subject of PFAS is still relatively sketchy. The list of chemical species that make up this family is not exhaustive, and the methods for identifying them are still being developed or are only partially applicable on a large scale and with certainty.

Limits to solutions

Investment in treatment solutions is an issue intrinsically linked to the regulations in force. As things stand, very few industrial facilities or infrastructures are equipped to effectively treat PFAS. There is also a great deal of uncertainty surrounding responsibility and the identification of the entities that will have to bear the costs associated with treatment.

“It’s time to end the worst pollution crisis in human history”

Letter to Ursula Von Der Leyen (European Commission President), from 94 European organisations

But these high-impact issues are also market opportunities.

To facilitate the market integration and acceptance of new PFAS treatment technologies, developers must address critical concerns identified by potential clients. The following key points should be integrated into technology development to enhance adoption and competitiveness.

1 Effectiveness Against Short-Chain PFAS, Particularly TFA

One of the **major limitations of existing technologies** is their **inability to effectively treat short-chain PFAS**, especially **trifluoroacetic acid (TFA)**.

- **Most industry stakeholders** expressed **strong demand** for **solutions capable of removing short-chain PFAS**, indicating a **significant market gap** that new technologies could fill.
- Any **new technology must demonstrate efficiency across the full PFAS spectrum**, including both **long-chain and short-chain compounds**.

2 Integration into Existing Water Treatment Systems

Water treatment processes operate within **complex, multi-stage systems**. Any new technology must be **designed for seamless integration** with existing infrastructure.

- **Compatibility is key**: A technology that requires **major retrofitting or high implementation costs**, will be challenging to be adopted by users.
- **Scalability must be considered**: Solutions must be adaptable for **small, medium, and large-scale facilities**, from industrial applications to municipal treatment plants.

3 Impact on Water Composition and Byproducts

Beyond removing PFAS, any treatment method must be **evaluated for its overall impact on water quality**.

Key questions to address:

- **Does the process create harmful byproducts?** Some treatment methods degrade PFAS but **generate new, potentially toxic fluorinated compounds**.
- **Does the method alter the chemical balance of the water?** This could impact **pH levels, mineral content, or other treatment steps**.
- **Can the system be adjusted to minimize secondary pollution?**
- **Does the technology require additional post-treatment steps?**

4 Cost Competitiveness and Long-Term Viability

The financial aspect is **critical** for technology adoption. A **comparative cost analysis** should be conducted to position the solution against **existing alternatives**, considering:

- **CAPEX (Capital Expenditure)**: Initial investment costs, including equipment and installation.
- **OPEX (Operational Expenditure)**: Ongoing costs, such as energy consumption, maintenance, and waste disposal.

Sustainability matters: Industry stakeholders increasingly favor solutions that offer **low operating costs and long-term reliability**.

Lifecycle analysis is crucial: The **durability and robustness** of the technology should be optimized to reduce **replacement frequency and maintenance needs**.

5 Regulatory Compliance and Market Readiness

Evolving PFAS regulations mean that treatment solutions must be **future-proofed** to meet **current and upcoming standards**.

Certifications & Validation:

- **New solutions may need certifications or independent validation before large-scale deployment**.
- **Industry acceptance will be faster if proven through pilot projects or real-world case studies**.

Positioning stakeholders regarding new treatment technologies

The stakeholders interviewed are key to bringing a new technology to market. By cross-referencing market information with the interviews conducted, we have been able to establish the expectations of these players, as well as the assistance they could provide.

Regulatory entities/ water companies

Development support

- They help set up demonstrators and provide assistance with market access, but they are not financially responsible for installing the technology.
- These are player whose role could change in the near future to contribute to investment in structures, with the probable emergence of a model based on the polluter pays principle and the payment of water charges.

Technology providers

Development support

- Potential partners for the development of integrated solutions.

Engineering and design

Development support

- Can provide infrastructures and partnership for pilot line and demonstrators.

Expectations

- Solutions specifically developed for the treatment of PFAS
- Solutions that can be integrated into different configurations with broad operating characteristics.
- These players seek to be at the cutting edge of technology and are open to all opportunities.

End-users

Expectations

- These organisations are on the front line when it comes to regulatory changes and are obliged to implement solutions.
- They need effective and competitive solutions in terms of both OPEX and CAPEX.

