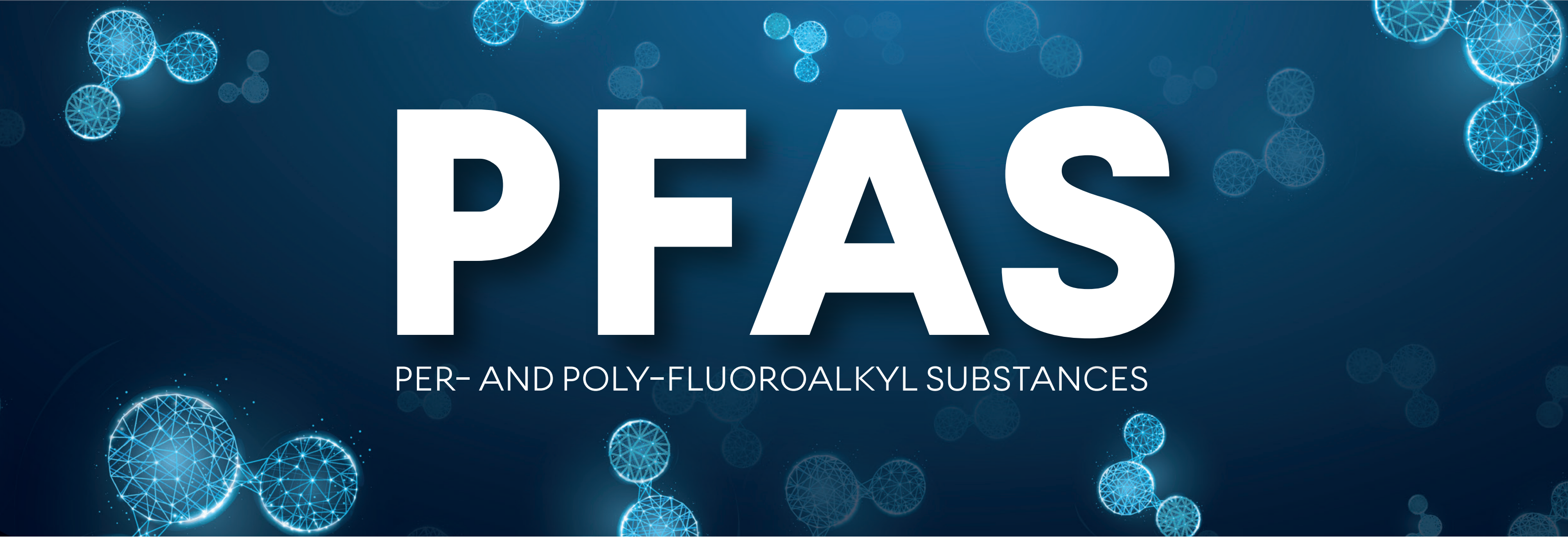

PFAS

PER- AND POLY-FLUOROALKYL SUBSTANCES

7th International Congress

Gestion des Risques Environnementaux & Sanitaires
Management of Environmental & Health Risks

16, 17, 18 & 19/06/2026 – Paris

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PFAS

PER- AND POLY-FLUOROALKYL SUBSTANCES

Gestion des Risques Environnementaux & Sanitaires

16, 17, 18 & 19 juin 2026 – Paris

Mardi 16 juin 2026

08h30
Accueil des participants

Contexte règlementaire international

Présidents :
• Laurence Lanoy, Avocate en Droit de l'Environnement - Laurence Lanoy Avocats, France
• Dr. Frank Karg, SFSE & ARET, Directeur scientifique Ginger Group - HPC (Inogen), Président d'Atlantis Développement & Expert Judiciaire, France

08h55
Discours de bienvenue & introduction au congrès
Dr. Frank Karg, Organisation et Président du Congrès International PFAS

09h00
Origine de la pollution par les PFAS dans les sols et l'eau provenant de boues industrielles
Anne-Françoise Stoffel, Directrice R&D & Laure Pommier, Ingénieur de Recherche - Eurofins Environnement (France)

09h30
Cadre réglementaire des PFAS : évolution, harmonisation et enjeux de conformité aux niveaux national et international
Joanna Peltzman, Avocate - Osborne Clarke (France)

10h00
Nouvelles applications MVA, notamment multivariables, multi-statistiques, apprentissage automatique, regroupement (IA) et vaste base de données sur les spectres environnementaux et chimiques des produits PFAS commerciaux (historiques) dégradés et non dégradés, pour l'identification et la différenciation des sources de contamination par les PFAS
Dr. Frank Karg, SFSE & ARET, Directeur scientifique Ginger Group - HPC (Inogen), Président d'Atlantis Développement & Expert Judiciaire (France)

10h30
Pause-café & thé

11h00
Les enjeux juridiques et les implications financières des PFAS
Laurence Lanoy, Avocate - Spécialiste en Droit de l'Environnement - Laurence Lanoy Avocats (France)

11h30
Entre hétérogénéité et incertitude réglementaire, comment se protéger au mieux du risque PFAS ?
Élodie Simon, Avocate associée & Gaspar Cottard, Avocat collaborateur senior - Jones Day (France)

12h00
Premier retour d’expérience : surveillance, le choix crucial des composés PFAS analysés
Jérôme Texier, Ingénieur R&D - XSEM (France)

12h30
Déjeuner

14h00
Conversion d'un système d'extinction d'incendie AFFF
- *Rick Parkman, Responsable PFAS - Ramboll Europe (Royaume-Uni)*
- *Frédéric Leveau, Responsable PFAS - Ramboll (France)*

14h30
Faire progresser les technologies de traitement et la gestion intégrée des risques pour l'eau, le sol, les sédiments et l'air dans les écosystèmes africains vulnérables
Paul Orengoh, Consultant principal - JP Consult & Associates, Ltd (Kenya)

Identification & Caractérisation des sources des PFAS (Part. 1)

15h00
Différences inter-laboratoires pour la détermination des PFAS dans la végétation aquatique
Ivar Lanting, Conseiller principal Environnement & Energie - Antea Group / Inogen (Pays-Bas)

15h30
Pause-café & thé

16h00
Calibration en temps réel par PTR-ToF-MS et mesures des émissions de PFAS en tube d’écoulement à partir de matériaux de consommation
Marie-Joe Akiki, Doctorante - Laboratoire de Chimie de l’Environnement, Aix Marseille Université (France)

16h30
Évaluation de l’exposition aux PFAS dans l’air ambiant : méthodes d’échantillonnage actif validées au service de l’analyse des risques
Paola Verza, Responsable technique des projets spéciaux - Mérieux NutriSciences (Italie)

17h00
PFAST : un instrument d'analyse portable pour la détection rapide sur le terrain des PFAS avec une sensibilité de l'ordre du ppt
Vincent Bouchiat, Chercheur - Grapheal Fluorograph (France)

17h30

Retours d’expérience consolidés de transitions pour différents systèmes anti-incendie contenant des émulseurs fluorés : du diagnostic à l'élimination – perspectives

Matthieu Hirrien, Responsable Projets Spéciaux & Innovation - Veolia, Hazardous Waste Europe (France)

18h00

Fin de la première journée

Tuesday, June 16, 2026

08h30
Welcoming participants

International Legal Context

Presidents:
- *Laurence Lanoy, Lawyer in Environmental Law - Laurence Lanoy Avocats, France*
- *Dr. Frank Karg, SFSE & ARET, Scientific Director of Ginger Group - HPC (Inogen), CEO of Atlantis Développement & Court Expert, France*

08h55
Welcome speech & introduction to the congress
Dr. Frank Karg, Organization & President of International PFAS Congress

09h00
Origin of PFAS pollution in soils and water from industry sludges
Anne-Françoise Stoffel, R&D Director & Laure Pommier, Research Engineer - Eurofins Environnement (France)

09h30
PFAS regulatory framework: Developments, harmonisation and compliance challenges at national and international levels
Joanna Peltzman, Lawyer - Osborne Clarke (France)

10h00
New MVA applications, including multivariances, multi-statistics, machine learning, clustering (AI) and a large data-bank of enviro-chemical spectrums of (historical) commercial PFAS products for identification & differentiation of PFAS contamination sources
Dr. Frank Karg, SFSE & ARET, Scientific Director of Ginger Group - HPC (Inogen), CEO of Atlantis Développement & Court Expert (France)

10h30
Coffee & Tea break

11h00
The legal issues and financial implications of PFAS
Laurence Lanoy, Lawyer - Specialist in Environmental Law - Laurence Lanoy Avocats (France)

11h30
Between heterogeneity and regulatory uncertainty, how can we best protect ourselves from PFAS risk?
Élodie Simon, Partner & Gaspar Cottard, Senior Associate - Jones Day (France)

12h00
First feedback: Monitoring the crucial choice of the PFAS compounds analyzed
Jérôme Texier, R&D Engineer - XSEM (France)

12h30
Lunch

14h00
AFFF Fire System Conversion
- *Rick Parkman, PFAS Lead - Ramboll Europe (United Kingdom)*
- *Frédéric Leveau, PFAS Lead - Ramboll (France)*

14h30
Advancing treatment technologies and integrated risk management for water, soil, sediment, and air in vulnerable african ecosystems
Paul Orengoh, Principal Consultant - JP Consult & Associates, Ltd (Kenya)

Identification & characterization of PFAS Sources (Part. 1)

15h00
Inter-laboratory differences in PFAS determination in aquatic vegetation
Ivar Lanting, Senior Advisor Environment & Energy - Antea Group / Inogen (Netherlands)

15h30
Coffee & Tea break

16h00
Real-time PTR-ToF-MS calibration and flow-tube PFAS emissions measurements from consumer materials
Marie-Joe Akiki, PhD student – Environmental Chemistry Laboratory, Aix Marseille University (France)

16h30
Assessing ambient air PFAS exposure: validated active sampling methods for risk evaluation
Paola Verza, Special Projects Technical Manager - Mérieux NutriSciences (Italy)

17h00
PFAS with ppt sensitivity
Vincent Bouchiat, Researcher - Grapheal Fluorograph (France)

17h30

Consolidation of returns of experience for the change out of fluorinated AFFF in different firefighting systems : from characterization to waste treatment – perspectives

Matthieu Hirrien, Responsable des projets spéciaux et de l'innovation - Veolia, Hazardous Waste Europe (France)

18h00

End of the first day

ORIGINE DE LA POLLUTION PAR LES PFAS DANS LES SOLS ET L'EAU PROVENANT DE BOUES INDUSTRIELLES

ORIGIN OF PFAS POLLUTION IN SOILS AND WATER FROM INDUSTRY SLUDGES

Anne-Françoise Stoffel, Directrice R&D & Laure POMMIER ingénieur de recherche - Eurofins Environnement (France)
Anne-Françoise Stoffel, R&D Director & Laure POMMIER research ingenior - Eurofins Environnement (France)

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Caractérisation et quantification des PFAS dans des échantillons de boues industrielles, de sols agricoles et d'eaux de ressource.

CONTEXTE :

Du fait de leur présence dans les produits de consommation et les procédés industriels, les PFAS se retrouvent dans les eaux usées traitées par les stations d'épuration urbaines et industrielles. Les stations d'épuration sont identifiées comme l'une des voies de transfert de PFAS dans l'environnement. En France, environ 75 % des boues de stations d'épuration urbaines et environ 60 % des boues de stations d'épuration industrielles sont valorisées en agriculture. Ces boues d'épuration utilisées pour l'amendement de parcelles agricoles peuvent devenir une source de contamination en PFAS des sols, et par voie de conséquence des denrées alimentaires et des ressources en eau utilisées pour la production d'eau potable.

RESUME :

Dans ce contexte, le choix du site étudié a été réalisé en connaissance d'une pollution en PFAS avérée dans l'eau potable de distribution (source ARS- agence régionale de santé). Or dans cette zone à dominante rurale, des boues industrielles ont été épandues sur des parcelles agricoles. Notre hypothèse de départ a donc été d'échantillonner autour de ce site représentatif d'une pollution avérée en PFAS pour identifier les sources de contamination.

Le laboratoire EUROFINS a donc mené une étude visant à établir un profil de contamination en PFAS sur différents compartiments environnementaux. Ainsi, les échantillons de boues, sols et eaux de captage du site étudié ont été analysés en mettant en œuvre la combinaison de plusieurs méthodes analytiques. Sur chaque milieu, les analyses suivantes ont été réalisées :

- Un nombre de PFAS target incluant les PFAS à chaines ultra-courtes (TFA), courte (C4-C6) et longues (>C10-C14) , les perfluorés sulfoniques et carboxyliques ainsi que certains PFAS précurseurs pertinents.
- Le TOP Assay pour déterminer la concentration maximisée en PFAS perfluorés après oxydation des précurseurs sensibles
- Le Total Organique Fluor (TOF) pour inclure les polymères PFAS ou autres pesticides PFAS.

La présentation de ces résultats devrait permettre de caractériser la contribution de chaque composé au profil global d'une part et d'autre part d'identifier d'éventuels marqueurs caractéristiques d'une source de pollution. L'analyse des trois matrices (boue, sol et eau) en utilisant toutes les approches méthodologiques -PFAS target, TOPA et TOF- peut également permettre d'émettre des hypothèses quant au transfert de certains polluants PFAS de la boue vers le milieu naturel.
En conclusion, cette étude ouvre la voie vers un outil de diagnostic qui pourrait servir demain à caractériser les sources de pollutions et leur origine éventuelle appuyée par des méthodes analytiques robustes et harmonisées.

Characterization and quantification of PFAS in industrial sludge, agriculture soils and resource waters samples.

CONTEXT : Due to their presence in consumer products and industrial processes, PFAS are found in wastewater treated by urban and industrial treatment plants. Wastewater treatment plants are identified as one of the pathways for the release of PFAS into the environment. In France, around **75% of sludge from urban treatment** plants and around **60% of sludge from industrial** treatment plants **is used in agriculture**. This sewage sludge, when used to improve agricultural land, can become a source of PFAS contamination in soil and, consequently, in foodstuffs and water resources used for drinking water production.

RESUME : In this context, the site under study was selected in the knowledge that there was confirmed PFAS contamination in the drinking water supply (source: ARS – Regional Health Agency). However, in this predominantly rural area, industrial sludge has been spread on agricultural land. Our initial hypothesis was therefore to take samples around this site, which is representative of confirmed PFAS contamination, to identify the sources of contamination.

So EUROFINS' lab conducted a study aimed at establishing a PFAS contamination profile across various environmental compartments.

Consequently, samples of sludge, soil and groundwater from the site under study were analyzed using a combination of several analytical methods.

The following analyses are carried out on each matrix:

- A number of target PFAS, including ultra-short-chain (TFA), short-chain (C4-C6) and long-chain (>C10-C14), perfluorinated sulfonic and carboxylic acids, as well as certain relevant PFAS precursors.
- The TOP Assay to determine the maximum concentration of perfluorinated PFAS following oxidation of sensitive precursors;
- Total Organic Fluorine (TOF) to account for PFAS polymers or other PFAS pesticides.
- Due to their presence in consumer products and industrial processes, PFAS are found in wastewater treated by urban and industrial treatment plants. Wastewater treatment plants are identified as one of the pathways for the release of PFAS into the environment. In France, around **75% of sludge from urban treatment** plants and around **60% of sludge from industrial** treatment plants **is used in agriculture**. This sewage sludge, when used to improve agricultural land, can become a source of PFAS contamination in soil and, consequently in foodstuffs and water resources used for drinking water production.

The presentation of these results should enable us to characterize the contribution of each compound to the overall profile, on the one hand, and to identify potential markers characteristic of a source of pollution, on the other.
Analysis of the three matrices (sediment, soil and water) using a combination of methods – PFAS target, TOPA and TOF – should also enable us to formulate hypotheses regarding the transfer of PFAS contaminants from sludge into the natural environment.

To conclude this study is the first step towards a diagnostic tool that would be used in the future to characterize sources of pollution and their possible origin, supported by robust and harmonized analytical methods.

Mots clés : Boue, PFAS marqueurs, stratégie analytique pour les PFAS
Keywords: Sludge, PFAS markers, analytical strategy for PFAS

The regulatory framework for PFAS: developments, harmonisation and compliance challenges at national and international levels

Joanna Peltzman, Partner — Osborne Clarke | 7th Congress — 16 June 2026

Long viewed primarily through an environmental and health lens, the issue of per- and polyfluoroalkyl substances (‘PFAS’) has now emerged as a major legal, economic and litigation challenge.

The unique nature of these substances, their extreme persistence, their widespread distribution and the complexity of their characterisation are testing traditional regulatory frameworks and forcing authorities to adopt increasingly comprehensive and structured approaches.

In this context, the regulation of PFAS is part of a multi-level dynamic (international, European and national), characterised by a continuous tightening of standards, a growing emphasis on the polluter-pays principle, and an intensification of litigation risks for economic actors.

1. Legal challenges: colossal costs, liability and increasing litigation

The PFAS issue can no longer be analysed solely from the perspective of pollution: it now constitutes **a massive financial risk, centred on a fundamental question: the allocation of decontamination costs**.

The available estimates reflect the scale of the phenomenon.

Notably, a European Commission report from January 2026 highlights that a scenario involving a comprehensive ban under REACH by 2030 would, paradoxically, be the least costly option (~€330 billion), compared to the status quo (~€440 billion) or management limited to water quality standards (~€1,700 billion).

The *Forever Lobbying Project (*January 2025) estimates the cost of treating legacy long-chain PFAS at €4.8 billion per year, and that of all PFAS at nearly €100 billion annually, amounting to over €2 trillion over twenty years.

Two structural factors undermine operators’ legal certainty:

- **Persistent scientific uncertainty**: difficulties in comprehensively identifying PFAS, constantly evolving toxicological thresholds, and uncertainties regarding cumulative effects;
- **A gap between standards and industrial feasibility**: a lack of technically equivalent substitutes for certain critical uses and particularly high substitution costs.

In terms of litigation, the issue is increasingly being taken to court, as evidenced by a growing body of case law and ongoing legal proceedings: an action for wrongful failure to act by the State before the Paris Administrative Court, filed on 21 May 2026 and brought by several associations, as well as the so-called ‘200 against PFAS’ action, civil proceedings against manufacturers, particularly in the Vallée de la Chimie.

2. International and European framework: towards structured and comprehensive regulation

At the international level: anchoring within the POPs regime

The 2001 **Stockholm Convention** constitutes the applicable international legal framework for substances exhibiting the characteristics of persistent organic pollutants (POPs): persistence, bioaccumulation, toxicity and long-range transport.

Certain categories of PFAS, notably the most stable perfluorinated PFAS, meet these criteria. Their gradual inclusion in the Convention’s annexes reflects their legal classification as POPs.

This classification has major implications: a ban, restrictions or an obligation to reduce emissions, as appropriate.

EU law has, moreover, transposed these commitments through Regulation (EU) 2019/1021 (the 'POPs Regulation'), leading in particular to the ban on PFOS since 2009, on PFOA since July 2020, and on PFHxS since June 2022.

A European regulatory framework that is becoming more comprehensive

Alongside existing instruments, the European Union is moving towards a shift in the scale of regulation, considering for the first time a **comprehensive approach by substance class under the REACH Regulation**.

In January 2023, a consortium of five Member States (Germany, Denmark, the Netherlands, Sweden and Norway), with the support of France, submitted a proposal for a universal restriction on PFAS to the European Chemicals Agency (ECHA).

This proposal, in an unprecedented move, no longer targets specific individual substances but the entire PFAS family, subject to strictly regulated exemptions.

The evaluation procedure follows the standard REACH framework, based on a dual scientific and socio-economic assessment:

- The Committee for Risk Assessment (RAC), in its opinion published on 26 March 2026, came out in favour of a broad restriction, considering that the risks to human health and the environment justify a comprehensive approach;
- The Socio-Economic Analysis Committee (SEAC), in a draft opinion submitted for consultation, adopts a more nuanced position, advocating targeted exemptions for certain uses deemed essential or for which no technically or economically viable alternative is currently available.

This dialogue between the imperative of protection and industrial constraints illustrates the fundamental tension at the heart of the PFAS issue. SEAC's final consolidated opinion is expected by the end of 2026, ahead of a regulatory proposal from the European Commission in 2027.

If successful, this initiative would represent a major development in chemicals law, establishing horizontal regulation of PFAS and marking the shift from a substance-by-substance approach to a comprehensive management approach for a chemical family, with significant compliance implications for economic operators.

Furthermore, **European regulation is also becoming more comprehensive on a sector-by-sector basis**; examples include:

- Regulation (EU) 2023/915 already restricts PFAS in food of animal origin;
- The Packaging Regulation ('PPWR') (EU) 2025/40 prohibits, with effect from 12 August 2026, food packaging exceeding certain PFAS thresholds;
- Directive (EU) 2024/3019: strengthening the monitoring of PFAS in urban water and considering extended producer responsibility.

3. The French framework: rapid but still incomplete development

France is part of this trend, with an accelerated strengthening of its regulatory framework, although certain details still need to be consolidated.

An **interministerial PFAS action plan (2024**) organises public policy around five key areas: knowledge, monitoring, risk reduction, innovation and information.

Law No. 2025-188 of 27 February 2025 introduces a phased ban on certain products:

- from 2026: cosmetics, ski waxes, clothing textiles (excluding protective equipment);
- by 2030: extension to furnishing textiles (subject to conditions).

Furthermore, the **regime for classified facilities** ('ICPE') now imposes enhanced monitoring of water and atmospheric emissions, as well as, following the law of February 2025, ambitious reduction targets of a 70% reduction by 2028 and 'zero discharge' by 2030.

Finally, the introduction of a **levy on PFAS discharges into water**, marking the first concrete application of the polluter pays principle, reflects a shift towards economic instruments. However, its effective implementation remains under debate and has been postponed until September 2026.

4. Outlook: towards greater effectiveness of the polluter pays principle

The **polluter pays principle**, enshrined in international and European law, appears to be the key lever for addressing the issue of PFAS in a sustainable manner.

Current academic discussions on the subject point towards the coordinated deployment of three instruments:

- **Extended producer responsibility** (EPR), the scope of which remains to be defined;
- **Environmental levies** to fund decontamination measures;
- **Integration into the** existing **environmental tax system** (notably through general taxes on polluting activities (TGAP)).

In this context, the creation of a dedicated compensation and decontamination fund, financed by industry or through the proceeds of litigation, also constitutes a key option, enabling the cost of pollution to be transferred to those responsible.

The regulatory framework applicable to PFAS is thus undergoing a profound and rapid transformation, characterised by its internationalisation, increasing complexity and shift towards comprehensive, substance-specific approaches.

Beyond the environmental implications, the issue has now come to be seen as a matter of systemic financial and legal responsibility, requiring economic actors to adapt their strategies and existing legal frameworks to be strengthened.

The growing prominence of the 'polluter pays' principle heralds, in this respect, a lasting reorganisation of the distribution of costs associated with environmental contamination.

To be continued…

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International PFAS Congress
Paris 16 - 19 June 2026

Nouvelles applications de la MVA, incluent des Multivariances, Multi-Statistiques, Machine Learning, Clustering (IA) et une grande Banque des données des Spectres Enviro-chimiques des Produits Commerciaux (historiques) PFAS, dégradés et non-dégradés pour l'Identification & la Différenciation des Sources des pollutions par les PFAS

New MVA Applications, including Multivariances, Multi-Statistics, Machine Learning, Clustering (AI) and a large Data-Bank of Enviro-chemical Spectrums of (historical) commercial PFAS Products for Identification & Differentiation of PFAS Contamination Sources

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1. Introduction

Environmental PFAS contaminations and especially Groundwater Pollution Plumes are constituted mostly by multi-contamination Sources. The principal question is which PFAS Contamination Sources are responsibles for which part of the complete PFAS contamination. The following Article is showing the approach of MVA-AI to differentiate the responsibilities for each contamination source's pollution part. This is important, for the Industry, different polluters, Insurance Companies, Authorities and in case of Court Disputes, to share correctly and in Transparency the financial charges for Remediation and pollution Management.

Since the 1960s, PFAS monomers (Per- & Polyfluoro-Alkyl Substances) have gradually become a major environmental and public health problem in industrialized countries, due to their multiple and wide-ranging applications (historical and still current). This threat to the environment and to public health has been gradually coming to the fore since the 2010s and will be considered to a greater extent in 2022 - 2024. As a result, PFAS are now found in the soil at polluted sites, in groundwater, in food, drinking water, in soil gas and in ambient air (volatile PFAS, e.g. FTOH: Fluorotelomer alcohols, etc.). Between 9,000 and 12,000 synthetic PFAS pollutants have been produced, with some publications indicating as many as 15,000 molecules.

Polymeric PFASs such as Teflon (or PFTE etc.) are not very bioavailable and are therefore much less toxic than monomeric PFASs. These monomeric PFAS are the subject of the work presented below. PFASs are known for their toxicological effects as endocrine disruptors, hepatotoxicity, immunotoxicity, effects on fetal development and, in some cases, carcinogenicity (e.g. PFOA).

An important characteristic of PFASs is their behavior in Environmental Chemistry, since only polyfluorinated PFASs are modified by microbiological bio-transformation into perfluorinated PFASs, which remain totally stable and non-degradable, and even bio-accumulable.

Particularly in the case of groundwater pollution by PFAS, it is becoming increasingly important to identify and, above all, differentiate the contribution of each PFAS source to pollution plumes. This need for clarification regarding the contribution of each PFAS source to pollution, e.g. in the vicinity of drinking water wells, etc., is becoming crucial for the protection of water resources, (shared) responsibilities and the search for the (multiple) origins of pollution in the context of legal court expertise.

Sources of pollution by PFAS are varied and can be found on industrial sites that have used these products, sites that have suffered fires or fire training sites where fire-fighting foams have been used. **(AFFF : Anti Fire Fighting Foams or Aqueous Film Forming Foam, e.g. at airports)** have been used. Agricultural land is also a source of PFAS pollution, due to the input of sewage sludge, which contains accumulated PFAS.

The following (historical) activities may be the source of PFAS pollution:

☐ Fire-fighting training,
☐ Airport or air base on a military site,
☐ Fire site and use of AFFF,
☐ Electrochemical galvanisation,
☐ Production of waxed paper and cardboard,
☐ Manufacture of waterproof textiles,
☐ Sprays, paints, waterproofing lacquers,
☐ Production and application of Teflons (PTFE, etc.),
☐ Petroleum and chemical industry sites and/or production and application of paints, dyes, inks, pigments, chemical waxes and polishing products,
☐ Solvent applications (garages, dry cleaners, laundries, etc.),
☐ Landfill sites and former municipal landfill sites, etc. (ISDD, ISDND, ISDD, etc.),
☐ Dyeing & Tanning,
☐ Carpets, rugs, fabrics and plastics with flame retardants,
☐ Production of objects and furniture containing surfaces,
☐ Production of cleaning products,
☐ Photographic chemistry (laboratories, paper and film production, etc.),
☐ Production of electronic components,
☐ Production and application of pesticides and biocides,
☐ Production of cosmetics,

- Sites receiving WWTP sludge.

2. Environmental chemistry of PFAS

The environmental chemistry of PFAS is particularly important and complicated. There is no group of pollutants with a more complex environmental chemistry than PFAS. In particular, there are **more than 9,000 PFAS substances**, divided into **33 categories of substances**.

The mostly known PFAS are Perfluoroalkane sulphonic acids (PFASs), Perfluoroalkyl carboxylic acids (PFCAs), Perfluoroalkyl phosphates and their esters, Fluorotelomer alcohols (**FTOH**), etc. (including more than 29 other groups …). Some of them, such as the **PFOA :** Perfluorooctanoic acid and **PFOS** : Perfluoro-octane-sulphonate are banned (and **prohibited in EC and USA & Canada**) by the **Stockholm Convention** in the category of **POPs** : Persistent Organic Pollutants. PFOA is carcinogenic. **Commercial products** mainly contain **mixes**.

The reason for the high solubility in water, associated with lipophilicity, is based on the fact that **PFAS** :

- **Anionics** (e.g. sulphonates, sulphates, carboxylates and phosphates),
- **Cationics** (e.g. quaternary ammonium),
- **Amphoteric** (e.g. betaines and sulpho-betaines): base + acid and
- **Non ionic** (e.g. polyethylene glycols, acrylamide oligomers).

It is very important to emphasize that poly-fluorinated PFAS that are not fully fluorinated (‘precursors’) can be converted by bio-transformation into persistent, fully fluorinated chemicals, per-fluorinated PFAS. The complete microbiological degradation of PFAS has not yet been demonstrated.

In recent AFFFs (since about 2006 – 2015) the part of 6,2-FTAB and 6,2-FTS is very dominant and especial that one of 6,2-FTAB (Capstone B).

Figs. 1a & 1b show an **example of the biotransformation of 6 :2-FTAB & 6 :2-FTS** in soil and water to volatile Fluorotelomer Alcohols (FTOHs) which then migrate into soil gas (vapor) and ambient air. FTOHs are then microbiologically transformed into stable per-fluorinated PFASs. For example, 6:2-FTOH is biotransformed into PFHxA, PFPeA and PFBA and 8:2-FTOH into PFOA, PFHpA, PFHxA, PFPeA and PFBA. Fig 1c shows the Photolysis pathways of 6:2-FTAB.

In top-soils and in surface waters an additional chemo-transformation happens by UV-based photolysis. In this case the final degradation products could be even ultrashort PFAS, like PFPrA (Perfluoro propionic Acid) and TFA (Trifluoro acetic acid), beside PFHxA, PFPeA and PFBA (Naveed, A. et al 2024, cf. Fig 1c).

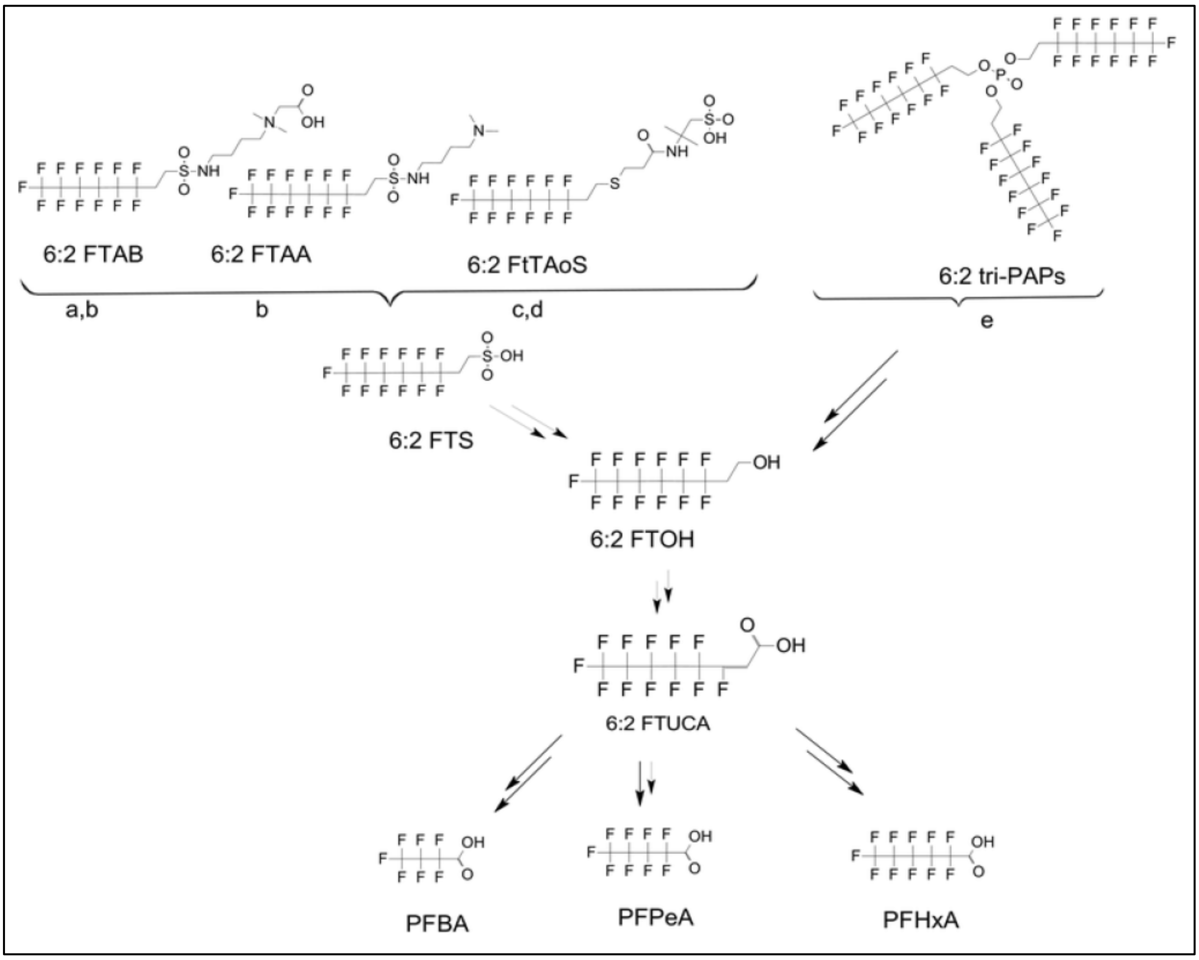


Fig. 1a : Biotransformation scheme of polyfluorinated PFAS (Precursors): Example: 6 :2 FTAB (Capstone B) and its degradation via 6 :2 FTS and 6 :2 FTOH to per-fluorinated PFAS PFBA, PFPeA and PFHxA (LaFond et al. 2023, D.M.J. Shaw et al. 2019,Ying Shi, 2018 and V. Mendeza et. al. 2022)

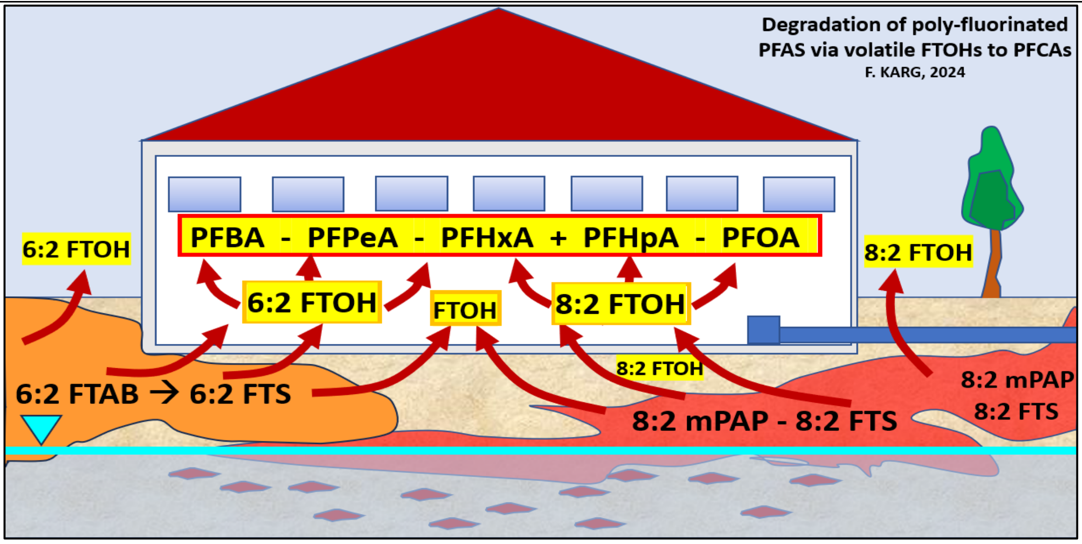


Fig. 1b : Example of the biotransformation of 6 :2 FTAB, 6 :2 FTS, 8 :2 FTS and polyfluorinated alkyl phosphates (PAP) in soil and water to Fluorotelomer alcohols (FTOH) and per-fluorinated PFAS, e.g. to PFOA, PFHpA, PFHxA, PFPeA and PFBA (L. KOPF / HPC, 2017 and F. KARG, 2022 & 2024).

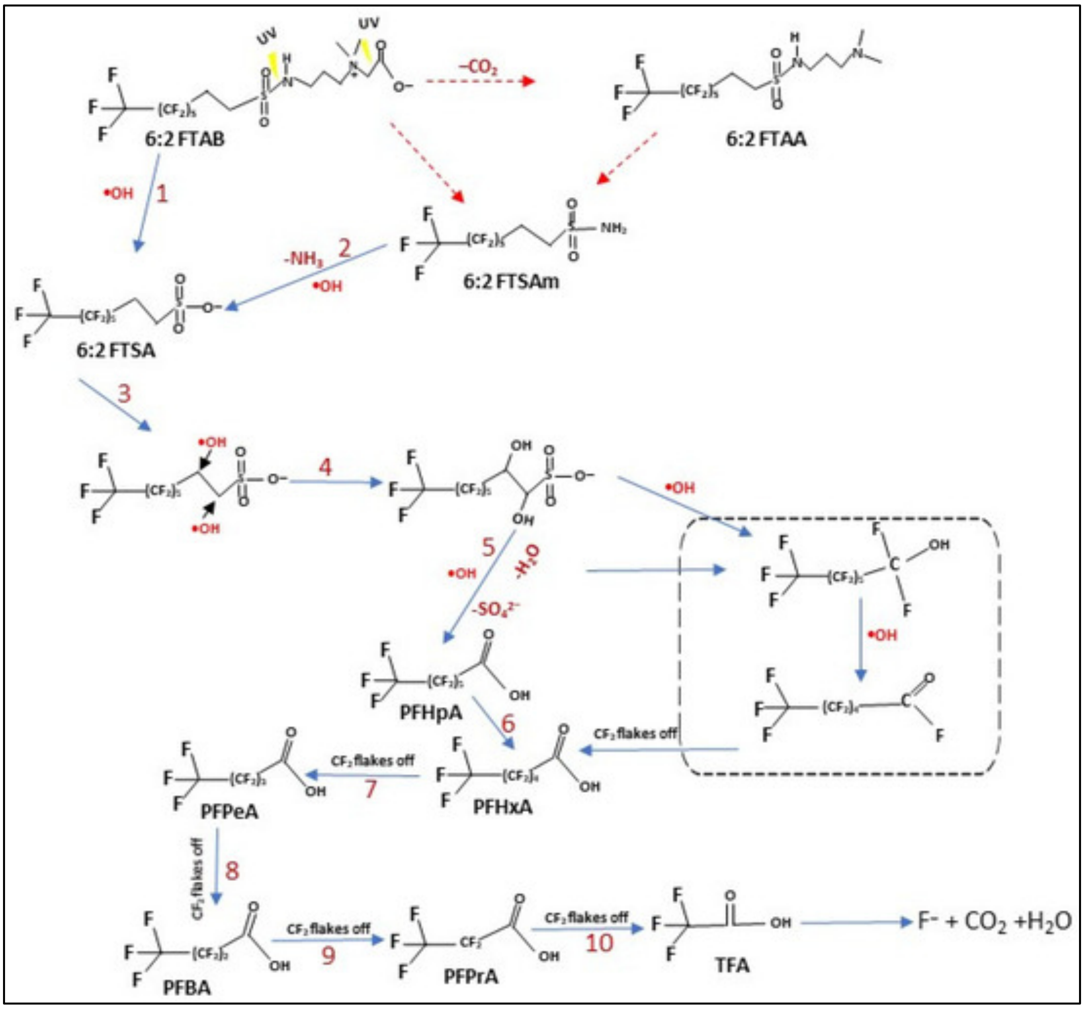


Fig. 1c: Photolysis of 6:2-FTAB to ultrashort PFAS, like PFPrA (Perfluoro propionic Acid) and TFA (Trifluoro acetic acid), beside PFHxA, PFPeA and PFBA (Naveed, A. et al 2024)

In the event of a change in pH, some PFAS may become more or less soluble, which also has an impact on emissions of volatile fluorinated telomers such as FTOH, etc. in soil gas (vapor). Certain precursors could change their solubility (and their extractable properties during chemical analysis procedures). For example, the intrusion of seawater into the aquifer could result in an increase in the basic pH and therefore in the solubility of Capstone B. This was observed in 2022 in the port area of Hamburg/Germany following seawater flooding and groundwater intrusion (see Fig. 2). These effects could result in groundwater concentrations more than 10 times higher than before seawater intrusion into the soil and groundwater.

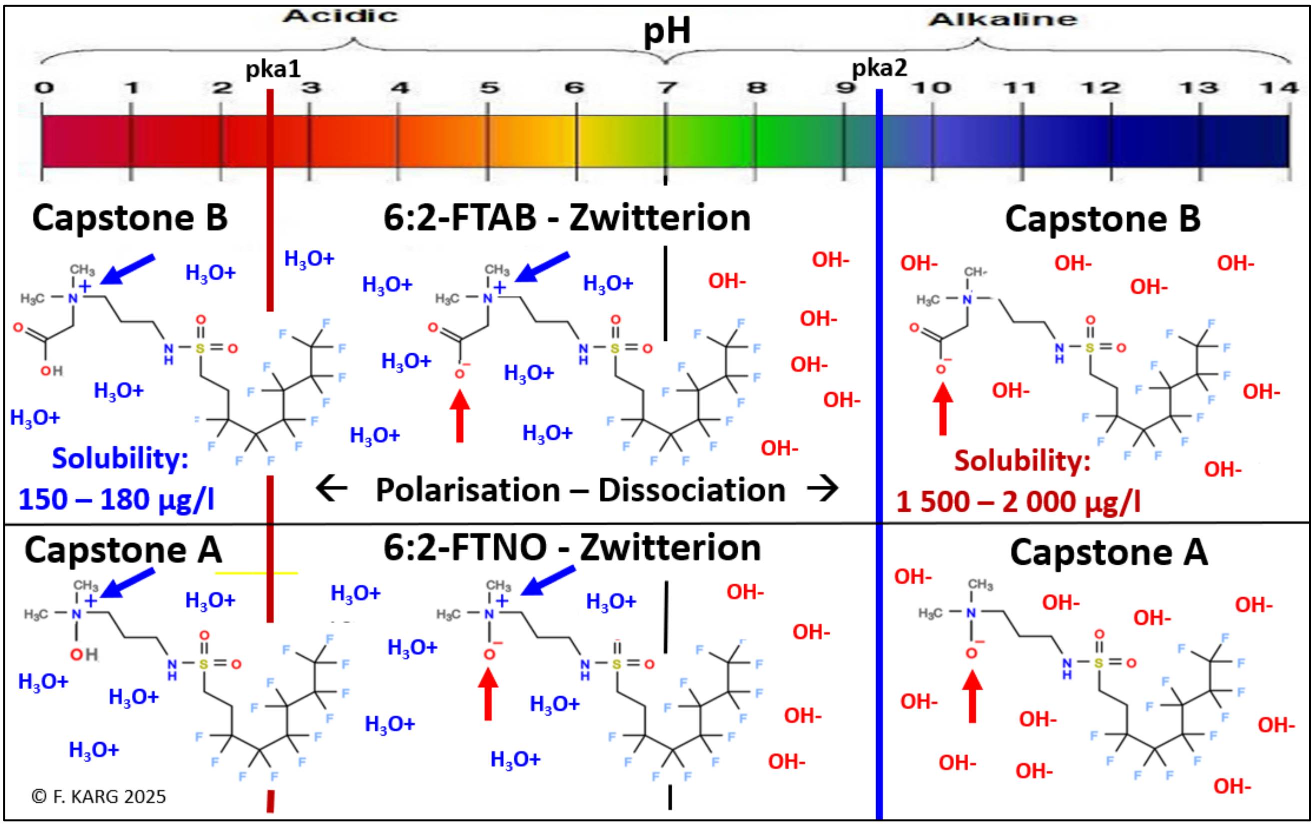


Fig. 2 : Solubility of 6:2-FTAB & 6:2-FTNO according to pH (example: before and after seawater intrusion into an aquifer and change to a slightly alkaline pH)

3. Differentiation of sources of PFAS pollution

Pollution of soil, groundwater and surface water by PFAS is frequently a mixture of several sources of commercial products and sources of pollution. It is possible to carry out complete screening of individual PFAS substances to identify between 9,000 and 12,000 molecules, but in the day-to-day management of pollution in the environment this is not applicable due to the limits of technical and economic feasibility.

For this reason, it is necessary to reduce the number of PFAS compounds to be analysed during environmental assessments by means of **the chemical Identification** of commercial products suspected of being the source of contamination. As PFAS are a family of more than 9,000 compounds, it would be impossible to quantify them all.

Typical sources of pollution caused by PFAS include, for example, applications of fire-fighting foams (AFFF = Aqueous Film Forming Foam or Anti Fire Fighting Foams), for example during fire drills and fires at airports, refineries and oil depots, industries involved in the production and processing of PFAS polymers, galvanizing activities such as chromium plating, the agricultural application of sewage WWTP sludge or fertilizers containing PFAS, the application of water-repellent coatings to paper, cardboard and textiles, etc., but also when they are used as flame retardants in the electrical and electronics industries... The list of sources of PFAS in the environment is long, and there are also volatile PFAS pollutants that can enter indoor air via soil gases, such as fluorotelomer alcohols (FTOH).

One of the current challenges in managing environmental problems linked to PFAS is to identify the various sources of pollution caused by PFAS or their commercial products, for example in the case of major contamination of groundwater by PFAS.

Experience and assessments of more than 800,000 PFAS analyses in soil, groundwater and surface water show the presence of various PFAS clusters and substances, such as perfluorinated carboxylic acids (PFCAs), perfluorinated sulphonic acids (PFSAs) and others, which are typical of certain industrial sectors. Other important PFAS groups are fluorotelomer sulphonic acids (FTS), fluorotelomer alcohols (FTOH) and fluorinated sulfo-betaines (FTAB), from a total of 33 different PFAS groups.

When identifying and differentiating PFAS sources, various relative concentration distributions, relationships with perfluorinated carboxylic acids (PFCAs) and with various poly-fluorinated PFASs as ‘precursors’, as well as various statistical distribution models, are taken into account.

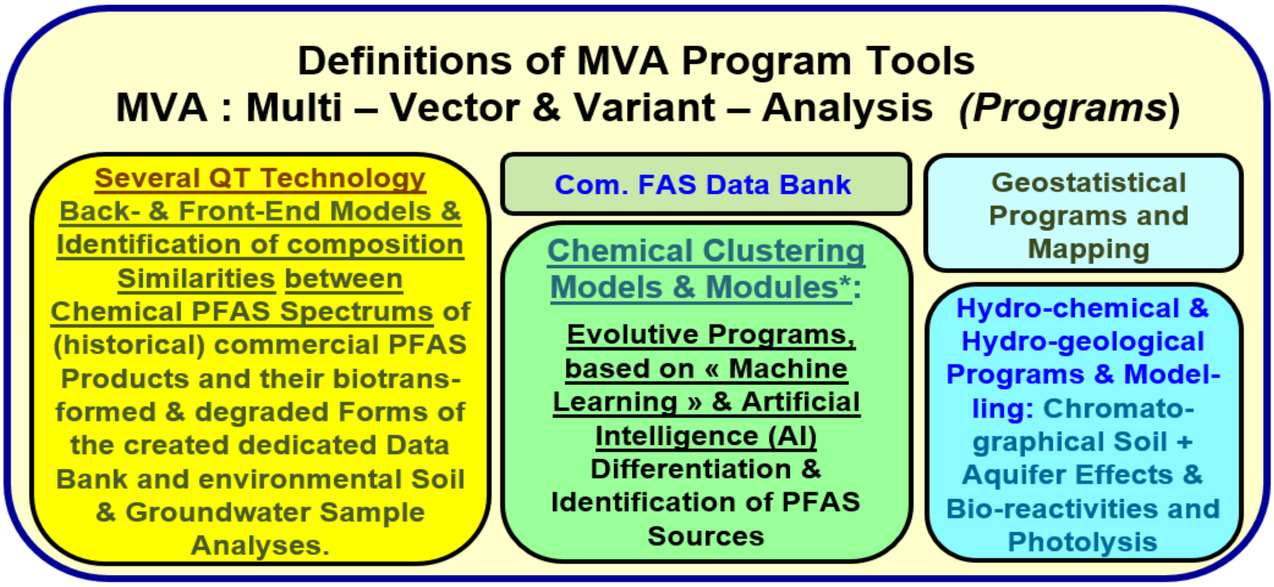
Commercial PFAS products are examined using non-target analyses to identify as many individual PFAS substances as possible present in PFAS products. To this end, percolation tests to simulate the ageing of ‘fresh’ commercial PFAS products are being carried out on lysimeters, with bacteriological degradation allowing the biotransformation of poly-fluorinated PFAS (precursors) to per-fluorinated PFAS, and to identify the chromatographic effects of soils (F. Karg et al.: 2023 and 2024).

The purpose is to record the resulting mixtures of individual PFAS molecules by HR-MS (high-resolution mass spectrometry). The results obtained are typical fingerprints of fresh and degraded commercial PFAS products for the complete database of parent mixtures of PFAS products.

PFAS sources can be identified from this database using standard analyses and a multivariate statistical identification program. Multi-Vector-Analysis (MVA) is carried out in several dimensions using artificial intelligence (machine learning), so that PFAS sources can also be determined in the event of groundwater pollution containing a mixture of several different PFAS sources.

The next figure shows:

- the different MVA program applications of Several Statistical QT Technology Back- & Front-End Models & Identification of composition Similarities between Chemical PFAS Spectrums of (historical) commercial PFAS Products and their biotransformed & degraded Forms of the created dedicated Data Bank and environmental Soil & Groundwater Sample Analyses.
- Chemical Clustering Models & Modules*: Evolutive Programs, based on « Machine Learning » & Artificial Intelligence (AI) Differentiation & Identification of PFAS Sources.
- Associated Geostatistical Programs & Mapping and Hydro-chemical & Hydro-geological Programs & Modelling for Chromato-graphical Soil + Aquifer Effects and Bio-reactivities & Photolysis.



Definitions of MVA Program Tools
MVA : Multi – Vector & Variant – Analysis *(Programs)*

Several QT Technology Back- & Front-End Models & Identification of composition Similarities between Chemical PFAS Spectrums of (historical) commercial PFAS Products and their biotrans-formed & degraded Forms of the created dedicated Data Bank and environmental Soil & Groundwater Sample Analyses.

Com. FAS Data Bank

Chemical Clustering Models & Modules*:

Evolutive Programs, based on « Machine Learning » & Artificial Intelligence (AI) Differentiation & Identification of PFAS Sources

Geostatistical Programs and Mapping

Hydro-chemical & Hydro-geological Programs & Model-ling: Chromato-graphical Soil + Aquifer Effects & Bio-reactivities and Photolysis

Fig.: Definitions of MVA Program Tools: Multi – Vector & Variant – Analysis (Programs)

In addition to the use of standard environmental analyses of polluted sites for MVA identification of the different sources of PFAS pollution, other analytical tools may also be applicable, such as the ‘Top Assay’ (Houtz & Sedlak: 2012, Glöckner et al.: 2021) to best determine the mass of poly-fluorinated precursors present, which can be oxidized to perfluorinated carboxylic acids (PFCAs) (see Fig. 3). In addition, measurements of isotope ratios between PFAS source areas and plume areas can be carried out to determine PFAS sources (Quian et al. 2023), as well as the use of comprehensive ‘untargeted analyses’, in which hundreds of individual PFAS molecules can be identified and at least semi-quantified.

Such applications are more time-consuming and expensive than the normal standard PFAS analysis for polluted sites, which is mainly used to identify PFAS sources. The MVA application can avoid this and be more cost-effective.

More than 9 000 – 12 000 PFAS have been polluting the environment and our health for decades. This also includes volatile PFAS, such as fluorotelomer alcohols (6:2 or 8:2 FTOH, etc.). The problem in investigating PFAS-contaminated sites lies mainly in the huge quantity of poly-fluorinated PFASs, which are biotransformed into per-fluorinated PFASs over time. Individual poly-fluorinated PFASs may also be relatively resistant in the environment and transform only very slowly into perfluorinated PFASs (such as Capstone B - FTAB, FTS or FTOH). In order to improve transparency and knowledge of this large number of PFAS pollutants, there are several approaches to the investigation, risk assessment and remediation of PFAS.

An important characteristic of PFASs is their chemical behavior in the environment, as poly-fluorinated PFASs (precursors) are converted to stable perfluorinated PFASs by biotransformation. The risk assessment of individual cases via a QSRA* (or RRA*) can estimate the future risks of most of the “precursors”, since an analysis based on 28 to 70 individual PFASs is carried out before and after examination by the ‘Top Assay’ test (see Fig. 3). In the Top Assay, poly-fluorinated PFAS are converted into stable per-fluorinated PFAS by oxidation via persulphate, into which they are generally biotransformed after a certain residence time in the environment (see also Fig. 2a & b). Thanks to the ‘Top Assay’ test, investigations and risk assessments include almost all transformable ‘precursors’ as well as the remaining per-fluorinated PFAS end products.

(*EQRS & *ARR: Quantitative Health Risk Assessment and Residual Risk Analysis).

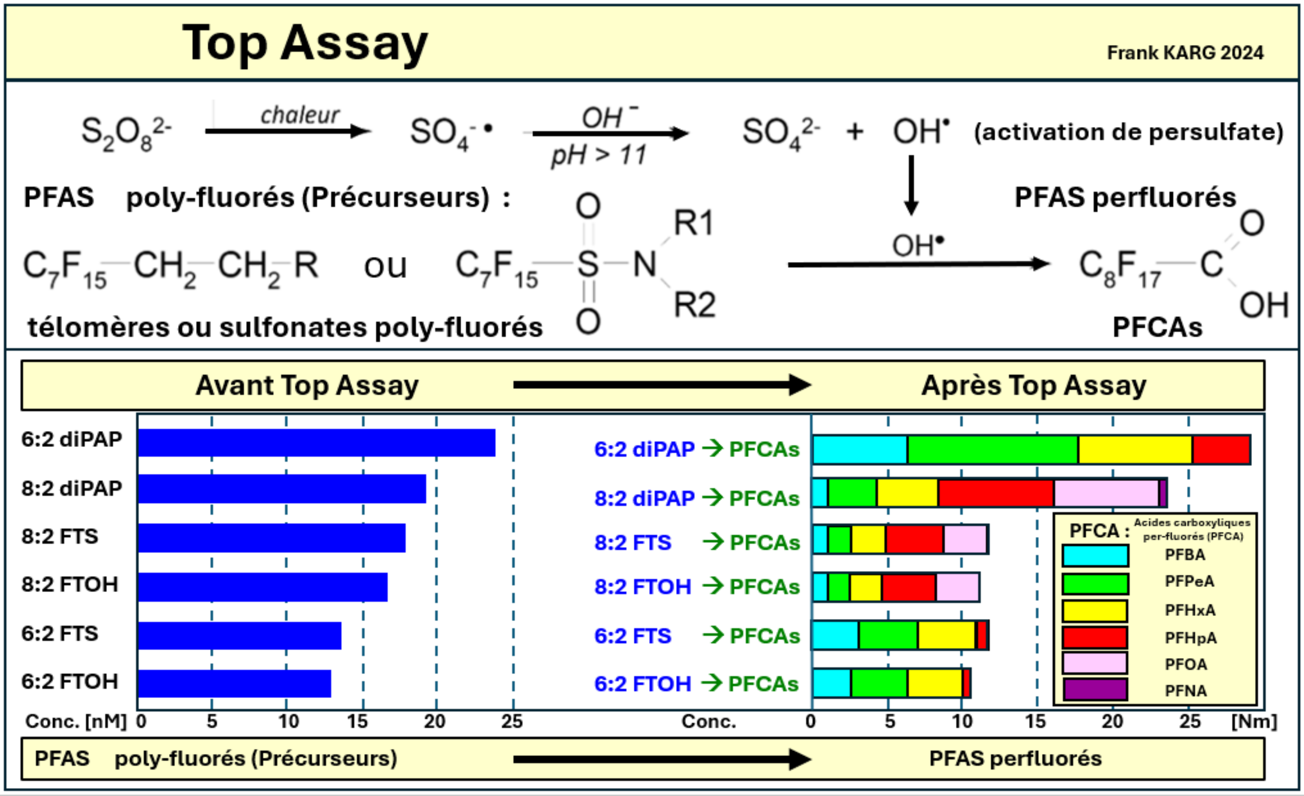


Fig. 3 : *Top Assay (Total Oxidizable Precursor method) to quantify oxidizable poly-fluorinated PFAS, transformable into per-fluorinated carboxylic acids (F. Karg 2015, Houtz & Sedlac 2012, Glöckner et al.: 2021).*

The following examples illustrate some of the ways in which sources of PFAS can be identified and differentiated using certain standard analyses, taking into account experience of MVA (Multi-Vector-Analysis) applications based on artificial intelligence in Europe (EU) and the United States.

Typical sources of PFAS include areas that have experienced fire and fire training events, civil and military airports (anti fire-fighting foams / AFFF), but other activities can also cause PFAS contamination in soils and groundwater.

These activities include, for example, the spreading of sewage sludge from wastewater treatment plants, galvanic chromium plating, landfill leachates, paper production, textile impregnation, the electrical and electronics industries, paint companies, cleaning products and fluor-polymer production, etc.

Various statistical analyses and visualizations, based on experiments and PFAS clusters from over 800,000 soil and groundwater analyses (NAS: 2023, F. Karg: 2024), help to identify PFAS sources.

The methodology for differentiation of PFAS sources can be divided into three main categories:

I. Analysis of data and (historical) information available that can be used to identify potential sources of PFAS at different sites (specific industrial sites airports, landfills, etc.).

II. Laboratory methods for analyzing PFAS in environmental samples.

III. Advanced forensic investigations to identify potential sources of PFAS more precisely.

Category I. includes the following phases :

- Historical investigation of potential sources of PFAS from suspect areas. The objective is to list and map the areas of potential sources of PFAS pollution.
- Study the hydrogeological zones above the suspected areas to determine whether there are (or have been) activities that use (or have used) PFAS.
- To obtain a detailed understanding of the geology, hydrogeology, hydrology, stormwater infrastructure and surface water run-off of the sites. This also includes the nature of the soil, the location and depth of nearby wells, and the depth and direction of surface and groundwater flow.
- Prepare a conceptual plan of the site concerning PFAS sources, transfer paths and exposure paths to targets.

Categories II and III focus on :

- Evaluation of PFAS chemical analysis data as a screening step to determine whether indications or evidence of source differentiation can be identified.
- Analysis of advanced PFAS forensics on selected samples to differentiate potential sources of PFAS (e.g. by structural isomerism, isotopic studies, Top Assay, MVA applications, etc.).

The general differences between PFAS's commercial products can be identified, for example, through the following distinctions:

- Modern anti fire-fighting foams (AFFF) are based on fluoro-telomers, mainly with C6-PFAS molecules. Although these firefighting foams do not contain PFOA or PFOS, when emitted into the environment they can degrade to other shorter-chain PFAS, such as perfluorohexanoic acid (PFHxA), perfluoro-pentanoic acid (PFPeA), buntanonic acid and 5:3 fluorotelomer carboxylic acid (FTCA).

- In the early 2000s (following general requests from the US and European authorities), the chemical industry began to phase out anti fire-fighting foams based on C8-PFAS, as PFOS and PFOA were classified as being “too toxic”. Producers of fluorotelomer-based firefighting foams then turned to the use of short-chain forms of PFAS with six fluorinated carbons (called C6-PFAS), which did not contain PFOS or PFOA (and could not be broken down into these products either). These C6-PFAS firefighting foams can also contain PFHxA, PFPeA and 6:2-fluorotelomersulphonate (6:2-FTS) as well as fluorotelomers, which can be transformed over time into their end groups, perfluoro carboxylic acids with less than six carbon atoms. The exact period of transition from C8-PFAS fire-fighting foams to C6-PFAS fire-fighting foams varies according to the application site (civil or military airports, fire training areas, oil sites, etc.).

- Before 2016, many firefighting foams contained PFAS with eight fluorinated carbon chains. Some of these long-chain firefighting foams, or C8 PFASs, contained PFOS until the early 2000s, and PFOA and other long-chain PFCAs until around 2015, when these products were withdrawn from the market.

- Analyses of the molecular chemical structures of PFASs can be useful in relation to existing information such as origin, period and likely use. Structural differences include, for example, structural isomerism (linear and branched isomers, etc.). For example, if a particular cyclic PFAS with an eight-carbon chain, such as perfluoroethyl-cyclohexane sulphonate (PFECHS: CAS 335-24-0) is observed, it could originate from a corrosion inhibitor used in aircraft hydraulic fluids (MPART: 2020). PFECHS is not known to be a component of fire-fighting foams.

- Specific PFASs can be used as markers in the production of fluoropolymers, food packaging and paper coatings, as well as cosmetics. They are not currently thought to be related to fire-fighting foam products.

- Some PFASs can be chemically biotransformed (i.e. broken down into smaller, stable chemicals), but these poly-fluorinated PFASs (precursors) often transform into other PFASs, particularly per-fluorinated PFAAs.

Identifying and differentiation of PFAS Contamination Sources:

The standard environmental analyses used during investigations of sites polluted by PFAS can, in principle, be used to identify and differentiate sources of PFAS. Between 30 and 70 individual PFAS substances are analyzed. The analytical data obtained can be very complex due to the presence of many different PFAS in an environmental sample and pose a challenge in interpreting the data. For this reason, a computerized MVA application with artificial intelligence is required.

Because of this complexity, large amounts of data need to be interpreted on the basis of statistical experience gained from large amounts of analysis in multi-vector analysis (MVA or poly-topic analysis) with artificial intelligence, so that the sources of PFAS can be identified and differentiated with a very high probability. This can only be done as part of a parallel analysis of different pieces of evidence, as each analysis on its own is generally not sufficiently significant. The basis for this are ‘target’ (and ‘non-target’) analyses as well as the ‘Top Assay’, total organic fluorine (TOF) or **AOF (adsorbable total organic fluorine) and isotopic analyses.**

The following Experiences can be applied for Identifying and differentiation of PFAS Contamination Sources:

- **TOF or Total Organo Fluorine is measuring PFAS Monomers & Polymers and other organo-fluorine Compounds, like Pesticides, Pharmaceuticals, etc. No Compound Identification is realized. The use of TOF can’t be really recommended for PFAS analysis appreciation.**
- **AOF: Adsorbable Organic Fluorine is only measuring compounds which were priorly adsorbed in Water samples. AOF is measuring PFAS Monomers, small PFAS Polymer particles and other organo-fluorine Compounds, like Pesticides, Pharmaceuticals, etc. No Compound Identification is realized. The use of AOF can’t be really recommended for PFAS analysis appreciation.**
- **NTA: Non-Target Analysis is the semi-quantitative Identification of up to 12 000 Compounds of PFAS Monomers. The costs and time needs are very important.**
- **QTA: Quantitative Target Analysis of up to 500 – 700 Compounds of PFAS Monomers (in general 20 – 70 compounds).**
- **QTA + TA: Quantitative Target Analysis after Top Assay of 20 - 200 Compounds PFCA Monomers (in general 20 – 70 compounds). Only per-fluorinated PFAS are analyzed, including poly-fluorinated PFAS after transformation to PFCA by persulfate.**

Recommended are QTA: Quantitative Target Analysis of about 70 choosen compounds before and after Top Assay. Its important to analyse via the QTA also the ultrashort PFCA, like TFA (trifluoro-acetic acid), PFPrA (perfluoro-propanoic acid), TFMS (trifluoro-methane-sulfonic acid), PFES (perfluoro-ethane-sulfonic acid) and PFPrS (perfluoro-propane-sulfonic acid).

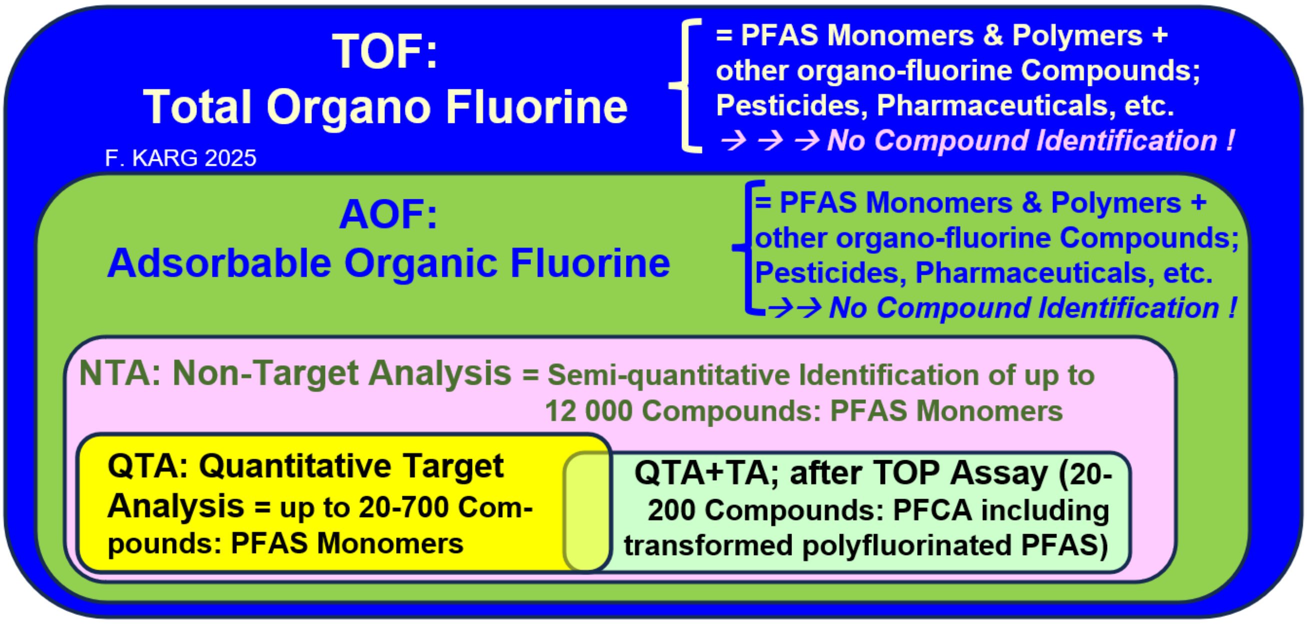


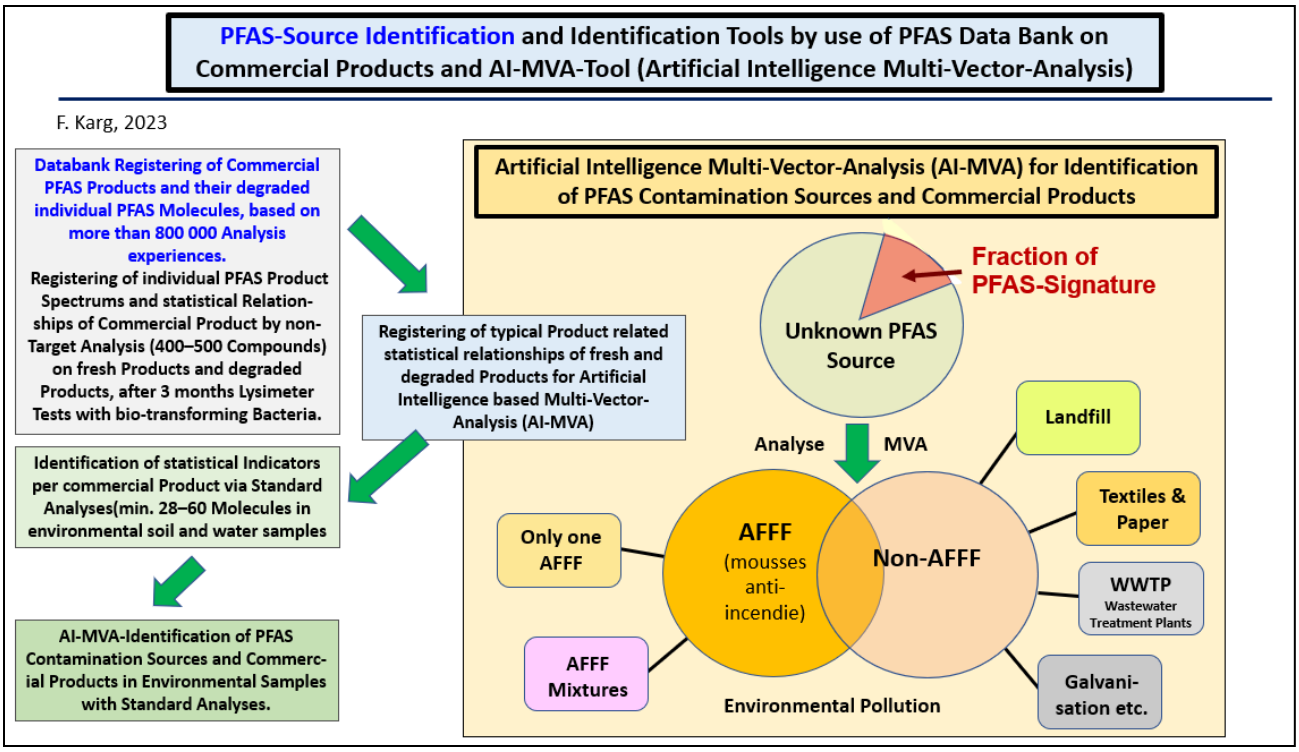
Fig. 4 : Analytical procedures for the identification and differentiation of PFAS sources using multi-vector analysis (MVA or poly-topic analysis) with artificial intelligence.

Figure 5 shows the procedure for identifying and differentiating potential sources of PFAS using MVA based on artificial intelligence (e.g. AFFF fire-fighting foams, sewage sludge, electroplating activities, textile and paper industries, waste dumps, etc.).

The procedure principles for identifying and differentiating potential PFAS Sources are the following:

A. **Lots of different Statistical Comparisons of Sample analyses with registered Standards** of chemical PFAS Spectrums on about 70 analyzed compounds from commercial PFAS Products (AFFF, Galvanic products, Paper related production Products, Surfactants mixtures, etc.).

B. Identification and Differentiation of PFAS Clusters by MVA on Artificial Intelligence via Clustering.



PFAS-Source Identification and Identification Tools by use of PFAS Data Bank on Commercial Products and AI-MVA-Tool (Artificial Intelligence Multi-Vector-Analysis)

F. Karg, 2023

Databank Registering of Commercial PFAS Products and their degraded individual PFAS Molecules, based on more than 800 000 Analysis experiences.

Registering of individual PFAS Product Spectrums and statistical Relationships of Commercial Product by non-Target Analysis (400–500 Compounds) on fresh Products and degraded Products, after 3 months Lysimeter Tests with bio-transforming Bacteria.

Registering of typical Product related statistical relationships of fresh and degraded Products for Artificial Intelligence based Multi-Vector-Analysis (AI-MVA)

Identification of statistical Indicators per commercial Product via Standard Analyses(min. 28–60 Molecules in environmental soil and water samples

AI-MVA-Identification of PFAS Contamination Sources and Commercial Products in Environmental Samples with Standard Analyses.

Artificial Intelligence Multi-Vector-Analysis (AI-MVA) for Identification of PFAS Contamination Sources and Commercial Products

Fig. 5 : MVA analysis approach based on artificial intelligence to identify and differentiate sources of PFAS (e.g. AFFF fire-fighting foams, sewage sludge, galvanic activities, textile and paper industries, waste dumps, petroleum sites, etc.) (F. Karg et al.: 2023 & 2024).

Because of the many individual PFASs within this chemical family, ‘non-target analysis’ also offers the possibility of identifying unknown molecules, as the result is open-ended without any limitation on a standard list of pre-calibrated pollutants. Hundreds of individual compounds can be identified. The disadvantage is that non-targeted analysis is relatively expensive and time-consuming. Figure 6 shows the differences compared with standard analysis of selected PFAS parameters.

Figure 6a shows different AFFFs in Soil samples and the 6:2-FTAB & 6:2-FTS domination. The similarity of these analytical results needs the MVA-Application for product identification. In Fig. 6b Biolysimeter-Tests are shown for obtaining different intermediary AFFFs’ bio-transformation steps under aerobic and anaerobic conditions. Figure 6c shows different stages of AFFF bio-transformation, example of “H4 (Hydral 3)”.

Figures 7 and 8 show PFAS cluster analyses to differentiate between several PFAS sources and Figure 9 shows PFAS Cluster Sources Overlapping and percentage parts of Groundwater pollution plume participation.

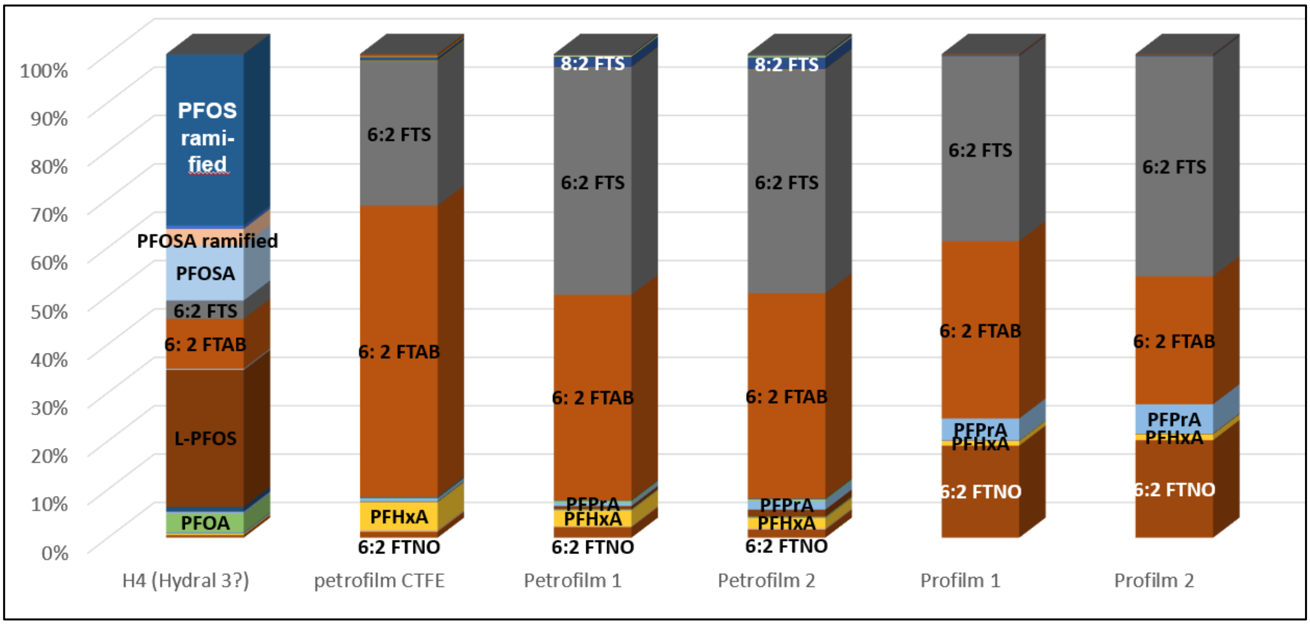
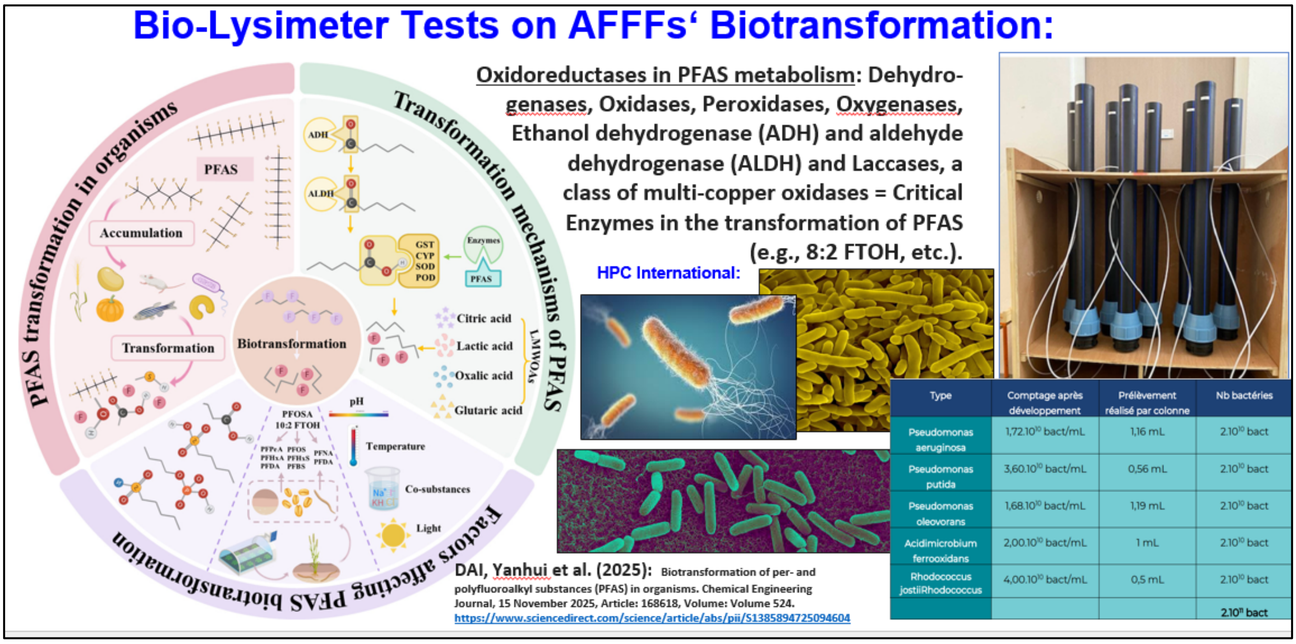


Fig. 6a: Different AFFFs in Soil samples and the 6:2-FTAB & 6:2-FTS domination.



Bio-Lysimeter Tests on AFFFs' Biotransformation:

Oxidoreductases in PFAS metabolism: Dehydrogenases, Oxidases, Peroxidases, Oxygenases, Ethanol dehydrogenase (ADH) and aldehyde dehydrogenase (ALDH) and Laccases, a class of multi-copper oxidases = Critical Enzymes in the transformation of PFAS (e.g., 8:2 FTOH, etc.).

HPC International:

Type	Comptage après développement	Prélèvement réalisé par colonne	Nb bactéries
Pseudomonas aeruginosa	$1{,}72.10^{10}$ bact/mL	1,16 mL	2.10^{10} bact
Pseudomonas putida	$3{,}60.10^{10}$ bact/mL	0,56 mL	2.10^{10} bact
Pseudomonas oleovorans	$1{,}68.10^{10}$ bact/mL	1,19 mL	2.10^{10} bact
Acidimicrobium ferrooxidans	$2{,}00.10^{10}$ bact/mL	1 mL	2.10^{10} bact
Rhodococcus jostiiRhodococcus	$4{,}00.10^{10}$ bact/mL	0,5 mL	2.10^{10} bact
			2.10^{11} bact

DAI, Yanhui et al. (2025): Biotransformation of per- and polyfluoroalkyl substances (PFAS) in organisms. Chemical Engineering Journal, 15 November 2025, Article: 168618, Volume: Volume 524. https://www.sciencedirect.com/science/article/abs/pii/S1385894725094604

Fig. 6b: Biolysimeter-Tests for obtaining different intermediary AFFFs' bio-transformation steps under aerobic and anaerobic conditions.

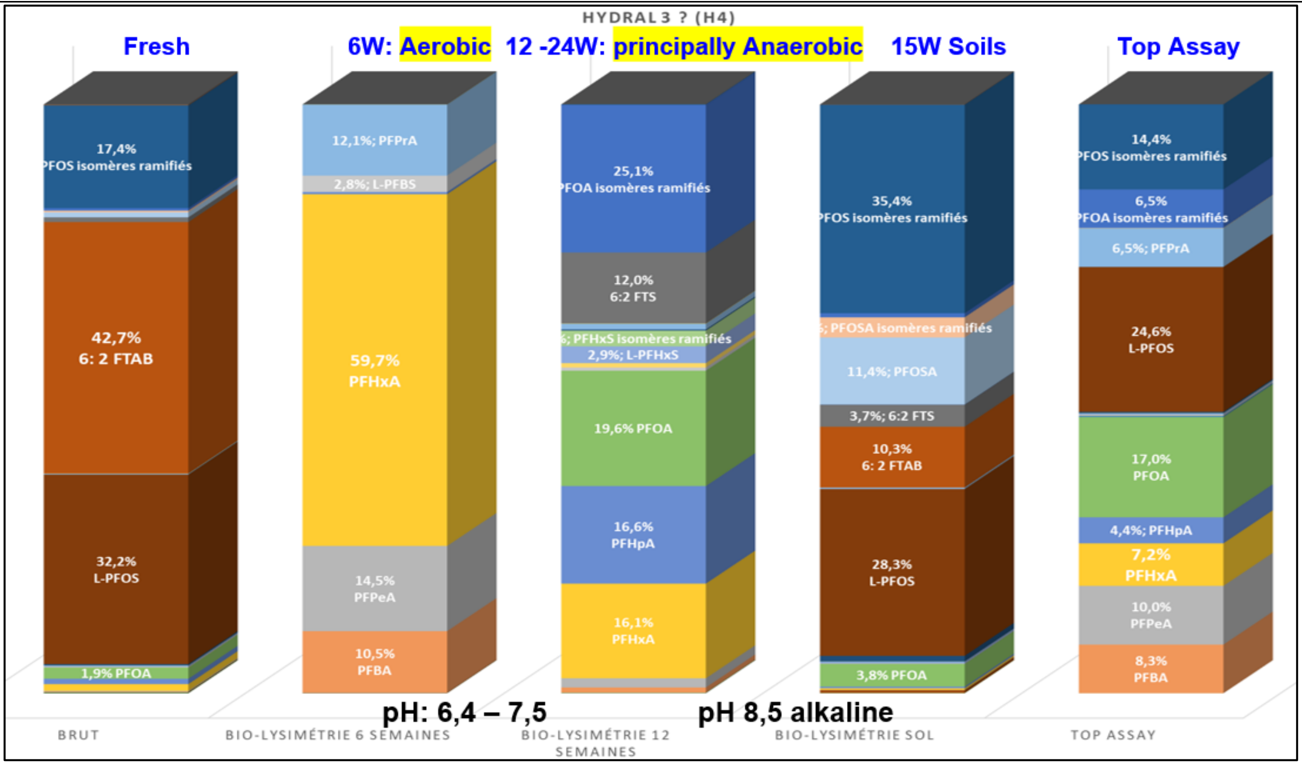


Fig. 6c: Different stages of AFFF bio-transformation, example of AFFF “H4 (Hydral 3)”.

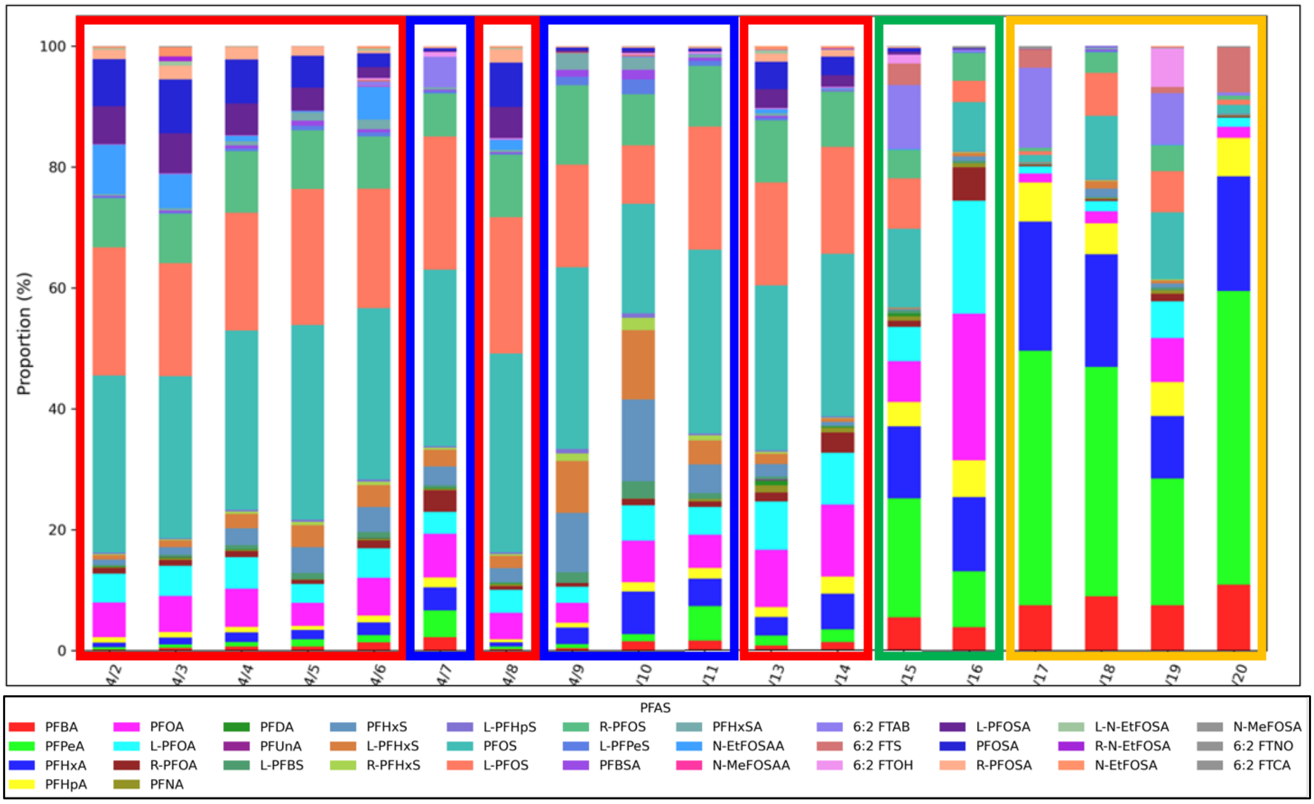


Fig. 7: Various PFAS Clusters and Cluster Mix, identified to determine the sources of PFAS

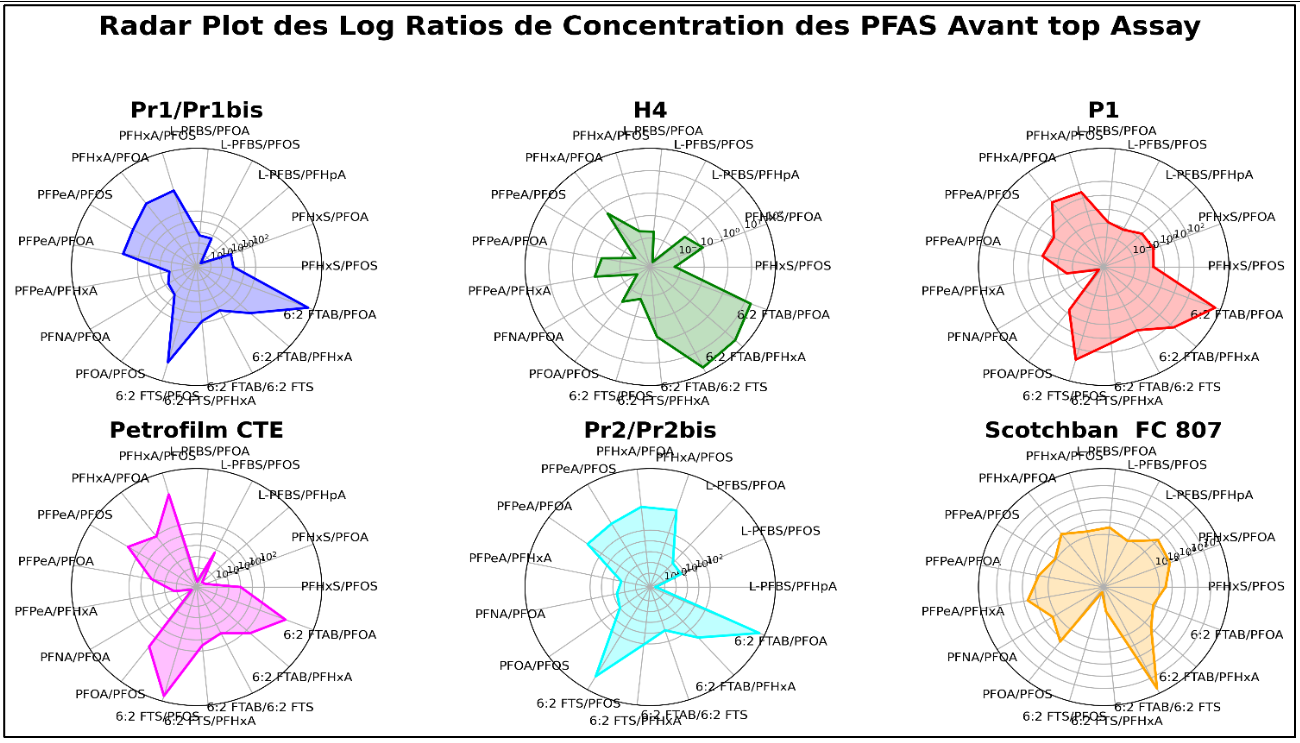
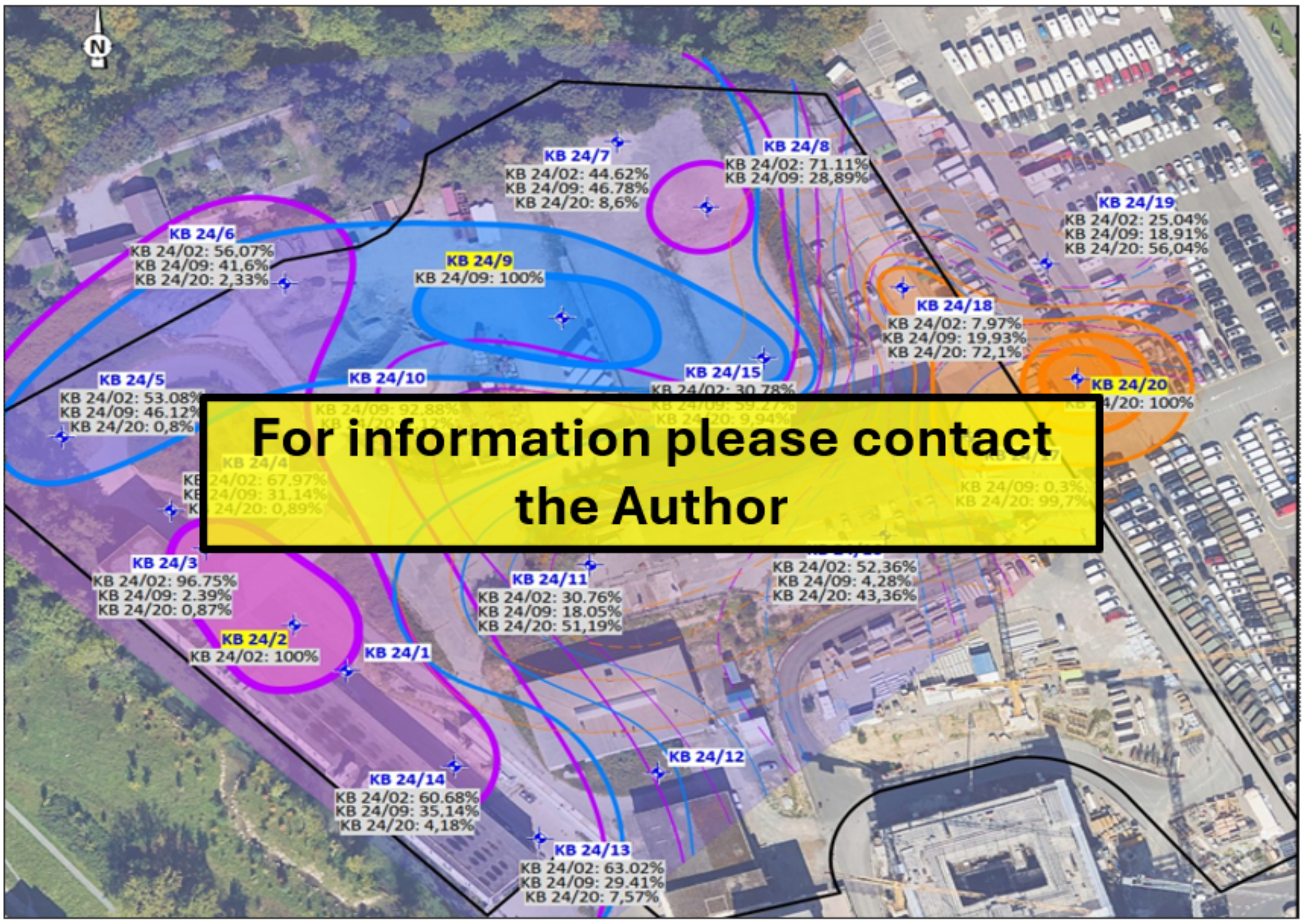


Fig. 8 : Various PFAS Clusters:Commercial PFAS Products and their chemical signature in Radargrams



For information please contact the Author

Fig. 9 : Identification and differentiation of 4 different Sources of 3 different PFAS Clusters and commercial

PFAS products on the basis of groundwater analysis and MVA-AI.

The multi-vector analysis (MVA) computer tool with artificial intelligence to identify and differentiate the sources of PFAS clusters was created on real commercial PFAS Product and environmental analyses.

The basis is, among others, the experiences of the US Airport Cooperative Research Program (ACRP), the Airports Council International - North America (ACI-NA), the American Association of Airport Executives (AAAE), the USA National Academy of Sciences Guide (NAS: 2023), as well as chemical cluster determinations of fresh commercial PFAS products and aged commercial PFAS products (according to degradation procedures applied by HPC International; F. Karg et al. 2023 - 2024) as standards for the MVA-PFAS database. The ageing of commercial PFAS products was carried out using bio-lysimetric tests in 2024 & 2025 with exposure to degrading bacteria for biotransformation of poly-fluorinated PFAS into per-fluorinated PFAS (F. Karg et al. 2023 – 2024, NAS, 2023).

The analysis of PFAS clusters takes into account the environmental chemistry of PFAS and in particular the metabolism or biotransformation of poly-fluorinated PFAS into stable per-fluorinated PFAS, e.g. the metabolism of poly-fluorinated PFAS into stable per-fluorinated PFAS, for example 6 :2 FTAB → 6:2-FTS → 6:2-FTOH → PFHxA + PFPeA + PFBA etc. to determine the 'precursors' and final products in the event of environmental contamination by mixtures of PFAS through the biotransformation chain.

Site-specific investigations and the identification and differentiation of PFAS sources include the following multi-criteria applied in the MVA tool. All the criteria are always applied at the same time:

A. **Concentration ratios between PFAS:** this is a simple first screening technique, where one or more concentration ratios between two or more different PFAS compounds can be applied. For example, PFHxS/PFOS ratios within a certain range have been used as an indicator of a source of fire-fighting foam (McGuire et al. 2014), and PFHxS/PFOA ratios have been identified as markers of other sources of industrial PFAS production (Guelfo and Adamson 2018).

B. **Circular diagrams and other data visualizations:** These are statistical graphs showing **the relative contribution of several molecules** to the total PFAS concentration in the same study area.
They can help identify compositional differences between PFAS mixtures in different samples to determine whether there are chemical clues or evidence from different PFAS sources. It can also identify the mixing of different PFAS sources or changes in source signatures along a transport pathway (e.g. migration in groundwater) and also reveal biotransformations and soil chromatography effects.

C. **Isomer ratios:** Individual PFAS can exist in **different isomeric forms** and the relative abundance of different isomers in a sample can be used to infer the source of PFAS (Charbonnet et al. 2021). **The presence of branched isomers (structural isomers) in a sample can be measured using standard methods** (which analyse around 60 to 70 individual substances). **The two different PFAS production processes, ECF (electrochemical fluorination) and telomerisation, result either in a mixture of branched and linear PFAS (ECF) or in isomers of purely linear PFAS.**

This information could be useful as evidence to identify sources of PFAS. **Branched isomers indicate that PFAS come from the specific electrochemical fluorination (ECF)** manufacturing process**.** The proportion of branched isomers in ECF products falls within a relatively narrow range (ITRC 2022 a&b). If the proportion of branched isomers in a sample is below this range, this may indicate that products containing PFAS generated by telomerisation-based manufacturing processes are also present.

Modern firefighting foams (AFFFs) contain PFASs that are produced solely by telomerization processes. Older AFFF blends may contain PFAS produced by ECF manufacture or telomerization. In the USA and somewhat later in Western Europe, the production of AFFF mixes using ECF production was discontinued in the early 2000s.

Another important fact is that branched isomers of some PFAS (e.g. PFOS) propagate more rapidly in groundwater than linear isomers of the same compound (different chromatographic effects in soil) due to the different interactions of the isomers with the soil. This can lead to enrichment of **ramified isomers** in groundwater hydro-geologically downstream of a PFAS source (Nickerson et al. 2020).

D. **Analysis of the main components of PFAS and hierarchical classification study of PFAS clusters:** These statistical methods are used to analyze data associated with many variables (e.g. measured PFAS) in order to identify differences between clusters of PFAS that can be visualized graphically. This data analysis facilitates the identification of different groups (or clusters) of PFAS mixtures (each of which may come from different sources or commercial PFAS products (see Figs. 7 & 8), which clusters may overlap).

E. **Research methods (screening): identification and characterization of sources of PFAS :**

- **Frequency of detection:** Experimental statistics (from over 800,000 individual analyses from different PFAS source locations) on the relative detection of individual PFAS (in each analysis data set) help to distinguish between different PFAS sources. The absence (or low frequency of detection) of specific PFAS in samples from one type of site can also be used in the same way. Experiments with over 800,000 individual analyses of samples from various PFAS source locations show very clearly these differences depending on the PFAS source (NAS: 2023).