Positioning Promisces technologies



In work packages 3 and 4 of PROMISCES, 8 different technologies were tested and assessed regarding their potential to remove and/or destroy PFAS and iPM(T) compounds.

It is important to note that, as this Market Study Analysis is a public deliverable, only technologies related to public results, which have been communicated by project members, are included in the individual analysis hereafter.

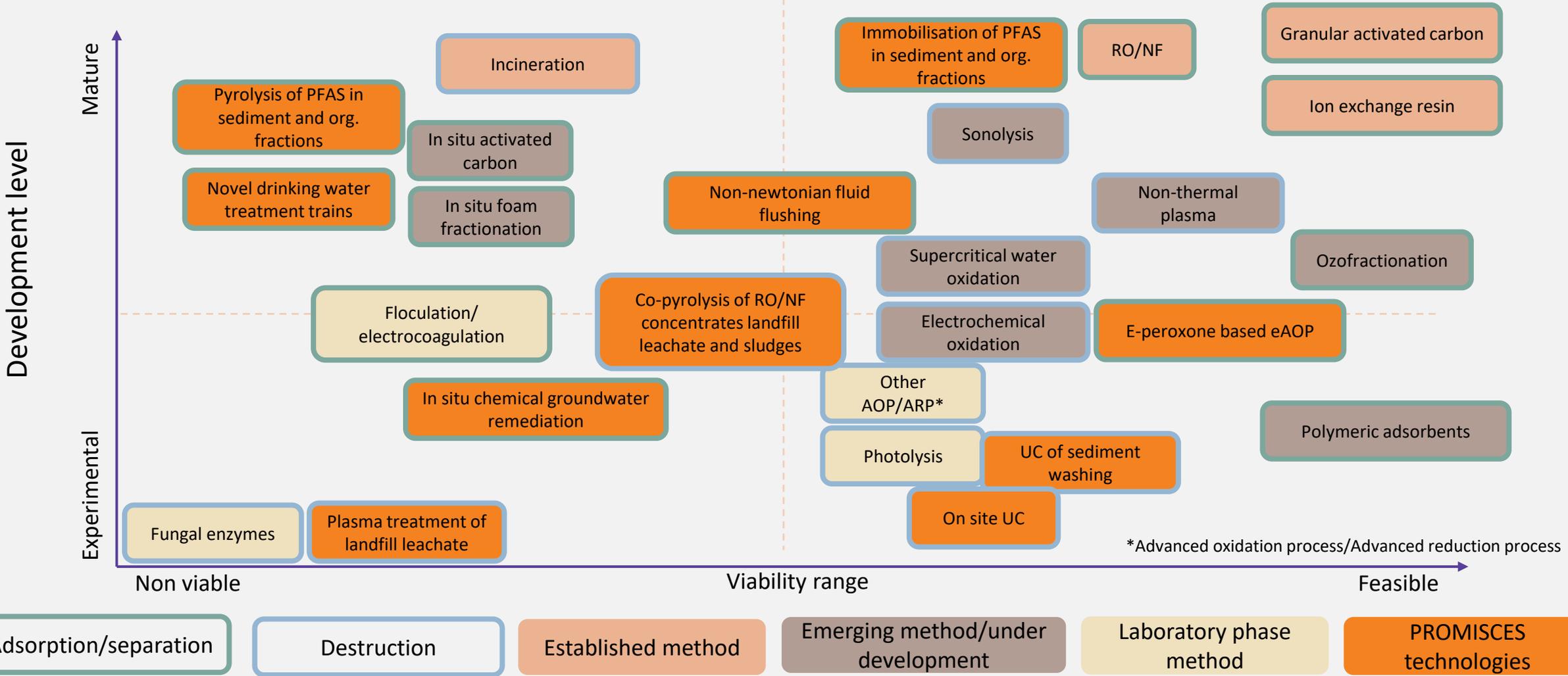
The two technologies highlighted hereafter are the public ones that have at least led to the creation of a prototype, which, after further development, could potentially be sold for PFAS treatment.

However, all technologies in the table above have been compared to previously introduced technologies p. 30 in the following page.