- **Concentration distributions:** These data help to determine the relative distribution of individual PFAS found in environmental samples from different locations. The average concentration of individual PFAS from the samples examined is used in the MVA assessment (see Fig. 7a - d). These data provide information on the relative proportion of different PFAS sources in a given site type, as well as the relative presence of PFAS associated with different sources.

- **PFAS composition ratios:** These ratios show the general distribution of PFAS within the sample groups. This includes the percentage of perfluoroalkyl carboxylic acids (PFCAs), perfluoroalkyl sulphonic acids (PFSAs) and non-perfluoroalkyl acids (non-PFAAs) relative to the total of overlapping PFAS mixtures (e.g. present in groundwater). The application of this methodology also includes the quantification of concentration ratios between frequently detected individual PFASs.

- **Statistics for identifying and characterizing sources of PFAS using multi-vector analysis (MVA):**

The results of the PFAS source determination are presented in five different types of statistical visualizations of PFAS source categories. These five types of MVA are:

- **MVA1 : PFAS composition circular diagrams,**
- **MVA2 : Boxplot distribution of concentrations and PFAS histograms,**
- **MVA3 : Average PFAS concentrations and detection frequency: Heat-Maps,**
- **MVA4 : Average PFAS concentration and detection frequency: 'Cross-plots',**
- **MVA5 : Report of PFAS logarithmic average concentrations: Relative and radial point diagrams.**

Additionally AI based Clustering is used for cartographical visualization of geographical PFAS Clusters.

Figure 10 shows a summary of the parameters evaluated for the identification and differentiation of AI-MVA (artificial intelligence-based multi-vector analysis) PFAS sources.

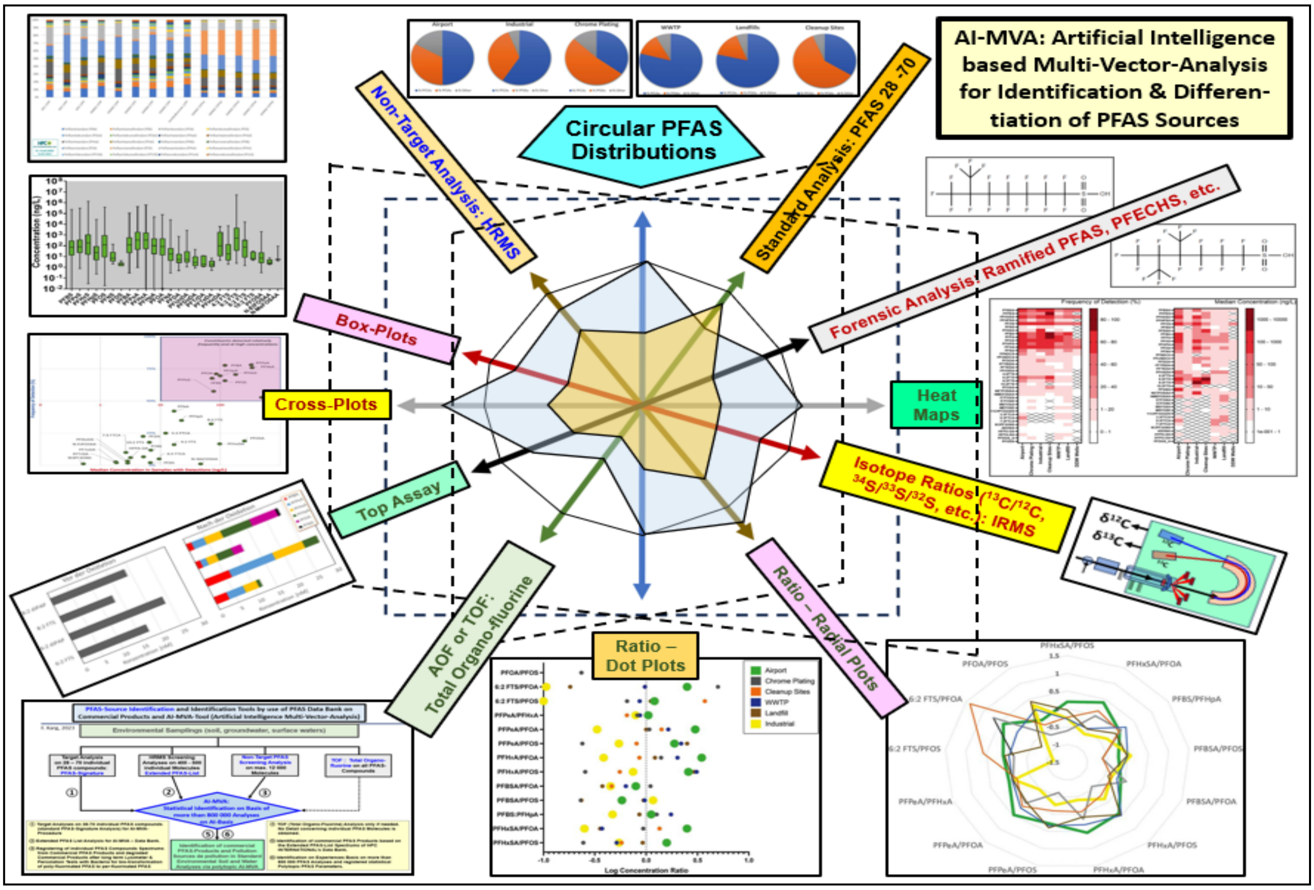
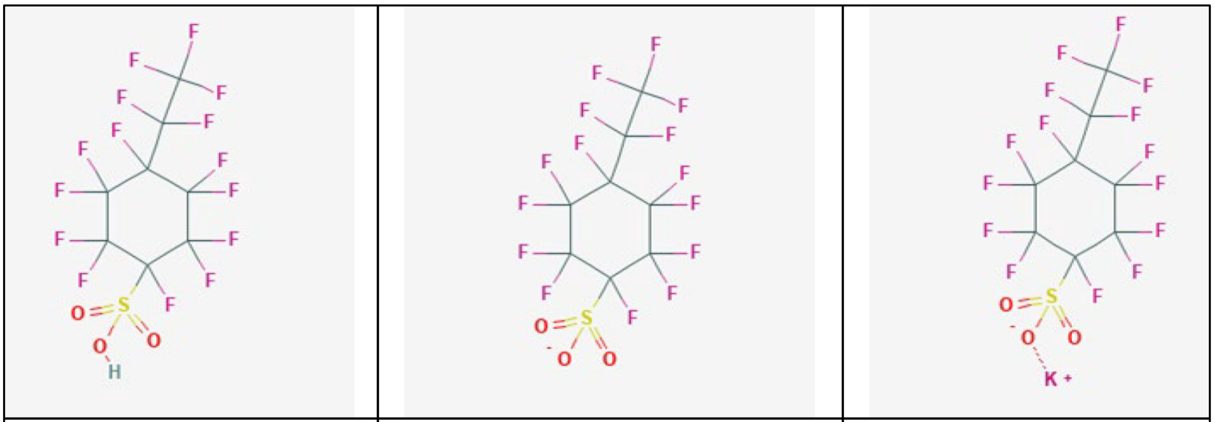


Fig. 10 : Parameters evaluated for the identification and differentiation of PFAS sources additional to AI-Clustering using AI-MVA (artificial intelligence-based multi-vector analysis),

Difficulties:

Some PFAS shows severe problems of laboratory extraction & analysis capabilities, for ex. the perfluoro PFAS of PEFCHS speciations, typical for Aviation Hydraulic oils. The reasons are the different polarities, according the PH Environments, cf. Fig. 11. In this case environmental samples should be treated by extractions under different pH conditions (alkaline, acid and neutral) before analyses.



$C_8HF_{15}O_3S$	$C_8F_{15}O_3S^-$	$C_8F_{15}KO_3S$

Fig. 11: The perfluoro PFAS speciations of PEFCHS, typical for Aviation Hydraulic oils under different pH conditions (alkaline, acid and neutral) before analyses.

Table 1a & b shows the recommended standard analysis parameters for using the multi-vector analysis (MVA) computer tool with artificial intelligence to identify and differentiate sources of PFAS.

PFAS	LQ Eaux		CAS	VTR	Dir. CE EP2020/ 2184	AM 20/06/23 France
PFBA (acide perfluorobutanoique)	ng/l	1	375-22-4	🟩	🟩	🟩
PFPeA (acide perfluoropentanoique)	ng/l	5	2706-90-3	🟩	🟩	🟩
PFHxA (acide perfluorohexanoique)	ng/l	1	307-24-4	🟩	🟩	🟩
PFHpA (acide perfluoroheptanoique)	ng/l	1	375-85-9	🟩	🟩	🟩
PFOA linéaire (acide perfluorooctanoique)	ng/l	1	335-67-1	🟩	🟩	🟩
PFOA ramifié (acide perfluorooctanoique)	ng/l	1	335-67-1	🟩	🟥	🟥
PFOA totale (acide perfluorooctanoique)	ng/l	1	335-67-1	🟩	🟥	🟥
PFNA (acide perfluorononanoique)	ng/l	1	375-95-1	🟩	🟩	🟩
PFDA (acide perfluorodecanoique)	ng/l	1	335-76-2	🟩	🟩	🟩
PFUnDA (acide perfluoroundecanoique)	ng/l	1	2058-94-8	🟩	🟩	🟩
PFDoDA (acide perfluorododecanoique)	ng/l	2	307-55-1	🟩	🟩	🟩
PFTrDA (acide perfluorotridecanoique)	ng/l	1	72629-94-8	🟩	🟩	🟩
PFTeDA (acide perfluorotetradecanoique)	ng/l	1	376-06-7	🟩	🟥	🟩
PFHxDA (acide perfluorohexadecanoique)	ng/l	2	67905-19-5	🟩	🟥	🟩
PFODA (acide perfluorooctadecanoique)	ng/l	1	16517-11-6	🟩	🟥	🟩
PFBS (acide perfluorobutane sulfonique)	ng/l	1	375-73-5	🟩	🟩	🟩
PFPeS (acide perfluoropentane sulfonique)	ng/l	1	2706-91-4	🟩	🟩	🟩
PFHxS linéaire (acide perfluorohexane sulfonique)	ng/l	1	355-46-4	🟩	🟩	🟩
PFHxS ramifié (acide perfluorohexane sulfonique)	ng/l	1	355-46-4	🟥	🟥	🟥
PFHxS totale	ng/l	1	355-46-4	🟥	🟥	🟥
PFHpS (acide perfluoroheptane sulfonique)	ng/l	1	375-92-8	🟩	🟩	🟥
PFOS linéaire (acide perfluorooctane sulfonique)	ng/l	1	1763-23-1	🟩	🟩	🟥
PFOS ramifié (acide perfluorooctane sulfonique)	ng/l	1	1763-23-1	🟥	🟥	🟥
PFOS totale (acide perfluorooctane sulfonique)	ng/l	1	1763-23-1	🟥	🟥	🟥
PFDS (acide perfluorodecane sulfonique)	ng/l	1	335-77-3	🟩	🟩	🟥
4:2 FTS (acide 4:2 fluorotelomer sulfonique) H4-PFOS	ng/l	1	757124-72-4	🟩	🟥	🟥
6:2 FTS (acide 6:2 fluorotelomer sulfonique)	ng/l	1	27619-97-2	🟩	🟥	🟥
8:2 FTS (acide 8:2 fluorotelomer sulfonique)	ng/l	1	39108-34-4	🟥	🟥	🟥
10:2 FTS (acide 10:2 fluorotelomer sulfonique)	ng/l	1	120226-60-0	🟥	🟥	🟥
MePFOSAA (acide N-méthylperfluorooctane sulfonamide acétique)	ng/l	1	2355-31-9	🟥	🟥	🟥
EtFOSAA (acide N-éthylperfluorooctane sulfonamide acétique)	ng/l	1	2991-50-6	🟥	🟥	🟥
PFOSA linéaire (perfluoro-n-octanesulfonamide)	ng/l	2	754-91-6	🟩	🟥	🟥
PFOSA ramifié (perfluoro-n-octanesulfonamide)	ng/l	2	754-91-6	🟥	🟥	🟥
PFOSA totale (perfluoro-n-octanesulfonamide)	ng/l	2	754-91-6	🟥	🟥	🟥
MeFOSA linéaire (N-méthylperfluorooctanesulfonamide) (MePFOSA)	ng/l	1	31506-32-8	🟥	🟥	🟥
6:2-FTAB (6 :2 fluorotelomer sulfonamido propyl betaine) Capstone B	ng/l	10	34455-29-3	🟥	🟥	🟥

Table 1a: Recommended standard analysis parameters for using the multi-vector analysis (MVA) computer tool with artificial intelligence to identify and differentiate sources of PFAS.

PFAS	LQ Eaux		CAS	VTR	Dir. CE EP2020/ 2184	AM 20/06/23 France
MeFOSA ramifié (N-méthylperfluoro-n-octanesulfonamide) (MePFOSA)	ng/l	1	31506-32-8	🟥	🟥	🟥
MeFOSA totale (N-méthylperfluoro-n-octanesulfonamide) (MePFOSA)	ng/l	1	31506-32-8	🟥	🟥	🟥
8:2 DiPAP (8:2 polyfluoroalkyl phosphate diester)	ng/l	1	678-41-1	🟥	🟥	🟥
HFPO-DA (acide hexafluoropropyleneoxide dimer) Gen X	ng/l	1	13252-13-6	🟥	🟥	🟩
EtFOSA linéaire (N-éthylperfluorooctanesulfonamide) (EtPFOSA)	ng/l	1	4151-50-2	🟥	🟥	🟥
EtFOSA ramifié (N-éthylperfluorooctanesulfonamide) (EtPFOSA)	ng/l	1	4151-50-2	🟥	🟥	🟥
EtFOSA totale (N-éthylperfluorooctanesulfonamide) (EtPFOSA)	ng/l	1	4151-50-2	🟥	🟥	🟥
MeFBSAA (perfluorobutanesulfonamide(N-méthyl)acetate)	ng/l	5	159381-10-9	🟥	🟥	🟥
5:3-FTCA: 5:3 acide carboxylique fluorotélomère)	ng/l	1	914637-49-3	🟥	🟥	🟥
6-2-FTCA: 6:2 acide carboxylique fluorotélomère	ng/l	5	53826-12-3	🟥	🟥	🟥
8:2 FTUCA (acide 2H-perfluoro-2-décenoique)	ng/l	1	70887-84-2	🟥	🟥	🟥
DONA (acide 4,8-dioxa-3H-perfluorononanoique)ADONA	ng/l	1	919005-14-4	🟩	🟥	🟩
MeFBSA (n-méthylperfluorobutanesulfonamide)	ng/l	1	68298-12-4	🟥	🟥	🟥
PFBSA (perfluorobutanesulfonamide)	ng/l	1	30334-69-1	🟥	🟥	🟥
PFECHS (acide perfluoro-4-éthylcyclohexanesulfonique)	ng/l	1	646-83-3	🟥	🟥	🟥
PFNS (acide perfluorononane sulfonique)	ng/l	1	68259-12-1	🟩	🟩	🟩
PFDoDS (acide perfluorododecane sulfonique)	ng/l	1	79780-39-5	🟩	🟩	🟩
6:2 diester de phosphate fluorotélomérique. 6:2 diPAP	ng/l	10	57677-95-9	🟥	🟥	🟥
6:2 8:2 diester de phosphate fluorotélomérique. 6:2 8:2 diPAP	ng/l	10	943913-15-3	🟥	🟥	🟥
PFHxSA (perfluorohexanesulfonamide)	ng/l	1	41997-13-1	🟥	🟥	🟥
PFUnDS (acide perfluoroundecane sulfonique)	ng/l	2	749786-16-1	🟩	🟩	🟩
PFTrDS (acide perfluorotridecane sulfonique)	ng/l	2	791563-89-8	🟩	🟩	🟩
EtFOSE (2-(N-ethylperfluoro-1-octanesulfonamido)-ethanol)	ng/l	5	1691-99-2	🟥	🟥	🟥
MeFOSE (2-(N-methylperfluoro-1-octanesulfonamido)-ethanol)	ng/l	5	24448-09-7	🟥	🟥	🟥
NFDHpA (Nonafluoro-3,6-dioxaheptanoic acid)	ng/l	1	151772-58-6	🟥	🟥	🟥
PFMPA (Perfluoro-3-methoxypropanoic acid)	ng/l	1	377-73-1	🟥	🟥	🟥
PFMBA (perfluoro-4-methoxybutanoic acid)	ng/l	1	863090-89-5	🟥	🟥	🟥
C6O4 (Perfluoro([5-methoxy-1,3-dioxolan-4-yl]oxy)acetic acid)	ng/l	10	1190931-41-9	🟩	🟥	🟩
6:2-FTOH (6:2 fluorotelemer alcohol) FHET	ng/l	20	647-42-7	🟩	🟥	🟩
8:2-FTOH (8:2 fluorotelemer alcohol) FOET	ng/l	10	678-39-7	🟩	🟥	🟩
PFAS Ultrashorts :						
TFA (trifluoroacetic acid)	ng/l	10				
PFPrA (perfluoropropanoic acid)	ng/l	10				
TFMS (trifluoromethanesulfonic acid)	ng/l	10				
PFES (perfluoroethanesulfonic acid)	ng/l	10				
PFPrS (perfluoropropanesulfonic acid)	ng/l	10				

Table 1b: Recommended standard analysis parameters for using the multi-vector analysis (MVA) computer tool with artificial intelligence to identify and differentiate sources of PFAS.

Summary

In the context of groundwater pollution by PFAS, it is becoming increasingly important to identify and, above all, to differentiate the contribution of each PFAS source to pollution plumes. This need for clarification of the contribution of each PFAS source to pollution, e.g. in the vicinity of catchments (for drinking water, etc.), is becoming increasingly crucial for the protection of water resources, (shared) responsibilities and the search for the (multiple) origins of pollution in the context of legal expertise.

Some PFAS shows severe problems of laboratory extraction & analysis capabilities, for ex. the perfluoro PFAS of PEFCHS speciations, typical for Aviation Hydraulic oils. The reasons are the different polarities, according the pH Environments. In this case environmental samples should be treated by extractions under different pH conditions (alkaline, acid and neutral) before analyses.

To conclude, it is now possible (using comprehensive statistical, graphical & chemical-mathematical studies, including Artificial Intelligence based Clustering with Machine Learning) to use the Multi-Vector-Analysis (MVA) in several dimensions to identify and differentiate the sources of PFAS pollution in soils, groundwater and surface water, and in some cases even to identify the commercial PFAS products causing the pollution.

The procedure principles for identifying and differentiating potential PFAS Sources are the following:

A. Lots of different Statistical Comparisons of Sample analyses with registered Standards of chemical PFAS Spectrums on about 70 analyzed compounds from commercial PFAS Products (AFFF, Galvanic products, Paper related production Products, Surfactants mixtures, etc.).

B. Identification and Differentiation of PFAS Clusters by MVA on Artificial Intelligence via Clustering.

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The legal issues and financial implications of PFAS

Per- and polyfluoroalkylated substances (PFAS) consist of approximately 10, 000 substances presenting non-stick, heat-resistant and waterproofing properties. Yet the PFAS belong to a large family of endocrine disruptors and constitute harmful pollutants to the environment and human health.

PFAS contamination at both European and national scales is well documented and has been confirmed through various channels, requiring action to mitigate its health and environmental impacts and to control the financial costs of decontamination.

French law no°2025-188 of February 27, 2025, aiming at protecting the population from the risks associated with PFAS, strengthens the regulatory framework starting on January 1st, 2026, by prohibiting certain PFAS-containing products, including cosmetics, clothing and wax products. A broader ban under the REACH Regulation no°1907/2006 of Decembre 18, 2006, is currently discussed at the European level and could be adopted by 2027.

In the water sector, the regulatory framework is also evolving on January 1st, 2026, with the decree implementing PFAS law no°2025-1287 of December 22, 2025, which requires French Regional Health Agencies to monitor drinking water quality and to analyze the twenty priority substances identified in the European Union Drinking Water Directive of December 16, 2020. This monitoring will be extended as of January 1st, 2027, to two additional substances: the 6:2 fluorotelomer sulfonic acid (FTSA) and trifluoroacetic acid (TFA), marking an improvement of the regulatory framework. The European Union has recently highlighted the need to update the lists of the twenty priority substances in surface waters and groundwaters and to include the TFA in light of the latest scientific evidence.

The recent European Commission's assessment of the financial costs associated with PFAS contamination at the European level emphasizes the importance of implementing concrete measures to reduce societal costs. In France, the PFAS law of February 27, 2025, completed by the financial law of February 2nd, 2026, introduces a fee on PFAS-related water pollution and implements measures to address PFAS pollution by applying the polluter-pays principle.

Laurence Lanoy, a lawyer specializing in environmental law, will give an overview of evolutions in the regulatory framework for these substances of concern, and present the issues relating to decontamination and its financial cost.

* * *

A lawyer since 1990 and holder of a doctorate in law, Laurence Lanoy developed an in-depth practice in environmental law before founding Laurence Lanoy Avocats in 2005. She advises and assists national and international companies, public authorities and international law firms, notably in environmental and sustainable development law, mining law and energy law.

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Les enjeux juridiques et les implications financières des PFAS

Les substances per- et polyfluoroalkylées (PFAS) regroupent environ 10 000 substances présentant des propriétés antiadhésives, imperméables, résistantes aux fortes chaleurs, qui appartiennent à une grande famille de perturbateurs endocriniens et qui ont un impact sur la santé publique et l'environnement.

La contamination aux PFAS sur le territoire européen et en France est avérée par le biais de différents vecteurs imposant d'agir pour en limiter les impacts sanitaires et environnementaux et maitriser à terme les coûts financiers de la dépollution.

En France la loi n°2025-188 du 27 février 2025 visant à protéger la population des risques liés aux PFAS fait évoluer la réglementation en interdisant dès le 1^er^ janvier 2026 certains produits contenant des PFAS, comme les cosmétiques, les vêtements ou encore les produits de fart. Une interdiction généralisée dans le cadre du Règlement REACH du 18 décembre 2006 est par ailleurs en cours de discussion à l'échelle européenne et devrait aboutir en 2027.

La réglementation évolue également en matière d'eau avec le décret d'application de la loi PFAS n°2025-1287 du 22 décembre 2025 qui impose, à compter du 1^er^ janvier 2026, de rechercher les 20 substances prioritaires dans le cadre du contrôle sanitaire de la qualité des eaux potables réalisé par les Agences Régionales de Santé. Ce contrôle est élargi à l'acide 6 : 2 fluorotélomersulfonique (FTSA) et à l'acide trifluoroacétique (TFA) à compter du 1^er^ janvier 2027, marquant une véritable évolution de la réglementation. L'Union européenne a d'ailleurs récemment souligné la nécessité de mettre à jour la liste des substances PFAS prioritaires pour les eaux de surface et souterraines et notamment d'y intégrer le TFA afin de tenir compte des dernières données scientifiques.

Enfin, la récente évaluation du coût financier de la pollution aux PFAS à l'échelle européenne réalisée par la Commission européenne illustre la nécessité de prendre des mesures concrètes afin de limiter considérablement les coûts sociétaux. En France, la redevance pour pollution de l'eau par des substances PFAS insérée par la loi du 27 février 2025 et précisée par la loi de finances du 2 février 2026 est une mise en œuvre de la prise en charge de la pollution par les PFAS en appliquant le principe pollueur-payeur.

Laurence Lanoy, avocat spécialiste en droit de l'environnement, effectuera un tour d'horizon des évolutions du cadre réglementaire concernant ces substances préoccupantes, en présentant les enjeux relatifs à la dépollution et à son coût financier.

* * *

Avocat depuis 1990 et Docteur en droit, Laurence Lanoy a développé une pratique approfondie en droit de l'environnement avant de fonder en 2005 le cabinet Laurence Lanoy Avocats. Elle conseille et assiste des entreprises nationales et internationales, des collectivités publiques et des cabinets d'avocats internationaux notamment en droit de l'environnement et du développement durable, en droit minier et en droit de l'énergie.

Between heterogeneity and regulatory uncertainty, how can we best protect ourselves from PFAS risk?

Elodie Simon, Partner
Gaspar Cottard, Senior associate

Presentation summary:

PFAS regulation is currently highly heterogeneous, constituting a source of persistent legal and technical uncertainties at both the French and European levels, making it a profoundly strategic issue for economic operators.

The coexistence and rapid evolution of sectoral standards, threshold limit values — whether binding or otherwise — varying by use (water, soil, industrial emissions, products), and still-divergent approaches among Member States, create a fragmented and unstable regulatory environment. This situation generates significant legal uncertainty for economic operators and public authorities alike, in a context where scientific knowledge itself continues to advance and directly influence regulators' decisions.

The challenge facing operators is no longer limited to compliance; it extends to the ability to anticipate developments, to closely track regulatory shifts, and to integrate these parameters into a comprehensive management framework addressing legal, industrial, and financial risk.

This presentation aims precisely to demonstrate how rigorous regulatory and scientific monitoring has become a decisive tool for securing decision-making and managing risk in the context of the complex interplay between science, law, and decision-making by both private and public operators.

Introduction:

Observation of a highly fragmented regulatory and normative framework in Europe and France. At present, no harmonised standards exist. They differ according to the specific PFAS substances involved, the relevant operators, and the environmental media concerned (e.g. standards exist for water intended for human consumption, raw water, and food, but not for industrial wastewater — with the exception of PFOS). As regards substances, mixtures, or articles, the POPs Regulation targets only three PFAS substances, whereas the ECHA's current work concerns a proposal for a universal restriction covering all such substances.

In France, the Act of 25 February 2025 imposes a total ban on the use of PFAS substances, but only for certain applications (cosmetics, ski waxes, clothing textiles).

With regard to reference or health-based values, these are even more fragmentary. There is no harmonization at European level, and following the 2024 ministerial action plan, ANSES has published toxicity reference values (TRVs) for only four PFAS substances. The US EPA has published alternative values.

This coexistence of sectoral standards, threshold limit values — whether binding or otherwise — varying by use, together with their rapid evolution, creates an unpredictable, unstable environment and thus a source of legal uncertainty for both private and public operators.

I – Overview of the consequences of this uncertainty for economic operators

The primary source of risk arising from the legal uncertainty surrounding PFAS management is the difficulty of short- and medium-term anticipation, affecting numerous stakeholders.

1. **Banking operators**, for example: certain banks have recently been challenged by NGOs in connection with their financing of entities that produce or use PFAS.

2. **Industrial operators**
   a. The absence of established values for these emerging pollutants is a source of difficulty, as these values constitute the targets to be achieved and determine the scale of investments and infrastructure to be deployed.
   b. In M&A transactions, PFAS risk is difficult to assess. Risk evaluation is rendered more complex when valuing an industrial asset depending on the presence or absence of a PFAS dimension. Where such exposure exists, the financial exposure is not necessarily quantifiable for either the seller or the purchaser.

3. **Litigation risk is increasing**. Recent developments have shown that such litigation involves both private and public actors (e.g. an action for failure to act brought against the State on 21 May 2026 by several NGOs before the Administrative Court of Paris).

II – How to protect against PFAS risk

1. **Implementation of both regulatory and scientific monitoring**.
   In France, in Europe, but also at a broader scale.
   By way of example, the DGPR guidance note of 31 October 2014 invites industrial operators to identify applicable values in France as well as abroad, while setting aside certain foreign values.

2. **Precise assessment of applicable regulatory** obligations according to the relevant sector of activity. Mapping both the existing and prospective regulatory landscape enables control and anticipation.

3. **Contractual safeguards** throughout the value chain (e.g. certificates of PFAS-free status).

4. **Tips and key takeaways**:
   Whether in dealings with competent authorities, commercial exchanges, or asset transactions, operators should refer to best available techniques as well as business and best practices and avoid improvisation (for instance by following the methodological frameworks or guidelines issued by the competent authorities).

First feedback: Monitoring the crucial choice of the PFAS compounds analyzed

Premier retour d'expérience : Surveillance, le choix crucial des composés PFAS analysés

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Keywords: *PFAS, Industrial release, pollution, diagnostic, saturated area, analyses choice, feedback, remediation,*

Objectives:

Provide initial feedback on the analytical strategy used for PFAS monitoring in groundwater, within a shifting regulatory framework and in a context involving major downstream hydraulic challenges (water catchment areas)

Present the choices made regarding the PFAS parameters monitored and their impact on environmental monitoring.

Identify possible origins of downstream contamination.

Innovative nature of the project:

This work is based on a real case study of a site impacted by PFAS. It presents the proposed strategy for characterizing and identifying the origin of groundwater contamination in the context of industrial releases. The strategy will focus on the selection of PFAS parameters monitored (targeted analyses, AOF global parameters, TOP Assay, etc.) and on the consideration of PFAS precursors.

Abstract:

PFAS are ubiquitous industrial pollutants that pose serious risks to human health and the environment. Their persistence and ability to spread through groundwater and surface water make them a major concern. Since 2023, PFAS screening campaigns have been carried out in industrial discharges. In 2026, the first feedback is beginning to provide insight into the extent of these emissions in the environment. At the same time, systematic PFAS screening in drinking water facilities is increasingly revealing the presence of these compounds. One of the main challenges is therefore to determine the origin of these contaminations. Identifying these sources is complicated by the complexity of PFAS pollution: the large number of substances involved, substances that are not analyzed, and molecules that may degrade over time, such as precursors.

In this context, analyses carried out at drinking water abstraction points located downstream of the studied site revealed the presence of short-chain PFAS. However, analyses conducted upstream did not identify the source of this contamination. The industrial area under study, located upstream, was therefore subject to several analytical campaigns, none of which revealed significant PFAS presence in groundwater or wastewater. We therefore propose feedback on the characterization of pollutants both in industrial wastewater and groundwater. The aim is to demonstrate the value of the various indicators associated with PFAS presence in this context, and how they can be interpreted to explain the origin of downstream contamination.

At this site, XSEM chose to expand the analytical panel to include more than 50 PFAS compounds (targeted analyses), to combine this with the use of a global indicator (AOF), and to perform TOP Assays on selected samples. The results of these investigations revealed the presence of high concentrations of PFAS compounds that had not previously been analyzed. Combined with an understanding of the local hydrogeological system, including multiple aquifers, the results made it possible to propose possible origins for the downstream contamination.

AFFF Fire System Conversion

Developing a site-specific strategy to remove PFAS containing Aqueous Film Forming Foam (AFFF) from fixed fire fighting systems and apparatus.

- Frederic Leveau, Principal, Ramboll France, PFAS Lead for France (co-presenter);
- Rick Parkman, Principal, Ramboll UK, PFAS Lead Europe (co-presenter); and
- Michael Jannito, Senior Managing Consultant, Ramboll US, AFFF Transition Services SME Lead (co-author)

Aqueous Film Forming Foam (AFFF) has long been the industry standard for Class B (flammable liquid) fire suppression, but with increasing restrictions and bans being introduced for per- and polyfluoroalkyl substance (PFAS), this is driving a global transition of AFFF based fire suppression systems to fluorine-free alternatives.

The presentation will provide a high-level overview of some of the key regulatory drivers and deadlines for the removal of certain PFAS for which restrictions or bans regarding their use in AFFF are already in place or proposed, with a particular focus on the EU.

For facility assets or sites where a need for an alternative fire suppression system is identified, the presentation will provide an overview of a structured, site-specific approach for converting fixed fire suppression systems away from PFAS-containing AFFF in a way that meets regulatory requirements, limits operational disruption, remains cost-effective, and reduces future environmental liabilities.

Conversions are a multi-step process and shaped by several external drivers (regulations, environmental liability, insurance requirements, health and safety) and internal drivers (business disruption and cost). Every situation is different and success depends on establishing clearly defined goals, detailed planning and robust record keeping. Three key pillars for a successful conversion are:

1. Assessment & Planning — Reviewing as-built drawings and designs of existing systems, assessing standards and risks; performing on site reviews of a fire systems layout and key components, gathering details on the history of foam use, coordinating with relevant stakeholders, including the regulators, and assessing the potential for suitable fluorine-free alternatives and whether conversion or full replacement of the fire suppression system would be more appropriate and cost effective.

2. Implementation — Designing decontamination procedures; removing and disposing of legacy AFFF components; installing, retrofitting, or replacing components; upgrading containment; and providing oversight and temporary fire protection during downtime.

3. Commissioning — Securing regulatory approvals, testing, operator training, monitoring, inspections, and maintenance.

One of the key technical challenges in the conversion process is system cleaning. No approved cleaning standards exist; and various methods have been tested to remove PFAS from the fire suppression system; however, these methods do not typically address PFAS which may have sorbed and/or permeated layers on equipment surfaces in contact with the fire suppression liquids (e.g., pipe walls). The potential for PFAS to "rebound" from slowly desorbing pipe-wall layers means future fire system discharges and fire system test waters must continue to be managed as potential PFAS-containing media.

Disposal and treatment of AFFF concentrate, stock, and rinse waters add further complexity. Various options exist both on and off site which will be briefly discussed, for which costs vary depending on chosen option, geographic location, regulatory acceptance and appetite for risk.

The presentation will conclude by summarising some of the key considerations for achieving a successful fire system transition away from AFFF.

Inter-Laboratory Differences in PFAS Determination in Aquatic Vegetation

Speaker: Ivar Lanting
Written by: Antea Group Netherlands
Ivar Lanting, Marleen van Tilborg, Lorenzo Djokarijo

Keywords: Inter-laboratory study, PFAS in vegetation, Methods of PFAS-analysis, case study.

Summary

PFAS (per- and polyfluoroalkyl substances) are mobile and persistent compounds that spread through soil, water, air and are now also detected in vegetation. Various studies show that PFAS are absorbed by trees, grass, and also aquatic plants. Through these plants, PFAS continues to spread throughout the ecosystem. Currently, there are no guidelines for conducting PFAS research in vegetation, in contrast to the guidelines that do exist for researching PFAS in soil. Yet For plants there are no standard methods for when it comes to analyzing PFAS in vegetation. Every laboratory uses their own method, resulting in significant differences in reported PFAS in vegetation between labs.

1. Introduction

In the Netherlands it is a common practice to analyze the amount of PFAS in soil. Dutch legislation describes a rule which is called the duty of care. This describes that harm must be prevented, and parties dealing with soil must act responsibly when dealing with it and anything that affects it. This principle ultimately applies to everything added to the soil, even if what is added is not soil itself. The municipality of Leeuwarden, located in the province Friesland in the Netherlands discovered the meaning of this act when the results showed that PFAS had accumulated in aquatic plants. This is problematic, since the aquatic plants are normally removed from the watercourse and placed on the neighboring agricultural land. After a couple of days, the vegetation is incorporated into the soil, functioning as organic fertilizer. In this way the plant can act as added organic material, improving soil health.

Any commercial party that involves activities which move soil requires the soil to be investigated on the presence of contaminates including PFAS. There are guidelines on how to conduct such an investigation and against what concentrations the results must be compared. For PFAS, concentration levels are set for soil and groundwater depending on their assigned function[1]. There are international protocols that describe standards to measure PFAS in water (such as ISO 21675) and in development for soil and sediment (ISO 25652). For other matrixes, such as vegetation or vegetable foodstuffs, standardized protocols remain absent. Leading to laboratories setting up their own methodologies to measure PFAS in these matrixes.

The focus of our work presented in this paper will be about an inter-laboratory study that we conducted to gain insight into how the different methodologies that laboratories use to measure PFAS in vegetation impact the reported data.

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[1] e.g. groundwater with consumption or without consumption for public use, soil for agriculture or nature, soil for living residential areas or soil for industrial areas.

2. Materials and Methods

Sampling was performed in week 28 of 2025, after the longest day, when PFAS concentrations are expected to peak due to the plants' shift from growth to reproduction. For sampling, a transect of the watercourse was made. The following sampling points were selected for the transect (Also visualized in Figure 1):

Bank plants (such as reed) are generally cut during mowing, so roots do not end up in the cut material. Therefore, the root zone of these plants was excluded. Aquatic plants are usually raked during mowing, pulling the entire plant from the sediment, so roots are often included—these are relevant for cut material. Only the most dominant species were sampled to keep the number of samples proportional to research intensity. This also allows comparison of PFAS concentrations in different plants or plant parts (such as roots).

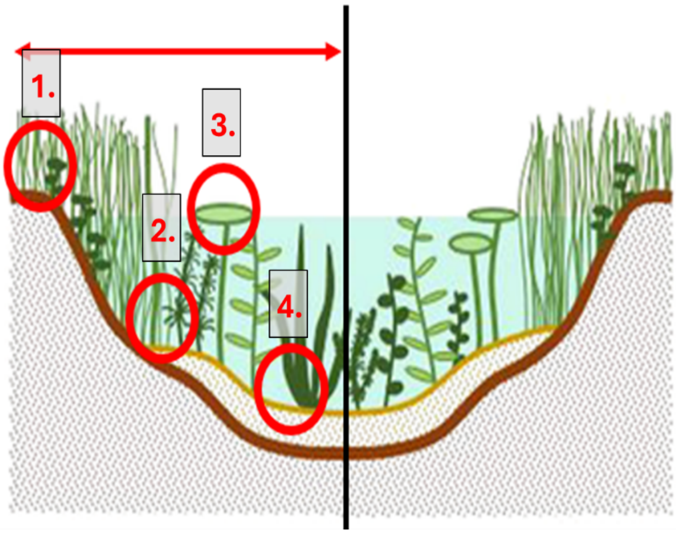

Figure 1: Transect with different type of plants in and around the watercourse. The following locations indicate which plant types were gathered from them: 1.; bank plants, 2. aquatic plants halfway down the slope (including root zone), 3. floating plants, 4. aquatic plants from the bottom of the riverbed (including root zone)

Plants were delivered to the lab whole (stem, leaves, flowers). Each sampling point filled one 10-liter bucket with about 500 grams of plant material, including roots and any soil or sludge. Material was drained for a few seconds to remove excess water but was not rinsed or thoroughly cleaned, as mowing would not involve more than brief draining. The whole plants and plant parts were homogenized to one sample, so there would be no difference between the PFAS uptake in stems, leaves or flowers. After the laboratories reported the PFAS content in the vegetation, the dry matter content and EFSA-4 PFAS content in each of the plant species were plotted. The EFSA-4 describes four PFAS most found in food: PFOA, PFOS, PFNA, and PFHxS. The mean and standard error were calculated and used to highlight the differences between the reported laboratory data for dry matter content and EFSA-4 PFAS.

The methodologies of the four laboratories were inventoried. Each laboratory was requested to provide a description of their methodology that they used to measure PFAS in vegetation. General interviews were held with specialists in the laboratory to assist in creating this overview of inventoried laboratory techniques. The differences of each laboratory were highlighted and were compared with the purpose of identifying factor(s) which could be responsible for the found spread in EFSA-4 PFAS content.

3. Results & Discussion

3.1 Outcome EFSA-4 concentrations laboratories

As described in Table 1, each laboratory determined the dry matter content of the plants using different methods. Most laboratories used the dry matter percentage to convert PFAS concentrations measured in wet samples. Consequently, variation in dry matter content directly affects the spread of PFAS results. Therefore, the variation in dry matter content is discussed first.

Erreur ! Source du renvoi introuvable. shows only four measurements (n = 4) per plant, in line with analysis that were performed (one per laboratory), the spread between laboratories is high. Generally, more data points reduce variability. The smallest standard deviations were found for reed and cattail (plant) at 8.4 and 8.1, respectively. For duckweed, cattail (root), and water lily (plant + root), standard deviations were 16.0, 16.5, and 16.9. The graph also shows that Lab 1 consistently reported the highest dry matter values for all plants except reed, exceeding the standard deviation. This lab indicated this may be due to high sand or sludge content in the samples. Although all samples were collected on the same day, under identical conditions, the amount of soil included may vary.

The method of Lab 4 (drying at 103 °C until stable weight) is considered the most reliable for determining dry matter. For all plants, Lab 4 and Lab 3 reported the lowest dry matter values, which are regarded as most accurate. Higher values likely contain residual moisture. Thus, Lab 4 and Lab 3 data are considered most trustworthy. For reed, Lab 3 reported a lower value than the other three laboratories. No clear explanation was found; differences in sand or sludge content may also play a role.

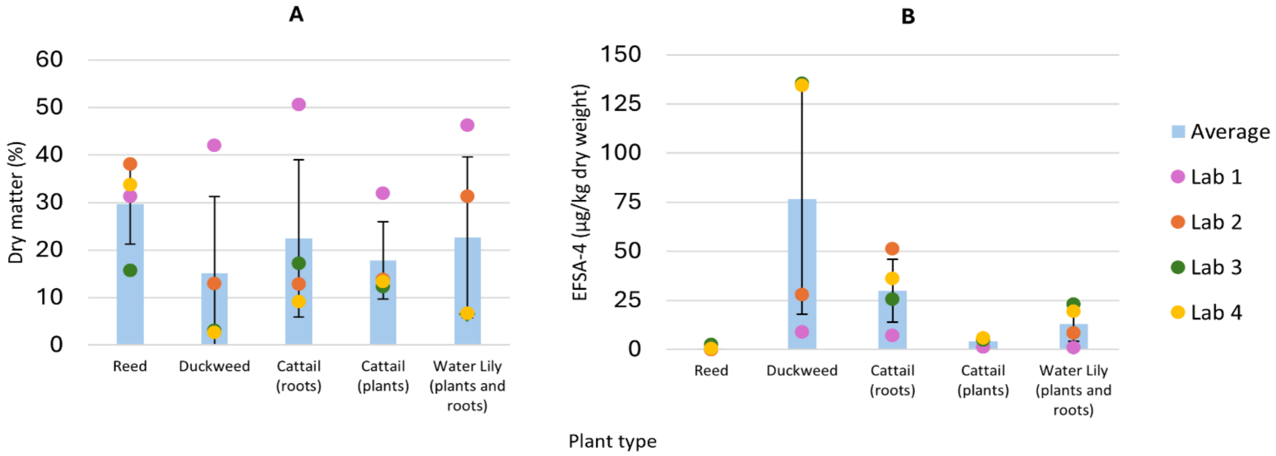

Figure 2: Plot A shows the average measured dry matter (%) per plant and the spread of the data from the four laboratories; the black bars indicate the standard deviation (n = 4). For the water lily series (plant + root), the value for lab three is underneath that of lab 4. Plot B shows Average measured EFSA-4 concentration (µg/kg dry weight) per plant and the spread of the data from the four laboratories; the black bars indicate the standard deviation (n = 4). For the water lily series (plants and roots), the value of Lab 3 is below that of Lab 4.

In Figure 2, plot B, the average EFSA-4 value from the four laboratories is visualised. This graph also shows that lab 4 and lab 3 give similar value (in line with what is seen in the data of the dry matter). The low values of Lab 1 can be explained by the high values for dry matter. Dry matter is negatively correlated with the PFAS-concentration as shown in formula 1.

$$[PFASx](\mu g/kg\ ds) = [PFASx] * \left(\frac{100}{droge\ stof\ (\%)}\right) \qquad (1)$$

3.2 Evaluation of methods of the four laboratories

The evaluation of laboratories revealed that three factors; the drying process, the solvent type and the general cleanup procedure may be responsible for the reported spread in PFAS concentrations. Most laboratories report that samples were measured on the wet material, and that the dry matter content was determined using conventional oven drying. Only laboratory 2 analyzed PFAS on the homogenized dry material. Laboratory 3 used freeze drying to determine the dry matter content. The laboratories that performed their analysis on the wet material used the dry matter content to calculate the PFAS content in ug/kg dry weight, using formula 1. Each laboratory used different temperatures and timespans to determine the dry matter content. The solvents used show that overall laboratories seem to use either methanol and/or acetonitrile, though the ratios of the solvents remain undisclosed. The ratio determines which PFAS (short or long chain) end up in the solvent, and are measured. General cleanup procedures show that virtually all laboratories use some form of column chromatography, though each laboratory prepares the sample with other methodologies such as QuECHeRS or centrifugation.

Table 1. Method of analysis for four different laboratories.

Laboratory	Drying process	Solvent used	General Cleanup
Lab 1	Dry matter content at 105 °C, including dredged sediment. Analysis was performed on homogenized wet material.	Mixture of solvents that were not disclosed.	Multi- QuEChERS*, column chromatography (activated carbon, ion exchange)
Lab 2	Samples were dried at 40 °C for two weeks. Analysis was conducted on homogenized dry material.	Methanol for general extraction, undisclosed solvent for concentrating	Unknown
Lab 3	Dry matter was determined by freeze-drying. Analysis was performed on homogenized wet material.	Acetonitrile	QuEChERS, followed by centrifugation and SPE cleanup cartridge
Lab 4	Dry matter content was measured by drying samples at 103 ± 2 °C until stable weight. Analysis was performed on homogenized wet material.	Combination with Methanol and Acetonitrile	Multiple centrifugation steps, use of mixed mode weak anion exchanger cartridge

*QuEChERS describes a standard method commonly used in analytical labs to further clean samples before measurement.

The laboratory inventory reveals that the methodologies each laboratory use to analyze PFAS are different from each other. Despite each laboratory reporting that their methodology is in line with general EU regulation 2022/1428. The impact of these different methodologies on the reported PFAS is unknown. Input from interviewees revealed that the approach a laboratory can take may impact the reported PFAS content. Consequently, the observed EFSA-4 differences observed in Figure 3B can be attributed to a single factor, or a summation of all factors found in Table 1.

4. Recommendations

To improve comparability and reliability in this study, all participating laboratories should start with a well-homogenized sample, dividing one homogenized batch among labs. This minimizes variability from sample preparation. Additionally, harmonizing the analysis package to include the same PFAS compounds across labs would enable fairer comparison of methods and performance.

Collecting multiple samples, including variants without sand or sludge, could provide valuable insights. This study intentionally analyzed “dirty” samples (plant material with sludge) to reflect material produced during mowing. However, this increases variability. Clean samples could reveal PFAS levels in pure plant tissue, which may be lower than in mixed samples. This is relevant for assessing the quality of cut material for reuse, as washing to remove sand/sludge could reduce PFAS concentrations. Explicitly studying washed vs. unwashed material would help justify reuse options under current standards.

Furthermore, only five plant samples were analyzed in single replicates. Providing duplicate samples would improve reproducibility assessment. A broader sample set would make the ring test more robust and allow labs to validate methods under varied conditions.

Finally, using a standardized dry matter content for all samples could eliminate differences in PFAS concentrations caused by varying moisture levels, reducing data spread.

For the vegetation methodologies, we recommend that laboratories increase their transparency in terms of their validation results of the methodology for each PFAS. Additionally, the differences in methods can also be attributed to the lack of standardized protocols which in turn result from a lack of legislative limit values for PFAS in foodstuffs. Therefore, it is recommended to introduce legislative limit values for PFAS in foodstuffs/vegetation, so that standardized protocols for determining PFAS in vegetation may be developed and distributed to different laboratories.

Real-time PTR-ToF-MS calibration and flow-tube PFAS emissions measurements from consumer materials

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Per- and polyfluoroalkyl substances (PFAS) constitute a large family of synthetic fluorinated compounds widely used in industrial and consumer products due to their exceptional thermal and chemical stability. Their strong carbon–fluorine bonds confer high resistance to degradation, leading to long environmental persistence and global distribution through atmospheric and oceanic transport. Although extensive research has focused on PFAS contamination in water systems, considerably less attention has been devoted to volatile and semi-volatile PFAS in air. This work therefore aimed to investigate the atmospheric behavior of selected volatile PFAS using Proton Transfer Reaction Time-of-Flight Mass Spectrometry (PTR-ToF-MS) under controlled laboratory conditions.

The study focused on several representative PFAS families, including fluorotelomer alcohols (FTOHs), fluorotelomer acrylates (FTACs), fluorotelomer methacrylates (FTMACs), fluorooctane sulfonamides (FOSAs), and fluorooctane sulfonamidoethanols (FOSEs). These compounds differ in functional groups and molecular polarity, which strongly influence their ionization behavior and environmental fate.

A PTR-ToF-MS system was employed for the online analysis of volatile and semi-volatile PFAS in the gas phase. Ionization primarily occurred through proton transfer reactions with hydronium reagent ions (H3O+). To ensure accurate quantification, a dedicated calibration setup was developed to continuously generate PFAS in the gaseous phase. This system enabled controlled injections and real-time monitoring of instrument response under varying experimental conditions.

The influence of humidity was systematically investigated by varying relative humidity while maintaining constant drift voltage conditions. The results demonstrated that PTR-ToF-MS ionization behavior strongly depends on humidity. Three major ion forms were identified for several PFAS compounds: protonated, hydrated, and dihydrated ions These clustering phenomena might have affected the sensitivity of the instrument.

In addition to humidity, drift tube conditions strongly influenced ion distribution and fragmentation patterns. Increasing drift voltages enhanced the energy of ion–molecule collisions, promoting the dissociation of weakly bound water clusters. The observed variations in the relative abundances of protonated, hydrated, and dihydrated species as a function of drift voltage highlight the important role of drift conditions in controlling PTR-ToF-MS ion chemistry and spectral characteristics.

The strongest signals were generally observed under dry conditions and at intermediate drift voltages, corresponding to an optimal balance between ion–molecule reaction time and declustering efficiency.

Sub-ppb detection limits obtained under optimized conditions (RH = 0% and Udrift = 370 V) demonstrated the high sensitivity of PTR-ToF-MS for several volatile PFAS. The lowest detection limits were achieved for FTMAC compounds while higher limits were observed for longer-chain FTOHs such as 12:2 FTOH.

To investigate PFAS emissions from consumer products, a second experimental setup based on a heated flow tube was developed. Materials such as rain pants were introduced into the system, and emitted compounds were continuously monitored using PTR-ToF-MS. PFAS identification relied on several criteria, including mass accuracy below 20 ppm, detection of protonated and clustered ion forms, and comparison of hydrated-to-protonated ion ratios with calibration standards.

The analysis of rain pants revealed the presence of fluorotelomer alcohol emissions, predominantly 8:2 FTOH and 10:2 FTOH. Mass spectra confirmed the characteristic distribution observed during calibration experiments, with hydrated species constituting the dominant contribution. However, several measured concentrations remained close to or below the instrumental detection limits, highlighting the need for further methodological improvements to investigate low-level PFAS emissions from consumer materials.

Overall, this work demonstrates the applicability of PTR-ToF-MS for the online analysis of volatile and semi-volatile PFAS and provides important insights into the influence of humidity and drift tube conditions on PFAS ionization mechanisms. Although only limited emissions were detected from the consumer products investigated in this study, the developed methodology remains highly relevant for environments where elevated PFAS emissions are expected, particularly during industrial manufacturing and treatment processes involving fluorinated materials. The real-time capability of PTR-ToF-MS could therefore represent a valuable tool for industrial monitoring, rapid detection of emission sources and process optimization.

Assessing ambient air PFAS exposure: validated active sampling methods for risk evaluation
Évaluation de l’exposition aux PFAS dans l’air intérieur : méthodes d’échantillonnage actif validées au service de l’analyse des risques

Speaker: Paola Verza, Special Project Technical Manager, Mérieux NutriSciences; paola.verza@mxns.com

Innovative Nature of the Proposed Topic

The proposed topic is innovative because it addresses a still under-characterized exposure pathway for PFAS: ambient and indoor air. It presents the development of sampling methodologies in a context where there are no official methods.

Keywords

- PFAS
- PFOA
- PFOS
- PFHxS
- HFPO-DA (Gen-X)
- Ambient air exposure
- Indoor air
- Risk evaluation
- Environmental monitoring

General Objective

To improve the assessment of human exposure to PFAS via ambient air by implementing validated active sampling methodologies suitable for risk evaluation.

Abstract

Recent advances in toxicological and epidemiological research have significantly strengthened the evidence on the adverse health effects of PFAS exposure.

In early 2025, the International Agency for Research on Cancer (IARC) classified PFOA as Group 1 (carcinogenic to humans) and PFOS as Group 2B (possibly carcinogenic)**,** while identifying PFHxS and HFPO-DA (Gen-X) as high-priority substances for further evaluation. These classifications reinforce the need to better understand all potential exposure pathways, including those that are still poorly characterized. While ingestion has historically been considered the dominant route, growing attention is now being paid to ambient and indoor air as a relevant vector for PFAS transport and human exposure, particularly in occupational settings and in proximity to industrial sources.

Although no mandatory regulatory limits for PFAS in air currently exist and harmonized official methods for PFAS sampling and analysis in air are still lacking, in Europe or the United States, the technical landscape is rapidly evolving, with authorities and industrial operators increasingly implementing passive and active air monitoring programs. Our intention for the speech is to present two internal validated active sampling approaches: a low-volume method suitable for personal monitoring, and a high-volume method designed to be used when there's the necessity to filter a high volume of air and decrease the limits of quantification. Both approaches allow the determination of PFOA, PFOS, PFHxS, HFPO-DA and other medium- and long-chain PFAS, achieving recoveries above 70%. These methodologies contribute to robust exposure assessments and support data-driven risk evaluation and remediation strategies.

PFAST : a portable biosensing platform for rapid field detection of PFAS with ppt sensitivity

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Current PFAS analyses, mostly based on LC-MS/MS, are plagued with significant turnaround times and logistic burdens, which make real-time control impossible. This severely limits field surveys, as well as optimized remediation and preventive measures. Moreover, water treatment plants, particularly industrial wastewater facilities, face considerable operational costs related to PFAS capture and destruction. To control these expenses, while ensuring effluent quality, they must be able to optimize filters replacement based on actual saturation rather than predetermined schedules.

The Fluorograph consortium has developed PFAST, a disruptive PFAS analytical device, based on Grapheal's portable high-sensivity sensing platform. They are based on Graphene Field effect Transistor on polymer, which enable femtomolar detection thresholds. We have tested its performance on industrial PFAS contaminated wastewater samples. Our results show that it is possible to measure short, medium, and long-chain PFAS compounds in real field matrices. While discrimination is still limited to specific range of molecular weight, detection threshold is less than 10 ng/L for middle and long chains PFAS. As an example, the titration of perfluorobutanoic acid (PFBA) in field sampled wastewater matrices on PFAST sensors exhibits a level of quantification of ca. 10 ng/L. (see Fig. 1, right).
This technology offers industrial and drinking water treatment plant operators three decisive advantages:

- Speed: results in minutes rather than weeks, offering novel types of best practice
- Economic accessibility: cost per analysis at a fraction of laboratory analysis costs
- On-site deployment: complete autonomy without dependence on external laboratories

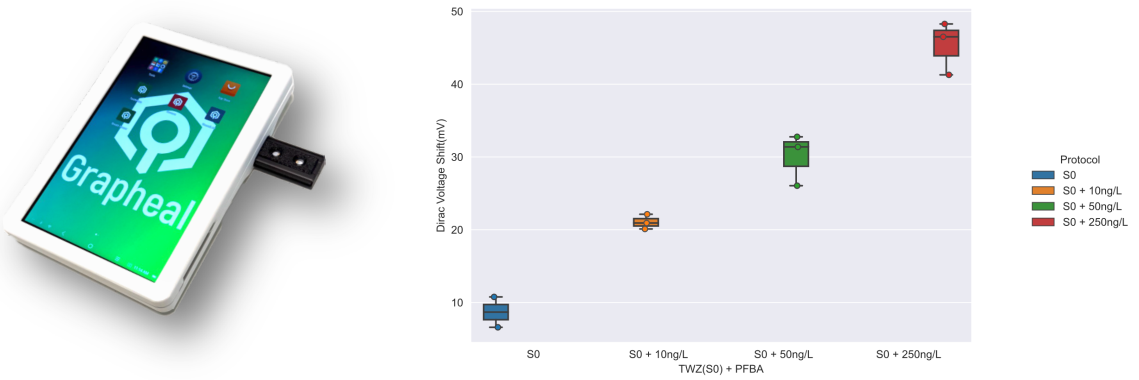

Fig. 1. Portable PFAST sensing platform in developement. Right: Sensor signal obtained upon controlled addition method of Perfluorobutanoic acid, added to a real matrix of treated industrial wastewater (TWZ(S0) sample provided by VEOLIA)

Congrès PFA - Paris Juin 2026

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Retours d'expérience consolidés de transitions pour différents systèmes anti-incendie contenant des émulseurs fluorés :
Du diagnostic à l'élimination - perspectives

MATTHIEU HIRRIEN / RESPONSABLE EXPERTISE PROJETS SPECIAUX - RESPONSABLE INNOVATION
MAËLYS ROUX / CHEFFE DE PROJET
MOTS CLES : PFAS / AFFF / ANALYSES / NETTOYAGE/ EAU DE LAVAGE/ DESTRUCTION/ TRANSITION

Les émulseurs anti-incendies de type AFFF sont historiquement composés de PFAS avec des teneurs très importantes, de l'ordre de plusieurs dizaines de g/L. Il s'agit donc aujourd'hui des sources parmi les plus importantes de transfert de PFAS dans l'environnement.

En effet, leur très large présence et leur utilisation passée ou future, notamment dans le cas d'exercice ou de déclenchements, induisent des pollutions avérées ou potentielles disséminées à travers tous les territoires.

La réglementation européenne en a interdit l'usage selon certains critères, depuis décembre 2025. Aujourd'hui, des dérogations liées à des seuils spécifiques subsistent jusqu'en 2030.

La transition des systèmes anti-incendies est donc un enjeu majeur et actuel pour de nombreux industriels, services (pompiers) et les populations au sens large.

Il est à noter que l'opération de transition peut rendre indisponible les réseaux anti-incendies pendant les opérations. Pour cela une bonne gestion et l'optimisation du processus, mis en place pour la vidange et le nettoyage des réseaux, est primordiale.

Une transition est bien plus complexe que la simple vidange et destruction des émulseurs, des nettoyages sont nécessaires, lesquels génèrent des effluents à traiter et des déchets concentrés. De plus, les matériels non réutilisables car obsolètes doivent être décontaminés pour pouvoir être gérés en tant que déchets.

Par ailleurs, la diversité des designs des systèmes incendies et la variabilité des historiques rendent souvent difficile l'application d'une recette standardisée. La capitalisation des Retours d'Expérience est donc essentielle.

Aussi, la présentation décrit la gestion globale de différentes transitions d'émulseurs fluorés basées sur des exemples concrets et variés tels que des bâtiments industriels entiers, des petits systèmes, des engins mobiles, … Elle en fait émerger les principaux enseignements et les perspectives d'amélioration pour faciliter et optimiser ces opérations, dont la nécessité à court terme est critique.

La présentation reprend les étapes clés d'une transition :

- définition des besoins ;
- diagnostic des systèmes et contenus (émulseurs, eaux mélangées) ;
- nettoyage voire démantèlements des cuves de stockages et équipements (pompes, doseurs) ;
- nettoyage des réseaux anti-incendies (sprinklers fermés et ouverts, boîtes à mousse…) ;

- gestion des déchets liquides (émulseurs, concentrats) et solides ;
- traitements des eaux de rinçages ;
- remplacement de certains équipements et mise en œuvre du nouvel émulseur ou substituts.

Pour chaque étape sont détaillées : les approches techniques sélectionnées, les difficultés rencontrées, les solutions apportées.

Consolidation of Returns of Experience for the change out of fluorinated AFFF in different firefighting systems : From characterization to waste treatment - perspectives

MATTHIEU HIRRIEN / SPECIAL PROJECTS AND EXPERTISE DEPARTMENT MANAGER - HEAD OF INNOVATION
MAËLYS ROUX / PROJECT MANAGER
KEY WORDS : PFAS / AFFF / ANALYSIS / CLEANING / RINSE WATER / DESTRUCTION / TRANSITION

AFFF-type fire-fighting foams have historically been composed of PFAS with very high contents, up to several tens of g/L. Therefore, today they represent one of the most significant sources of PFAS transfers into the environment.

Indeed, the abundant presence of fluorinated AFFF and their past or future uses, particularly in the case of training or emergency, lead to proven or potential pollution disseminated across all territories.

European regulations have banned their use, according to certain criteria, since December 2025. Today, exemptions related to specific thresholds remain until 2030.

The transition of fire-fighting systems is therefore a major and current issue for many industrial operators, services (firefighters) and populations.

It should be noted that during the transition operations the fire-fighting networks can be unavailable. For this reason, good management and optimization of the process, implemented for draining and cleaning networks, is essential.

A transition is much more complex than simply draining and destroying AFFF foams. Cleaning is necessary, and generates wastewaters to be treated and concentrated waste. Moreover, non-reusable equipments must be decontaminated in order to be managed as waste.

Therefore, the diversity of fire system designs and the variability of histories often make it difficult to apply a standardized protocol. So the capitalization of return of experience is essential.

This presentation will describe the overall management of different fluorinated AFFF based on practical and varied examples, such as industrial buildings, small systems, mobile equipments, etc. It will highlight the main returns of experience and perspectives for improvement, in order to facilitate and optimize operations. Indeed, fluorinated AFFF transitions are already critical, and have to be deployed quickly.

The presentation will cover the key stages of a transition :

- definition of needs ;
- characterization of systems and contents (AFFF, mixed waters) ;
- cleaning and / or dismantling of storage tanks and equipments (pumps, proportioners) ;
- cleaning of fire-fighting networks (closed and open sprinklers, foam boxes, etc.) ;
- management of solid and liquid waste (AFFF, concentrates) ;

- treatment of rinse / soak waters ;
- replacement of parts and implementation of the new foam or substitutes.

For each stage, the technical approaches selected, the difficulties encountered, the solutions provided will be detailed.

Mercredi 17 juin 2026

08h30
Accueil des participants

Identification & Caractérisation des sources des PFAS (Part. 2)

Présidents :
• Philippe Bodenez, Chef du service Santé, Environnement et Économie circulaire à la Direction Générale de la Prévention des Risques - Ministère de la Transition Écologique, de l'Énergie, du Climat et de la Prévention des Risques, France
• Dr. Frank Karg, SFSE & ARET, Directeur scientifique Ginger Group - HPC (Inogen), Président d'Atlantis Développement & Expert Judiciaire, France

09h00
Ce que vous devez savoir sur l'acide trifluoroacétique (TFA) et les autres PFAS à chaîne ultra-courte
Jacques Martelain, Consultant en environnement spécialisé dans la criminalistique environnementale et expert judiciaire - Terraquatron (France)

09h30
PFAS dans les mousses anti-incendie : réglementation et approches analytiques
Anne Le Cudonnec, Ingénieure commerciale - SGS Environmental Analytics (France)

10h00
Caractérisation des PFAS dans les retombées atmosphériques des sites industriels
Jessica Queron, Responsable d'unité - Institut national de l'environnement industriel et des risques, Ineris (France)

10h30
Pause-café & thé

11h00
Retour d'information des installations de traitement des déchets dangereux sur les campagnes de surveillance des émissions atmosphériques de PFAS menées en France en vertu de l'arrêté ministériel du 31 octobre 2024 et évaluation des risques sanitaires associés à ces émissions
Azevedo Gonçalves, Chargé de mission de suivi environnemental - Syndicat français des professionnels du recyclage, de la valorisation, de la régénération et du traitement des déchets dangereux, Sypred (France)

Investigations des sites, Chimie Environnementale et Modélisation des transferts
Évaluation des risques environnementaux et sanitaires, Toxicologie & Épidémiologie

11h30
Gestion des PFAS impactant les réseaux d'extinction incendie : solution d'audit des composés en présence et enjeux de décontamination
• Dr. Raphaël Tur, Spécialiste en chimie des PFAS & Ingénieur R&D, Colas Environnement (France)• Jonathan Senechaud, Responsable Développement d'Activités, Colas Environnement (France)

12h00
Prise en compte des précurseurs poly-fluorés des PFAS et leurs métabolites intermédiaires et finaux dans le cadre des évaluations des risques pour la santé (EQRS & ARR) : La question des FTOHs dans les sols, des eaux et de l'air
Dr. Frank Karg, SFSE & ARET, Directeur scientifique Ginger Group - HPC (Inogen), Président d'Atlantis Développement & Expert Judiciaire (France)

12h30
Déjeuner

13h45
Les PFAS relargués par nos déchets enfouis : quelle efficacité des traitements en place ?
Alice Senet, Doctorante CIFRE - Serpol & INSA (France)

14h15
Tendances et mesures relatives aux PFAS au Danemark
Dorte Harrekilde, Responsable d'équipe - Ramboll (Danemark)

14h45
Prise de décision basée sur le flux de PFAS : une étude de cas industrielle
William Leys, Responsable PFAS Europe - AECOM (Belgique)

15h15
Pause-café & thé

15h45
Potentiel de transfert des PFAS à travers la barrière passive d'une installation de stockage de déchets dangereux (ISDD)
• Jean-Yves Richard, Responsable innovation - Syndicat Professionnel pour le Recyclage et l'Élimination des Déchets Dangereux, SYPRED (France)
• Maxime Cochennec, Ingénieur chercheur en sites et sols pollués - Bureau de Recherches Géologiques et Minières, BRGM (France)

16h15
Premières mesures quantitatives de PFAS en air ambiant sur la métropole de Lyon
Albane Barbero, Ingénieure d'études en chimie (polluants émergents) - Atmo AuRA (France)

16h45
Mesurer les PFAS dans l'air - La prochaine frontière
Heather Lord, Responsable monde des pratiques PFAS - ALS Global (Canada)

17h15
INOGEN : Gestion des risques liés aux PFAS à l'ère numérique
- *Scott Recker, Vice-Président, Consultant Senior - Antea Group / INOGEN (États-Unis)*
- *Annika Taylor, Associate - Peter J. Ramsay & Associates / INOGEN (Australie)*
- *Heikki Kalle, COO - DGE Group / INOGEN (Danemark)*

17h45
Fin de la seconde journée

PFAS

PER- AND POLY-FLUOROALKYL SUBSTANCES

Management of Environmental & Health Risks

June 16, 17, 18 & 19, 2026 – Paris

Wednesday, June 17, 2026

08h30
Welcoming participants

Identification & characterization of PFAS Sources (Part. 2)

Presidents:

- *Philippe Bodenez, Head of the Health, Environment, and Circular Economy Department at the Directorate-General for Risk Prevention - French Ministry of Ecological Transition, Energy, Climate, and Risk Prevention, France*
- *Dr. Frank Karg, SFSE & ARET, Scientific Director of Ginger Group - HPC (Inogen), CEO of Atlantis Développement & Court Expert, France*

09h00
What you should know about trifluoroacetic acid (TFA) and other ultra-short chain PFAS
Jacques Martelain, Environmental consultant specializing environmental forensics & Judicial expert - Terraquatron (France)

09h30
PFAS in fire-fighting foams: regulation and analytical approaches
Anne Le Cudonnec, Sales Engineer - SGS Environmental Analytics (France)

10h00
PFAS in atmospheric fallout from industrial sites
Jessica Queron, Head of Department - French National Institute for Industrial Environment and Risks, Ineris (France)

10h30
Coffee & Tea break

11h00
Industrial feedback of hazardous waste treatment facilities on the monitoring campaigns of air emissions of PFAS conducted in France under the ministerial order of October 31st, 2024, and evaluation of health risks associated with the emissions
Azevedo Gonçalves, Environmental Monitoring Officer - French union of professionals in recycling, recovery, regeneration and treatment of hazardous waste, Sypred (France)

Site Investigations, Environmental Chemistry and Transfer Modelling
Environmental and Health Risk Assessments, Toxicology & Epidemiology

11h30
Management of PFAS affecting fire-fighting systems: a solution for auditing the compounds present and the challenges of decontamination
• Dr. Raphaël Tur, PFAS Chemistry Specialist & R&D Engineer - Colas Environnement (France)• Jonathan Senechaud, Business Development Manager - Colas Environnement (France)

12h00
Consideration of poly-fluorinated PFAS precursors and their intermediary and final metabolites for Human Health Risk Assessments (HHRA & TERQ): The Question of the FTOHs in soils, water and air
Dr. Frank Karg, SFSE & ARET, Scientific Director of Ginger Group - HPC (Inogen), CEO of Atlantis Développement & Court Expert (France)

12h30
Lunch

13h45
PFAS released by landfill waste: how effective are the treatments?
Alice Senet, CIFRE Doctoral Student - Serpol & INSA (France)

14h15
Trends and actions on PFAS in Denmark
Dorte Harrekilde, Team lead – Ramboll (Denmark)

14h45
PFAS flux-based decision-making: an industrial case study
William Leys, PFAS Lead Europe - AECOM (Belgium)

15h15
Coffee & Tea break

15h45
Potential for PFAS transfer through the passive barrier of a hazardous waste landfill
• Jean-Yves Richard, Head of Innovation - Professional Association for Recycling and Disposal of Hazardous Waste, SYPRED (France)
• Maxime Cochennec, Research Engineer in Contaminated Sites and Soils - Geological and Mining Research Bureau, BRGM (France)

16h15
First PFAS quantitative ambient air measurements in the vicinity of Lyon Metropolis
Albane Barbero, Chemical Research Engineer (Emerging Pollutants) - Atmo AuRA (France)

16h45
Measuring PFAS in Air - The next frontier
Heather Lord, Global PFAS Practice Lead - ALS Global (Canada)

17h15

INOGEN: PFAS risk management in a digital age

- *Scott Recker, Vice President, Senior Consultant - Antea Group / INOGEN (USA)*
- *Annika Taylor, Associate - Peter J. Ramsay & Associates / INOGEN (Australia)*
- *Heikki Kalle, COO - DGE Group / INOGEN (Denmark)*

17h45

End of the second day

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What you should know about trifluoroacetic acid (TFA) and other ultra-short chain PFAS

Trifluoroacetic acid, also known as TFA, is an ultra-short chain PFAS that is extremely stable and therefore particularly persistent in the environment. As it is highly mobile and very soluble in water, it can be found in all environments.

Furthermore, standard drinking water treatment processes cannot remove TFA that is by far the PFAS most commonly found in the water we drink!

By accumulating in water and soil, TFA is also present in crops, with concentrations increasing since the widespread use of PFAS pesticides.

Globally, the main source of TFA pollution is a group of fluorinated refrigerants known as F-gases. These gases have been used since the late 1980s to replace refrigerant gases that destroyed the ozone layer. Fluorinated gas emissions disperse globally, settling largely in the oceans and contaminating rainwater.

PFAS in fire-fighting foams: regulation and analytical approaches

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Anne Le Cudonnec – Sales Engineer - SGS Environmental Analytics France
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PFAS (Per- and Polyfluoroalkyl Substances) represent a large family of synthetic chemicals comprising an estimated 10,000 compounds, of which only a limited number, such as PFOA and PFOS, have been extensively studied. Current analytical approaches provide only a partial assessment of PFAS contamination, particularly due to the diversity of compounds and the presence of precursor substances that are not systematically detected by conventional targeted analyses. PFAS have been widely used across various industrial applications, notably in fire-fighting foams, which have been identified as a major source of environmental contamination. Numerous studies have highlighted the persistence, mobility, and widespread occurrence of PFAS originating from these products. Consequently, fire-fighting foams have become a key focus for both regulatory authorities and environmental stakeholders due to increasingly stringent regulations and the analytical challenges associated with these complex matrices.

The objective of this work is to contribute to the development and improvement of analytical methodologies dedicated to PFAS characterization, including in fire-fighting foam formulations. The proposed approach combines complementary analytical and detection techniques to provide reliable and comprehensive data to stakeholders such as environmental consultants, industrial site owners, remediation companies, and regulatory authorities. Accurate characterization of PFAS contamination is essential to support risk assessment, regulatory compliance, and remediation strategies.

In recent years, European regulations have progressively targeted PFAS across multiple sectors, with particular attention given to fire-fighting foams. These regulatory frameworks no longer focus solely on a restricted list of target PFAS compounds but also address precursor substances capable of degrading into persistent terminal PFAS in the environment. PFOS, PFOA, PFCAs C9-C14, PFHxA, PFHxS and more recently all the PFAS [1] are concerned by the European regulation on fire-fighting foams. As a result, the implementation of the TOP assay (Total Oxidizable Precursor assay) has become more important for comprehensive PFAS assessment.

The TOP assay is based on an oxidative conversion process that transforms precursor PFAS compounds into terminal perfluoroalkyl acids, which can then be more effectively detected and quantified using conventional analytical methods. In this study, the TOP assay was specifically adapted to the fire-fighting foam matrix to ensure compliance with current regulatory requirements. This analysis is part of the PFASafe® concept elaborated by SGS incorporating various techniques to determine PFAS in various matrices to cope with the different types of PFAS found in the environment and get an insight into the total amount of organic fluorine and thus the PFAS risk of a sample. The approach consists of the following steps:

- Total Organic Fluorine (TOF): determination of organic fluorine in fire-fighting foam samples
- Adsorbable Organic Fluorine (AOF): determination of organic fluorine in water samples
- Extractable Organic Fluorine (EOF): determination of organic fluorine in solid samples
- PFAS-analysis: classical target analysis of a selected number of classically known PFAS congeners, but also including other, newer PFAS
- Total Oxidizable Precursors (TOP): oxidation of PFAS precursors, consisting of weaker bonds and which are then cleaved and after identification result in stable, perfluorinated PFAS

- Q-TOF screening: purely qualitative determination of unknown PFAS (no quantitative information)

This methodological adaptation enables a more exhaustive characterization of PFAS present in fire-fighting foams and contributes to a better understanding of the PFAS precursors degradation like 6:2 FTAB or 6:2 FTS [2].

By integrating complementary analytical strategies with an optimized TOP assay protocol, this work supports the development of more robust and representative PFAS assessment methodologies, thereby improving environmental monitoring and assisting PFAS management and remediation in the fire-fighting foam context or for soil and water investigation.

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2. LaFond, Jessica A., Paul B. Hatzinger, Jennifer L. Guelfo, Kayleigh Millerick and W. Andrew Jackson (2023) : Department of Civil, Environmental & Construction Engineering, Texas Tech University, Lubbock, TX 79409, USA. Royal Society of Chemistry. DOI: 10.1039/D3VA00031A (Tutorial Review) Environ. Sci.: Adv., 2023, 2,1019-1041.

Characterization of PFAS in Atmospheric Deposition from Industrial Sites

Jessica QUERON
Direction Milieux et Impacts sur le Vivant
Responsable de l'unité Caractérisation du milieu air en PROXimité de source

The monitoring of per- and polyfluoroalkyl substances (PFAS) in the environment has gained significant attention due to their persistence, bioaccumulation, and toxicity. While research has primarily focused on their detection in soils and water, the analysis of PFAS in air whether from: industrial emissions; ambient air, or atmospheric deposition; remains understudied. This gap stems from the diverse physicochemical properties of PFAS (polar, non-polar, volatile, or semi-volatile) and the complexity of the sampling and analytical methods required.

This presentation summarizes the latest advancements in standardization and standardized methods for monitoring PFAS in air, both internationally and nationally. It includes preliminary results from a pilot study on:

- Sampling of ambient air and atmospheric deposition,
- Evaluating the effectiveness of methodologies for PFAS with carbon chain lengths ranging from C1 to C18, under real-world and controlled conditions,
- Inter-laboratory comparison of different analytical approaches for sample preparation and analysis, involving three independent laboratories.

This work aims to address methodological gaps and propose robust protocols for reliable atmospheric PFAS survey.

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Industrial feedback of hazardous waste treatment facilities on the monitoring campaigns of air emissions of PFAS conducted in France under the ministerial order of October 31st, 2024, and evaluation of health risks associated with the emissions

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- **Interest of the subject**

This subject presents a major interest as it provides a first comprehensive vision of air emissions of PFAS from an industrial sector in France and tackles elements of risk assessment as a basis for interpretation of the results.

- **Key words**

PFAS, air emissions, risk assessment, hazardous waste

- **Objectives**

This industrial feedback aimed to present an overview of the results of the monitoring campaigns of air emissions of PFAS prescribed under the ministerial order of October 31st, 2024.

In this vein the levels of air emissions of PFAS associated with the sector of hazardous waste treatment were presented, which allowed to build a first picture of air emissions of this family of substances in France. Based on the results of the measured emissions, a health risks assessment was carried out.

- **Substances considered**

The substances considered for the monitoring and the health risk assessment correspond to the 50 PFAS listed in *appendix I* of the ministerial order of October 31st, 2024, issued by the French ministry in charge of the environment, relating to the analysis of PFAS in air emissions from installations classified for environmental protection (ICPE) under the category of Authorization.

- **PFAS analysis in air emissions**

PFAS were sampled by using the French standard XP X 43-126 aiming the *Emissions from stationary sources - Sampling and analysis of semi-volatile polar per- and polyfluoroalkyl compounds* (PFAS). Analysis of the supports were performed using techniques such as LC-MS/MS (Liquid Chromatography coupled to tandem Mass Spectrometry) and detection by MRM (Multiple Reaction Monitoring).

- **Approach for the risk assessment**

The health risk assessment utilized an approach based on the study of toxicological reference values (TRVs) and applied the INERIS guidelines to carry out an integrated approach for management of the emissions of chemical substances from industrial facilities (Ineris-200357-2563482-v1.0, 2021).

The criteria considered for the acceptability of the health risk are those prescribed by the circular of august 09th 2013. They are namely:

- for a substance with a threshold TRV: the acceptability criterion consists in a hazard quotient (HQ) inferior to 1 (HQ < 1).

- For a substance with non-threshold TRV: the criterion of acceptability consists in an excess individual risk (EIR) below 10^{-5}.

Once the level of risks was quantified, various conclusions were drawn in terms of impact of PFAS air emissions of health and the implications in terms of risk management.

- **Exposure scenario for the risk assessment**

INERIS guidelines prescribe the construction of an exposure scenario based on overall conservative assumptions. Therefore, the exposure scenario in this study was constructed accordingly. In the frame of this study, for the quantification of health risks, hazardous waste treatment facilities that were representative of the levels of emissions of the sector and that are associated with health and environmental vulnerabilities within their local context.

Three emission scenarios were considered: low emissions, average emissions and high emissions, each being defined by the mass rate emission in a year. For each of these scenarios, an industrial facility was retained for risk assessment. Emissions were then modelled to obtain concentrations in ambient air (for risks related to inhalation) and atmospheric deposition levels, which were used to calculate PFAS transfer throughout the food chain (for risks related to ingestion).

- **Calculation models for risk assessment**

Ambient air concentrations and particle deposition levels were obtained via the calculations based on ARIA IMPACT and ADMS models. As for food chain transfers, INERIS' MODULERS model was employed.

- **Results**

For the sum of all 50 PFAS measured and for a total of 70 waste treatment facilities, cumulated emissions (calculated for a functioning rate of 100%) range from 0,4 g/day to 6 g/day (cumulated emissions for the sector). For a facility taken individually, the average emissions levels for total PFAS were calculated around a value of 0,04 g/day.

Risk levels were quantified as such for threshold effects:

- For each facility, overall sums of HQ levels for inhalation and ingestion were quantified at levels inferior to 1.

Risk levels were quantified as such for non-threshold effects:

- Overall EIR for ingestion were quantified at levels inferior to 1×10^{-5}.

The results show that for the average hazardous waste treatment facility, expected health risks levels related to PFAS emissions into the air amount to levels of risk below the regulatory thresholds.

Management of PFAS Contamination in Fire Suppression Systems: Auditing Compounds Present and Decontamination Challenges

Speakers:
Raphaël TUR, PhD, PFAS Chemistry Specialist & Engineer
Jonathan SENECHAUD, Business Development Manager

Objectives: Through this presentation, COLAS Environnement will showcase the development of a patented PFAS flushing technology designed to meet European regulatory requirements related to the Foam Transition, particularly impacting industrial stakeholders (i.e., replacement of AFFF foams and decontamination of fire suppression systems).

Using practical case studies, COLAS Environnement will present the outcomes of its research projects focused on the development of PFAS flushing and degradation technologies for contaminated sites and soils, the regulatory framework associated with industrial foam transition, the PFAS compounds requiring diagnosis and auditing in this context, the deployment of flushing technology beyond contaminated site remediation, and PFAS behavior through rebound effect assessments.

Abstract:

As the oldest French environmental remediation company, Colas Environnement has specialized in the remediation of contaminated soils and groundwater, as well as the rehabilitation of polluted or degraded sites (brownfields, industrial sites...), since 1981.

Committed to the development of innovative technologies, Colas Environnement actively contributes to national and international R&D initiatives in collaboration with major stakeholders such as BRGM, a key partner in the European PROMISCES project.

PFAS are characterized by exceptional chemical and thermal stability, primarily due to their strong carbon–fluorine bonds. Often referred to as “forever chemicals,” their high-water solubility, combined with their strong tendency to adsorb onto soils and other environmental matrices has led to widespread accumulation and both diffuse and localized contamination depending on the investigated areas.

In this context, for more than four years, COLAS Environnement and its partners have been fully committed to developing methods to flush PFAS from soils, concentrate PFAS from contaminated water, and degrade PFAS: three key components of the PROMISCES research project, whose preliminary results will be presented as an introduction during this session.

This research project marked the first step in COLAS Environnement’s broader commitment to combating PFAS contamination in the environment first and brought the company face-to-face with the issue of AFFF foam concentrates contaminating fire suppression systems.

Recent European regulations, including the regulation dated October 2, 2025, have established maximum allowable thresholds for residual PFAS concentrations in fire protection equipment following cleaning. Specifically, the total concentration of investigated PFAS must not exceed 50 mg/L, while concentrations of PFOS, PFHxS, PFOA, PFHxA, and the sum of PFCA C9–C14 compounds must remain below 25 µg/L. These regulatory requirements aim to reduce PFAS at the source and accelerate the transition toward fluorine-free technologies.

These regulations will be reviewed in detail, alongside the technical solutions developed by COLAS Environnement to support industrial operators and stakeholders during this Foam Transition, illustrated through feedback from fire suppression system cleaning operations deploying the patented technology developed through PROMISCES.

To address this issue, a new technology for the recovery and desorption of PFAS from a porous media has been developed and tested as part of the PROMISCES project described above. This technology, which was patented in December 2025, involves injecting a foaming solution composed of water, a surfactant-type additive and gas into the PFAS-contaminated porous media (Figure 1). This solution, prepared in advance at our mobile production unit and then injected under low pressure, enables optimal PFAS recovery from the contaminated media by exploiting the hydrophilic and hydrophobic properties of these molecules. This technology was first tested under pseudo-field conditions within an 86 m³ multi-metric pilot (PMP), filled with a mixture of sand, clay and organic matter. Water circulation was also generated in depth (saturated zone) of the PMP to simulate the presence of a deep groundwater part. The soil (unsaturated zone) was subsequently contaminated with a highly concentrated AFFF C6 (PFHxA) fluorinated firefighting foam solution (approximately 146 g of total PFAS injected), which also contaminated the underlying groundwater via gravity. Finally, the soil was decontaminated by injecting in stages our washing solution over a period of three months. PFAS concentrations in the water of the underlying aquifer were also analyzed.

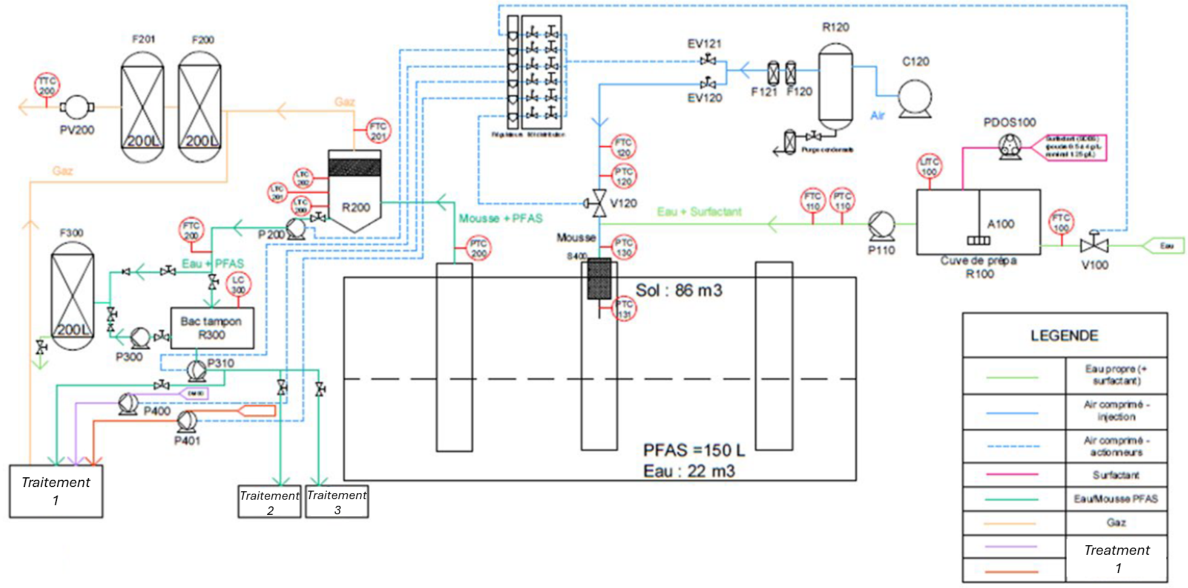


Figure 1: Piping & Instrumentation diagram (P&ID) of the foam injection and the wastewater treatment in the PMP

The results obtained in these experiments was grouped into two families, short chains PFAS (PFBA, PFHxA, 4:2 FTSA) and long chains PFAS (PFOA6:2 FTSA, 8:2 FTSA, 10:2 FTSA, 6:2 FTAB, 6:2 FTSaAM).

Figure 2 shows PFAS concentrations in the PMP outflow and the mass of PFAS extracted from the PMP as a function of time respectively. The PFAS concentrations in the water recovered from the PMP outlet were 2918 and 18 µg/l respectively for long chain and short chain PFAS at the very beginning of the experiment (05/02/2025). They decreased to reach a plateau (until 07/03/2025) of 350 and 3 µg/L for long chain and short chain PFAS respectively. This corresponds to a decrease in concentration in the aqueous phase of almost 90%. It is noted that the change in the quality of the foam (from 07/03/2025) and subsequently the position of the injection zone from 10/03/2025) made it possible to desorb the long chain and short chain PFAS significantly.

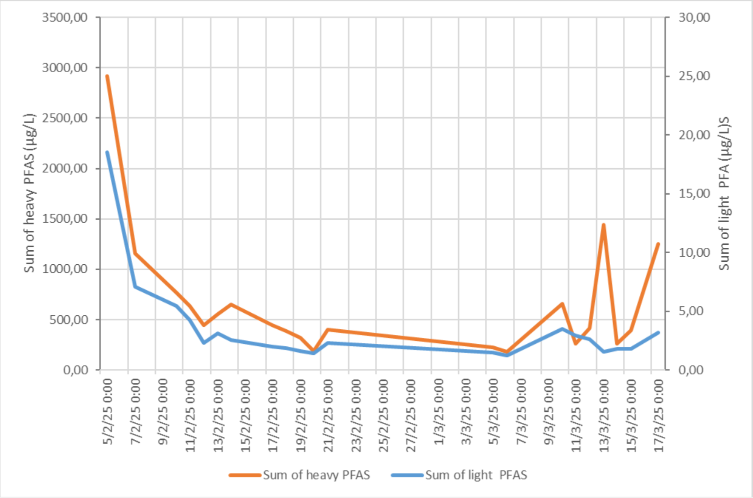


Figure 2: Short chain and long chain PFAS concentrations in the PMP outlet as a function of time

The mass of PFAS extracted during the experiment is presented in Figure 3. The mass of PFAS extracted until 10/03/2025 was 31.86 g (short chain PFAS: 0.19 g; long chain PFAS: 31.67 g). Between 10/03/2025 and the end of the experiment (when the foam injection was carried out directly in the unsaturated zone at the heart of the spill), the mass of PFAS extracted was 11.64 g (short chain PFAS: 0.04 g; long chain PFAS: 11.64 g). The total mass of extracted PFAS was 43.50 g at the end of the experiment (short chain PFAS: 0.23 g; long chain PFAS: 43.27 g). We can distinguish 4 phases: i) initial conditions, ii) stabilization of conditions, iii) first change of the operating mode, iv) second change of the operating mode. Figure 4 presents the recovery yield of PFAS. The calculation was based on the difference between the mass of PFAS injected and the mass of PFAS extracted. The first step corresponds to the foam propagation and stabilization phase. At the end of this step, the recovery yield (RY) is 2.5 g/h. After (second step) we observe a stabilization of the recovery yield (mainly between 2 and 3 g/hr). The change in operating conditions (i.e. increase in foam strength) made it possible to achieve a RY of 6 g/hr. This operation was stopped because the foam rose to the soil surface. The fourth step corresponds to the last operating conditions (injection of the foam into the unsaturated zone; this made it possible to achieve a recovery rate of 7 g/hr.

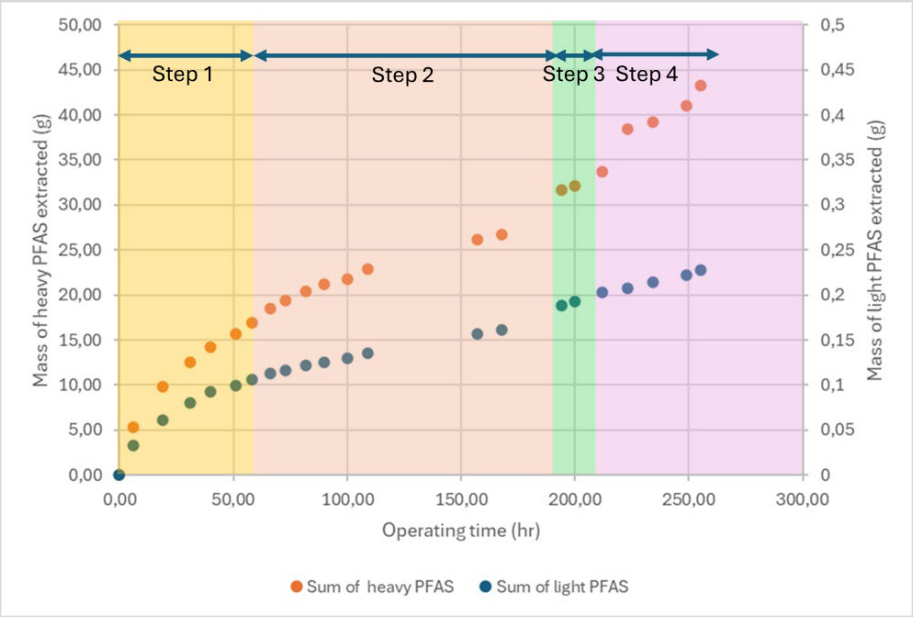


Figure 3: Mass of extracted short chain and long chain PFAS as a function of operating time

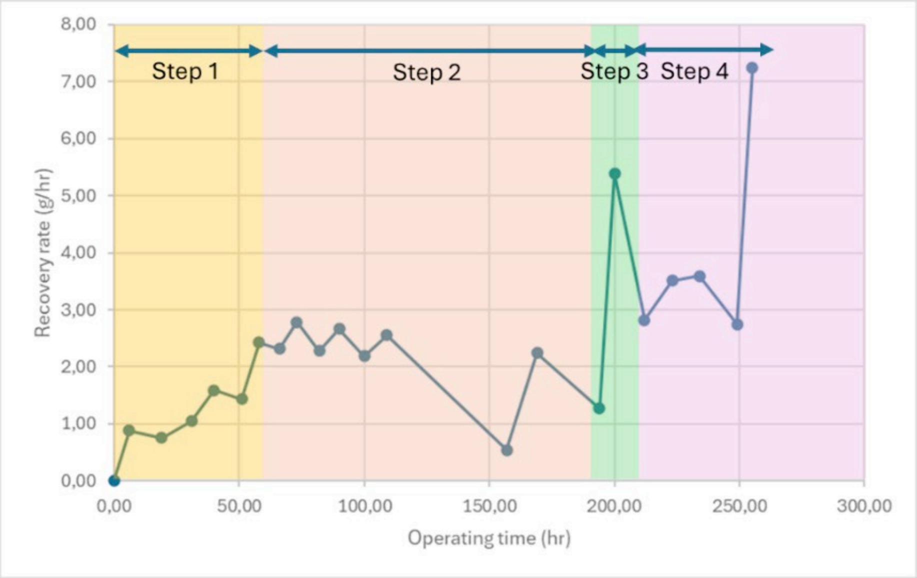


Figure 4: Recovery rate of PFAS as a function of operating time

Once the technology's effectiveness had been demonstrated on a porous media such as contaminated soil, trials were first conducted on a laboratory scale in a fire protection pipe heavily contaminated with AFFF fluorinated foam concentrate, and then on a field scale with the decontamination of an entire fire protection system. The aim of adapting this technology to this new context was to combine the advantages of the solution developed (Figure 5) with the emerging challenge of cleaning fire protection equipment effectively and within the reference thresholds defined by Europe.

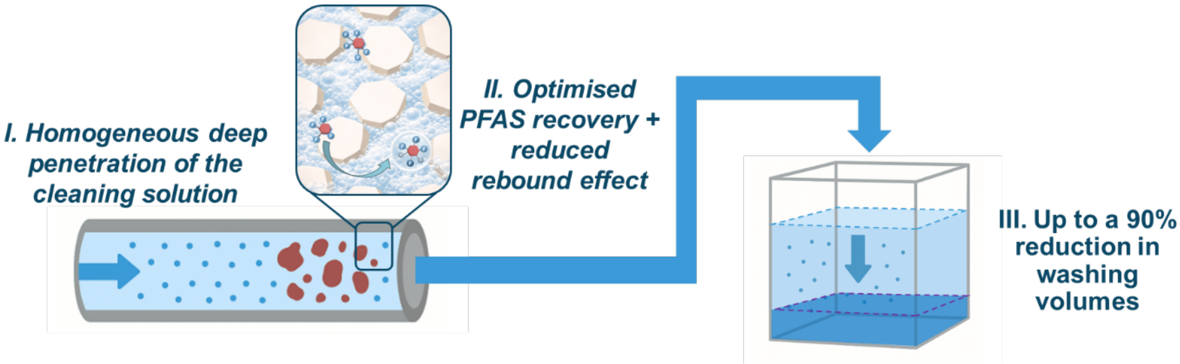


Figure 5: Schematic representation of the advantages of the washing solution

Figure 6 shows the decrease of regulated PFAS concentrations (∑PFAS, PFOA, PFHxA, PFOS, PFHxS, ∑PFCA C9-C14) before and after the cleaning of a pipe. Analyses revealed significant contamination levels for ∑PFAS (12,124.86 µg/L), PFOS (216.53 µg/L), PFHxS (270 µg/L) and PFHxA (786.9 µg/L), which, following cleaning, were significantly reduced to levels complying with the regulatory thresholds outlined above, confirming the effectiveness of this process on this type of contaminated porous medium.