Tech #	WP	Technology description	TRL Start-End
1	3	In situ vadose zone and groundwater remediation by non-Newtonian fluid flushing	TRL 4-6
2	3	In situ chemical groundwater remediation	TRL 4-6
3	3	On site ultrasonic cavitation and biological groundwater remediation	TRL 3-5
8.1	3	Ultrasonic cavitation treatment of sediment washing solution	TRL 4-5
8.2	3	Immobilisation or pyrolysis of PFAS substances in contaminated fine sediment and organic fractions	TRL 4-6
4	4	Novel drinking water treatment trains	TRL 4-6
5	4	E-peroxone based electrochemical advanced oxidation process (eAOP) combined with constructed wetlands	TRL 4-6
6	4	Co-pyrolysis of RO/NF concentrates of landfill leachate and contaminated sewage sludge	TRL 4-6
7	4	Plasma treatment of landfill leachate	TRL 4

Overview of existing treatment methods

Despite the prevalence of 3 industrialized treatment methods, various other technologies are currently being developed.



Source : modified from Ross, I. et al.(2018). A review of emerging technologies for remediation of PFASs. *Remediation Journal*, 28(2), 101-126

A technology with a great potential of interest with a unique value proposition and an unrivalled level of efficiency that could solve a number of problems that the market does not yet know how to address.

Technology #3.1 : On-site ultrasonic cavitation

Ultrasonic cavitation (UC) technology can be integrated into a **groundwater treatment train** for **on-site PFAS remediation**.

UC occurs when a liquid is exposed to **high-power ultrasound**, leading to the formation of **microscopic bubbles**. These bubbles act as **tiny liquid-gas reactors**, generating **intense energy** capable of breaking even **highly stable chemical bonds**.

As a **chemical-free degradation technology**, ultrasonic cavitation can be **combined with other oxidation techniques** and is suitable for **industrial applications**.

At the end of its development, this solution will be capable of **treating water in a continuous flow system**, achieving an **average PFAS degradation yield of 97%**, **regardless of carbon chain length**.





Attractiveness

- The UC technology is highly attractive for its ability to achieve **on-site mineralisation of PFAS**, eliminating the need for downstream destruction.
- Unlike **most current remediation technologies** (e.g. adsorption on activated carbon, ion exchange resins, or foam fractionation), which **only capture PFAS** and require **subsequent incineration at >1 100 °C** for final destruction — an energy-intensive and costly process — **UC allows for direct degradation** in water, thus **removing the need for transport, handling and high-temperature disposal of contaminated residues**.
- While UC involves a **high CAPEX** (linked to ultrasonic reactor and power supply), the **OPEX remains moderate** because:
 - **No chemical reagent or oxidants** are required (hence “no destruction cost” previously mentioned);
 - **Maintenance needs are minimal**, as the transducers are robust and remotely controlled;
 - The **main operational cost is electricity consumption**, which depends on power density and flow conditions.

Based on PROMISCES experiments:

Energy performance

- Laboratory-scale batch tests (PFOS 1 mg/L) at **400 W/L** reached an **EEO of 412 kWh/m³**, i.e. **≈ 77 €/m³**.
- For PFAS-contaminated groundwater, **EEO = 384–657 kWh/m³** (**≈ 72–123 €/m³**), depending on PFAS concentration.
- In continuous recirculation mode, **EEO = 166 kWh/m³**, i.e. **≈ 31 €/m³**.
- Energy efficiency improves at higher PFAS concentrations, confirming the relevance of **closed-loop or concentrated effluents**.

For comparison

- **Ozone and UV-based AOPs**: < 1 kWh/m³ but **ineffective on PFAS**;
- **Electrochemical oxidation**: 5 000–20 000 kWh/m³ for PFOA/PFOS;
- UC therefore represents an **order of magnitude better energy efficiency** among **true PFAS destruction technologies**.

A technology with a great potential of interest with a unique value proposition and an unrivalled level of efficiency that could solve a number of problems that the market does not yet know how to address.



Key market insights for upscaling ultrasonic cavitation

Feasibility

- Acceptance of the technology by the treatment market will depend on the **ability of carriers to reduce the energy demand** associated with the use of the technology.
- The critical development phases will have to **focus on integrating this technology into the treatment chain**: identifying complementary solutions, the flows to be treated, etc.
- Although the first experiments on identifying potential by-products have shown good results, the confidence of future customers will be facilitated by a **precise study of the by-products generated** and the **degradation residues**.

Competitiveness

- The technology could stand out from other solutions if it has a **proven effect on short-chain PFASs**.

Technology developer insights and upscaling roadmap

- Current work focuses on **optimising energy transfer, cavitation homogeneity and temperature control** in continuous mode.
 - The **reactor design** (transducer configuration, flow rate, and power density) is being refined to **reduce energy consumption** while maintaining high mineralisation rates.
 - Pilot trials at TRL 5 demonstrated **99% PFAS removal in 400 minutes (Initial PFAS concentration: $\Sigma\text{PFAS} = 0.4 \text{ mg/L}$)**, confirming the scalability of continuous UC treatment.
-
- UC stands out for its **chemical-free operation, ability to treat both short- and long-chain PFAS**, and **integration potential** within existing treatment chains.
 - Its **operating costs** (31–123 €/m³ depending on configuration) compare favourably to the **hidden costs of conventional technologies**, which require **collection, concentration, transport and high-temperature incineration** of PFAS residues.
 - Further optimisation of energy efficiency and process automation should **reduce EEO**, reinforcing UC's position as a **competitive and sustainable PFAS destruction solution**.

A versatile solution that has no alter ego on the PFAS treatment market, but whose by-products have yet to be studied.



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Technology #6.1 : Co-pyrolysis of RO/NF concentrates of landfill leachate

This technology involves a non-oxidative thermochemical treatment process applied to reverse osmosis (RO) and nanofiltration (NF) concentrate and sludge at a high temperature of 600 °C. The treatment ensures the physical and chemical destruction of organic compounds, particularly targeting PFAS. The process generates syngas, oil, and char, with the potential for syngas thermal energy recovery.

The process applies to wastewater treatment plant sludge, landfill leachate treatment plant sludge, and dried concentrates from nanofiltration/reverse osmosis systems, with a processing capacity of 9 kg/hour. When tested, the pyrolysis reactor at 600 °C for 20 minutes successfully treated 30 PFAS compounds, with none detectable in the biochar (limit of quantification = 1 µg/kg). PFAS were transformed during thermal treatment, although trace levels were detected in both the stack emissions and bio-oil. The main source of PFAS contamination was identified as the NF/RO concentrate rather than the sludge. When pyrolysis was operated under suboptimal conditions (lower temperatures and altered reaction times), PFAS residues were present in the biochar.

Attractiveness

- The applicability of the solution to **different types of matrices** is a key opportunity for potential customers.
- **Compatibility with technologies that are already mature** and in use in certain industrial or wastewater treatment plant contexts means that the technology can be integrated more easily.
- **Novel, compact, and on-site applicable technology**, reducing the need for transporting sludge and concentrate to distant incineration plants.
- Unlike incineration (>1 100 °C), pyrolysis operates at **moderate temperatures (400–600 °C)** with **lower energy demand** and **limited formation of dioxins/furans**.
- Offers potential **energy recovery** from **syngas and bio-oil**, which can partly offset operating costs.
- **Thermal and electrical energy consumption** are substantially lower than incineration while providing **net positive thermal energy**.
- Enables a **closed-loop management** of PFAS-rich residues directly at landfill or leachate treatment sites.

Based on PROMISCES experiments:

Energy and cost aspects

- **Excess thermal energy from pyrolysis:** –18 200 MJ /d → **energy-positive system**.
- **Electrical energy demand:** ≈ 1 000 kWh /d for 1 000 t sludge · y⁻¹ (≈ 278 €/t).
- **Energy costs and OPEX** lower than for incineration (0.839 MJ heat + 0.518 MJ elec /kg).
- **CAPEX advantage:** compact, modular on-site unit → lower investment than centralised incinerators.

A versatile solution that has no alter ego on the PFAS treatment market, but whose by-products have yet to be studied.



Key market insights for upscaling ultrasonic cavitation

Feasibility

- The confidence of future customers will be facilitated by a precise study of the by-products generated and the degradation residues.