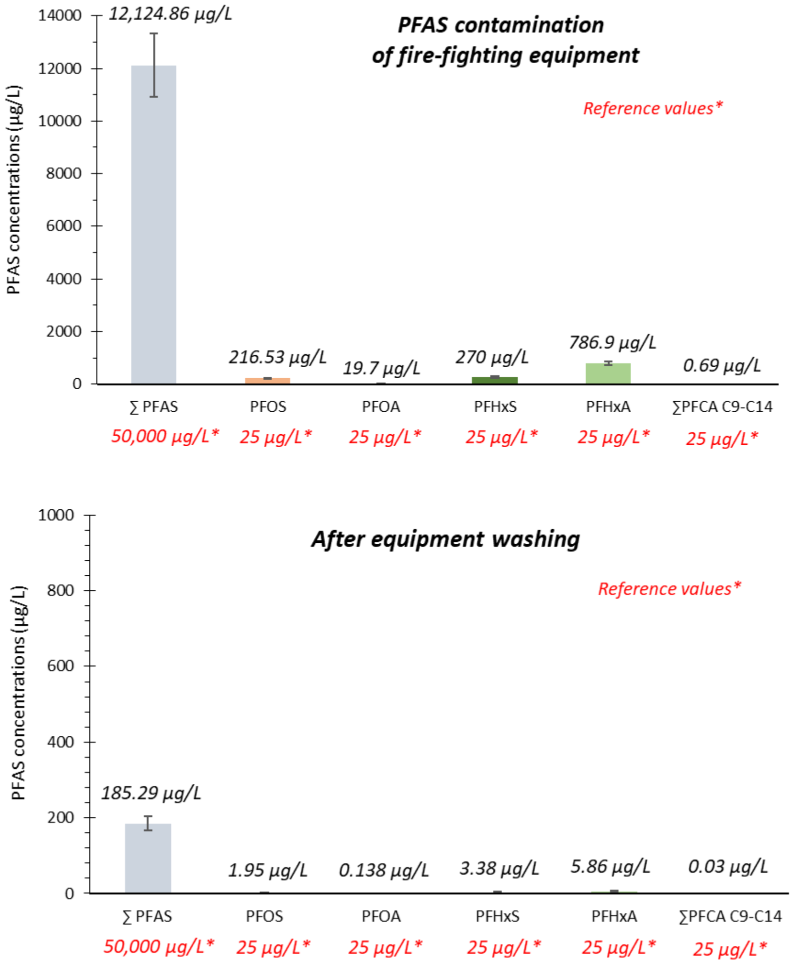
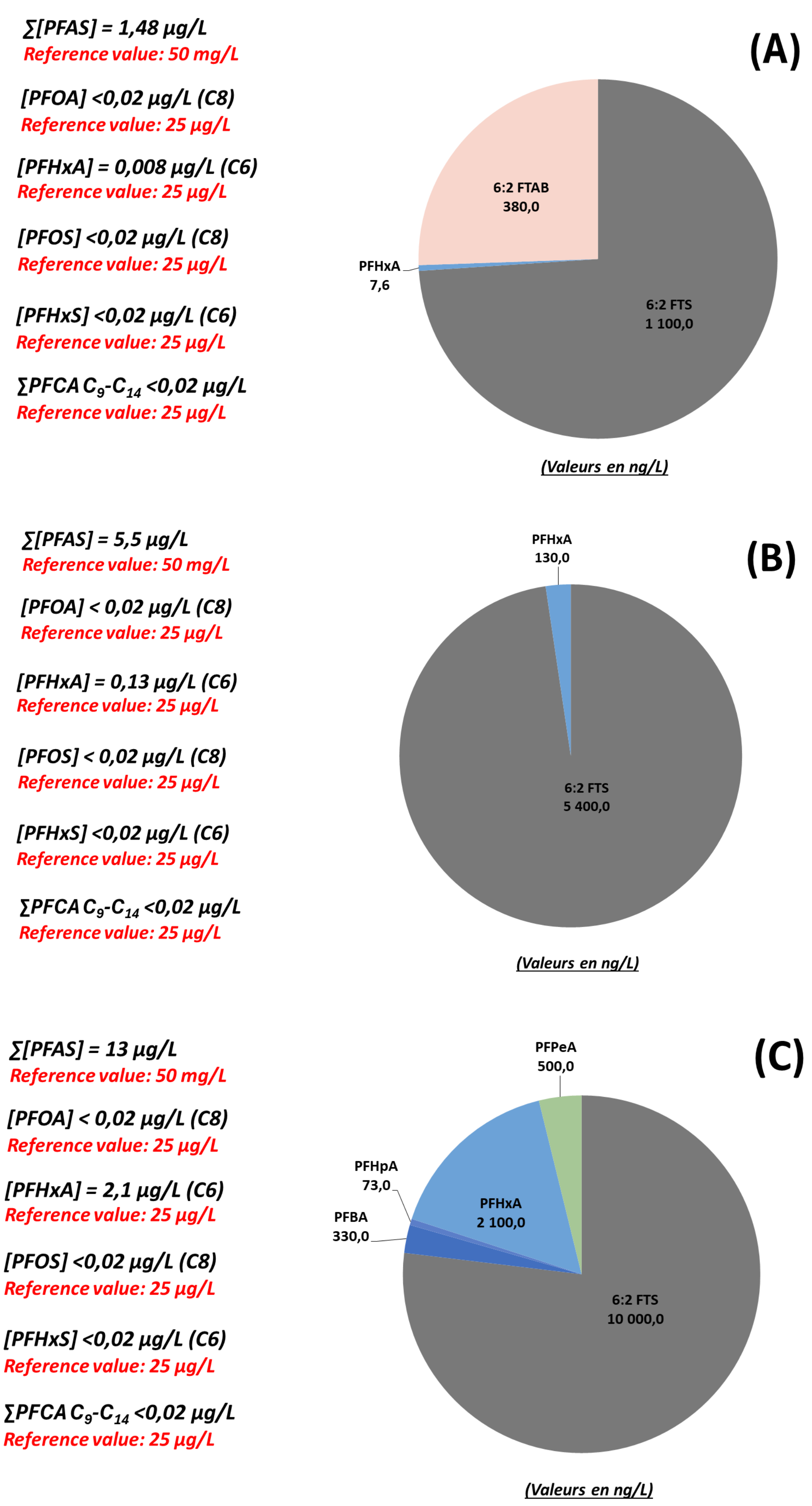


Figure 6: Efficiency of fire-fighting equipment washing by comparison of PFAS concentrations before and after washing

The field-scale application of technology is shown in Figure 7. It presents the residual concentrations of regulated PFAS following the cleaning of a polymer tank (A), a stainless-steel network and dosing system (B) and, finally, a steel test pipe (C), respectively. The results demonstrate that regulatory thresholds were met for each cleaning operation carried out, regardless of which part of the fire protection system was cleaned and confirm the feasibility of the technology for field application as part of the transition to foam.



(A)

∑[PFAS] = 1,48 µg/L
Reference value: 50 mg/L

[PFOA] <0,02 µg/L (C8)
Reference value: 25 µg/L

[PFHxA] = 0,008 µg/L (C6)
Reference value: 25 µg/L

[PFOS] <0,02 µg/L (C8)
Reference value: 25 µg/L

[PFHxS] <0,02 µg/L (C6)
Reference value: 25 µg/L

∑PFCA C_9-C_{14} <0,02 µg/L
Reference value: 25 µg/L

(B)

∑[PFAS] = 5,5 µg/L
Reference value: 50 mg/L

[PFOA] < 0,02 µg/L (C8)
Reference value: 25 µg/L

[PFHxA] = 0,13 µg/L (C6)
Reference value: 25 µg/L

[PFOS] < 0,02 µg/L (C8)
Reference value: 25 µg/L

[PFHxS] <0,02 µg/L (C6)
Reference value: 25 µg/L

∑PFCA C_9-C_{14} <0,02 µg/L
Reference value: 25 µg/L

(C)

∑[PFAS] = 13 µg/L
Reference value: 50 mg/L

[PFOA] < 0,02 µg/L (C8)
Reference value: 25 µg/L

[PFHxA] = 2,1 µg/L (C6)
Reference value: 25 µg/L

[PFOS] <0,02 µg/L (C8)
Reference value: 25 µg/L

[PFHxS] <0,02 µg/L (C6)
Reference value: 25 µg/L

∑PFCA C_9-C_{14} <0,02 µg/L
Reference value: 25 µg/L

Figure 7: Residual PFAS concentrations after fire-fighting equipment washing

Atlantis Développement

PFAS
PER- AND POLY-FLUOROALKYL SUBSTANCES
Paris – France : 16, 17, 18 & 19 June / Juin 2026

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Prise en compte des Précurseurs poly-fluorés des PFAS et leurs métabolites intermédiaires et finaux dans le cadre des évaluations des risques pour la santé (EQRS & ARR) : La question des FTOHs dans les sols, des eaux et de l'air.

Consideration of poly-fluorinated PFAS Precursors and their intermediary and final Metabolites for Human Health Risk Assessments (HHRA & TERQ): The Question of the FTOHs in Soil, Water and Air.

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Abstract & Summary

The methodology of Toxicological Exposure Risk Quantification (TERQ) or Human Health Risk Assessment (HHRA), applicable to exposure to PFAS, their biotransformation products and their mixtures is described by the quantification of oral exposure (e.g., in the case of ingestion of water and food or passive soil & dust ingestion), inhalation of contaminated dust and volatile PFAS (like FTOHs etc.), as well as by dermal contact (e.g., soil & dust and water) or, for example, on contaminated sites or in contaminated buildings. The work presents the TERQ & HHRA methodology for exposure to PFAS mixtures especially concerning the high number of polyfluorinated PFAS.

PFAS (per- and polyfluoroalkyl substances) have gradually become a major environmental problem since the 1960s, also for public health, due to their toxic exposure effects based on water, soil, air and food pollution. These pollutions are based on their multiple and extensive applications (historical and current), for example, in detergents, fire-fighting foams (AFFF), the treatment and waterproofing of textiles, paper, cardboard, and wood, in galvanizing, in paints and lacquers, in electronic components, certain hydraulic oils, and in the production of fluoropolymers.

Other sources of environmental pollution (air, water, soil, and food) are leachate from (old) landfills and the spreading of certain wastewater treatment plants' sludge on agricultural land, and even incinerator emissions, which are still poorly characterized. This environmental and public health threat of PFAS has gradually been recognized in Europe since the 2010s, and the issue has been widely publicized and increasingly managed and regulated since 2022. PFAS are now found in soil, groundwater, food, and drinking water, as well as in soil vapor and ambient air. Between 9,000 and more than 12,000 synthetic PFAS pollutants have been produced.

Polymeric PFAS of the "Teflon" type (or PFTE) do not have good bioavailability and are considered much less toxic (or even non-toxic) than monomeric PFAS. However, their manufacture and disposal can result in the release of toxic PFAS. The toxicity of monomeric PFAS is the most studied, at least for some of them, and is the subject of the present work presented below. In total, thirty-

three (33) chemical families of monomeric PFAS exist, such as perfluorinated carboxylic or sulfonic acids or various polyfluorinated PFAS (or "precursors") that can be (bio-)transformed into stable perfluorinated PFAS.

This work describes the quantitative human health risk assessment in case of PFAS presence and their biotransformation products in the environment and the human exposure pathways and their toxicological effects.

The greatest unknown in the effects of PFAS mixtures concerns the large proportion of polyfluorinated PFAS. It is recommended to apply the PFAS analyses of PFAS-65 + 5 ultrashort PFAS before and after the “Top Assay” for the needed minimum PFAS analyses in exposure media (food, drinking water, bathing water, soil, dust, and ambient air (not forgetting soil gases for volatile PFAS).

The "Top Assay" (Total Oxidizable Precursor), according to Houtz and Sedlak: 2012 [63], transforms polyfluorinated PFAS into perfluorinated PFAS. In the environment, all polyfluorinated PFAS (Precursors) are biotransformed into stable perfluorinated PFAS. Via the "Top Assay", it is possible to integrate also perfluorinated PFAS products of nearly all polyfluorinated PFAS biotransformations in an exposure scenario into the health risk assessment.

However, it is not sufficient to conduct health risk assessments solely on perfluorinated PFAS after the "Top Assay," as the dose-effects thresholds (TDVs) or toxicological Reference Doses (TRD) of certain polyfluorinated PFAS may be significant in subchronic and chronic exposures, such as for volatile PFAS (like FTOH: fluorotelomer-alcohols, etc.).

A description of the scientific selection criteria for TDVs (Toxicological Dose-Effect Values) is provided to choose well-founded TDV. For certain important PFAS that are highly prevalent in the environment, TDVs may be defined, e.g., based on NOAELs, such as for 6:2-FTAB (Capstone B) and 6:2-FTNO (Capstone A) or on Unit Risks or Slope Factors for carcinogenic PFAS, like PFOA and PFOS…

1. Introduction

L’objectif du travail ci-présent est la méthodologie de l’évaluation quantitative des risques sanitaires (EQRS), applicable concernant les PFAS, leurs produits de bio-transformation et leurs mélanges dans le cas des expositions orales (par ex. dans le cas de l’ingestion des eaux ou aliments) ou dans le cas de l’inhalation des poussières contaminés et PFAS volatils mais aussi dans le cas des contacts cutanés (par ex. aux poussières et eaux superficielles) ou par ex. sur des sites pollués. L’article présente la méthodologie de l’EQRS dans le cas des expositions aux mélanges des PFAS.

Les PFAS : per- & poly-fluoro-alkyl substances sont devenus progressivement depuis des années 1960 un problème environnemental majeur, également pour la Santé Publique du fait de leurs effets sur la santé humaine et leur application multiple et vaste (historique et actuelle) par exemple dans les détergents, des mousses anti-incendies (AFFF), le traitement et l’imperméabilisation des textiles, papiers, cartons et bois, pour la galvanisation, dans les peintures et laques, dans les éléments électroniques, certaines huiles hydrauliques et pour la production des fluoro-polymères.

D'autres sources de pollution de l'environnement (air, eaux, sols et aliments) sont les lixiviats des anciennes décharges et les épandages des certaines boues de stations d'épurations sur des terrains agricoles voire les émissions des incinérateurs encore mal caractérisées. Cette menace environnementale et pour la santé publique des PFAS est peu à peu prise en compte en Europe depuis les années 2010 et la problématique médiatisée et de plus en plus gérée et réglementée depuis 2022.

Les PFAS se retrouvent aujourd'hui dans les sols, les eaux souterraines, les aliments et l'eau potable ainsi que dans les gaz du sol et l'air ambiant. Entre 9 000 à 12 000 polluants synthétiques de PFAS ont été produits.

Les PFAS polymères du type « Teflon » (ou PFTE) ne disposent pas une bonne biodisponibilité et sont considérés comme beaucoup moins toxiques (voir non-toxiques) que les PFAS monomères. Cependant leur fabrication et élimination peut engendrer des rejets de PFAS toxiques. La toxicité des PFAS monomères est la plus étudiée, du moins pour quelques-uns d'entre eux et fait l'objet du chapitre présenté ci-après. Au total, trente-trois familles de PFAS monomères existent, comme par ex. les acides carboxyliques ou sulfoniques per-fluorés ou divers PFAS poly-fluorés (ou « Précurseurs ») qui peuvent être (bio-)transformés en PFAS perfluorés stables.

2. Métabolisation des PFAS

Selon Y. DAI et al. (2025 [91]), certains PFAS subissent une biotransformation au sein des organismes, produisant des PFAS à chaîne courte potentiellement plus toxiques. Les phénomènes et voies de biotransformation des PFAS chez les humains, les animaux, les plantes et les micro-organismes sont extrêmement importants et surtout la bio-transformation des PFAS poly-fluorés vers les PFAS per-fluorés ainsi que l'ensemble des métabolites intermédiaires. Les fluorotélomère-alcools (FTOH), le 3-phosphoadénosine-5-phosphosulfates (PAP), le N-éthyl-perfluorooctane-sulfonamido- éthanol (N-EtFOSE) et les sulfonates de fluorotélomères (FTSA) peuvent subir des processus de défluorination, d'oxydation, de décarbonylation et de désulfonamidation pour former de nouveaux types de PFAS, tels que l'acide perfluorooctanoïque (PFOA) et l'acide perfluorooctanesulfonique (PFOS) can cérigènes. Les enzymes (par exemple, les oxydoréductases et les transférases) présentes dans les organismes sont les principaux médiateurs de ces bio-transformations des PFAS.

Y. DAI et al. (2025 [91]) indique aussi, que parmi les précurseurs des PFCA (Acides perflouro-carboxyliques), les FTOH subissent une oxydation dans les hépatocytes, catalysée par des enzymes oxydatives telles que le cytochrome P450 (CYP45). Cette oxydation enzymatique génère deux intermédiaires : les fluorotélomères-aldéhydes (FTAL) et les fluorotélomères-acides-carboxyliques (FTCA), qui sont ensuite défluorés pour former des PFCA. Il a été rapporté que les FTAB (par ex. le 6 :2 FTAB ou « Capstone B ») sont convertis en FTSA par déméthylation dans le blé de farine (Triticum aestivum L.), tandis que les FTSA peuvent être transformés en 6 :2 FTOH par désulfonation, une réaction catalysée par la souche NB4-1Y de Gordonia sp. Concernant les précurseurs du PFSA, le N-EtFOSE subit une oxydation et une décarboxylation par des micro-organismes aérobies (par exemple, Pseudomonas, Rhodococcus, Sphingomonas et Mycobacterium) dans le sol pour former du FOSA, qui subit ensuite une désamination et une hydroxylation pour finalement donner directement du PFOS par des enzymes du sol, par exemple, l'oxydase, la déshydrogénase (Y. DAI et al. (2025 [91]).

L'ensemble de ces métabolites sont successibles de se trouver dans l'organisme humaine par expositions via des aliments, de l'eau et de l'air ambiant (et notamment par les FTOH volatils).

3. Toxicité des PFAS :

L'OCDE (OCDE, 2021 [1]) définit les PFAS comme des substances contenant au moins un « un méthylène totalement fluoré sans être lié à un atome d'hydrogène ou à un autre halogéné ». Les PFAS constituent donc un large groupe de congénères qui diffèrent par la longueur de leur chaîne fluor- carbonée, la présence d'une chaine alkylénique (poly-fluorée) et la fonctionnalisation de leur terminaison hydrophile (carboxylique ou sulfonique par exemple). Par contre, cette simple définition des PFAS par est couramment critiquée, car elle concerne également certains médicaments (monomères), fluor-polymères inertes (comme des dispositifs médicaux d'implantation, etc.) et d'autres produits plutôt bénéfiques en industrie aérospatiale, automobile etc. Uniquement les PFAS monomères toxiques sont visées par les Evaluations Quantitatives des Risques Sanitaires (EQRS).

Parmi les congénères perfluorés, possédant une fonctionnalisation carboxylique (PFCA) ou sulfonique (PFSA), on distingue les composés à longue chaine (PFCA avec plus de 7 atomes de carbone (p.ex. PFOA et PFNA) et PFSA avec plus de 5 atomes de carbone (p.ex. PFOS et PFHxS). Les composés à chaines courtes (p.ex. PFBA) et à chaines très courtes (p.ex. TFA, acide trifluoro-acétique) complètent le tableau.

Les caractéristiques des congénères influencent leurs paramètres toxicocinétiques mais également leurs propriétés toxico-dynamiques, à savoir notamment l'interaction avec des récepteurs nucléaires.

Les effets délétères associés aux PFAS sont nombreux et touchent des cibles biologiques diverses. Les données toxicologiques sont historiquement obtenues avec des composés à chaines longues. Les récentes évaluations réalisées par des organismes nationaux ou supranationaux (ATSDR, 2021 [2] ; IARC, 2016 [3]; US-EPA, 2016a,b [4, 5] ; Zahm et al., 2023 [6], US-EPA 2024a [7], 2024b [8]) indiquent que certains PFAS à longue chaine sont (sur base de données souvent issues de l'étude du PFOA et du PFOS) cancérigènes, reprotoxiques, immuno-toxiques et perturbateurs endocriniens. En outre, ils exercent une toxicité sur le métabolisme des lipides.

3.a. Effets non-cancérigènes (effets systémiques):

Les PFAS sont hépatotoxiques chez le rongeur. La toxicité hépatique, mise en évidence essentiellement pour des composés à longues chaines, se caractérise par une hypertrophie hépatocellulaire due à une augmentation du nombre et de la taille des peroxysomes. Les PFAS sont susceptibles d'augmenter l'α-oxydation des acides gras. D'une manière générale les PFAS perturbent le métabolisme lipidique. De récentes publications montrent une association positive entre les taux circulant de PFOS et les taux de cholestérol total et de cholestérol non HDL (« mauvais cholestérol ») (Ho, 2022 [9]; Rosen, 2022 [10]).

Dans l'ensemble, les effets hépatotoxiques rapportés dans les études disponibles sont des indicateurs potentiels d'altérations induites par le PFHxS dans la fonction hépatocytaire, qui pourraient éventuellement conduire à un métabolisme hépatique anormal et à une accumulation d'acides gras entraînant une stéatose hépatique. L'accumulation hépatique excessive et prolongée d'espèces lipidiques lipotoxiques (par exemple, le cholestérol libre et les acides gras libres) (US-EPA-IRIS, 2025 [69], Younossi et Henry, 2024 [74] ; M et al., 2024 [75]) est associée à une stéatose hépatique, à la promotion de la lipotoxicité, aux réponses pro-inflammatoires, à la cytotoxicité et à la progression de la stéatose hépatique vers la stéatohépatite. L'exposition au PFHxS (60 à 110 mg • kg^{-1} • jour^{-1} ou mg polluant par kg poids corporel par jour) pendant 12 semaines a augmenté les taux d'ARNm hépatique de la cytokine pro-inflammatoire (IL-1β) et du facteur pro-fibrogène Col1α (He et al., 2022 [78]). L'IL- 1 β et Col1 α jouent un rôle dans la perte des fonctions hépatiques et la progression de la stéatose hépatique vers la stéatohépatite et des lésions fibrotiques (US-EPA-IRIS, 2025 [69], Vesković et al., 2024 [76]; Sultan et al., 2017 [77]; He et al., 2022 [78]).

Le TFA présente également une toxicité hépatique mise en évidence dans plusieurs études par une perturbation des enzymes hépatiques (ASAT, ALAT, phosphatases alcalines). Dekant et Dekant (2023) [11] signent une revue récente de la littérature sur le sujet. Il faut souligner qu'une grande partie du TFE en environnement se trouve dans les eaux de surface (rivières etc.) du fait de la photolyse de plusieurs grouppes des polluants, y compris des pesticides fluorés.

L'immunotoxicité des PFAS a été étudiée sous différents aspects, notamment l'hypersensibilité, la réponse auto-immune et la réduction de la production d'anticorps (Bil & Ehrlich et al., 2023 [12]). Dans ce contexte, l'EFSA (EFSA, 2020 [13]) a défini une dose hebdomadaire tolérable (TWI : total weekly intake) en se basant sur l'étude d'Abraham et al. (Abraham, 2020 [14]). Cette recherche a révélé des associations significatives entre les concentrations sériques de PFOA (mais non de PFOS) et les taux ajustés d'anticorps contre Haemophilus influenzae type b (Hib, r = 0.32), contre l'anatoxine tétanique (Clostridium tetani, r = 0.25) et l'anatoxine diphtérique (Corynebacterium diphtheriae, r = 0.23). Après avoir converti ces données à l'aide d'un modèle PBPK, l'EFSA [13] a fixé une TWI de 4,4 ng/kg de poids corporel par semaine pour la somme des PFOA, PFNA, PFHxS et PFOS.

L'ATSDR (ATSDR, 2021 [2]) a retenu des effets reprotoxiques, spécifiquement liés au développement, pour établir les niveaux minimaux de risque (MRL) de trois composés : le PFOA, le PFOS et le PFNA. Les effets critiques identifiés ont été observés chez la souris et incluent, pour le PFOA, une altération du squelette (Koskela, 2016 [15]), pour le PFOS, une réduction du poids des portées et un retard dans l'ouverture des yeux (Luebker, 2005 [16]), et pour le PFNA, une diminution du poids des portées ainsi qu'un retard dans le développement (Das, 2015 [17]). Pendant la grossesse et le développement précoce, les perturbations de la fonction thyroïdienne par les PFAS et particulièrement par le PFHxS peuvent avoir des répercussions sur la croissance normale et le développement neurologique de la progéniture (US-EPA-IRIS, 2025 [69], Zoeller et Rovet, 2004 [70]; Y et al., 2024 [71]; Street et al., 2024 [72]; Stagnaro-Green et Rovet, 2016 [73]).

Les MRL, calculés pour une durée d'exposition chronique et intermédiaire, sont respectivement fixés à 3, 2 et 3 ng/kg de poids corporel par jour pour le PFOA, le PFOS et le PFNA.

Concernant le PFHxS, l'ATSDR (ATSDR, 2021 [2]) a sélectionné un autre effet critique, illustrant la diversité des dangers liés aux PFAS : son impact sur la thyroïde, en tant que perturbateur endocrinien. L'effet critique, identifié par Butenhoff et al. (Butenhoff, 2009 [18]), est l'hyperplasie/l'hypertrophie de l'épithélium des follicules thyroïdiens chez le rat. Sur cette base, l'ATSDR a calculé un MRL oral intermédiaire de $2\cdot10^{-5}$ mg/kg de poids corporel (pc) par jour. Malgré cela, l'ATSDR souligne, à travers la revue de nombreuses études épidémiologiques, que la relation entre les PFAS et les perturbations thyroïdiennes reste controversée. Les observations épidémiologiques ont mis en évidence une réduction des poids de naissance des nouveau nées associée à une sur-exposition aux PFAS (Engström, 2022 [19]).

3.b. Effets cancérigènes :

L'IARC (agence de l'OMS spécialisée dans l'évaluation des effets cancérigènes) avait classé en 2016 [20] le PFOA (acide perfluoro-octanoïque) en catégorie 2B (L'agent est peut-être cancérigène pour l'Homme) sur la base d'éléments de preuve limités tant chez l'Homme (cancers des testicules et du rein) que chez l'animal.

L'IARC [20] a pris en considération deux études épidémiologiques relatives à l'exposition professionnelle (par inhalation) au PFOA : Steenland et Woskie (Steenland et Woskie, 2012 [21]) et Raleigh et al. (Raleigh et al., 2014 [22]). L'étude de Raleigh et al. (2014 [22]) ne conclut pas à l'existence d'une association entre les effets critiques observés et l'exposition au PFOA (en l'occurrence son sel d'ammonium). Toutefois, l'IARC considérait que, dans cette étude, l'incidence et la mortalité du cancer de la vessie sont associées à l'exposition au PFOA (sel d'ammonium), bien qu'aucun de ces paramètres ne conduise à une association statistiquement significative.

En 2023, L'IARC (Zahm et al., 2023 [6]) a revu sa position et classé le PFOA comme une substance cancérigène pour l'humain (Groupe 1). La classification du PFOA repose aujourd'hui sur des preuves suffisantes de cancers chez l'animal (exposé via l'alimentation) (foie et pancréas) et sur des preuves fortes relatives aux mécanismes pouvant être mis en œuvre chez l'Homme. Le lien entre le PFOA et l'apparition de carcinome des cellules rénales et de cancer des testicules reste limité. Le PFOS a été classé comme potentiellement cancérigène pour l'humain (Groupe 2B).

Au vu des processus industriels mettant en œuvre ces composés, il n'est pas aisé d'établir dans les études épidémiologiques la distinction entre exposition au PFOS/PFOA et autres PFAS.

En 2016, l'US-EPA, dans un health advisory PFOA (US-EPA, 2016a [4]) pour l'eau de boisson, proposait un OSF (Oral Slope Factor / estimateur quantitatif du risque de cancers) de 0,07 $(mg/kg\ pc\cdot j)^{-1}$ dérivé de l'étude de Butenhoff (Butenhoff, 2012 [23]) analysant les tumeurs dans les cellules de Leydig chez le rat mâle. En 2024, (huit ans après), l'US-EPA (US-EPA, 2024a [7]) propose un nouvel OSF de 0,0293 $(mg/kg\ p.c.\cdot j)^{-1-1}$ soit 29,300 $(ng/kg\ p.c.\cdot j)^{-1}$. Ce nouvel OSF est basé sur l'apparition de carcinome des cellules rénales mis en évidence par Shearer et al. (2021) [24]. Le nouvel OSF est près de 500.000 fois plus précautionneux.

Pour le PFOS, les données de l'étude de Buttenhoff et al. [23] ont notamment été utilisées par l'US-EPA pour produire un « Oral Slope-Facteur » : OSF de 39,5 $(mg/kg\ p.c.\cdot j)^{-1}$.

Le TFA n'apparaît ni mutagène (le test de Ames avec et sans activation métabolique est globalement négatif), ni clastogène. Le TFA n'est pas classé cancérogène.

3.c. Mécanismes d'actions toxicologiques

i. Mécanisme médié par le récepteur PPAR-alpha

La principale cible des PFAS est le récepteur PPAR- α (peroxisome proliferator-activated receptor – alpha) chez l'animal de laboratoire (rongeurs). Toutefois, il est nécessaire de signaler que d'une manière générale, les rats et les souris possèdent des récepteurs PPAR-α plus sensibles aux PFAS que ceux des primates (humains et non-humains). Les différences entre espèces s'expliquent notamment par l'expression du récepteur dans les tissus.

Le récepteur PPAR-α est un récepteur nucléaire présent dans de nombreux organes caractérisés par un taux élevé de catabolisme des acides gras (foie, rein, cœur …). Ses ligands endogènes sont principalement les acides gras, ainsi que, dans une moindre mesure, certains dérivés des eicosanoïdes... Les gènes activés par le récepteur PPAR-α (après translocation nucléaire) sont responsables, entre autres, de l'absorption cellulaire des acides gras et de leur oxydation métabolique (Boelsterli, 2007 [25]; Landry, 2019 [26]).

Les congénères PFOA*, PFOS*, PFUnA*, PFHpA* et PFDoDA* activent le récepteur PPAR-alpha. Les congénères sulfoniques sont réputés moins puissants que les congénères carboxyliques. La puissance augmente en fonction de la longueur de la chaîne fluorocarbonée. (* : cf. aussi le tableau 9.1 & 9.2. et la nomenclature des PFAS dans les chapitres – fiches du Guide de gestion des PFAS de la SFSE [46]).

Les gènes dont l'expression est augmentée appartiennent au métabolisme des acides gras, à la biosynthèse des peroxysomes et à la structure et à l'organisation des protéasomes. Les gènes dont l'expression est diminuée interviennent notamment dans la réponse inflammatoire.

ii. Le mécanisme médié par d'autres voies

Les mécanismes indépendants de l'activation de PPAR-alpha peuvent être médiés par d'autres récepteurs nucléaires tels PPAR-gamma, CAR (constitutive androstane receptor) ou ER-alpha. Des réactions de stress oxydant mises en évidence en particulier par la présence de 8-OH-dG peuvent résulter soit d'une activation via Nrf-2 ou via PPAR-alpha (Boelsterli, 2007 [25]; Landry, 2019 [26]).

3.d. Toxicocinétique

L'EFSA (2020 [13]) a réévalué la toxicocinétique des PFAS, en particulier chez l'Homme. L'exposition humaine est principalement due à l'ingestion d'aliments contaminés (eau de boisson contaminée, produits de la mer, etc.) ainsi que l'inhalation de l'air intérieur. Les substances PFOS et PFOA sont majoritairement absorbées par voie orale, cette voie d'exposition étant plus significative que l'inhalation ou la voie transdermique (Sunderland, 2019 [27]). Dans certains cas, la modélisation de la toxicocinétique nécessite l'utilisation de logiciels PBPK.

Pour le PFOA et le PFOS, leur distribution dans l'organisme se caractérise par une liaison à l'albumine plasmatique. Ces composés ne sont pas connus pour être métabolisés. Leur élimination se fait par les voies biliaire et urinaire. Par exemple, le PFOA subit une réabsorption tubulaire via des transporteurs d'anions organiques (OAT, pour "organic anion transporters"), tandis que la réabsorption biliaire joue également un rôle majeur. La demi-vie des PFOS et PFOA se mesure en années. Les données concernant les composés à chaînes courtes et ultra-courtes laissent supposer qu'ils présenteraient une demi-vie bien plus courte (quelques jours) (Fenton, 2021 [28], Boutonnet, 1999 [29]). Concernant les composés poly-fluorés comme le 8 :2 FTOH, Nabb et al. (Nabb et al., 2007 [30]) ont démontré à l'aide de microsomes humains la métabolisation du 8 :2 FTOH en composés perfluorés. Les observations de Nilsson et al. (Nilsson et al., 2013 [31]) suite à l'exposition de travailleurs fartant des skis **avec** de la cire contenant du 8 :2 FTOH confirment les résultats expérimentaux.

4. Valeurs Toxicologiques de Référence (VTR) :

Les valeurs présentées dans cet article sont issues des rapports rédigés par des institutions nationales et supra-nationales (cf. Tableau 1 à 3) :

Tableau 1 : Organismes proposant des VTR pour les PFAS

ANSES	Agence nationale de sécurité sanitaire de l'alimentation, de travail (France)
ATSDR	Agency for Toxic Substances and Disease Registry (États-Unis)
EFSA	European Food and Safety Authority
IRIS	Integrated Risk Information of Substances (États-Unis)
UBA	Umweltbundesamt (Allemagne)
BfR	Bundesintitut für Risikobewertung (Allemagne)
OEHHA	Office of Environmental Health Hazard Assessment (États-Unis)
WHO	World Health Organization
RIVM	Netherlands Environmental & Health Institute (Pays-Bas)
MDHHS	Michigan Department of Health and Human Services, Division of Health (États-Unis)
TCEQ	Texas Commission on Environmental Quality (États-Unis)
NJ-DWQIHES	New Jersey Drinking Water Quality Institute Health Effects Sub-committee (États-Unis)
SLU	Swedish University of Agricultural Science (Suède)

Il peut exister par ailleurs, dans la littérature scientifique des « Points of Departures (POD) » et VTR plus récentes ou plus spécifiques. Le choix des VTR constitue une étape importante de l'EQRS car leur évolution est rapide en ce qui concerne les PFAS. Par ex., l'ANSES a publié en 2017 un guide

PFAS comportant certaines VTR pour les PFAS (ANSES, 2017 [32]). Aujourd'hui, les VTR publiées sont devenues beaucoup plus sévères, comme le montre l'évolution des VTRs publiées par l'EFSA depuis 2015 [33] (cf. Tableau 2).

Tableau 2 : Évolution des VTR orales pour des PFAS publiées par l'EFSA de 2005 à 2020 (EFSA 2005 [33] et 2020 [13])

Année de publicatio	**Voie**	**Substance(s)**	**VTR**
2020	Ingestion	Σ4 PFAS	TWI = 4,4 ng/kg pc·semaine
2018	Ingestion	PFOA	TWI = 6 ng/kg pc·semaine
2018	Ingestion	PFOS	TWI = 13 ng/kg pc·semaine
2005	Ingestion	PFOA	TDI = 1500 ng/kg pc·jour

Il est important de prendre en compte que les administrations de certains Etats américains sont très avancées dans la recherche toxicologique et la publication de VTR concernant les PFAS, du fait de la forte présence sur leur territoire d'industries chimiques et pétrolières (avec une utilisation historique importante de mousses anti-incendie) ainsi que de vastes décharges industrielles (avec les pollutions environnementales associées). Il s'agit notamment des Etats du Texas (TCEQ, 2023 [34]), du Michigan (MDHHS, 2019 [35]) et de New Jersey (NJ-DW-QI, 2017 [36]). Ces VTR servent souvent de bases pour les VTRs des PFAS proposées par l'US-EPA.

Afin de s'assurer du bon choix des VTR des PFAS, il est recommandé d'appliquer des critères de choix scientifiques et non des critères nationaux. Le tableau 3 montre des critères de choix de VTR applicables, afin de prendre en compte les meilleures connaissances toxicologiques concernant les relations de dose à effet des PFAS.

Tableau 3.1. : Critères de choix qualitatifs des VTR applicables dans les cas de présence de plusieurs VTR (F. Karg, 2022a,b – 2024a-g [41 - 46])

N°	Critères de choix des VTR	Appréciation			
		Favorable	**Correct**	**Not favorable**	**Exclusion**[1]
1	Variabilité des VTR	(+/- 0%)	≤ (+/-30%)	> (+/-30%)	
2	Classe cancérogène EC: Classe 3 US-EPA: Class B2, C / IARC: Group 1	CE, US-EPA, IARC, etc.	2 organisations	1 organisation	
3	Plusieurs organisations montrent des VTRs similaires (+/-50%)	3 organisations	2 organisations	1 organisation	
4	Age de l'étude de base	≤ 15 années	15-25 années	> 25 années	
5	Etude de base toxicologique mécanistique de base (par ex. génotoxicité)	Epidémiologie	In vivo	In-Vitro/In-sillico	
6	Etude de base[2]: Critères de qualité Klimisch	Classe 1	Classe 2	Classe 3	Clases 3
7	Pureté vérifiée du polluant étudié	Oui	< 95%	Non	
8	Excipient potentiellement toxique	Non	Négligeable	Yes	
9	Présence d'une population ou cohorte sans exposition (test témoin)	Oui	Indirecte en comparaison	Non	
10	Critères généraux de qualité (Klimisch) des études d'effets toxicologiques	Etude standardisée (OCDE, UE, US-EPA, FDA, etc.)	Etude standardisée sans détails mais suffisamment documentée	Document insuffisant pour l'évaluation des déficiences	
11	Dose de départ des effets toxiques = « Point of Departure (POD) »	Données Epidémiologiques quantifiées : BMLD, etc. (PBPK)	NOAEL et NOAEL sensible	LOAEL et LOAEL sensible, autres	
12	Facteurs d'incertitudes = « Uncertainty (or Assessment) Factors »	1 – 100	> 100 – 1000	> 1000 – 10000	> 10000
13a	Transpositions entre des voies d'exposition	Non	Argumenté	Oui	
13b	Transpositions: Animal vers l'Humain	Non	Oui, argumenté	Oui	

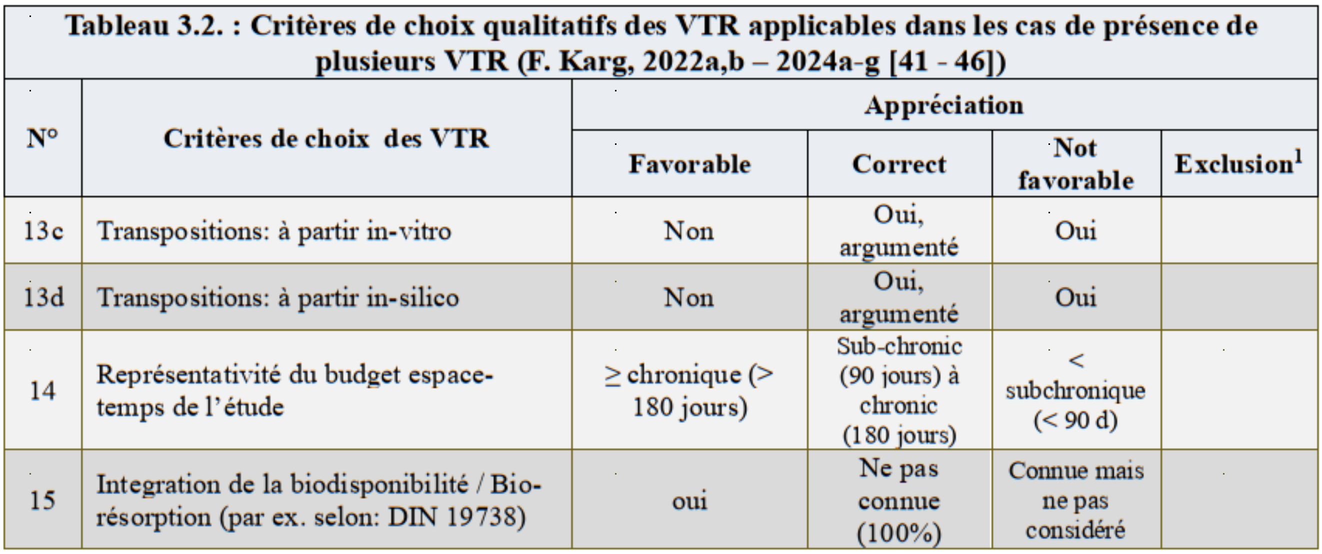

Tableau 3.2. : Critères de choix qualitatifs des VTR applicables dans les cas de présence de plusieurs VTR (F. Karg, 2022a,b – 2024a-g [41 - 46])

N°	Critères de choix des VTR	Appréciation			
		Favorable	Correct	Not favorable	Exclusion[1]
13c	Transpositions: à partir in-vitro	Non	Oui, argumenté	Oui	
13d	Transpositions: à partir in-silico	Non	Oui, argumenté	Oui	
14	Représentativité du budget espace-temps de l'étude	≥ chronique (> 180 jours)	Sub-chronic (90 jours) à chronic (180 jours)	< subchronique (< 90 d)	
15	Integration de la biodisponibilité / Bio-résorption (par ex. selon: DIN 19738)	oui	Ne pas connue (100%)	Connue mais ne pas considéré	

(1 : uniquement applicable pour les critères 6 & 12,
2 : Base Study concernant les effets et mécanismes toxicologiques)

Une **Dose Hebdomadaire Tolérable** (DHT) de 4,4 ng/kg pc·semaine (ou une Dose Journalière Tolérable (DJT) de 0,63 ng/kg pc·j) pour la somme de 4 PFAS (PFOA, PFOS, PFNA et PFHxS) a été publiée par l'**EFSA**, le 17/09/2020 [13]. En 2020, des **facteurs d'équivalence de toxicité** (RFP : Relative Potency Factors) par rapport au PFOA ont aussi été publiés par Bil et al. (2020) [37], 2021 [47] et 2023 [12] pour tenir compte de la toxicité de mélanges de PFAS.

L'application de ces critères de choix, début 2025, conduit à sélectionner, par ex., les VTR indiquées dans le Tableau 4 :

Tableau 4.1. : Exemple de choix des VTR en 2024 pour les PFAS en appliquant les critères du tableau 3 (F. Karg et al. 2023a – 2024g [38 - 46])

Subst.	CAS Nr.	C: Cancerogène / NC: non cancerogène	Valeure toxicologique d'exposition chronique			Espèce de l'étude	Sigle	Facteure de sécurité & origine	Organisation & date
			Voie d'éx-position	Organe ou effet cible	Valeur				
PFBA	375-22-4	NC	oral	Hépatotoxique	1 µg/kg/j	Rat	RfD	POD$_{HED}$ / 900	TCEQ 2023 US-EPA IRIS 2022
			inhalation	Hépatotoxique	3,5 µg/m^3	Rat	RfC	from oral value	TCEQ 2023
PFPeA	2706-90-3	NC	oral	Hépatotoxique	0,5 µg/kg/j	Rat	RfD	POD$_{HED}$ / 90	TCEQ 2023
PFHxA	307-24-4	NC	oral	Hépatotoxique	0,5 µg/kg/j	Rat	RfD	POD$_{HED}$ / 90	TCEQ 2023 US-EPA IRIS 2023
PFHpA	375-85-9	NC	oral	Hépatotoxique	25 ng/kg/j	Rat	DJT	Extrapolation of DJT of Health Canada	ANSES 2017 TCEQ 2023

Tableau 4.2. : Exemple de choix des VTR en 2024 pour les PFAS en appliquant les critères du tableau 3 (F. Karg et al. 2023a – 2024g [38 - 46])

Subst.	CAS Nr.	C: Cancerogène / NC: non cancerogène	Valeure toxicologique d'exposition chronique			Espèce de l'étude	Sigle	Facteure de sécurité & origine	Organisation & date
			Voie d'éxposition	Organe ou effet cible	Valeur				
PFOA	**335-67-1**	NC	oral	Hématotoxique	0,86 ng/kg/j	Rat	TDI	BMDL 5	UBA 2023 BFR & EFSA 2018
				Hépatotoxique, Perturbateur endocrinien (mamelles), Hématotoxique	12 ng/kg/j	Souris	RfD	LOAEL / (81 * 300)	TCEQ 2023
				Immunotoxique, Fœtotoxique et effets cardiovasculaires	0,03 ng/kg/j	Epidémiologique	RfD	Several studies	US-EPA 2024 [7]
			inhalation	Hépatotoxique	4,1 ng/m³	Rat	RfC	NOAEL / (81 * 3 000)	TCEQ 2023
		C	oral	Perturbateur endocrinien (testicules), Néphrotoxique, Carcinogène.	2,52 x 10^{-6} $(ng/kg/j)^{-1}$	Epidémiologique	SF	-	New Jersey 2017
					0,0293 $(ng/kg/j)^{-1}$	Epidémiologique	SF	-	US-EPA 2024 [7]
PFNA	**375-95-1**	NC	oral	Hématotoxique	2,5 ng/kg/j	Souris	RfD	NOAEL / 300	US-EPA IRIS 2019 / New Hampshire DES 2019
			inhalation	Pulmotoxique	28 ng/m³	Rat	RfC	NOAEL / (81 * 30 000)	US-EPA IRIS 2019 TCEQ 2023
PFDA	**335-76-2**	NC	oral	Hépatotoxique	15 ng/kg/j	Rat	RfD	LOAEL / (81 * 1 000)	TCEQ 2023
				Immunotoxique, Fœtotoxique	0,002 ng/kg/j	Rat	RFD	BMDL / 30	US-EPA IRIS 2024
			inhalation	Hépatotoxique	53 ng/m³	Rat	RfC	from oral value	TCEQ 2023
PFBS	**375-73-5**	NC	oral	Hématotoxique, Néphrotoxique	1,4 µg/kg/j	Rat	RfC	NOAEL / (142*300)	TCEQ 2023
			inhalation		4,9 µg/m³	Rat	RfC	from oral value	TCEQ 2023
PFHxS	**355-46-4**	NC	oral	Hématotoxique, Perturbateur endocrinien (thyroïde)	3,8 ng/kg/d	Rat	RfC	LOAEL / (263*300)	TCEQ 2023
			inhalation		13 ng/m³	Rat	RfC	from oral value	TCEQ 2023
PFHpS	**375-92-8**	NC	oral	Hépatotoxique	0,43 ng/kg/d	Rat	TDI	Potency Factor : 0,6-2	UBA 2020, EFSA 2018, BfR 2018

VTRs des Fluorotélomère-alcools:

Subst.	CAS Nr.	C: Cancerogène / NC: non cancerogène	Valeure toxicologique d'exposition chronique			Espèce de l'étude	Sigle	Facteure de sécurité & origine	Organisation & date
			Voie d'éxposition	Organe ou effet cible	Valeur				
6:2-FTOH	**647-42-7**	NC	oral	Hepatotoxic	43 ng/kg/d	Rate	RfD	RPF based on PFOA's RfD x 0,02	RIVM / Bil et al. 2020 & 2021
8:2-FTOH	**678-39-7**	NC	oral	Hepatotoxic	21,5 ng/kg/d	Rate	RfD	RPF based on PFOA's RfD x 0,04	RIVM / Bil et al. 2020 & 2021
			oral		1,5 x 10^3 ng/kg/d	Rate	RfD	RfD assimilated to PFOA transformation Product 8:2-FTOH & Inhalation: 20 m^3/d	SLU 2018 (Sweden) (Ingestion based on EFSA 2008)

5. Évaluation des risques sanitaires :

Comme indiqué, cette évaluation consiste à mettre en relation les doses de PFAS ingérées ou inhalées avec les VTR.

Dans le cas des alcools fluoro-téloméres (FTOH) et d'autres PFAS volatils (TFA, etc.), présents dans les sols, eaux souterraines et gaz du sol, il faudra aussi réaliser des investigations dans l'air ambiant des bâtiments destinés à des usages sensibles (Etablissements Recevant du Public : Ecoles, Crèches, etc.) ou résidentiels., sur une base de seuils de quantification suffisamment bas et adaptés. Ainsi, les seuils de quantification des analyses chimiques ne devraient pas être plus élevés que les VTR applicables (cf. Bil et al. 2020, 2021 et 2023 [12, 37 et 47] et SLU 2017 [48]).

L'EQRS peut permettre de fixer des Concentrations Maximales Acceptables (CMA) dans des milieux d'exposition. Les CMA sont couramment utilisées sous forme de Valeurs de contrôle de conformité sanitaire, afin de vérifier ou de co-élaborer des objectifs de mesures correctives, voire des objectifs de dépollution ou des valeurs limites recommandées ou réglementaires. Ces évaluations sont réalisées substance par substance, des méthodes permettent d'intégrer des expositions combinées à de multiples PFAS, par exemple en additionnant les augmentations de risques du fait de l'exposition (Excès de risque individuel ou ERI), par pour les effets sans seuil (le plus souvent cancérigènes, par ex. d'un ERI > 10^{-5}) ou les Quotient de danger ou de risque (rapports niveau d'exposition sur VTR à seuil) pour les effets dits « à seuil » : Indice de Risque systémique de IR < 1 (= DJE / DJT : Dose Journalière d'Exposition par rapport à la Dose Journalière Tolérable).

L'évaluation des risques nécessite aussi une bonne prise en compte des précurseurs (PFAS polyfluorés) et de leur chimie environnementale, afin d'apprécier le potentiel de formation environnementale et dans l'organisme de PFAS per-fluorés stables. Les Figures 1a & b ci-dessous donnent des exemples des biotransformations de précurseurs poly-fluorés vers des PFAS per-fluorés stables via les 6 :2 et 8 :2 FTOHs. La Fig. 1c montre la Photolyse du 6:2-FTAB envers les PFAS ultrashorts, comme le PFPrA (Acide perfluoro- propionique) et TFA (Acide trifluoroacetic), à côté des PFHxA, PFPeA and PFBA (Naveed, A. et al 2024) [80], particulièrement applicable dans les eaux superficielles et la chaine alimentaire associée. La Fig. 1d indique la photolyse de quelques pesticides fluorés vers le TFA.

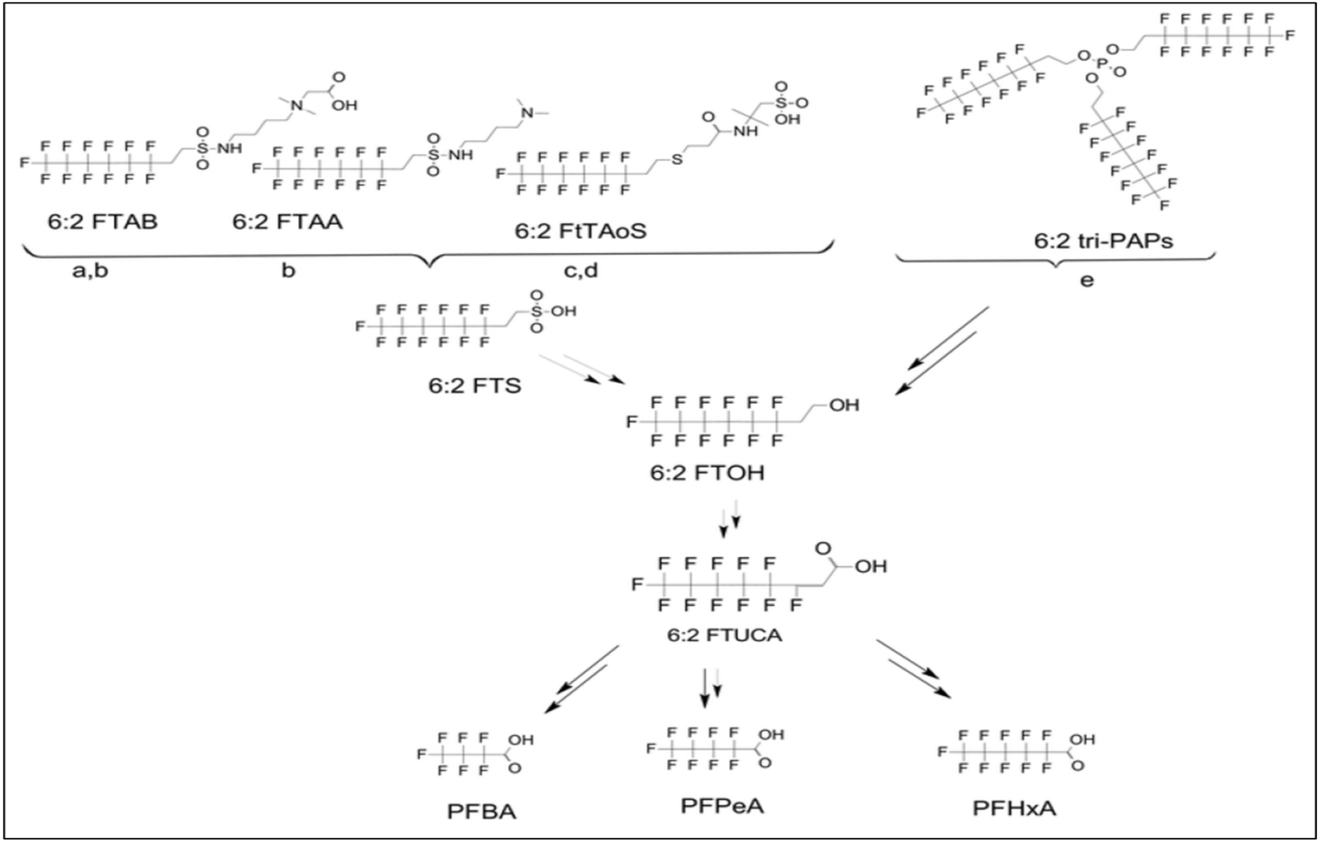

Fig. 1a : Exemple de biotransformation du 6 :2 FTAB (Cabstone B) vers des PFAS per-fluorés stables via le 6:2 FTOH selon LaFond et al. 2023, D.M.J. Shaw et al. 2019 ,Ying Shi, 2018 et V. Mendeza et. al. 2022.

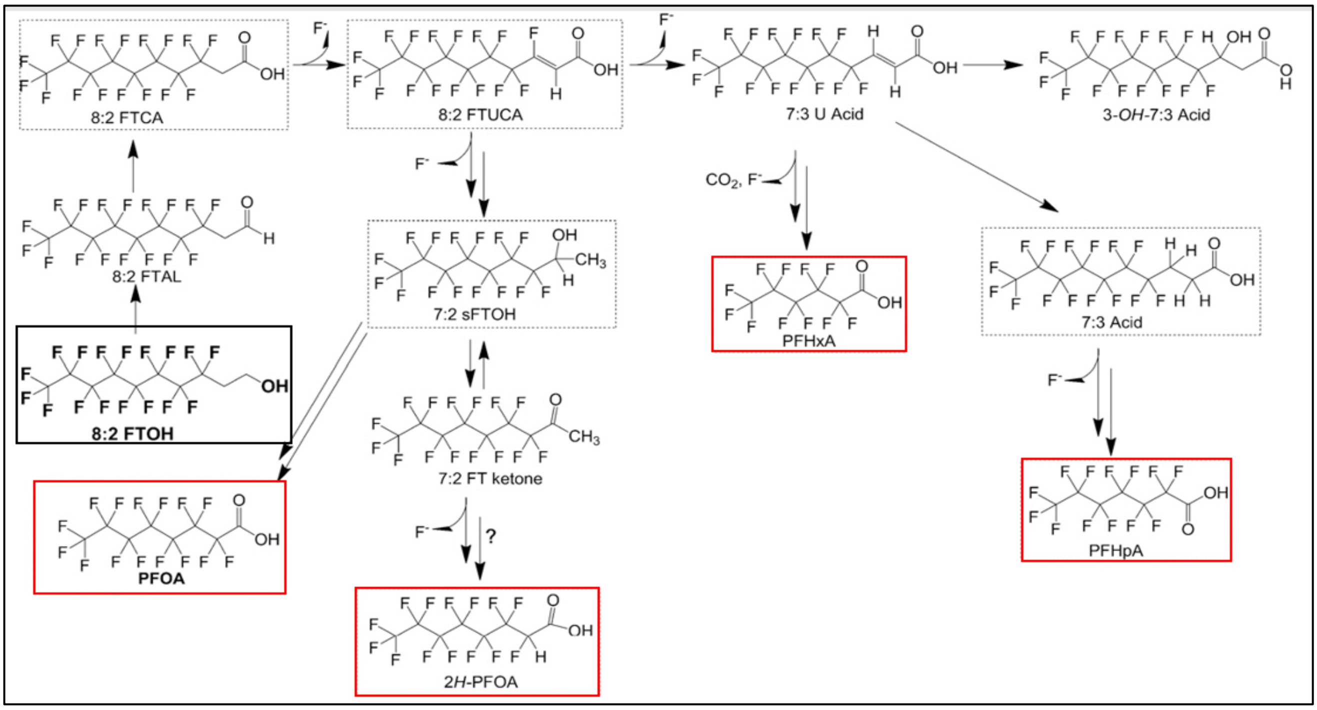

Fig. 1b : Exemple de biotransformation de précurseurs (PFAS poly-fluorés) vers des PFAS per- fluorés stables : le 8:2 FTOH est transformé en PFHxA, PFHpA et PFOA : Graphique modifié selon N. Wang et al. 2009 [49] et J. Liu & S. M. Avendaño, 2013 [50].

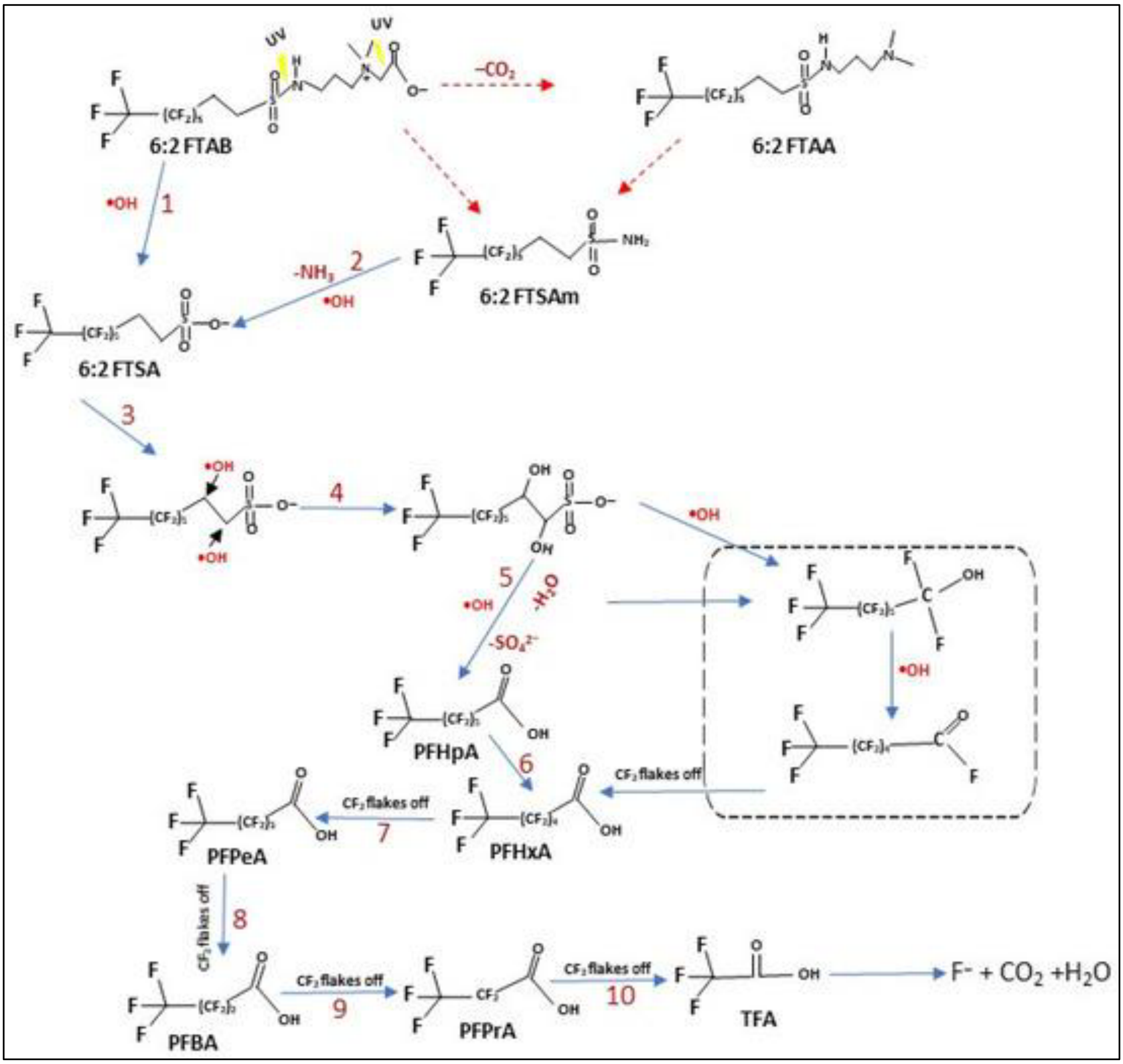

Fig. 1c : Photolyse du 6:2-FTAB envers les PFAS ultrashorts, comme le PFPrA (Perfluoro-propionic Acid) et TFA (Trifluoro-acetic-acid), à côté des PFHxA, PFPeA and PFBA (Naveed, A. et al 2024).

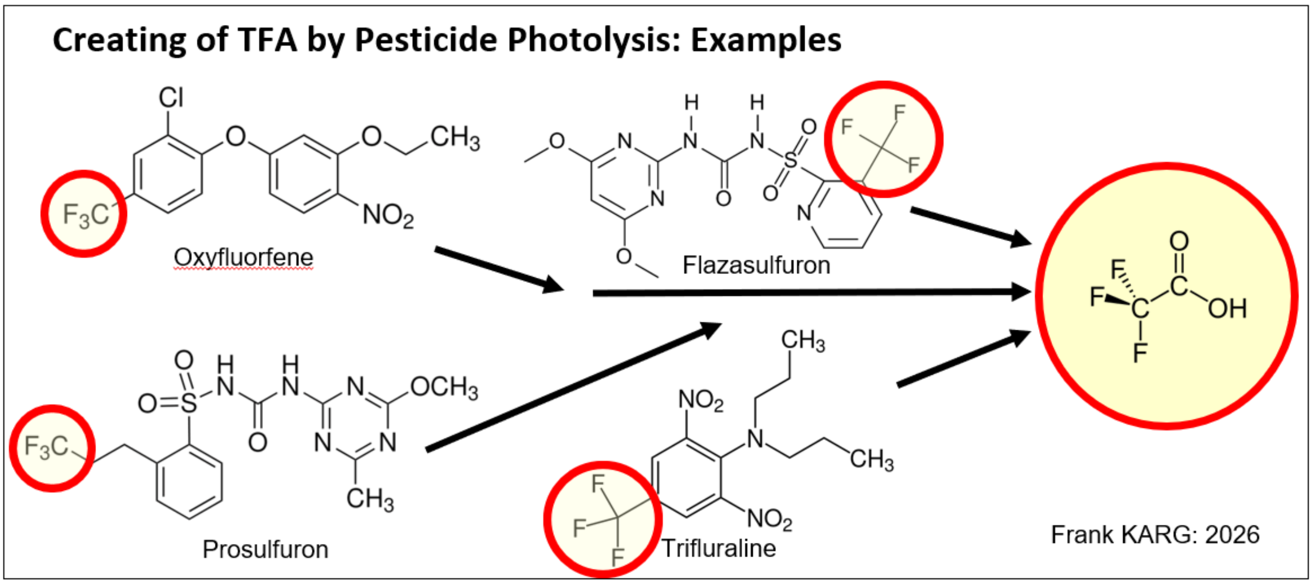

Fig. 1d. : Photolyse de quelques pesticides fluorés vers le TFA (Acide trifluoro-acetique).

Les quelques VTR présentées dans cet article sont issues des rapports rédigés par des institutions nationales et internationales (cf. le tableau 4). Pour sélectionner des VTR pour des PFAS, il est recommandé d'appliquer des critères de choix scientifiques et non des critères de gestion nationaux (cf. le tableau 3). Pour réaliser une EQRS il est recommandé d'appliquer les étapes suivantes :

5.1. Identification des scénarios et des voies d'exposition applicables :

Les voies d'exposition suivantes peuvent exister sur un site :

➢ **Inhalation** :

· de polluants sous forme gazeuse et particulaires ,
· de poussières sur lesquelles est adsorbé le polluant,
· de vapeur d'eau de distribution contaminée lors de la prise d'une douche ou d'un bain.

L'inhalation concerne les vapeurs des polluants PFAS (comme les FTOHs) et les poussières, principalement fines ou poussières alvéolaires, soit les particules dont le diamètre est inférieur à 10 µm de taille. Les poussières de dimension inférieure à 1 µm se déposent dans les alvéoles, où la vitesse de l'air est nulle.

➢ **Ingestion** :

· directe du sol (terres à l'extérieur d'un bâtiment) et de poussières (terres à l'intérieur d'un bâtiment),
· des aliments auto-produits (fruits, légumes, etc.),
· d'eau de distribution contaminée,
· d'eau lors de la prise d'une douche ou d'un bain, y compris dans une eau superficielle (étang, rivière, eau souterraine pompée, etc.).

- **Absorption cutanée** :

· de sol et de poussières,
· de polluant par l'eau de distribution contaminée lors de la prise d'une douche ou d'un bain,
· lors de la prise d'un bain dans les eaux superficielles (étang, rivière, eau souterraine pompée, etc.).

Chaque EQRS doit définir un scénario d'exposition avec des voies exposition dédiées. En principe, les scénarios d'exposition et les voies d'exposition associées sont à identifier via un schéma conceptuel (cf. Fig. 2), montrant les sources potentielles de pollution, des voies de transfert des polluants et les cibles concernées (adultes, enfants…).

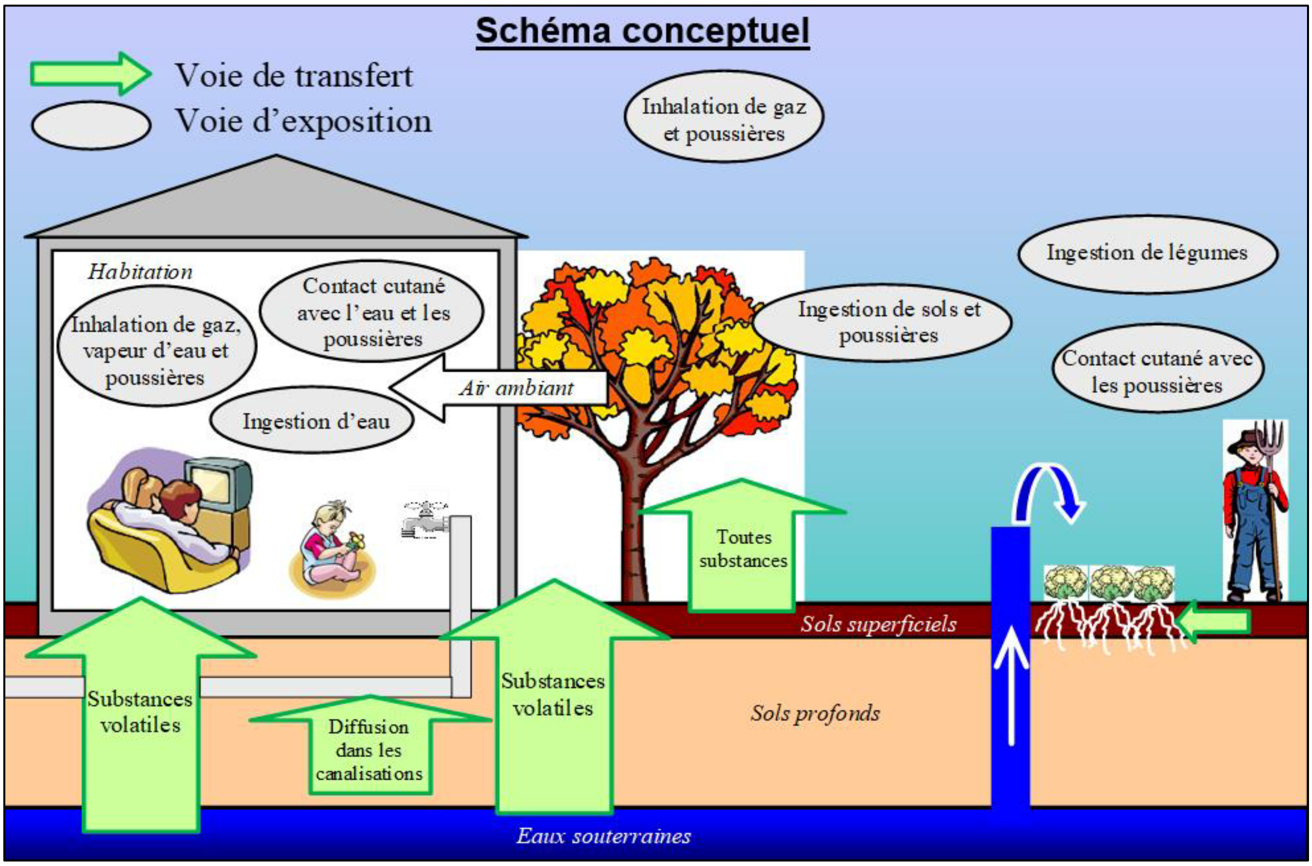

Fig. 2 : Exemple d'un schéma conceptuel, afin de bien visualiser les voies d'expositions applicables par scénario d'exposition (F. Karg & L. Robin-Vigneron 2023a [38]).

Une attention particulière doit être apportée aux PFAS volatils, comme par ex. les alcools fluorotélomères (FTOH), en particulier le 6 :2-FTOH et le 8 :2-FTOH. Le tableau 5 montre les voies d'expositions par scénario d'usage ou d'exposition d'un site.

Les taux de respiration sont dépendants selon les âges et les intensités des activités. Des exemples de taux de respiration, selon l'âge et des activités physiques sont indiqués dans le Tableau suivant (ALMBL 2000 [86] et INVS - CIBLEX [87]) :

Tableau 5 : Taux de respiration, selon l'âge et des activités physiques (ALMBL 2000 [86] et INVS - CIBLEX [87])							
Age	**< 1**	**1 – 3**	**4 - 6**	**7 - 9**	**10 - 14**	**15 - 19**	**20 - 75**
Repos (m^3/j)	**1,9**	**3,8**	**7,6**	**11**	**15**	**17**	**17**
Activité faible (m^3/j)	**3,8**	**7,6**	**15**	**23**	**30**	**34**	**34**
Activité moyenne (m^3/j)	**7,6**	**15**	**30**	**46**	**61**	**68**	**68**
Activité intense (m^3/j)	**13**	**27**	**53**	**80**	**106**	**120**	**120**

L'évaluation des risques sanitaires nécessite une adaptation du scénario d'exposition à la réalité, soit la correction des taux de respiration prises en compte dans les VTR de respiration.

Tableau 6.1. : Scénarios d'expositions et voies d'expositions associées sur des sites

Scénario d'exposition sur site / Voies d'exposition		**Industrie et Commerce**	**Parcs & Loisirs / Activités sportives**	**Jardins d'enfants**	**Résidentiel collectif et Crèches & Ecoles**	**Agricole et production des aliments**	**Résidentiel avec jardins individuels**
Inhalation	**Respiration de Vapeurs ou gaz : Gaz du sol → Air Ambient (Intérieur & Extérieur)**	**Oui**	**Oui**	**Oui**	**Oui**	**Oui**	**Oui**
	Respiration de poussières	**Oui**	**Oui**	**Oui**	**Oui**	**Oui**	**Oui**
	Respiration de vapeur contaminée pendant la douche ou d'un bain chaud*	**(Oui)**	**(Oui)**	**Non**	**Oui**	**Non**	**Oui**

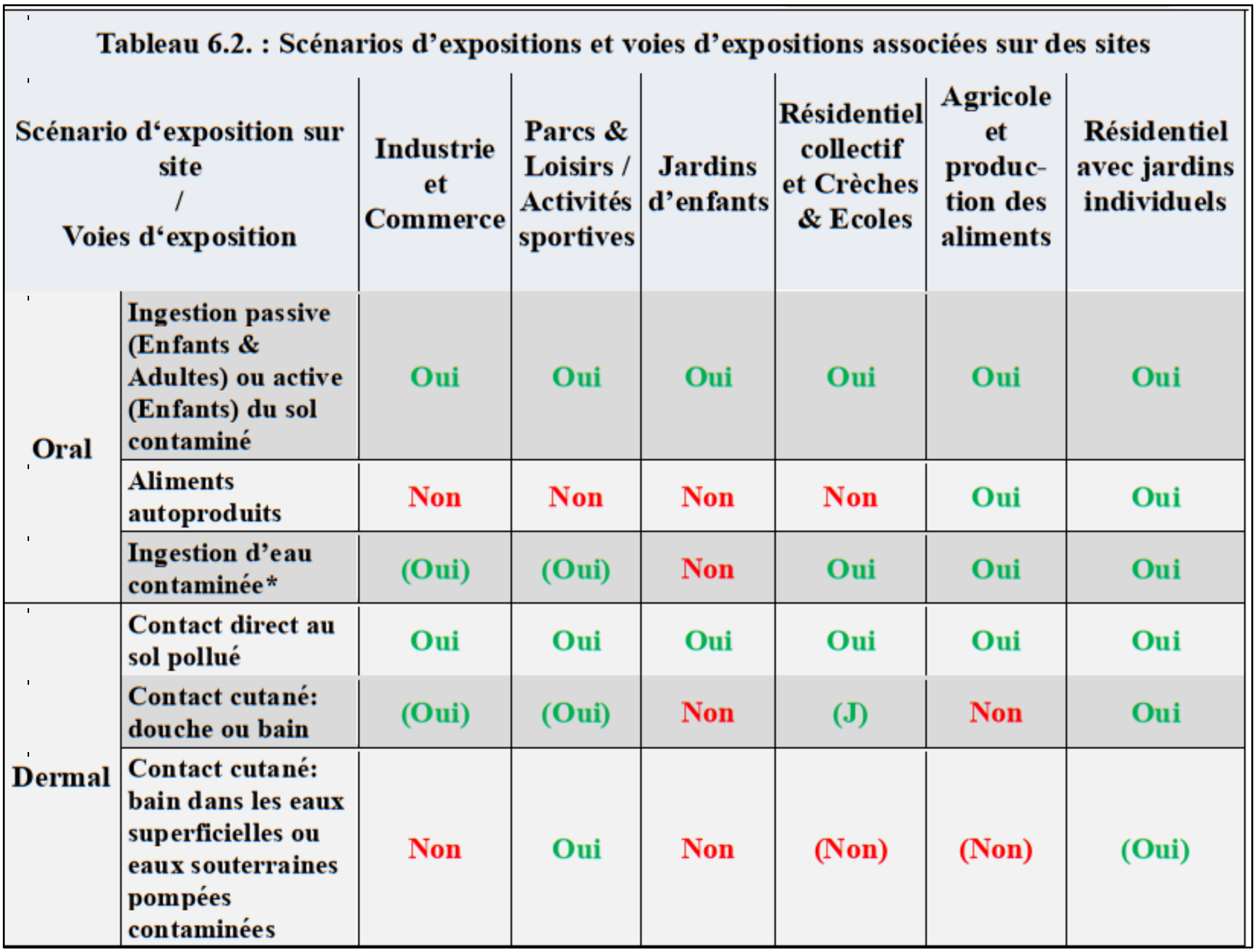

Tableau 6.2. : Scénarios d'expositions et voies d'expositions associées sur des sites

Scénario d'exposition sur site / Voies d'exposition		Industrie et Commerce	Parcs & Loisirs / Activités sportives	Jardins d'enfants	Résidentiel collectif et Crèches & Ecoles	Agricole et production des aliments	Résidentiel avec jardins individuels
Oral	Ingestion passive (Enfants & Adultes) ou active (Enfants) du sol contaminé	Oui	Oui	Oui	Oui	Oui	Oui
	Aliments autoproduits	Non	Non	Non	Non	Oui	Oui
	Ingestion d'eau contaminée*	(Oui)	(Oui)	Non	Oui	Oui	Oui
Dermal	Contact direct au sol pollué	Oui	Oui	Oui	Oui	Oui	Oui
	Contact cutané: douche ou bain	(Oui)	(Oui)	Non	(J)	Non	Oui
	Contact cutané: bain dans les eaux superficielles ou eaux souterraines pompées contaminées	Non	Oui	Non	(Non)	(Non)	(Oui)

(*) : par exemple dans le cas des conduites d'eau potable enterrées en sous-sol contaminé

5.2. Quantifier les doses journalières d'exposition (DJE) :

Les doses journalières d'exposition - DJEing (voie orale), DJEinh (voie respiratoire), DJEcut (voie cutanée) - sont toutes exprimées en mg polluant / kg poids corporel / jour [$\text{mg} \bullet \text{kg}^{-1} \bullet \text{j}^{-1}$] et dépendent :

- **des concentrations en polluants** dans les médias d'exposition (par ex. en mg/kg ou µg/l dans les aliments ou de l'eau potable ou en mg/kg ou µg/l dans les poussières ou eaux successibles de provoquer un contact cutané ou en µg/m^3 pour l'air ambiant) ;

Cm = Concentration en polluant dans le médium d'exposition : Csol [mg/kg], Ceau [mg/l], Caliment [mg/kg],
Ca = Concentration en polluant dans l'air [mg/m^3] intérieur et/ou extérieur,
Cs = Concentration en polluant dans le sol [mg/kg] ou dans les eaux (mg/l)

Deux grandes démarches sont applicables pour déterminer les concentrations en polluants dans les médias d'exposition : les mesures directes (prélèvements et analyses) et les modélisations par simulation des transferts de polluants vers les médias d'exposition.

Les modélisations des transferts des polluants entre des médias (par ex. des eaux souterraines ou des sols vers des gaz du sol et de l'air ambiant ou vers des aliments) sont possibles et pourront être calibrées via des analyses réelles des échantillons (recommandé, si possible).

Concernant la prise en compte des concentrations des polluants dans les sols, les gaz du sol, l'air ambiant, les eaux souterraines et les eaux superficielles, il est possible d'appliquer, pour les expositions chroniques (supérieures à 6 mois) uniquement, des concentrations moyennes prenant en compte l'atténuation naturelle mesurée. Cette atténuation naturelle de dégradation des PFAS concerne uniquement la biotransformation des PFAS poly-fluorés mais pas des PFAS per-fluorés (cf. par ex. la Fig. 1).

- **des budgets espace-temps** (présence des personnes exposées dans le milieu pollué en tenant compte du nombre d'heures par jour, nombre de jours par an et nombre d'années),

Ex = Exposition totale par adulte ou enfant [a]
Ve = Années de la vie entière par adulte ou enfant [a]. En cas d'exposition aux substances avec seuil : Ve = Ex [a]
Fexa = Fréquence d'exposition annuelle [j/365 j]
Fexj = Fréquence d'exposition journalière [hrs/24 hrs]

- **des quantités d'aliments ou d'eau potable ingérés** (en kg/j) et/ou du volume d'air inhalé par jour (en m^3/j) et/ou de la quantité de sol ou de l'eau en contact avec la peau (par ex. en g/cm^2 de surface cutanée),

Qing = Quantité ingérée de sol et/ou aliment [kg/j] et/ou d'eau [l/j], distincte entre les adultes (Qinga) et les enfants (Qinge)
Qinh = Quantité inhalée d'air [m^3/j], distincte entre adultes (Qinha) et enfants (Qinhe)
Fa = Facteur d'absorption (par biorésorption) du polluant (à défaut : 100 % = [1])
Facut = Facteur d'absorption d'un polluant (à défaut : 100 % = [1]) ou vitesse d'absorption [m/h] pour la voie cutanée
Fsp = Fraction de sol dans la poussière (à défaut : 100 % = [1])
Spex = Surface de peau exposée, distincte entre les adultes et des enfants [m^2]
Qsp = Quantité du sol (ou poussières) sur la peau [kg/m^2]
- du poids corporel.
P(a) = Poids corporel d'un adulte [70 kg]
P(e) = Poids corporel d'un enfant [15 kg]

Les formules de la quantification des doses journalières d'exposition sont les suivantes :

Exposition orale par ingestion :
$DJEing = Cm \bullet Qing \bullet P^{-1} \bullet Fa \bullet Ex \bullet Ve^{-1} \bullet Fexa \bullet Fexj$
Exposition par inhalation * :
$DJEinh = Ca \bullet Qinh \bullet P^{-1} \bullet Fa \bullet Ex \bullet Ve^{-1} \bullet Fexa \bullet Fexj$

* Il est possible d'évaluer l'exposition via l'air ambiant extérieur séparément de **l'exposition via**

l'air ambient d'intérieur.

Exposition par contact cutané (sol, poussières, eaux) :

$$DJEcut = Cs \bullet Fsp \bullet Qing \bullet P^{-1} \bullet Facut \bullet Ex \bullet Ve^{-1} \bullet Fexa \bullet Fexj$$

Les paramètres applicables sont à justifier. Une application des valeurs par défaut des logiciels d'évaluation des risques de type « Black-Box » sont à prescrire, s'ils ne sont pas justifiables de façon transparente pour le scénario d'exposition concerné.

5.3. Sélection des VTR adaptées :

I : Les Effets sans seuil de dose :

- En général, il s'agit des effets cancérigènes, mutagènes ou teratogènes via un mode d'action génotoxique), à l'exception des effets épigénétiques.
- Dans ce cas, les Doses Journalières d'Exposition (DJE) sont multipliées par la VTR, (Excès de Risque Unitaire (ERU) dénommé également selon les organismes élaborateurs Slope Factor (SF) ou Unit Risk (UR), exprimés par ex. en [(mg/kg/j)$^{-1}$], soit :
  ERU .[(mg/kg/j)$^{-1}$]● DJE (mg/kg/j) = ERI (-) : Excès de Risque Individuel
- L'ERI doit rester inférieur à « 10^{-5} », valeur de gestion des risques sans seuil , sinon le risque est considéré comme non-acceptable.

II : Effets avec seuil de dose :

- Il s'agit des effets de toxicité apparaissant au-delà d'une certaine dose (neurotoxicité, hépatotoxicité, néphrotoxicité, etc.).
- Dans ce cas, les Doses Journalières d'Exposition (DJE) sont divisées par la VTR, sous forme de DJT (Dose journalière Tolérable), exprimée par ex. en [mg/kg/j], soit:
  DJE (mg/kg/j) / VTR (mg/kg/j) = QR (Quotient de Risque) ou QD (Quotient de Danger)
- Le QDQR doit rester inférieur à « 1 », sinon le risque est considéré comme non-acceptable.

Par ex. les VTR pour le PFOA existent pour les effet cancérigènes (ERU) et systémiques (DJT), cf. Tableau 4.

6. Effets de mélange

6.1. Géneralités

En général, les effets de mélange de polluants (ou « Combined Exposure to multiple Chemicals") sont considérés depuis 2009 par l'IPCS & OMS (WHO) [51] etc. via une additivité des doses d'exposition, si les organes cibles et les effets toxicologiques sont similaires. Les exceptions sont :

- **les synergies :** interactions qui montrent des effets toxicologiques plus importants que prévus selon l'additivité des doses ou

- **les antagonismes :** interactions qui provoquent des effets toxicologiques moins importants que prévus selon l'additivité des doses.

Selon l'IPCS & OMS (WHO) 2009 [51] etc., une différence doit être faite entre :

- **l'exposition agrégée** (« Aggregate Exposure ») à un même polluant par diverses voies d'exposition,

- **l'exposition cumulée** (« Cumulative Exposure ») évaluant un risque combiné par plusieurs polluants.

Dans le cas de l'évaluation d'une exposition cumulée, il faudra donc identifier les polluants montrant les mêmes mécanismes toxicologiques (ou organes cibles). Ces groupes de polluants sont appelés les « MOA: Common Toxic Mode of Action ».

L'addition des doses est prise en compte pour chaque groupe MOA montrant les mêmes mécanismes toxicologiques (ou organes cibles), par ex. via l'application suivante :

Quotient de Risque : QR = Exposition 1/DJT+ Exposition 2/DJT + ….
Excès de Risque Individuel : ERI = Exposition 1 ● ERU + Exposition 2 ● ERU + ….

Cette application est peut-être simplifiée, comme par exemple dans le cas des Facteurs d'équivalence de toxicité pour les Dioxines (PCDD/F) et les « Dioxine-like PCB », les HAP et aussi par des « Potency-Corrections » pour les PFAS, par ex. via les RPF : Relative Potency Factors, cf. ci-après (Tableau 7).

Afin de définir des valeurs guides pour la santé humaine pour un groupe de congénères aussi important (quelques milliers de molécules), pour des raisons éthiques et financières, l'expérimentation animale n'est pas possible sur un si grand ensemble de molécules (Cousins, 2020 [52]). D'autres approches, in vitro voire in silico, peuvent être envisagées pour récolter suffisamment d'informations afin d'établir ces valeurs.

En effet, les composés chimiques peuvent interagir lorsqu'ils sont combinés, produisant ainsi des effets synergiques ou antagonistes. En l'absence d'interaction, et si les substances partagent un mécanisme de toxicité et une cible biologique similaires, un modèle additif (par exemple, l'addition des concentrations) peut être envisagé pour décrire l'effet du mélange (Heys, 2016 [53]). A l'inverse, les informations obtenues sur des composés pris individuellement ne pourront pas être suffisent pas pour déterminer leur action en mélange.

6.2. Facteurs d'équivalence de toxicité

L'approche d'équivalence toxique s'applique aux mélanges dont les effets sont additifs. Elle est utilisée, notamment, pour interpréter l'effet de certains mélanges d'organochlorés (comme les chloro-dibenzo-p-dioxines, chloro-dibenzofuranes et polychloro-biphényls) qui partagent un mode d'action commun, médié par la liaison à un récepteur spécifique, le récepteur AhR (Guyton et al. 2018 [54]).

Étant donné que chaque congénère n'a pas la même efficacité, ils sont classés à l'aide de facteurs de puissance relative (Relative Potency Factors, RPF) par rapport à un congénère de référence, appelé composé index. Ce dernier est souvent le plus toxique ou celui dont les effets sont les mieux documentés. Pour les dioxines et furanes, la dioxine de Seveso (2,3,7,8-tétrachlorodibenzo-p-dioxine) est utilisée comme référence, avec un facteur de 1, et son facteur de toxicité est désigné sous le nom de Toxic Equivalency Factor (TEF).

L'usage de RPF reste toutefois soumis au respect de conditions strictes :

1. en application de la définition présentée ci-avant, les composés doivent partager un même mode d'action ;

2. l'effet critique identifié pour le composé de référence doit l'être également pour les autres composés. Autrement dit, un composé index présentant un effet critique neurotoxique ne peut servir de référence pour un autre composé dont la toxicité s'exprimerait principalement au niveau rénal, par exemple ;

3. idéalement, les composés devraient posséder des courbes de relation dose-réponse de même efficacité tout en se différenciant, bien évidemment, par des puissances différentes. En outre, les courbes devraient être congruentes, c'est-à-dire qu'elles ne se croisent pas. Ces conditions sont nécessaires à la comparaison des Benchmark doses (BMD*) pour un même niveau de réponse (Benchmark Response : BMR*). (* : Relation dose-réponse permet généralement de définir une dose avec un effet - réponse toxicologique critique, qui sert de « point de départ » pour la construction d'une VTR.)

Les chercheurs du RIVM (Bil et al., 2020, 2021 et 2023 [12, 37, 47] ; Zeilmaker et al., 2018 [55]) proposent une approche RPF appliquée à la toxicité orale de 14 PFAS et de deux précurseurs (6:2 FTOH et 8:2 FTOH). Ils ont sélectionné le PFOA (acide perfluoro-octanoïque [335-67-1]) comme composé index. Le PFOA est avec le PFOS (acide perfluorooctane-sulfonique [1763-23-1]), l'un des PFAS les plus étudiés. Parmi les effets toxiques attribués au PFOA (mais également au PFOS), ils identifient l'hypertrophie hépatique comme effet critique.

Le RPF est établi sur la base du rapport entre la BMD du PFOA et la BMD (Benchmark Dose) du congénère d'intérêt (équation 1).

Equation 1 :

$$\frac{BMD_{PFOA}}{BMD_{i}}$$

La BMD correspond à un BMR équivalent à 5% d'augmentation du poids du foie (absolu et relatif) établi sur des données continues ou à un excès de risque de 10 % d'hypertrophie hépatique. Cette dernière expression du risque est établie sur base de données dichotomisées. L'excès de risque est ajusté pour les taux d'incidence pour un même effet.

En 2023, le RIVM (Zeilmaker et al. 2023 [56] a complété ses premiers travaux en appliquant cette méthode au TFA.

L'approche de Zeilmaker [56] et Bil et al. 2020, 2021 et 2023 [12, 37 et 47] débouche sur la proposition de RPF résumée dans le Tableau 7.

Tableau 7 : RPF selon Bil et al. 2020, 2021 et 2023 [12, 37 et 47] et Zeilmaker et al. (2023) [56]

Congeners	Numéro CAS	RFP
Acides sulfoniques		
PFBS	375-73-5	0,001
PFPeS	2706-91-4	0,001 ≤
PFHxS	355-46-4	0,6
PFHpS	375-92-8	0,6 ≤
PFOS	1763-23-1	2
PFDS	335-77-3	2
Acides carboxyliques		
TFA	76-05-1	0,002
PFBA	375-22-4	0,05
PFPeA	2706-90-3	0,01 ≤
PFHxA	307-24-4	0,01
PFHpA	375-85-9	0,01 ≤
PFOA	335-67-1	1
PFNA	375-95-1	10
PFDA	335-76-2	4 ≤ RPF ≤ 10
PFUnDA	2058-94-8	4
PFTrDA	72629-94-8	3
PFDoDA	307-55-1	0,3 ≤ RPF ≤ 3
PFTeDA	376-06-7	0,3
PFHxDA	67905-19-5	0,02
PFODA	16517-11-6	0,02
HFPO-DA	13252-13-6	0,06
ADONA	919005-14-4	0,03
Alcools télomériques		
6:2 FTOH	647-42-7	0,02
8:2 FTOH	678-39-7	0,04

L'approche de Zeilmaker (Zeilmaker et al. 2023 [56] a été sélectionnée par l'Etat de Hawaï (State of Hawai - Department of Health, 2020; 2021 [57, 58]) afin d'établir certaines VTR orales (preliminary RfD oral) nécessaires à l'établissement des valeurs guides environnementales (eaux souterraines et sol).

L'emploi des RPF produits par Zeilmaker (Zeilmaker, 2018 et 2023 [48, 49]) et Bil (Bil et al., 2021 [40]) dans le cadre de l'évaluation des risques est fortement contesté par Rietjens (Rietjens, 2022 [59]). Rietjens et al. soutiennent l'usage de RPF dans les études de risques mais contestent la robustesse de ceux calculés par Bil (Bil et al. 2020, 2021 et 2023 [12, 37 et 47]). Rietjens et Bil s'opposent sur la sélection des données et sur l'impact du mode d'administration des PFAS chez les rongeurs. Bil et al. (Bil, 2022a [60]) rejettent ces critiques signalant que numériquement les valeurs ne diffèrent pas significativement en modifiant le jeu de données selon les recommandations de Rietjens.

Goodrum et al. (Goodrum et al., 2021 [61]) critiquent également l'approche de Bil et Zeilmaker en soulignant les différences dans le mode d'action des PFAS à chaînes courtes par rapport à ceux à chaînes longues (C>8). Les PFAS à chaines longues présenteraient la capacité de se fixer à un nombre plus important de récepteurs nucléaires (entre 6 et 16) que ceux à chaînes courtes qui seraient limités à deux récepteurs. Goodrum et al. contestent également l'existence d'une congruence dans les relations dose-réponse. La mise en œuvre de cette approche pour les PFAS à chaines ultra-courtes est également contestable.

Par conséquent, l'application des RPF n'est pas recommandée (en 2025), sauf dans exceptionnellement et avec une bonne argumentation.

Récemment, Bil et al. (Bil et al., 2022b [62]; Bil, 2023 [12] ; Vil et al., 2025 []) ont publié une approche similaire pour le biomonitoring humain (sang). Les RPF proposés sont résumés dans le tableau 8. Les RPF ont été établis sur la base de modèles toxicocinétiques conçus à partir d'expérimentations chez le rat.

Tableau 8 : RPF selon Bil et al, 2022b [62] pour le biomonitoring (sang)

Congénères	Numéro CAS	RPF
PFBS	375-73-5	0,2
PFHxS	355-46-4	0,6
PFOS	1763-23-1	3
PFBA	375-22-4	2
PFHxA	307-24-4	10
PFOA	335-67-1	1
PFNA	375-95-1	5
PFDoDA	307-55-1	10
HFPO-DA	13252-13-6	9

5.3. Application du Top Assay

La plus grande inconnue dans les effets des mélanges de PFAS concerne la grande partie des PFAS poly-fluorés. En fait, des milliers des PFAS poly-fluorés sont à évaluer, qui ne sont, dans leur plus grande partie, ne pas analysables (< 9 000 à 12 000 molécules). Ces substances pourront être évaluer sous leur forme finale des PFAS per-fluorés, produits de la bio-transformation naturelle. Le Top Assay acceler chimiquement via le persulfate cette transformation, afin de permettre d'évaluer la quasi-totalité des PFASpoly-fluorés dans leur forme finale des per-fluorés.

Il est recommandé d'appliquer les analyses des PFAS (28 – 70 molécules, cf. aussi l'Arrêté Ministériel en France du 20/06/2023) avant et après le « Top Assay ».

Le « Top Assay » (Total Oxidizable Precursor), selon Houtz et Sedlak : 2012 [63] transforme les PFAS poly-fluorés vers les PFAS perfluorés. Dans l'environnement, l'ensemble des PFAS poly-fluorés (Précurseurs) sont bio-transformés vers les PFAS per-fluorés stables. Via le « Top Assay » (cf. Fig. 3) il est possible d'intégrer dans l'évaluation des risques sanitaires immédiatement les PFAS per-fluorés, produits des bio-transformations dans un scénario d'exposition.

Par contre, il ne faut pas se contenter de réaliser l'évaluation des risques sanitaires uniquement sur les PFAS per-fluorés après le « Top Assay », car les effets avec-seuil de dose de certains PFAS poly-fluorés pourront être importants dans les expositions sub-chroniques et chroniques, comme par ex. concernant les PFAS volatils (FTOH : fluorotélomére-alcools, etc.) (Karg et al.2023a, 2024a-g, 2025 [38, 40 – 46, 68, 79]).

Conformément à la méthodologie présentée par Karg et al. 2024 et 2025 [81, 82, 84], Bil et al. 2025 [85] confirment la préférence d'une évaluation des risques sanitaires pour les expositions aux mélanges des PFAS par la prise en compte des substances PFAS individuelles via des additivités des risques, sans la prise en compte d'interaction des PFAS entre eux.

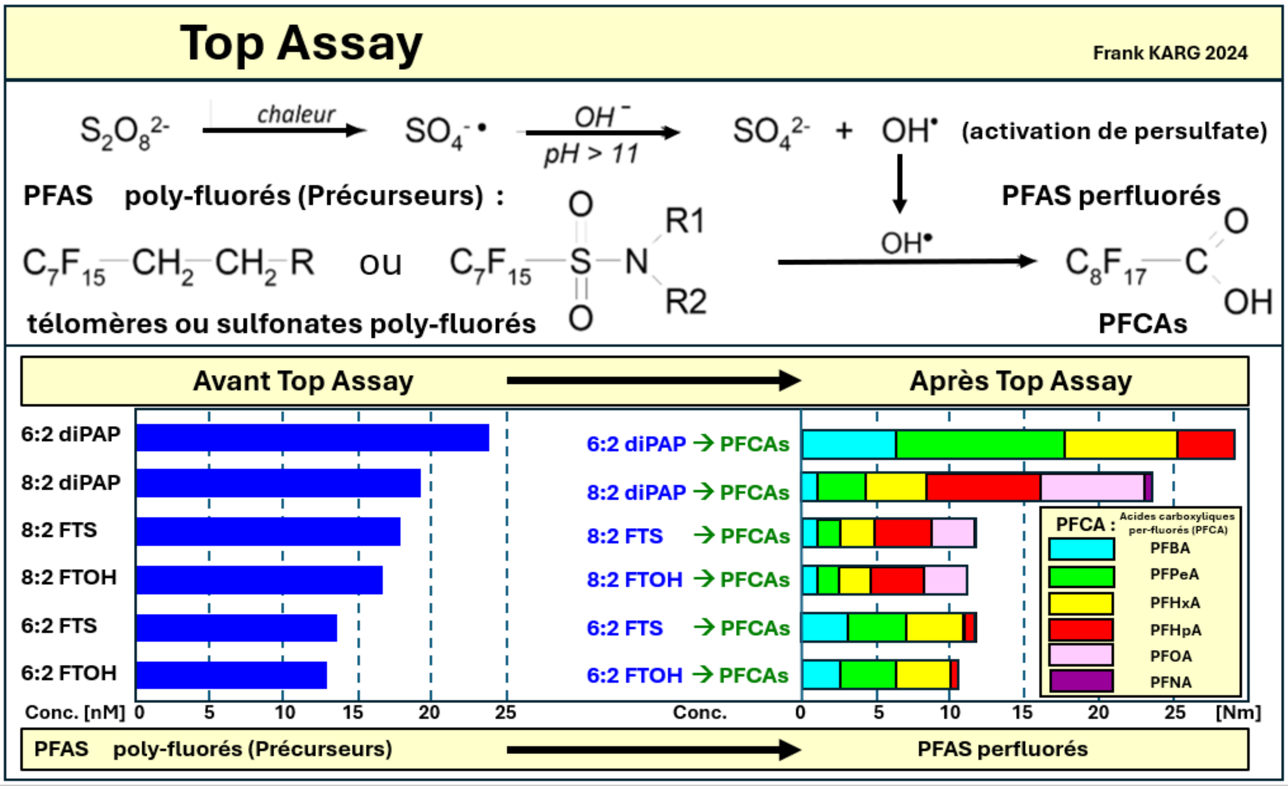

Fig. 3 : Top Assay (Total Oxidizable Precursor) : Example de quantification des PFAS poly-fluorés via leurs acides carboxyliques perfluorés finaux correspondants après dégradation (Houtz et Sedlak : 2012 [63]) et Karg et al. 2025 [84] prendre en compte dans une EQRS.

Certaines expositions aux mélanges sont à évaluer attentivement dans le cas d'une exposition aux mélanges de PFOA, bisphénol-A et méthyle-parabène provoque la prolifération des cellules épithéliales des seins par suppression de l'apoptose (Dairkee et al. 2018 [64] et Pesonen et al. 2024

[65].

L'exposition faible aux mélanges de PFOA et PFOS a montré un effet synergique, cancérigène en transformant des cellules épithéliales du sein (MCF-10A) en tumeurs malignes phénotypiques, ce qui permet la prolifération des métastases (Pierozan et al. 2023 [66] et Pesonen et al. 2024 [65]). Les auteurs ont aussi décrit des approches plus détaillées de l'EQRS, notamment avec une prise en compte large des PFAS poly-fluorés par Top Assay dans le Guide (fiches) de gestion des PFAS de la SFSE (Société Francophone de Santé et Environnement / Heilier et al. 2023 - 2024) [67] et F. Karg et al. 2023 - 2024 [68] et 2025 [79, 89 & 90].

7. Conclusion :

La méthodologie de l'évaluation quantitative des risques sanitaires (EQRS), applicable concernant les PFAS, leurs produits de bio-transformation et leurs mélanges est décrit dans l'article relatif aux expositions orales (par ex. dans le cas de l'ingestion des eaux ou aliments) ou dans le cas de l'inhalation des poussières contaminés et PFAS volatils mais aussi dans le cas des contacts cutanés (par ex. aux poussières et eaux superficielles) ou par ex. sur des sites pollués. L'article présente la méthodologie de l'EQRS dans le cas des expositions aux mélanges des PFAS.

L'article décrit la présence des PFAS et leurs produits de biotransformation en environnement et les voies d'exposition humaines, les effets toxicologiques et l'évaluation quantitatives des risques sanitaires (EQRS) dans le cas des expositions aux mélanges de PFAS.