Competitiveness

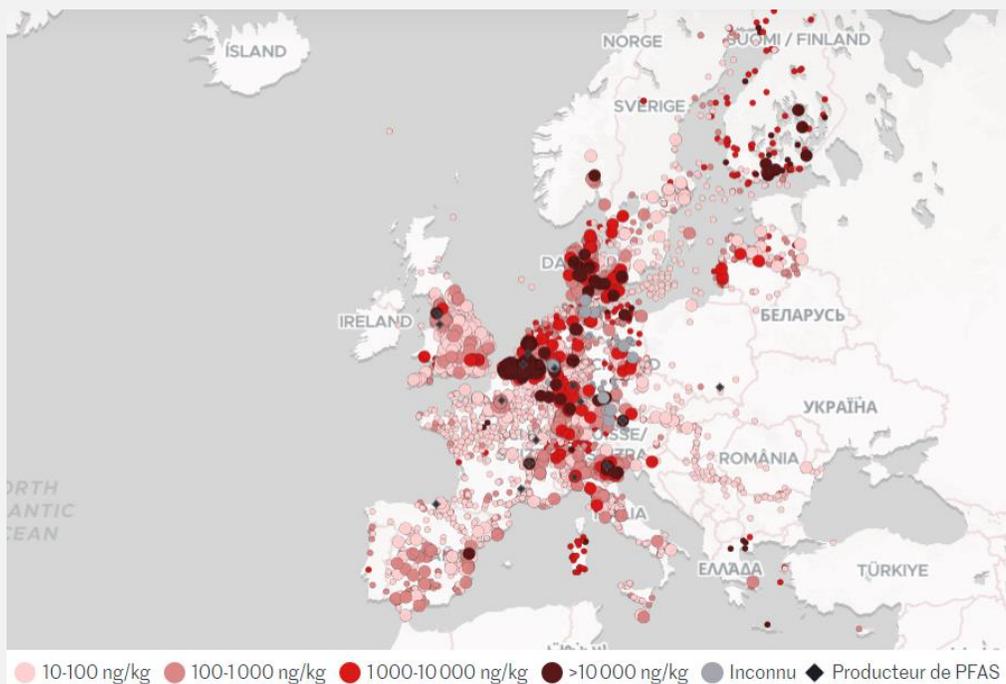
- Co-generation of value-added by-products is a differentiating asset that offers customers an attractive return on their investment.

Technology developer insights and upscaling roadmap

- **Main technical challenges:** tar formation, clogging, corrosion from inorganics, gas cleaning, and maintaining anaerobic conditions.
- **Automation and nitrogen recirculation systems** are key to reducing maintenance and energy costs.
- Further pilot testing is required to:
 - validate optimal sludge/concentrate ratios,
 - assess continuous operation,
 - and standardise **biochar management and disposal**.
- **Economic advantage:** energy-positive operation, reduced transport and incineration costs, compact design.
- **Environmental advantage:** lower GHG emissions and toxic by-products than incineration, improved social acceptance.
- **Estimated OPEX: ~278 €/t treated**, partly offset by **thermal energy recovery**.
- **CAPEX:** expected to be **lower** than incineration due to decentralised, modular setup.
- **Main limitation:** heavy-metal concentration in char restricts reuse; valorisation as waste fuel or energy source under study.

Potential actions to priorities for the development of technologies

Directing technologies towards a target type of treatment is a decision to be taken on the basis of the actions to be prioritized.



Opportunity: destructive solutions for hot spots

In 2023, one of Europe's first major PFAS remediation projects revealed the extent of PFAS contamination. Europe is heavily contaminated, with at least 23,000 pollution sites and 2,300 'hotspots', according to the revelations of the first season of the Forever Pollution Project collaborative survey conducted in 2023.

Opportunity: Actions on TFA

This chemical compound has been found in many European locations and is the subject of growing concern and controversy. Because of its very small size, this PFAS of worrying toxicity cannot be destroyed by any mature technology on the market. Moreover, the impact of this molecule on health is still poorly understood, and there is a need for further studies on the subject. The possible emergence of regulations concerning this TFA will drastically polarize the market for treatment solutions and make solutions capable of destroying it a priority for the purchase of treatment infrastructure.

Opportunity: Using combined technologies for other persistent problematic materials

In addition to PFAS, many other compounds of concern are present in water. These include antibiotics, which can bypass water treatment processes and end up directly in the environment. They are detected in rivers at very low concentrations and diluted more than a million times compared with the concentrations found in the human body. The ability of certain solutions to treat both PFAS pollution and other persistent compounds in the environment could enable effective differentiation on the market.

<https://foreverpollution.eu/>
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