La plus grande inconnue dans les effets des mélanges par des PFAS concerne la grande partie des PFAS poly-fluorés. Il est recommandé d'appliquer les analyses des PFAS (28 – 70 molécules, cf. aussi l'Arrêté Ministériel en France du 20/06/2023) et la liste des PFAS-65 + 5 PFAS ultrashorts avant et après le « Top Assay » (Tableaux 9.1. & 9.2.). Les Tableaux 9.1. & 9.2 montrent les PFAS à analyser en minimum dans les médias d'expositions (aliments, eau potable, eau de baignade, sols, poussières et air ambiant (sans oublient les gaz du sol concernant les PFAS volatils) (F. Karg et al. 2024 – 2025) [81 – 84].

Le « Top Assay » (Total Oxidizable Precursor), selon Houtz et Sedlak : 2012 [63] transforme les PFAS poly-fluorés vers les PFAS perfluorés. Dans l'environnement, l'ensemble des PFAS poly-fluorés (Precurseurs) sont bio-transformés vers les PFAS per-fluorés stables. Via le « Top Assay » (cf. Fig. 3) il est possible d'intégrer dans l'évaluation des risques sanitaires immédiatement les PFAS per-fluorés, produits des bio-transformations dans un scénario d'exposition.

Par contre, il ne faut pas se contenter de réaliser l'évaluation des risques sanitaires uniquement sur les PFAS per-fluorés après le « Top Assay », car les effets avec-seuil de dose de certains PFAS poly-fluorés pourront être importants dans les expositions sub-chroniques et chroniques, comme par ex. concernant les PFAS volatils (FTOH : fluorotélomére-alcools, etc.) (Karg et al.2023a, 2024a-g, 2025 [38, 40 – 46, 68, 79, 89 & 90]).

Une description des critères de choix scientifiques des VTR est indiquée, afin d'assurer une EQRS bien fondée. Pour certains PFAS importants et très présents en environnement des VTR pourront être définies, par ex. à partir des NOAEL, comme pour le 6 :2-FTAB (Capstone B) et le 6 :2-FTNO (Capstone A).

Tableau 9.1. : Paramètres PFAS à recommander pour les évaluations des risques sanitaires.

PFAS	CAS	Dir. CE EP2020/ 2184 [88]
PFBA (acide perfluorobutanoique)	375-22-4	🟩
PFPeA (acide perfluoropentanoique)	2706-90-3	🟩
PFHxA (acide perfluorohexanoique)	307-24-4	🟩
PFHpA (acide perfluoroheptanoique)	375-85-9	🟩
PFOA linéaire (acide perfluorooctanoique)	335-67-1	🟩
PFOA ramifié (acide perfluorooctanoique)	335-67-1	🟥
PFOA totale (acide perfluorooctanoique)	335-67-1	🟥
PFNA (acide perfluorononanoique)	375-95-1	🟩
PFDA (acide perfluorodecanoique)	335-76-2	🟩
PFUnDA (acide perfluoroundecanoique)	2058-94-8	🟩
PFDoDA (acide perfluorododecanoique)	307-55-1	🟩
PFTrDA (acide perfluorotridecanoique)	72629-94-	🟩
PFTeDA (acide perfluorotetradecanoique)	376-06-7	🟥
PFHxDA (acide perfluorohexadecanoique)	67905-19-	🟥
PFODA (acide perfluorooctadecanoique)	16517-11-	🟥
PFBS (acide perfluorobutane sulfonique)	375-73-5	🟩
PFPeS (acide perfluoropentane sulfonique)	2706-91-4	🟩
PFHxS linéaire (acide perfluorohexane sulfonique)	355-46-4	🟩
PFHxS ramifié (acide perfluorohexane sulfonique)	355-46-4	🟥
PFHxS totale	355-46-4	🟥
PFHpS (acide perfluoroheptane sulfonique)	375-92-8	🟥
PFOS linéaire (acide perfluorooctane sulfonique)	1763-23-	🟥
PFOS ramifié (acide perfluorooctane sulfonique)	1763-23-	🟥
PFOS totale (acide perfluorooctane sulfonique)	1763-23-	🟥
PFDS (acide perfluorodecane sulfonique)	335-77-3	🟥
4:2 FTS (acide 4:2 fluorotelomer sulfonique) H4-PFOS	757124-	🟥
6:2 FTS (acide 6:2 fluorotelomer sulfonique)	27619-	🟥
8:2 FTS (acide 8:2 fluorotelomer sulfonique)	39108-	🟥
10:2 FTS (acide 10:2 fluorotelomer sulfonique)	120226-	🟥
MePFOSAA (acide N-méthylperfluorooctane sulfonamide acétique)	2355-31-	🟥
EtFOSAA (acide N-éthylperfluorooctane sulfonamide acétique)	2991-50-	🟥
PFOSA linéaire (perfluoro-n-octanesulfonamide)	754-91-6	🟥
PFOSA ramifié (perfluoro-n-octanesulfonamide)	754-91-6	🟥
PFOSA totale (perfluoro-n-octanesulfonamide)	754-91-6	🟥
MeFOSA linéaire (N-méthylperfluorooctanesulfonamide) (MePFOSA)	31506-	🟥
6:2-FTAB (6 :2 fluorotelomer sulfonamido propyl betaine) Capstone B	34455-	🟥
MeFOSA ramifié (N-méthylperfluoro-n-octanesulfonamide) (MePFOSA)	31506-	🟥
MeFOSA totale (N-méthylperfluoro-n-octanesulfonamide) (MePFOSA)	31506-	🟥
8:2 DiPAP (8:2 polyfluoroalkyl phosphate diester)	678-41-1	🟥
HFPO-DA (acide hexafluoropropyleneoxide dimer) Gen X	13252-	🟥
EtFOSA linéaire (N-éthylperfluorooctanesulfonamide) (EtPFOSA)	4151-50-	🟥
EtFOSA ramifié (N-éthylperfluorooctanesulfonamide) (EtPFOSA)	4151-50-	🟥
EtFOSA totale (N-éthylperfluorooctanesulfonamide) (EtPFOSA)	4151-50-	🟥
MeFBSAA (perfluorobutanesulfonamide(N-méthyl)acetate)	159381-	🟥
5:3-FTCA: 5:3 acide carboxylique fluorotélomère)	914637-	🟥
6-2-FTCA: 6:2 acide carboxylique fluorotélomère	53826-	🟥
8:2 FTUCA (acide 2H-perfluoro-2-décenoique)	70887-	🟥
DONA (acide 4,8-dioxa-3H-perfluorononanoique)ADONA	919005-	🟥
MeFBSA (n-méthylperfluorobutanesulfonamide)	68298-	🟥
PFBSA (perfluorobutanesulfonamide)	30334-	🟥

Tableau 9.2. : Paramètres PFAS à recommander pour les évaluations des risques sanitaires.

PFECHS (acide perfluoro-4-éthylcyclohexanesulfonique)	646-83-3	🟥
PFNS (acide perfluorononane sulfonique)	68259-12-	🟩
PFDoDS (acide perfluorododecane sulfonique)	79780-39-	🟩
6:2 diester de phosphate fluorotélomérique. 6:2 diPAP	57677-95-	🟥
6:2 8:2 diester de phosphate fluorotélomérique. 6:2 8:2 diPAP	943913-15-	🟥
PFHxSA (perfluorohexanesulfonamide)	41997-13-	🟥
PFUnDS (acide perfluoroundecane sulfonique)	749786-16-	🟩
PFTrDS (acide perfluorotridecane sulfonique)	791563-89-	🟩
EtFOSE (2-(N-ethylperfluoro-1-octanesulfonamido)-ethanol)	1691-99-	🟥
MeFOSE (2-(N-methylperfluoro-1-octanesulfonamido)-ethanol)	24448-09-	🟥
NFDHpA (Nonafluoro-3,6-dioxaheptanoic acid)	151772-58-	🟥
PFMPA (Perfluoro-3-methoxypropanoic acid)	377-73-1	🟥
PFMBA (perfluoro-4-methoxybutanoic acid)	863090-89-	🟥
C6O4 (Perfluoro([5-methoxy-1,3-dioxolan-4-yl]oxy)acetic acid)	1190931-	🟥
6:2-FTOH (6:2 fluorotelemer alcohol) FHET	647-42-7	🟥
8:2-FTOH (8:2 fluorotelemer alcohol) FOET	678-39-7	🟥
TFA (trifluoroacetic acid)		
PFPrA (perfluoropropanoic acid)		
TFMS (trifluoromethanesulfonic acid)		
PFES (perfluoroethanesulfonic acid)		
PFPrS (perfluoropropanesulfonic acid)		

En vert : Les PFAS couverts par la Directive (UE) 2020/2184 du Parlement européen et du Conseil du 16 décembre 2020 relative à la qualité des eaux destinées à la consommation humaine [88]

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PFAS released by landfill waste: how effective are the treatments?

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Introduction

Per- and polyfluoroalkyl substances (PFAS) are chemicals that have been incorporated into many products such as fire-fighting foams and surface treatment agents. The widespread use and disposal of consumer products containing PFAS, coupled with the physical and chemical stability of these chemicals, has led to increased concentrations in municipal landfill leachate. PFAS concentrations in landfill leachate vary from 100 to over 100 000 ng/L, with 5:3 FTCA and other short-chain PFAS dominating across studies. Source analyses show major PFAS inputs from consumer products, especially carpets, textiles, paper, and food-contact materials.

Material and methods

ATOLIX (Ecotoxicological Analyses and Advanced Oxidation Treatment of PFAS in Leachate from Municipal Landfills) is a project partially funded by The French Agency for Ecological Transition (ADEME), aimed at studying PFAS in landfill leachate and developing a technology to destroy PFAS in leachate. For this project, samples will be collected on 10 French landfills, 6 of them will be presented here. All sites have different storage capacities as well as different ages. Samples included raw leachate, leachate undergoing treatment, and treated leachate. Samples were collected at the discharge valve in the leachate treatment plants or using Eurobailer® single-use polypropylene samplers in the ponds and/or lifts stations. Raw and treated leachates were sampled on the same day, which facilitates data analysis. Flasks and analysis were commissioned to an external laboratory. In this study, all concentration values identified under the limit of quantification have been considered equal to the limit of quantification.

Results & discussion

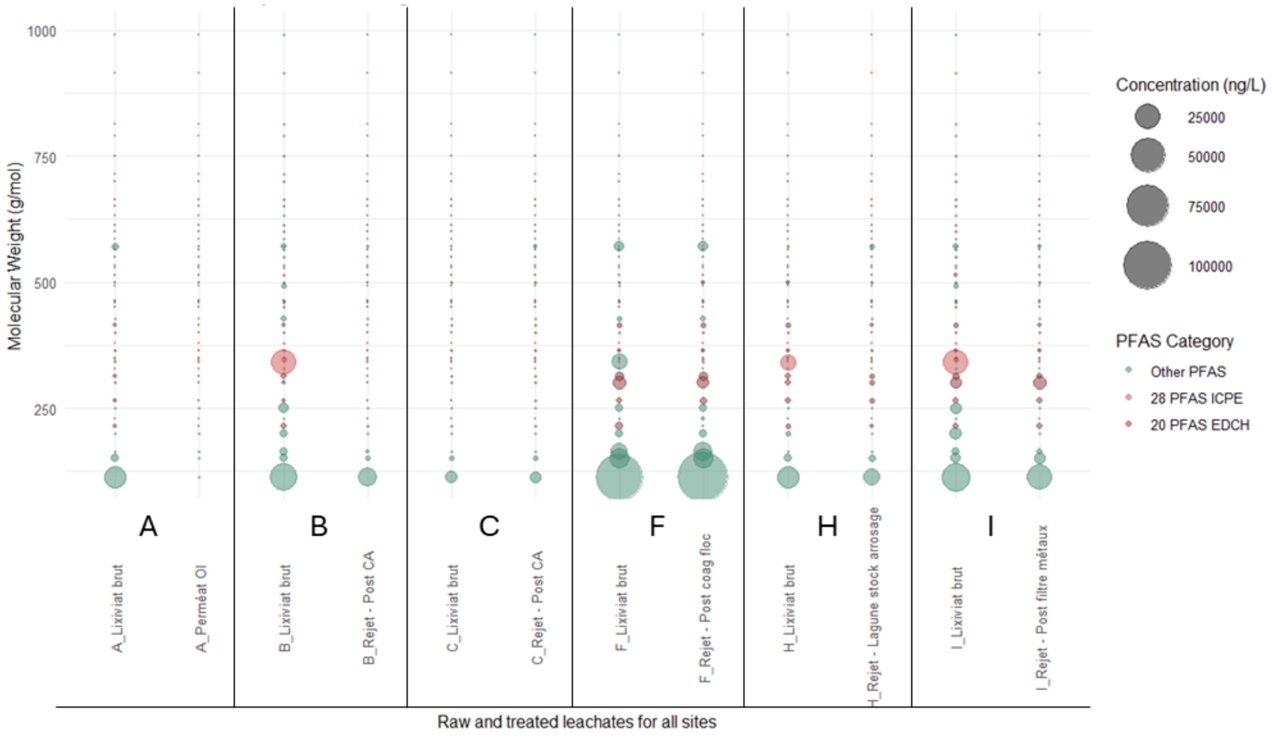

Figure 1: PFAS concentration by molecular weight in raw and treated leachates at all sites

Raw leachates

“All PFAS” in the ATOLIX project refers to the sum of 49 PFAS. In those 49 PFAS are perfluoro carboxylic and sulfonic acids, fluorotelomer based substances, per- and polyfluoroalkyl ether acids, etc. Overall concentrations of PFAS differ greatly across all sites as highlighted in Figure 1 by the differences in disks sizes. The lowest concentration for the sum of 49 PFAS being 8 623 ng/L and the highest 153 179 ng/L. That is, more than ten times higher. The five PFAS with the highest concentrations in raw leachates are: trifluoro acetic acid (TFA), perfluoro ([5-methoxy-1,3-dioxolan-4-yl]oxy) acetic acid (C_6O_4), trifluoromethanesulfonic acid (PFMeS), pentafluoropropionic acid (PFPrA) and perfluorobutane sulfonic acid (PFBS). The highest contributors to the overall PFAS concentration are “Ultra Short Chain” (USC) PFAS, i.e. those with the lowest molecular weight. TFA is the most important PFAS in raw leachate and yet it is not included in neither the European directive for drinking water (**dark red disks** in the Figure 1) nor the French “facilities classified for environmental protection” lists (**light red disks** in the Figure 1). Therefore, adding USC PFAS to monitoring lists would help grasp the overall concentration of PFAS in leachates. In May 2026, the EU has indeed updated its list of water pollutants to include newly identified substances that harm the environment and human health, such as TFA. For ATOLIX project, Extractible Organic Fluor (EOF) was analyzed for raw and treated leachate. For several sampling points the EOF value was lower than the sum of 49 PFAS. It appears that, for leachates, EOF is not a suitable method for estimating total PFAS concentration.

As part of the interministerial plan on PFAS, all French “facilities classified for environmental protection”, including landfills, have published data on PFAS concentrations in their effluent. In compliance with current regulations, only 28 PFAS were analyzed. USC compounds were not included. Average PFAS concentrations range from 41 to 3 923 ng/L in raw leachate. When selecting the same PFAS, the average for ATOLIX sites is 1 601 ng/L. For 8 landfills that published according to the interministerial plan, data on both raw and treated leachate were published, allowing for an estimation of the efficiency of the existing treatments in reducing PFAS levels, even though they were not designed with this purpose in mind. Indeed, more than 90% of PFAS present in raw leachate were removed. However, no information is available regarding the type of treatment in place and USC were not included.

Treatment efficiency

The different treatment techniques implemented on ATOLIX sites are treatment wetland, reverse osmosis (RO), ultra- (UF) and nanofiltration (NF), activated carbon (AC), granular ferric hydroxide filter, coagulation-flocculation, filter micron and denitrification / nitrification. In order to establish the efficiency of treatment wetland, other sampling campaigns will have to be carried out (sites B, C and H in Figure 1). Coagulation-flocculation with $FeCl_3$ + sodium hydroxide solution + cationic flocculant, has seemingly no impact on the concentration of PFAS overall (see site F in the Figure 1). The efficiency of AC is highly dependent on the filter saturation. Even though landfill leachate has high organic matter concentrations, AC efficiency is still relatively high, up to 73% for site B. In agreement with the literature, RO is the most efficient treatment included in the ATOLIX project: 98% removal efficiency for the sum of PFAS, without USC (see site A in Figure 1). NF is less efficient with 77% removal efficiency for the sum of PFAS, without USC (see site I in Figure 1).

Treated leachates

In treated leachate, USC PFAS remain the primary contributors to the overall PFAS concentration. At the leachate treatment plant discharge point, TFA accounts for between 59% and 85% of the total flow, depending on the site. The PFAS flow at the treatment plant discharge point ranges from 3 to 2 246 g/year for the 49 PFAS analyzed as part of the ATOLIX project. In the event of direct discharge into surface waters, PFAS released from landfills contribute to their dispersion in the environment

Conclusion

All techniques studied in this project are separation techniques that produce highly concentrated PFAS waste. PFAS molecules are not degraded. To that end, concentrated effluent (RO, NF, UF) and/or contaminated matrices (AC, sludge) will have to be further degraded, generating extra costs for the landfill owner.

Trends and actions on PFAS in Denmark

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Introduction

"Large amounts of hazardous PFAS have been found in the blood of 180 citizens in Korsoer" was a news headline that followed the detection of PFOS in cows near the firefighting school in Korsoer in 2021. 118 people had a level of PFOS in their blood at 21,2-600 ng/l, where 21,2 ng/l is considered "normal".

This national scandal strengthened the focus on PFAS in Denmark. It led to huge media interest and action on state level to manage PFAS pollution nationwide. Amongst others the Minister of the Environment in 2021 asked the Danish Regions to investigate 160 fire training sites to elucidate the extent and strength of PFAS-contamination.

The presentation will describe the state of PFAS management in Denmark and the triggers for national priorities and actions on PFAS.

Regulation and timeline

Danish environmental legislation largely follows EU directives. But as groundwater is the sole source of drinking water in the country, Denmark tends to select quality criteria for soil and groundwater that are stricter than EU requires. Furthermore, Denmark has a soil contamination act requiring the regional environmental authorities to investigate and remediate contamination that has taken place before 2001. This has resulted in a very good national overview of PFAS-contaminated sites, that is used to prioritize actions, and a guideline for investigation and remediation of PFAS contamination.

A timeline for Danish regulation on PFAS will be presented including an overview of development of quality criteria, analytical packages for PFAS (from 6-8 PFAS to todays 22-24 PFAS) and prioritization of sources of PFAS.

Besides the Korsoer cow scandal the following cases will be shortly introduced as they were instrumental in the need for a national PFAS action plan:

- PFAS in organic eggs
- PFAS in sea foam and subsequent contamination of soil along the western coast
- PFAS in drinking water on the island of Fanø

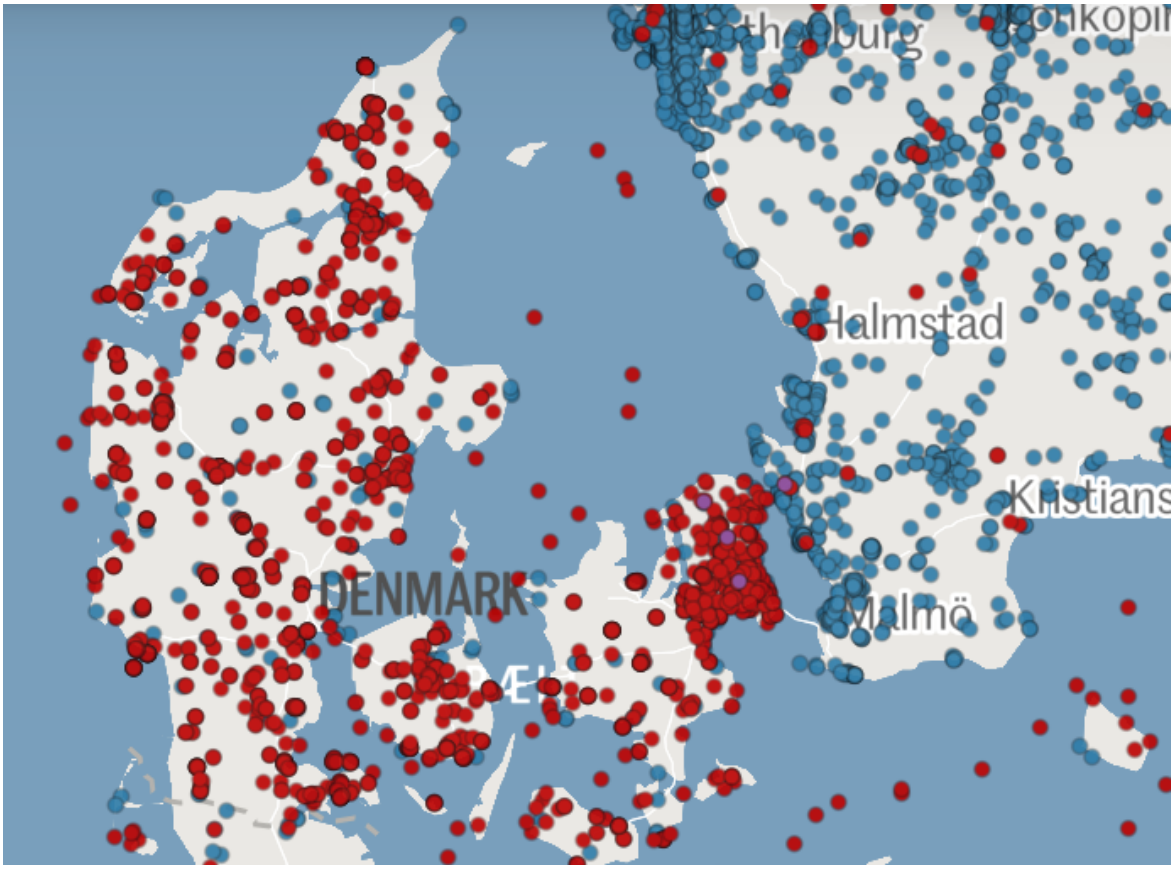
PFAS action plan

In 2024 a 4-year action plan for management of PFAS contamination was unanimously agreed upon in the Parliament. The plan aims at reducing, monitoring and mitigating PFAS-contamination. The key issues are a ban on PFAS in clothing/shoes and firefighting foams, monitoring PFAS in groundwater/surface water and foods and remediation of PFAS-impacted soil and groundwater.

The action plan will be presented including trends in the national management of PFAS pollution i.e. focus on PFAS-containing discharges from WWTP and industry, air emissions, landfills etc. Challenges still to overcome will be mentioned.

Technology development

The PFAS action plan resulted in the formation of a national PFAS Research Center and in selection of 3 test-sites that can be used for testing treatment of PFAS in soil and water. Furthermore, the Danish state has funded and funds innovative projects on PFAS management and mitigation. A short overview will be given on technology development and the nationwide benefits.



PFAS contaminated sites in Denmark. Source: Le Monde, Forever Pollution Project

PFAS flux-based decision-making: an industrial case study (Belgium)

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Co-authors: Bram Van Humbeeck (AECOM Belgium), Mathieu Charrier (AECOM France & Switzerland), Erik Bosmans (iFLUX), Marjan Joris (iFLUX)

Innovative nature of the proposed topic

This contribution presents a flux-based assessment framework as an important line of evidence building the Conceptual Site Model (CSM). The flux-based approach is an innovative and practice-oriented alternative to conventional concentration-driven PFAS evaluations. By integrating hydraulic profiling and time-integrated PFAS mass flux measurements into an adaptive investigation strategy, the approach enables robust differentiation between site-related and background PFAS impacts in complex, multi-source environments. The method improves regulatory defensibility, proportionality of response, and sustainability of decision-making.

Objectives

The objective is to provide feedback from a real-world industrial case demonstrating how PFAS mass flux measurements can be used to refine conceptual site models, reduce uncertainty regarding contaminant migration, and support technically sound, economically proportionate and environmentally justified regulatory decisions. Flux measurements as an additional line of evidence.

Background and context

At several adjacent industrial sites in Flanders (Belgium), extensive historical soil and groundwater investigations identified multiple PFAS sources, dominated by perfluorohexanesulfonic acid (PFHxS), perfluorooctanoic acid (PFOA) and, to a lesser extent, perfluorooctanesulfonic acid (PFOS). These contaminants were primarily associated with historical aqueous film-forming foam use since the 1960s, with minor contributions from production-related applications. The site of interest is located within a wider area affected by unrelated regional PFAS contamination, complicating the attribution of downgradient impacts on surface water, a deeper aquifer and neighbouring parcels. In parallel, the regulatory framework for PFAS evolved significantly during the investigation, requiring a robust and adaptable conceptual site model.

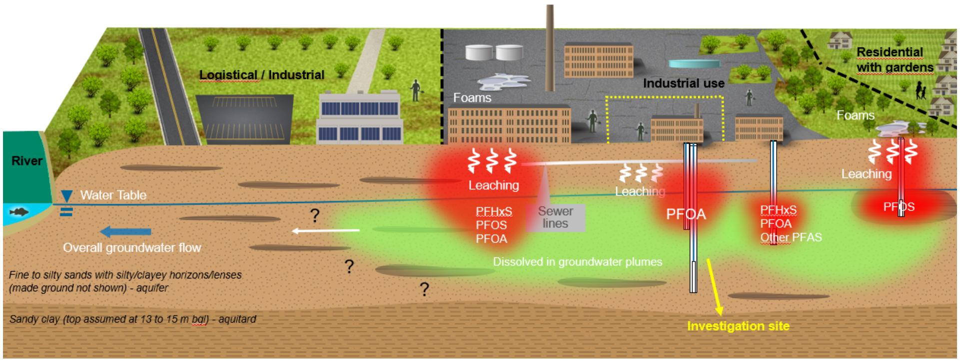

Figure 1: Conceptual site model showing the industrial site and contribution of multiple sources in the subsurface and to the groundwater

Approach and activities

To address remaining uncertainties after conventional investigations, a flux-based assessment strategy was implemented. Hydraulic profiling tool (HPT) screening was used to characterise vertical hydraulic variability and preferential flow paths, forming the basis for targeted installation of clustered monitoring wells. PFAS-specific flux cartridges were then deployed in selected wells for five-week periods to obtain time-averaged mass flux data. Seasonal groundwater dynamics were captured through six months of continuous groundwater level monitoring, after which flux measurements were repeated. This adaptive programme management approach ensured data integrity while accommodating evolving analytical and regulatory requirements.

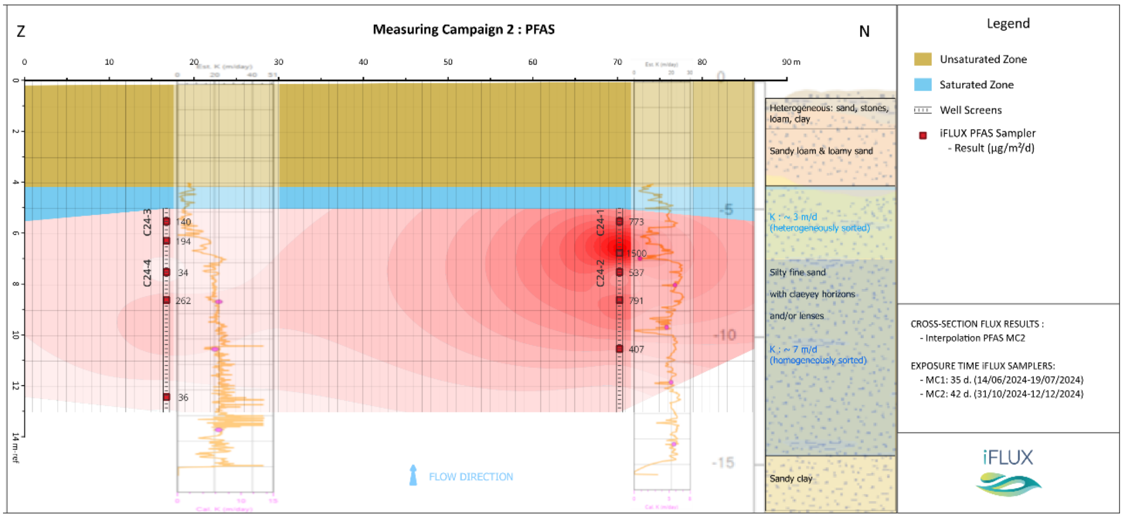

Figure 2 : Transect parallel to the flow direction with FLUX results (PFAS) at 5 different depth, HPT and soil profile

Results and lessons learned

The combined interpretation of hydraulic profiling and PFAS mass flux data resulted in a substantially improved understanding of the conceptual site model. Compared with snapshot concentration data, the flux-based approach provided clearer insight into actual contaminant transport and enabled differentiation between site-related and background PFAS contributions. Mass flux analysis demonstrated that the site did not contribute an unacceptable load to downgradient surface water, the deeper aquifer nor surrounding parcels. Technically, economically and environmentally, a disproportionate intervention with limited benefit could be agreed upon. Socially and regulatorily, the approach supported transparent communication and, in this case, resulting in a No Further Action as agreed upon by the competent authority.

Prospects and justification

This case illustrates that PFAS flux-based assessments provide a transferable and robust framework for decision-making in complex regulatory contexts. As PFAS standards continue to tighten, integrating mass flux concepts can support more sustainable, defensible and proportionate assessment and management of contaminated sites.

Potential for PFAS transfer through the clay passive barrier of a hazardous waste landfill

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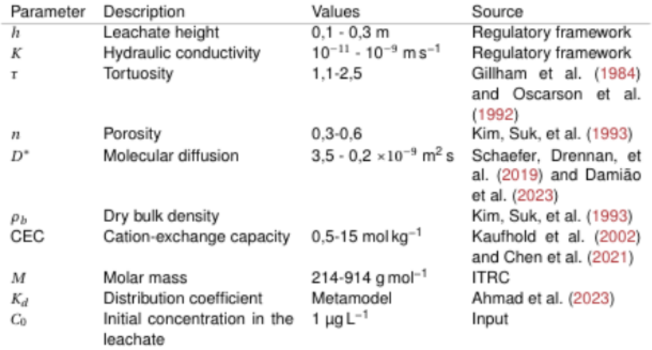
Context

Hazardous waste landfill (HWL) are industrial facilities specially designed for the secure storage of waste, ensuring environmental protection. HWL cells are equipped with a double safety barrier consisting of a geomembrane and a 5 meters thick compacted clay layer . This barrier must act as protection against the transport of pollutants from the contained wastes towards groundwater.

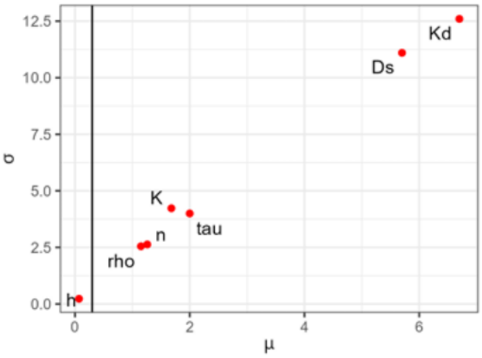
Per- and polyfluorinated substances (PFAS) are persistent and mobile pollutants. Twenty PFAS were studied in this study, and among them, the most currently monitored. The objective of the study was to assess the performance of a HWL barrier to stop the migration of PFAS to the natural environment. This study is part of a broader reflection on the need to specifically stabilize and store certain hazardous wastes strongly polluted by PFAS before storage.

Development of the digital model

Based on scientific literature concerning the adsorption of PFAS onto bentonite clays, a mathematical model was developed to estimate the potential for PFAS transfer through the passive clay barrier of HWLs. Several parameters are required to describe PFAS transport through the landfill's barrier system (see table below).



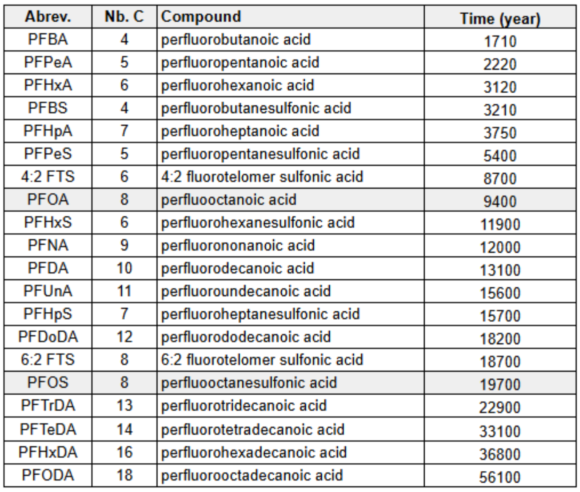
Parameter	Description	Values	Source
h	Leachate height	0,1 - 0,3 m	Regulatory framework
K	Hydraulic conductivity	10^{-11} - 10^{-9} m s^{-1}	Regulatory framework
τ	Tortuosity	1,1-2,5	Gillham et al. (1984) and Oscarson et al. (1992)
n	Porosity	0,3-0,6	Kim, Suk, et al. (1993)
D^*	Molecular diffusion	3,5 - 0,2 $\times 10^{-9}$ m^2 s	Schaefer, Drennan, et al. (2019) and Damião et al. (2023)
ρ_b	Dry bulk density		Kim, Suk, et al. (1993)
CEC	Cation-exchange capacity	0,5-15 mol kg^{-1}	Kaufhold et al. (2002) and Chen et al. (2021)
M	Molar mass	214-914 g mol^{-1}	ITRC
K_d	Distribution coefficient	Metamodel	Ahmad et al. (2023)
C_0	Initial concentration in the leachate	1 µg L^{-1}	Input



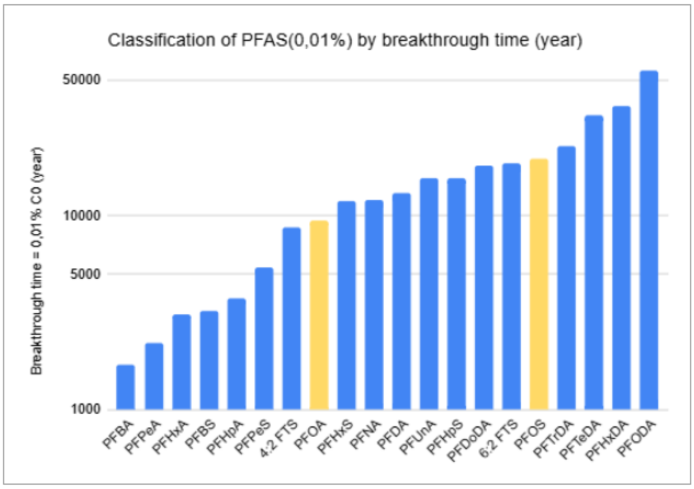
This model also integrates several characteristics specific to HWL such as pH, salinity and hydraulic conductivity and load. However, there are still many uncertainties regarding the fate and transport of PFAS in clay environments. For example, the molecular diffusion coefficient of PFAS is still little known, however, diffusion plays an important role in transport in clay environments. Similarly, the current state of knowledge does not allow for the consideration of competitive sorption phenomena. The effect of pH does not seem significant according to the results of the literature. On the other hand, the salinity of this type of leachate can probably increase the adsorption of PFAS and thus decrease the transfer potential across the barrier. The study highlights that an advection-diffusion equation with a retardation factor allows to evaluate the transport. The distribution coefficient to be integrated into the retardation factor is obtained from experimental results available in the literature, and which were then used as a basis for the generation of a metamodel obtained by kriging, in order to generate distribution coefficient graphs according to two parameters (the molecular weight of PFAS and the cation exchange capacity of clay). In doing so, the metamodel allows a much more precise interpolation between the available points than an empirical relationship obtained by regression. Finally, the physico-chemical data on PFAS, even for those that are most studied, remain partial and subject to uncertainties. When these uncertainties cannot be taken into account, the model is based on the most penalizing case. A sensitivity analysis was conducted to identify significant parameters. A screening using the Morris method allows to obtain a ranking of the most influential parameters (large μ) and those with a non-linear impact (large σ) (see graph above). The most significant parameter is the distribution coefficient (Kd), followed by the molecular diffusion coefficient. On the contrary, the height of leachate is not a significant parameter.

Application to hazardous waste storage

The numerical model developed is therefore a valuable tool for estimating the effectiveness of a hazardous waste landfill (HWL) to prevent PFAS migration from the stored waste into the natural environment. The bottom of an HWL includes a passive safety barrier (PSB) made of 5 m of clay with a permeability lower than 10^{-9} m/s and an active safety barrier (ASB) made of a 2 mm HDPE membrane. The ASB ensures complete impermeability during the operation phase of the HWL and the PSB ensures long-term impermeability. The numerical model allows simulation of long term PFAS migration through the PSB. The results presented below were obtained by applying the following parameters: K=10^{-9} m/s; PSB thickness = 5 m; porosity = 0.35; CEC = 60 cmol/kg; [PFAS]= 1 μg/L.



Abrev.	Nb. C	Compound	Time (year)
PFBA	4	perfluorobutanoic acid	1710
PFPeA	5	perfluoropentanoic acid	2220
PFHxA	6	perfluorohexanoic acid	3120
PFBS	4	perfluorobutanesulfonic acid	3210
PFHpA	7	perfluoroheptanoic acid	3750
PFPeS	5	perfluoropentanesulfonic acid	5400
4:2 FTS	6	4:2 fluorotelomer sulfonic acid	8700
PFOA	8	perfluooctanoic acid	9400
PFHxS	6	perfluorohexanesulfonic acid	11900
PFNA	9	perfluorononanoic acid	12000
PFDA	10	perfluorodecanoic acid	13100
PFUnA	11	perfluoroundecanoic acid	15600
PFHpS	7	perfluoroheptanesulfonic acid	15700
PFDoDA	12	perfluorododecanoic acid	18200
6:2 FTS	8	6:2 fluorotelomer sulfonic acid	18700
PFOS	8	perfluooctanesulfonic acid	19700
PFTrDA	13	perfluorotridecanoic acid	22900
PFTeDA	14	perfluorotetradecanoic acid	33100
PFHxDA	16	perfluorohexadecanoic acid	36800
PFODA	18	perfluorooctadecanoic acid	56100



The breakthrough time of the BSP is defined as the time after which the PFAS concentration below the BSP will be 10,000 times lower than the PFAS concentration in the leachate. Based on these parameters, most PFAS considered in the study are very effectively and safely confined in HWL over a very long term (10,000 years). All PFAS with more than 7 carbon atoms are perfectly confined and no longer pose any risk to the environment. The most mobile PFAS are the carboxylic acid PFAS with 4, 5, 6, and 7 carbons and the sulphonic acid PFAS with 4 and 5 carbon atoms. For the same number of carbons, carboxylic acid PFAS are more mobile than sulphonic acid PFAS. In HWL, the most mobile PFAS is perfluorobutanoic acid but it will not be detected below the BSP before 1700 years.

Conclusion

The numerical flow model adapted to the environmental conditions of hazardous waste landfill facilities (e.g. salinity, pH) shows that HWLs are a very effective and very safe method for the long-term management of PFAS contaminated waste. However, the clay barrier is not entirely impermeable to PFAS. Particular attention should be paid to 4, 5 and 6 carbon atoms PFAS which are the most mobile under the studied conditions. The confinement of highly PFAS-contaminated waste could be improved either by pre-treatment and stabilization (with or without solidification) before landfilling, or by optimising the PSB.

This study was funded by the Union of Recycling Professionals, Valorization, Regeneration and Treatment of Hazardous Waste (SYPRED)

First PFAS quantitative ambient air measurements in the vicinity of Lyon Metropolis
Premières mesures quantitatives de PFAS en air ambiant sur la métropole de Lyon

Barbero Albane[1], Salque-Moreton Guillaume[1], Bret Clément[1], Bourlon Mathilde[1], and Cozic Julie[1]
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Innovative aspects: First quantitative measurements of PFAS in ambient air
Objectives: First quantitative measurements of PFAS in ambient air
Keywords: PFAS, ambient air, urban background, industrial influence, HV-AAS

Technical abstract:

Per- and polyfluoroalkyl substances (PFAS) are persistent synthetic chemicals of major regulatory and public health concern. While regulatory frameworks and monitoring programs have significantly progressed for water and soil, the atmospheric compartment remains largely unregulated and insufficiently documented. This knowledge gap limits the understanding of PFAS transfers between environmental media (air, water, and soils) and hampers the assessment of human exposure by inhalation. To support surveillance and regulatory needs, Atmo Auvergne-Rhône-Alpes initiated an exploratory program in 2023 to develop and test an active sampling methodology for the quantitative measurement of PFAS in ambient air. High-volume air samplers were adapted to simultaneously collect particulate and gaseous/semi-volatile PFAS using quartz fiber filters and polyurethane foam (PUF). Attention was paid to contamination control, sampling duration, and analytical sensitivity, enabling quantification at ultra-trace levels (pg·m^{-3}). A total of 38 PFAS were analyzed by LC-MS, selected to ensure coherence with compounds targeted by drinking water regulations and recently introduced requirements for industrial atmospheric emission monitoring. Among the 38 identifiable and quantifiable PFAS, the different substances are classified and counted in different groups according to their chemical function: 13 perfluorocarboxylic acids (PFCA), 4 fluorotelomersulfonic acids (FTS), 2 perfluorooctanesulfonamidoacetic acids (FOSAA), 10 perfluorosulfonic acids (PFSA), 3 perfluorooctanesulfonamides (FOSA), 2 perfluoroalkane sulfonamide ethanol(FOSE or FASE), 2 commercial substitute substances (Adona and HFPO-DA (GenX), two PFOA substitutes for PTFE production), 2 fluorotelomer carboxylic acids (5:3 FTCA and 6:2 FTCA). The method was deployed between November 2023 and December 2025 at two sites in the Lyon metropolitan area (France): an urban background site (Lyon centre) and an urban site (Pierre Bénite) influenced by fluoropolymer manufacturing activities, within a territory identified as a pilot area of the French national PFAS action plan. Average total concentrations (gas + particle phases) were on the order of 25 pg·m^{-3} (n=17 samples) at the urban background site and 244 pg·m^{-3} at the industrially influenced site (n=26 samples) (Fig.1). PFHxA and 6:2FTS dominated the chemical profiles, reflecting local emission signatures, and confirming the role of the atmosphere as a transfer pathway from industrial sources toward surrounding environments. Legacy compounds such as PFOA and PFOS were also detected at lower levels, highlighting their long-term persistence despite regulatory bans.

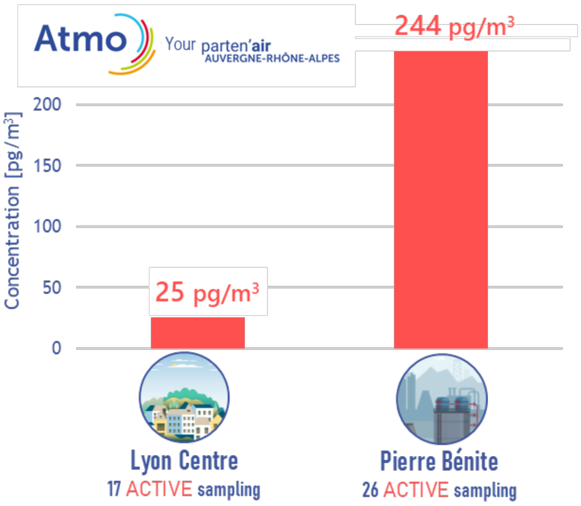

Figure 1:
Average of the 38 compounds (particulate + gaseous phases) measured at the Lyon centre (n=17) and Pierre Bénite (n=26) sites since 2023 for a limited number of measurements. Measurement uncertainty of around 50%.

Differences between atmospheric chemical profiles and those observed in soils and deposits suggest that ambient air contamination is not primarily driven by resuspension of historical pollution, but rather by ongoing emissions and atmospheric transport processes. These results provide the first quantitative reference data for PFAS in ambient air in France and contribute to bridging gaps between environmental surveillance, regulatory frameworks and exposure assessment. They underline the need to integrate air measurements into PFAS monitoring strategies and to further harmonize methodologies in support of future inhalation risk assessment and environmental transfer studies.

Measuring PFAS in Air – The Next Frontier

Heather Lord, ALS Laboratories, Waterloo, ON Canada

Stream: 4. Environmental and Health Risk Assessments, Toxicology & Epidemiology

PFAS researchers have documented releases to, and transport within, the atmosphere since the early 1950s through analyses of polar ice cores and Tibetan plateau sediments. Although volatile neutral PFAS, such as fluorinated telomer alcohols and fluorotelomer acrylates, have received significant attention in atmospheric studies, perfluoroalkyl acids also enter the atmosphere, typically by adhering to aerosols. Reported levels are generally lowest outdoors (<3 ng/m^3), higher in typical indoor environments, and highest in occupational settings, where concentrations sometimes exceed 100 ng/m^3.* [Lee 2026]

While PFAS concentrations are relatively low in most environments, their persistence, bioaccumulation, and toxicity, combined with the inevitability of inhalation, make inhalation an important exposure pathway. Despite growing concern about airborne PFAS exposure, standardized measurement methods remain limited. As a result, regulatory frameworks and exposure limits for PFAS in air are largely absent.

Since 2021, the U.S. EPA has published two standard methods for monitoring PFAS in stationary sources (stack gases); OTM-45 for semi-volatile and non-volatile PFAS and OTM-50 for volatile fluorinated compounds (VFC). Although originally designed to characterize emissions from PFAS incineration, the methods offer a useful framework for measuring a broad range of volatile and semi-volatile PFAS in air.

OTM-45 targets semi-volatile gaseous PFAS as well as particulate bound PFAS. Samples are withdrawn from the gas stream isokinetically (sampling velocity equal to the stack velocity), and collected in a sampling train containing a quartz or glass fiber filter, a packed column of XAD-2 adsorbent material and in a series of liquid impingers. A final XAD-2 trap may also be included to monitor for breakthrough.

In the lab, the target compounds are extracted from the individual collection media into 4 discrete sample fractions. Analysis is by LC-MS/MS with quantification is by isotope dilution. The target analytes are those typically reported for water and soil LC-MS/MS methods. The collection of blanks in replicate is particularly important for data interpretation, due to the fairly ubiquitous presence of PFAS in the environment.

Although intended for destruction process effluents, the method may also be applied to general air sampling where similar sets of reported compounds are required.

OTM-50 targets gas phase VFCs, mostly produced as a result of incomplete combustion/destruction. The 30 compounds reported fall into three classes: fluorinated alkanes/alkenes, refrigerants and industrial chemicals. The first category includes exclusively products of incomplete combustion as an early reaction in the degradation process is to remove the polar head group. Some of the refrigerants are known to be formed from larger PFAS during destruction. Gaseous emissions collected by this method are intended to be sampled from industrial source ducts, vents, stacks, etc.

Sampling involves active collection of VFCs – by way of a downstream pump - into evacuated passivated silicon ceramic lined stainless-steel canisters. Background samples and sample duplicates are highly recommended due to the ubiquitous presence of several refrigerants in ambient air.

VFCs are identified and quantified in gaseous canister samples by GC/MS/MS. Measurements of stack carbon dioxide (CO_2) are also required. It is applicable to VFC concentrations in undiluted samples ranging from the detection limit to approximately 1000 μg/m^3. Sample dilution in the laboratory can extend this range. While developed for incineration effluents, the method is being applied to other destruction technology gaseous effluent streams as well.

There is, however, a missing middle between these two methods: VFCs that are not fixed gasses (i.e. they may be reactive or easily liquified). In 2024, scientists from the U.S. EPA and Linköping University in Sweden published a comprehensive review of analytical methods for detecting PFAS in indoor and outdoor air. [Wallace] The majority of these methods used high or low volume sampling pumps to draw air through a glass tube containing XAD-2 resin sandwiched between two polyurethane foam (PUF) filters. An up-front glass or quartz fiber filter was typically used to trap particulates and other aerosols.

In the laboratory, the filter and other media are extracted and extracts are anaysed either separately or combined, by GC-MS/MS, LC-MS/MS, or both. The method is capable of reporting a broad range of PFAS and other VFC from ambient air streams other than incinerator stack gas. Applications are likely in indoor air environments, landfill gasses, wastewater treatment plants, remedial settings such as thermopiles, foam fractionation, and fence line monitoring.

ALS Laboratories is actively developing test methods worldwide for stationary sources and ambient air monitoring. In this presentation, we will share technical developments and initial results using these methods. We will discuss the measures we have taken to ensure high-quality, reliable data and describe the challenges encountered during method implementation. We aim for these advancements to support broader use of PFAS air monitoring data to inform global policy and regulatory decision-making.

Footnotes:

*A resting adult breathes approximately 12 m^3 per day.
Lee, M. et al., Safety and Health at Work, 2026, 17: 12-23. https://doi.org/10.1016/j.shaw.2026.01.002
Wallace, M.A.G, et al., Chemosphere, 2024, 358: 142129.

PFAS Risk Management in a Digital Age

Scott Recker, Vice President, Senior Consultant, Antea Group / INOGEN (USA)
Annika Taylor, Associate, Peter J Ramsay & Associates / INOGEN (Australia)
Heikki Kalle, COO, DGE Group / INOGEN (Denmark)
Isak Hjort Dahm, Head of Development, DGE Group / INOGEN (Denmark)

Per- and polyfluoroalkyl substances (PFAS) are synthetic compounds that have been widely used in industrial and consumer products for their resistance to heat, water, and oil since the 1950's. Their persistence in the environment and potential health risks have prompted sweeping regulatory and legal actions across the globe. From product bans, part per trillion clean-up goals, and complex reporting requirements across various regulatory regimes and geographies, it is nearly impossible for companies to track and remain in compliance with respect to PFAS, especially when they have facilities in multiple countries. This is further complicated by the need to assess your potential exposure to PFAS in your products and supply chain. This presentation highlights the latest developments in a digital, subscription-based solution to track and report upon PFAS regulation across the globe as well as a PFAS screening tool to help stakeholders identify and manage their potential PFAS risk in their supply chain and products.

Jeudi 18 juin 2026

08h30
Accueil des participants

Plans de gestion et objectifs de réhabilitation, Expériences de Gestion des PFAS à chaînes ultra courtes (TFA, etc.) et PFAS volatils (FTOH, etc.)

Présidents :
• *Pr. Géraldine Gouhier - Directrice commerciale CARNOT i2C & Professeur - Institut CARMeN, France*
• *Dr. Frank Karg, SFSE & ARET, Directeur scientifique Ginger Group - HPC (Inogen), Président d’Atlantis Développement & Expert Judiciaire, France*

09h00
Dégradation des PFAS dans les sols historiquement pollués : mise en évidence de processus biotiques
Lamyae El-Mrabet, PhD Student (PFAS) - Institut national de l’environnement industriel et des risques, Ineris (France)

09h30
Démonstrations sur le terrain d’un traitement destructif des PFAS utilisant une technologie innovante à base d’UV
Zhong (John) Xiong, Ingénieur principal - Haley & Aldrich, Inc. (États-Unis)

10h00
Réhabilitation in-situ combinée des PFAS par pré-traitement microbiologique des Précurseurs et lavage bio-chimique des sols et aquifères
Dr. Frank Karg, SFSE & ARET, Directeur scientifique Ginger Group - HPC (Inogen), Président d’Atlantis Développement & Expert Judiciaire (France)

10h30
Pause-café & thé

11h00
Élimination des composés PFAS à chaîne courte et longue à l'aide d'une résine échangeuse d'ions multi-régénérable dotée d'une technologie de commutation de charge
Farhad Farnia, Co-fondateur & Président-directeur général - Ecofilter Tek (Québec, Canada)

11h30
Traitement des PFAS par échange d'ions : Conformité mondiale à des réglementations en constante évolution
Catherine Swanson, Directrice du développement commercial pour les marchés émergents - Ecolab, Purolite Resins (États-Unis)

12h00
Solutions modulaires d'élimination des PFAS à chaînes courtes et ultra-courtes dans les effluents industriels et les eaux souterraines
Eleonore Morlas, Directrice commerciale - Oxyle (Suisse)

12h30
Déjeuner

14h00
Assainissement des aquifères contaminés par les PFAS et décontamination des systèmes d'extinction d'incendie à base d'AFFF à l'aide d'agents tensioactifs
George Ivey, Président - PFAS-SOL By Ivey International Inc. (Canada)

14h30
De la concentration au flux : stratégies intégrées d'analyse, de suivi et de remédiation pour une gestion durable des PFAS dans les sols et les eaux souterraines
Erik Bosmans, Chef de projets - iFlux (Belgique)

15h00
Stratégies d'anticipation pour les maîtres d'ouvrages en charge de l'eau potable face au risque PFAS
Cédric Masson, Responsable service traitement des eaux - Naldeo (France)

15h30
Pause-café & thé

Technologies de traitement pour l'eau, les sols, les sédiments et l'air (Part. 1)

16h00
Élimination et destruction complète des PFAS sur charbon actif: résultats des campagnes de mesure et validation industrielle
Lowie Bolle, R&D Project Lead - Desotec (Belgique)

16h30
Évaluation de l'efficacité d'un système d'osmose inverse (OI) à deux étages pour la rétention de l'acide trifluoroacétique (TFA) appliqué au traitement d'effluents industriels. Étude de cas à l'échelle semi-industrielle
Eric Harfmann, Directeur de site - Veolia Hazardous Waste Europe (France)

17h00
PFAS : progrès significatifs dans la gestion des eaux usées industrielles et des boues d'épuration en réponse au défi environnemental mondial
Delphine Steinmann, Ingénieur Recherche et Développement - Suez (France)

17h30

Rétention améliorée des PFAS grâce au charbon actif colloïdal : une méthode éprouvée et économique de dépollution des eaux souterraines et des sols

Scott Wilson, Président-directeur général - Regenesis (États-Unis)

18h00

Destruction UV extensible des PFAS dans les eaux souterraines du Minnesota après fractionnement par mousse

Zachary Rogers, Chargé de compte - Claros Technologies (États-Unis)

18h30

Fin de la troisième journée

PFAS

PER- AND POLY-FLUOROALKYL SUBSTANCES

Management of Environmental & Health Risks

June 16, 17, 18 & 19, 2026 – Paris

Thursday June 18, 2026

08h30
Welcoming participants

Remediation Plans and Remediation Goals, Management Experiences of ultrashort-chain PFAS (TFA, etc.) and Volatile PFAS (FTOHs, etc.)

Presidents:
- *Prof. Géraldine Gouhier - CARNOT i2C Sales Director & Professor - CARMeN Institute, France*
- *Dr. Frank Karg, SFSE & ARET, Scientific Director of Ginger Group - HPC (Inogen), CEO of Atlantis Développement & Court Expert, France*

09h00
Degradation of PFAS in historically contaminated soils: evidence of biotic processes
Lamyae El-Mrabet, Doctorant (PFAS) - French National Institute for Industrial Environment and Risks, Ineris (France)

09h30
Field Demonstrations of PFAS Destructive Treatment Using an Innovative UV-Based Technology
Zhong (John) Xiong, Principal Engineer - Haley & Aldrich, Inc. (USA)

10h00
Combined in-situ Depollution of PFAS, via microbiological pre-treatment of Precursors and biochemical aquifer and soil washing
Dr. Frank Karg, SFSE & ARET, Scientific Director of Ginger Group - HPC (Inogen), CEO of Atlantis Développement & Court Expert (France)

10h30
Coffee & Tea break

11h00
Removal of short- and long-chain PFAS compounds using a multi-regenerable ion-exchange resin with charge-switching technology
Farhad Farnia, Co-founder and CEO - Ecofilter Tek (Québec, Canada)

11h30
PFAS treatment with ion exchange: Worldwide compliance to everchanging regulations
Catherine Swanson, Director of Business Development for Emerging Markets - Ecolab, Purolite Resins (USA)

12h00
Modular solutions to eliminate short and ultra-short chain PFAS from industrial wastewater & groundwater
Eleonore Morlas, Chief Commercial Officer - Oxyle (Switzerland)

12h30
Lunch

14h00
Surfactant enhanced PFAS aquifer remediation and decontamination of AFFF fire suppression systems
George Ivey, President - PFAS-SOL By Ivey International Inc. (Canada)

14h30
From concentration to flux: integrated analytical, monitoring and remediation strategies for sustainable PFAS management in soil and groundwater
Erik Bosmans, Project Manager - iFlux (Belgium)

15h00
Anticipation strategies for drinking water authorities facing PFAS risks
Cédric Masson, Head of Water Treatment Services - Naldeo (France)

15h30
Coffee & Tea break

Treatment Technologies for Water, Soils, Sediments and Air (Part. 2)

16h00
Removal and complete destruction of PFAS on activated carbon: results from measurement campaigns and industrial validation
Lowie Bolle, Chef de projet R&D - Desotec (Belgium)

16h30
Evaluation of the efficiency of a two-stage reverse osmosis (RO) system for trifluoroacetic acid (TFA) retention applied to industrial wastewater treatment. Semi-industrial scale case study
Eric Harfmann, Site Director - Veolia Hazardous Waste Europe (France)

17h00
PFAS: Significant progress in industrial waste waters and sludge management in response to the global environmental challenge
Delphine Steinmann, Research and Development Engineer - Suez (France)

17h30
PFAS enhanced retention using colloidal activated carbon: Proven, low-cost remediation of groundwater and soil
Scott Wilson, CEO & President - Regenesis (USA)

18h00

Scalable UV destruction of PFAS in foam-fractionated Minnesota groundwater

Zachary Rogers, Account Executive - Claros Technologies (USA)

18h30

End of the third day

Degradation of PFAS in historically contaminated soils: evidence of biotic processes

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Keywords: contaminated sites and soils, PFAS, release; biodegradation, transfer.

Innovative aspect of the work: investigation of the biodegradation of a broad range of PFAS, including long-chain PFCA, FTS and FTAB, from a historically contaminated soil.

Objective: To understand PFAS biodegradation by identifying parent compounds, transformation products and associated half-lives.

Résumé

Per- and polyfluoroalkyl substances (PFAS) are a large family of synthetic organic compounds characterized by high chemical stability due to the strength of the carbon–fluorine bond. This persistence gives them desirable properties for numerous industrial applications [1], but also results in long-lasting contamination of soils and waters [2], [3]. Understanding the behaviour of PFAS in soils, particularly their release, transfer and degradation mechanisms, is essential to assess human exposure and to develop effective management and remediation strategies.

At the 2025 PFAS congress in Paris, we presented our first research results on PFAS release and transfer in soils and groundwater. These results showed that PFAS release from historically contaminated soils occurred through rapid kinetics and that these compounds were mobile to very mobile in these media according to the criteria of the German Environment Agency (UBA). Initial evidence also suggested the involvement of biotic processes during PFAS release. For the 2026 PFAS congress, we propose to present new research results that further investigate this topic.

PFAS biodegradation is most often studied using isolated bacterial strains specifically identified for their ability to degrade PFAS. However, in the specific context of contaminated sites and soils, and with a view to considering biodegradation as a site management option, no studies using historically PFAS-contaminated soils and therefore the indigenous microorganisms naturally present in these soils have been published, to our knowledge. Moreover, the available literature remains very limited and concerns only a restricted number of PFAS. Previous work has mainly focused on the degradation of precursor compounds such as 6:2 FTS (fluorotelomer sulfonate) [4], while some studies have shown that specific bacterial strains may induce defluorination of perfluorinated compounds such as PFOS or PFOA [5]. However, the degradation pathways of short-chain PFAS, as well as the associated yields, remain unknown to date[6]. The objective of our work is therefore to generate robust scientific knowledge on the biodegradation of these PFAS by identifying parent compounds, transformation products and associated half-lives.

In this context, a study was conducted on PFAS biodegradation in a historically contaminated soil collected from a former firefighting area. This sandy soil had a slightly alkaline pH (8.4), a low total organic carbon content (10 g.kg^{-1}) and a total PFAS concentration of 2,945 µg.kg^{-1}. The analysis revealed high concentrations of 6:2 FTAB (2 560 µg.kg^{-1}, 87 %), 8 :2 FTS (123 µg.kg^{-1}, 4 %), 6 :2 FTS (114 µg.kg^{-1}, 4 %) and PFOS (96 µg.kg^{-1}, 3 %), reflecting the historical use of firefighting foams. The quantification of fluorotelomer compounds at high concentrations highlights the need to broaden the list of the 20 PFAS regulated under the European Drinking Water Directive in order to more accurately assess contamination at these sites.

The experiments consisted of bringing 80 g of contaminated soil into contact with 400 mL of solution composed of demineralized water and calcium chloride ($CaCl_2$) at a concentration of 0,5 x 10^{-3} mol L^{-1} in polypropylene bottles. The soil–solution mixture was then shaken for 3 days, in order to reach release equilibrium as shown in our previous work The bottles were then stored in the laboratory for one year at 20 ± 2°C, and nine small-volume solution samples were collected over time (3 mL per sampling, in order not to disturb the equilibrium. The subsequent monitoring of concentration changes over time was then conducted to assess and quantify degradation. These experiments were performed in triplicate. The experiment was carried out both in the presence and in the absence of a bacterial inhibitor, sodium azide (NaN_3). The bacterial inhibitor was used to eliminate microbial activity in the soil and to isolate purely physicochemical pollutant release processes. In contrast, the absence of the bacterial inhibitor allows biological processes to be highlighted by comparison.

The results obtained in the presence of the bacterial inhibitor showed that the solution concentrations of the shortest-chain PFCA, particularly PFBA (C4) and PFPeA (C5), remained constant throughout the experiment (1 year). In contrast, for PFHxA (C6) and PFHpA (C7), concentrations in solution increased up to approximately 150 days, reaching about twice their initial values, and then stabilized. Several explanations may be proposed: a gradual decrease in inhibitor efficiency over time, an insufficient inhibitor concentration to fully eliminate microbial activity, or variable sensitivity of the bacterial communities present in the soil. Thus, residual microbial activity may persist despite the presence of the inhibitor and contribute to the progressive formation of short-chain PFCA from longer chain PFCA or FTS. In the absence of the bacterial inhibitor, the concentrations of these short-chain PFCA measured after 1 year of soil contact were nearly ten times higher than those measured after 3 days of contact, a duration for which the measured concentration in solution corresponded to the complete transfer into the solution of the PFAS mass initially present in the soil. This increase in solution concentration therefore cannot result from additional release, but rather from the biodegradation of precursors present in the soil, such as 6:2 FTS, forming PFCA containing 4 to 7 carbon atoms.

Nevertheless, 6:2 FTS concentrations remained stable over time, both in the presence and in the absence of the bacterial inhibitor. This apparent stability did not allow us to conclude that the monitored FTS are undergoing degradation, but it did not exclude the occurrence of transformation processes. A plausible hypothesis is the involvement of 6:2 FTS precursors present in the soil, particularly 6:2 FTAB, which was detected at a high concentration (2,560 $\mu g.kg^{-1}$). This compound could either be directly transformed into short-chain PFCA or first converted into 6:2 FTS. In the latter case, if the transformation of 6:2 FTAB into 6:2 FTS occurred at a rate comparable to that ofthe subsequent transformation of 6:2 FTS into PFCA, 6:2 FTS concentrations may remain relatively stable despite an active transformation dynamic. Ongoing analyses will allow these hypotheses to be confirmed or ruled out and will help clarify the transformation pathways involved.

For long-chain PFCA, particularly PFNA (C9) and PFDA (C10), solution concentrations also evolved over time. In the presence of the bacterial inhibitor, an increase of approximately 1.7-fold was observed until 175 days of soil-solution contact, relative to the initially released concentration, after which concentrations stabilized. In the absence of the bacterial inhibitor, concentrations measured after 1 year of experimentation were markedly higher, reaching approximately four times the initially released concentrations. Two hypotheses may explain this trend. First, the results show that the solution concentration of these compounds did not correspond to the complete transfer into solution of the initial mass present in the soil after 1 year of experimentation. Therefore, although our previous work showed that release equilibrium was reached under shaking conditions within less than 3 days, the extended contact time over 1 year used in the degradation experiments may have led to additional release of these compounds, explaining the increase in their solution concentrations over time. However, the behaviour of PFUnDA (C11) may support the hypothesis of biological transformation of long-chain PFCA into shorter-chain compounds. Indeed, PFUnDA was detected in the solutions in the presence of the bacterial inhibitor at concentrations close to the limit of quantification (10 $\mu g.L^{-1}$), whereas it was not detected in the absence of the bacterial inhibitor. This observation suggests possible degradation of the C11 compound into C9 and C10 compounds, which may contribute, at least partly, to the increase in their solution concentrations. However, at this stage, it is not possible to determine the relative contribution of this biodegradation mechanism to the overall increase in solution concentrations.

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Field Demonstrations of PFAS Destructive Treatment Using an Innovative UV-Based Technology

Demonstrations sur le terrain d’un traitement destructif des PFAS utilisant une technologie innovante à base d’UV

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Innovative Nature of the Proposed Topic:
Per- and polyfluoroalkyl substances (PFAS) are a large group of synthetic chemicals that have been used for decades in industrial processes and consumer products, including firefighting foams, nonstick coatings, stain repellents, and metal plating. PFAS share a common structural feature: a carbon chain with multiple fluorine atoms. This structure gives PFAS many useful properties such as resistance to heat, water, and oil. However, the same properties that make PFAS useful also make them difficult to remove from the environment. The carbon-fluorine bond in PFAS is one of the strongest bonds in organic chemistry. As a result, PFAS generally do not break down easily through natural biological, chemical, or physical processes. Many conventional remediation approaches that work well for petroleum hydrocarbons, chlorinated solvents, or other organic contaminants are ineffective at destroying PFAS.

An innovative technology has been developed to destroy PFAS by using hydrated electrons, highly effective reductants, produced in an ultraviolet (UV)/sulfite system. Laboratory tests have demonstrated close to 100% destruction of various PFAS classes can be achieved using this advanced reduction process. Haley & Aldrich scaled up this technology and designed and constructed a mobile and field-deployable treatment system, EradiFluor^{TM}, with research funding received from the U.S. Department of Defense (DoD)’ Environmental Security Technology Certification Program (ESTCP) and the U.S. Air Force Civil Engineering Center Broad Agency Announcement (AFCEC BAA) program.

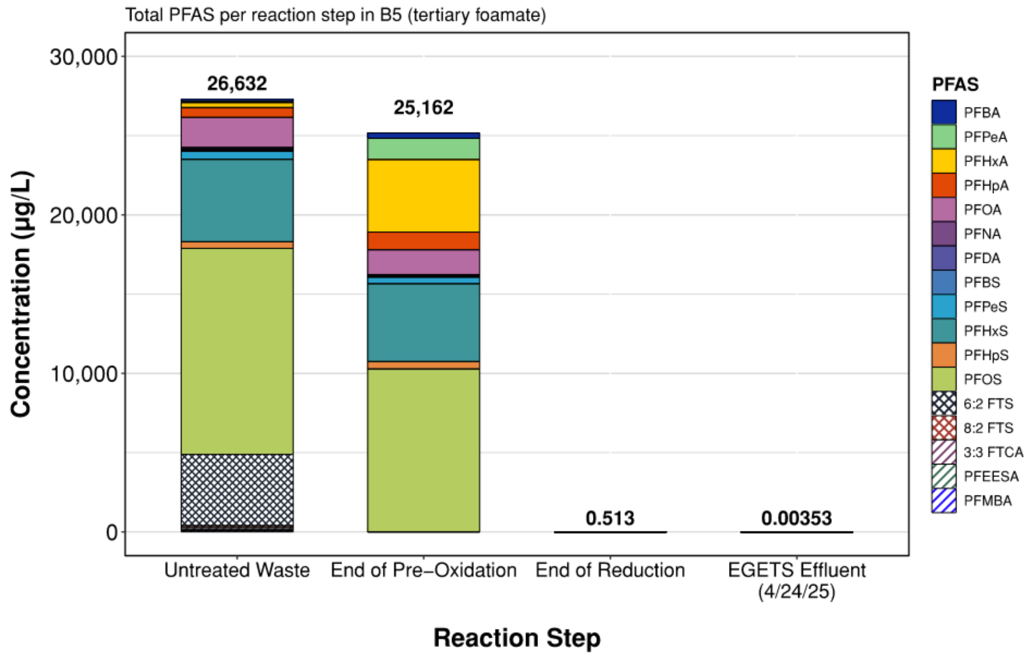
Two field demonstrations have been successfully completed that demonstrated the effectiveness of this technology in destroying PFAS. The first demonstration focused on PFAS destruction in a concentrated waste produced from an in-situ foam fractionation groundwater remediation system. The second demonstration project included a treatment train combining ex-situ foam fractionation for PFAS removal from groundwater and EradiFluor for destroying the high concentrations of PFAS in foam fractionate. Field test results showed that 1) EradiFluor is effective in degrading various classes of PFAS with near complete defluorination as demonstrated through many lines of evidence such as target PFAS analysis, fluorine mass balance, and total organic fluorine analysis; 2) it works for both long-, short-, and ultrashort-chain PFAS; 3) the system operates under ambient pressure and low temperature (less than 60°C) and therefore uses low energy and can be operated safely; 4) the treatment system uses “off-the-shelf” equipment which translates to low capital costs; 5) the system performs reliably with high operation uptime; and 6) closed-loop and zero-waste PFAS treatment can be achieved using a treatment train.

Table 1 shows that PFAS destruction percentage in both secondary and tertiary foamate during a field demonstration. Overall, the sum of target PFAS destruction was approximately 99.7 ± 0.2 percent (secondary foamate) and about 99.991 ± 0.007 percent (tertiary foamate), relative to initial concentrations.

Table 1. Average PFAS Destruction Percentages Observed During EradiFluor™ Treatment in Secondary and Tertiary Foamate

PFAS	Secondary Foamate	Tertiary Foamate
PFPeA	> 99.99	NA
PFHxA	> 99.99	99.998
PFHpA	> 99.98	99.996
PFOA	99.999	99.995
PFNA	99.997	99.99
PFBS	72	98
PFPeS	99	99.99
PFHxS	99.99	99.998
PFHpS	99.995	99.995
PFOS	99.997	99.996
6:2 FTS	99.99	99.999
8:2 FTS	>99.8	99.99

Figure 1 presents the PFAS concentration decrease and fluoride (i.e. final destruction product) concentration increase during the different steps of EradiFluor treatment and after a polishing step with an on-site granular activated carbon (EGETC) system.



Notes:
B = batch (e.g., B1 = Batch 1)

Figure 1. Target PFAS Analytical Results for Tertiary Foamate Treatment During the Destruction Treatment by EradiFluor.

Objectives:
This presentation aims to 1) provide a description of this innovative technology for PFAS destructive treatment; 2) present results of near-complete PFAS destruction using data from field applications; and 3) share lessons learned on the advantages and limitations of the technology based on laboratory studies and field applications.

Keywords: PFAS, treatment technology, water, destruction, ultraviolet, sulfite

Réhabilitation in-situ combiné des PFAS par pré-traitement microbiologique des Précurseurs et lavage bio-chimique des sols et aquifères

Combined in-situ Depollution of PFAS, via microbiological pre-treatment of Precursors and biochemical aquifer and soil washing

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Résumé

Actuellement, très peux des technologies de dépollution in-situ sont applicables aux pollutions par les PFAS dans les zones saturées et non saturées, à part du lavage via l'utilisation des ingrédients spécifiques comme les bio-polymères protéiniques ou les Béta-cyclodextrines. Les stratégies de dépollution mises en œuvre appliquent principalement des méthodes très coûteuses telles que l'excavation des sols pollués (& mise en décharge, lavage hors site et traitement thermique) ou le P&T (pump-and-treat) très coûteux en tant que technologie de dépollution hydraulique des eaux souterraines.

En raison de leur grande solubilité, de leur stabilité chimique, de leur mobilité dans l'environnement et de leur bioaccumulation, les substances alkylées poly- et perfluorées (PFAS) représentent une préoccupation importante en ce qui concerne leur impact potentiel sur l'environnement et la santé. Dans toute l'Europe (Belgique, France, Allemagne, Suisse, Italie et autres pays), de nombreux sites contaminés par des PFAS dans le sol, les eaux souterraines, les eaux de surface, etc. ont été identifiés, dont certains couvrent de vastes zones, comme la contamination de la couche arable de plus de 800 hectares dans la région de Rastatt (Baden-Württemberg, Allemagne), où des boues de compostage de papier et de stations d'épuration contenant des PFAS ont été utilisées comme fertilisants.

Des expériences montrent que certains PFAS, et notamment leurs précurseurs (PFAS polyfluorés) des types sulfobétaïnes et sulfonates, tels que le (N-)EtFOSA, le (N-EtFOSAA), les Capstones comme le 6:2-FTNO et le 6:2-FTAB, ou encore le 6:2-FTS (ou H4PFOS), sont très difficiles à lessiver des sols. En effet, sans l'application d'un pH fortement alcalin (pH > 9), la présence de minéraux argileux et de sesquioxydes empêche la désorption de ces PFAS. Cette situation change radicalement lors de la biotransformation ou de l'oxydation de ces molécules en PFAS per-fluorées finaux, tels que les acides perfluorosulfoniques et carboxyliques beaucoup plus solubles.

L'oxydation des substances polyfluoroalkylées (PFAS) est possible par voie chimique, par exemple au persulfate (F. KARG, 2024-2025), ou par prétraitement microbiologique utilisant des consortiums bactériens et les injections de l'air afin de garantir un environnement aérobie dans le sous-sol (sols et aquifères). L'avantage de la pré-oxydation chimique au persulfate réside dans sa rapidité d'application, mais son utilisation est parfois interdite en raison de risques de toxicité. La pré-oxydation microbiologique (Fig. 1) présente l'avantage d'une mise en œuvre relativement simple par percolation ou injection d'un consortium bactérien associé à une injection d'air, le Bio-Air-Sparging (BAS). Son inconvénient est sa durée, d'environ 6 à 12 semaines lorsque la teneur en argile est inférieure à 50 %. Par la suite, un lavage utilisant des biopolymères protéiques, des PFAS perfluorés crées, beaucoup plus solubles, est possible dans un circuit de régénération des lixiviats de lavage pour la séparation et l'élimination des PFAS (voir Fig. 5, F. KARG, 2024-2025).

Des expériences montrent qu'en l'absence de dégradation microbiologique aérobie, des précurseurs tels que le 6:2-FTAB, l'EtFOSAA, le 6:2-FTS, etc., peuvent persister à plus de 70 % des concentrations de PFAS dans les sols et les eaux souterraines pendant plus de 35 ans (F. Karg, 2024-2025). Pour cette raison une pré-oxydation préalable vers les PFAS per-fluorés plus solubles est nécessaire. Les Fig. 1a-c montrent les dispositifs de lavage in-situ sur un site à pollution AFFF.

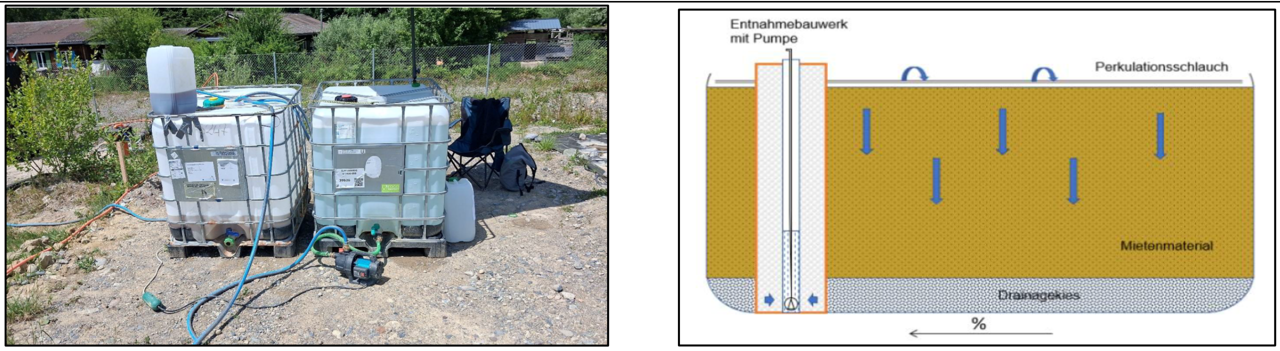

Fig. 1a : Dispositifs de lavage in-situ sur un site à pollution AFFF (réalisé par HPC & Sensatec).

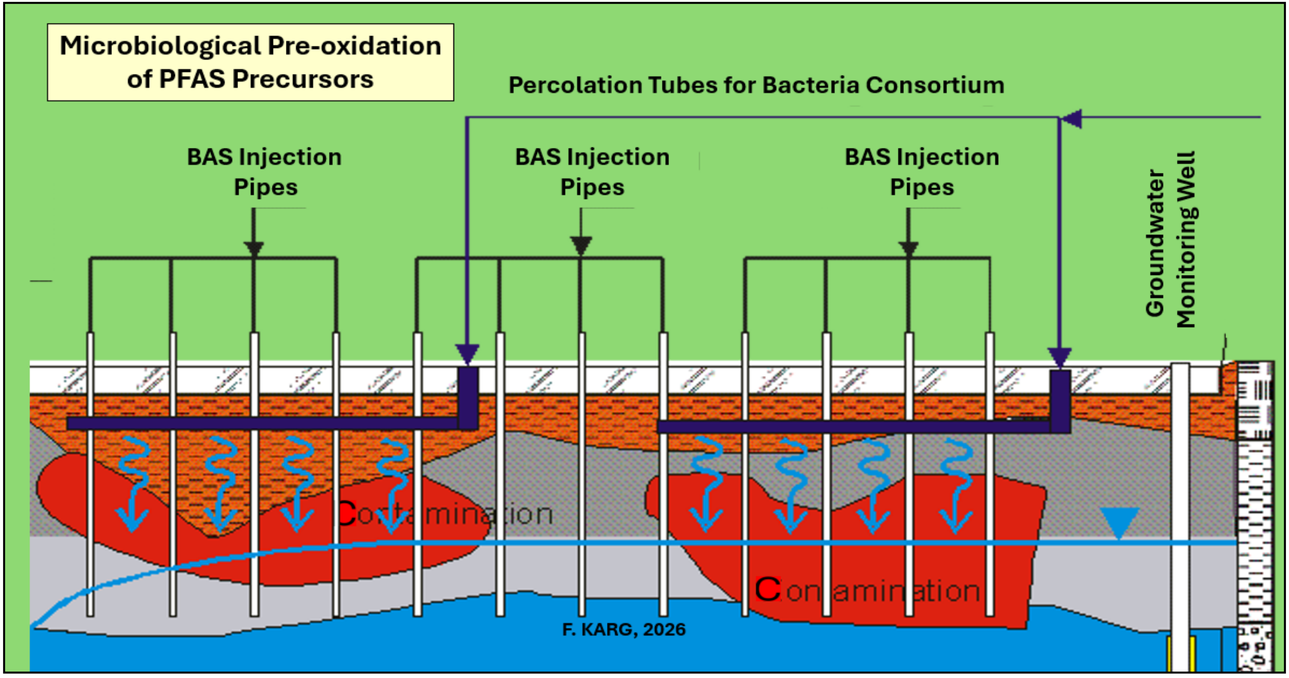

Fig. 1a. Pré-oxydation Microbiologique des Précurseurs PFAS du type 6 :2-FTAB, 6 :2-FTS, EtFOSA …

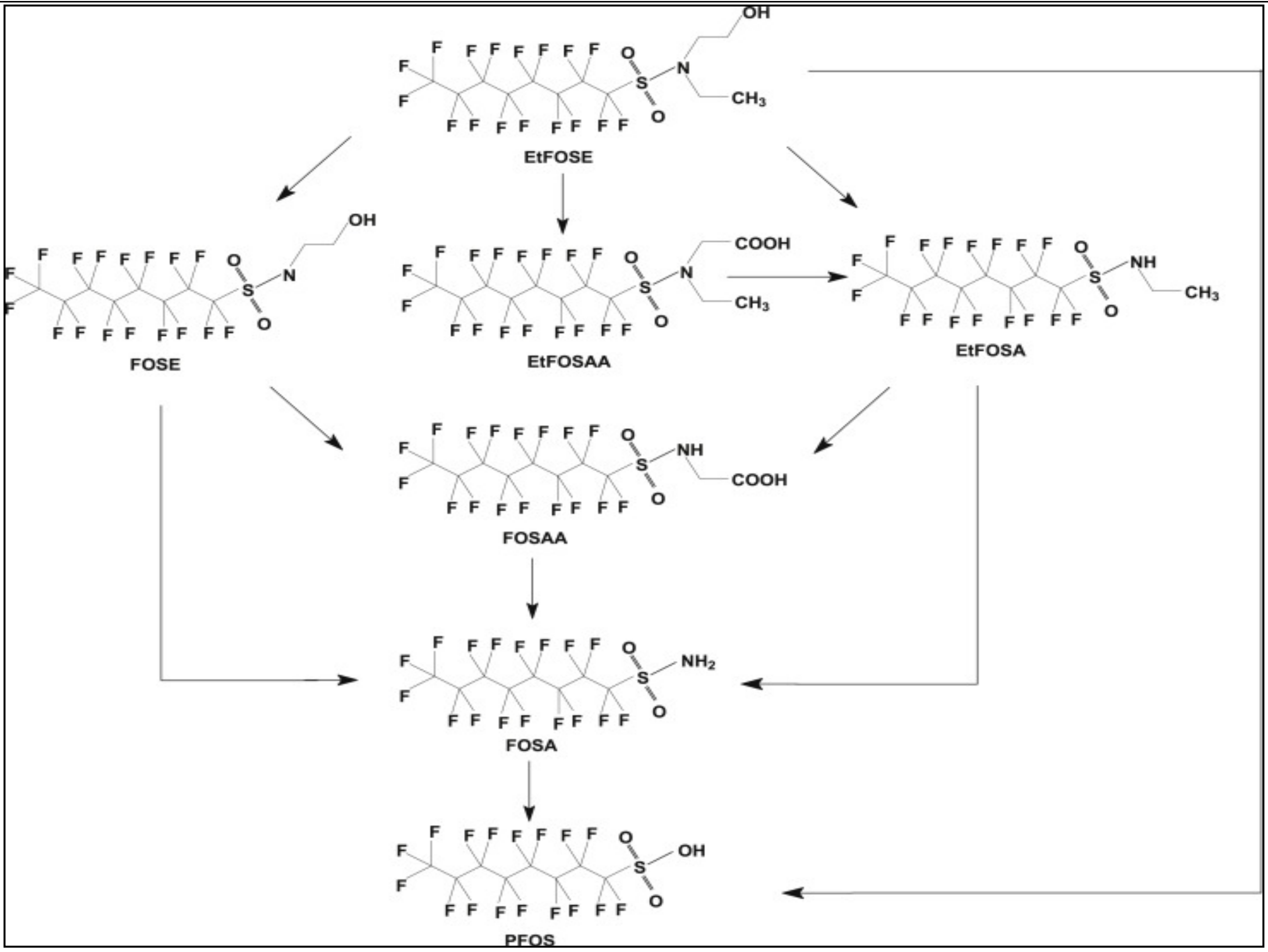

Fig. 2 : Biotransformation des Précurseurs poly-fluorés EtFOSE, EtFOSAA, FOSE, EtFOSA et FOSAA er FOSA vers le PFOS (S. Chen et al. 2021).

Après la pré-oxydation microbiologique des PFAS poly-fluorés (précurseurs), voir figures 2 et 3, par exemple le 6:2-FTAB, le 6:2-FTS et le 6:2-FTOH, en PFBA, PFPrA, PFPeA et PFHxA, beaucoup plus solubles, ou de l'EtFOSAA en PFOS, le lavage in situ (ou ex situ) des sols contaminés par les PFAS est parfaitement possible, par ex. via des consortiums des bactéries : Acidimicrobium sp. Strain A6, Acidimicrobium sp. Strain A6 et/ou Pseudomonas strain SYC ou Rhodococcus jostii RHA1 et Pseudomonas oleovorans, etc.

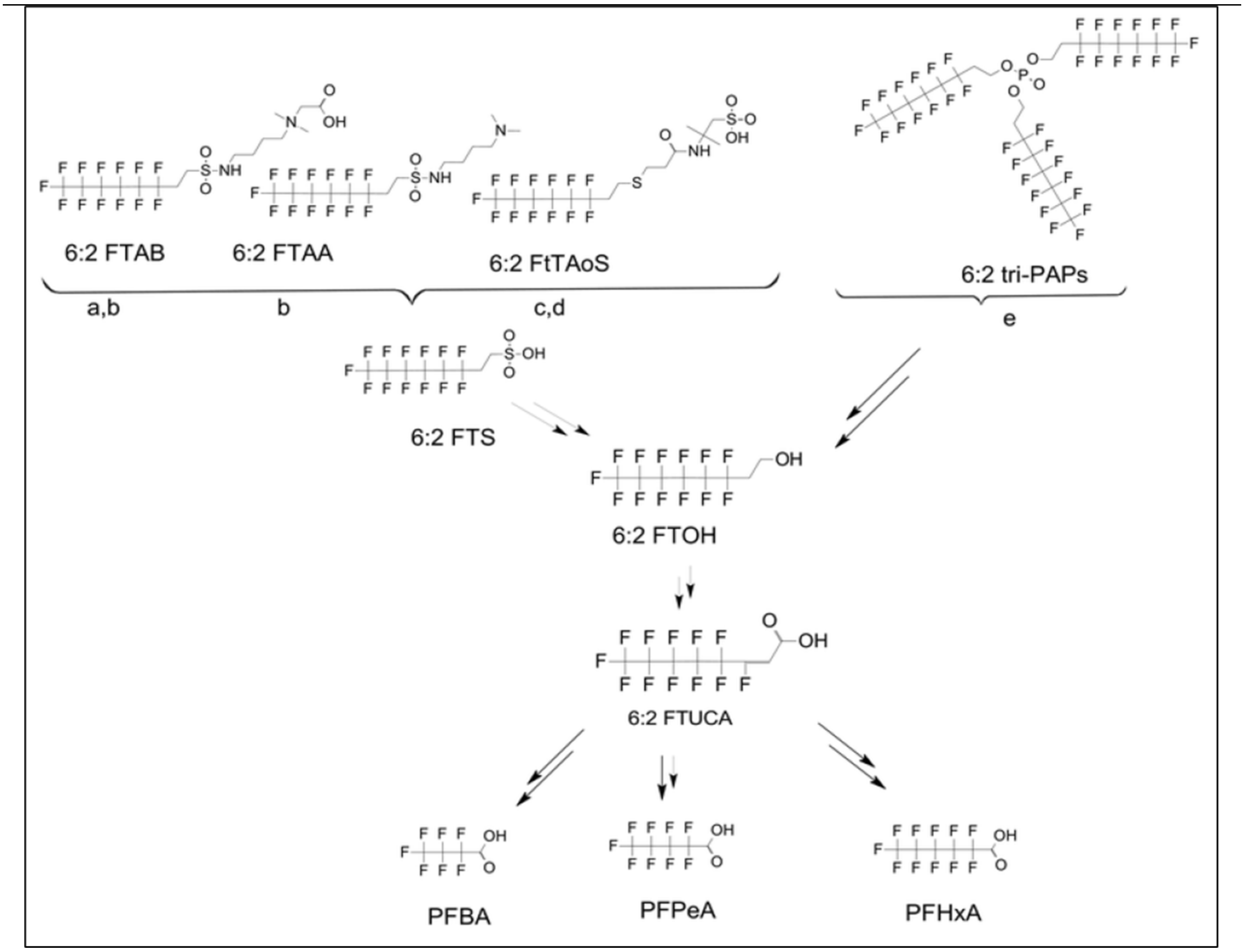

Fig. 3 : Biotransformation des précurseurs poly-fluorés 6 :2-FTAB, 6 :2-FTS, 6:2-FTOH ves les PFCA plus solubles ; PFBA, PFPeA et PFHxA (LaFond et al. 2023, D.M.J. Shaw et al. 2019 ,Ying Shi, 2018 et V. Mendeza et. al. 2022).

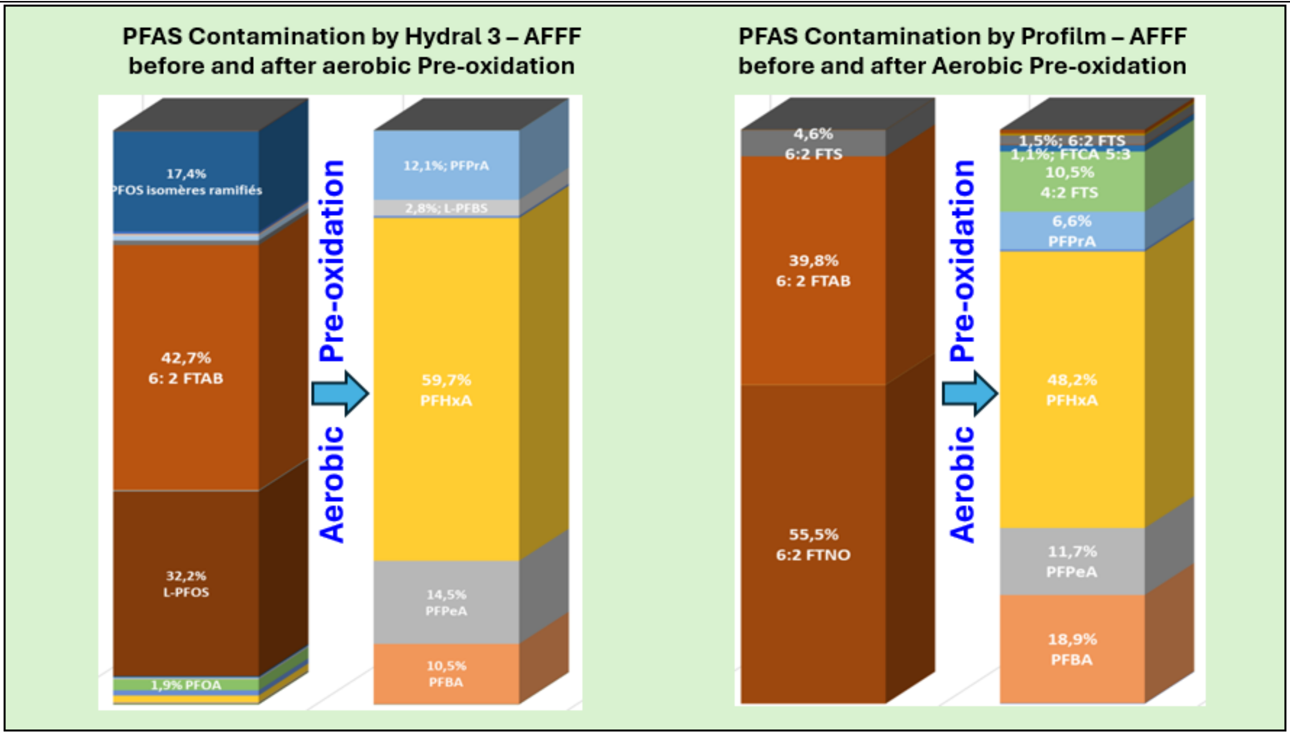

Fig. 4. : Biotransformation des précurseurs poly-fluorés 6 :2-FTAB et 6 :2-FTNO ves les PFCA plus solubles ; PFBA, PFPrA, PFPeA et PFHxA via 6 semaines d'oxydation microbiologique aérobie.

L'objectif des traitements par lavage in-situ des zones non-saturées et saturés (aquifères) après la pré-oxydation microbiologique (ou chimique) est d'appliquer un traitement alternatif de réhabilitation in-situ et sur site des PFAS des zones saturées et non saturées et des sols excavés, en utilisant un processus de lavage avec des composés de bio-polymères protéiniques biodégradables et des bêta-cyclodextrines (cf. Fig. 4). Les ingrédients biopolymères tensioactifs spécialement développés sont utilisés pour séparer correctement les PFAS du sol.

Le lixiviat de lavage a également une action positive sur les eaux souterraines et est ensuite pompé de l'aquifère au moyen d'un système de lavage hydraulique (cf. Fig. 4).

Cette technologie permet l'extraction in-situ et/ou sur place et l'élimination ultérieure des PFAS monomères dans les sols superficiels et profonds sans recourir à des méthodes destructrices telles que l'excavation. Cette approche ne nécessite pas la séparation des différentes fractions granulométriques du sol.

Au cours de la mise au point du processus, l'efficacité de cette approche technique de dépollution est d'abord testée par une étude de faisabilité en laboratoire, puis par une application pilote sur le terrain, suite à la pré-oxydation. La première étape consiste à effectuer des essais à petite échelle sur des colonnes bio-lysimètres de percolation de sol, puis dans les colonnes d'élution de sol et, après quelques semaines (3 à 4), dans le cadre d'une application pilote sur le terrain.

Les acides carboxyliques perfluorés à chaîne courte (comme le PFBA, le PFPeA, etc.) peuvent être lessivés de des sols en utilisant simplement de l'eau comme ingrédient de lavage. Les acides carboxyliques à chaîne plus longue > C8 (PFOA, PFNA, PFDA, PFUnDA, etc.) et les acides sulfoniques (PFOS, PFNS, etc.) sont moins mobiles. La technologie de lavage avec des bio-polymères protéiniques prouve clairement que ces composés peuvent être mobilisés au moyen des biotensides spécialement développés. Des tests lysimétriques ont montré qu'une réduction de 99,9 % de la concentration en PFAS dans le sol est obtenue en appliquant la nouvelle technologie développée. Des applications sur le terrain ont permis de réduire les concentrations de PFAS de plus de 80 % en l'espace de trois semaines.

En comparaison avec l'analyse coût-avantage, les traitements de lavage in situ sont environ 30 fois moins chers que les excavations ou le P&T : Pump and Treat. La technologie est également applicable aux PFAS volatiles, comme les FTOH (alcools fluorotélomères, etc.).

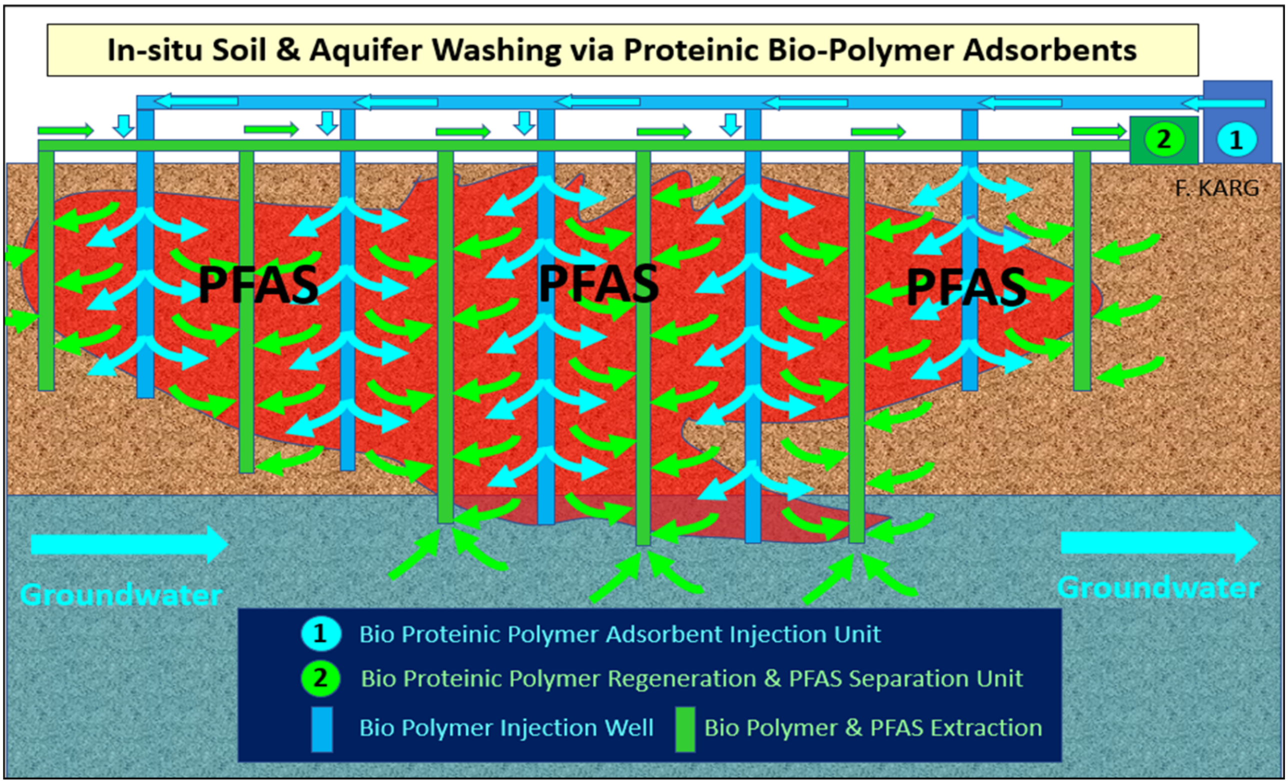

Fig. 5 : Lavage du sol in situ pour la décontamination des PFAS avec des bio-polymères protéiques ou les bêta-cyclodextrines (F. KARG 2024 – 2026).

Le processus développé offre la possibilité de traiter les sols contenant des PFAS in situ dans la zone saturée et non saturée en mobilisant les PFAS et en traitant ensuite les eaux souterraines à l'aide d'une technologie de pointe. Une autre application possible de la méthode développée qui est actuellement appliquée sur le terrain est le traitement ex-situ des sols excavés contenant des PFAS (sur site et hors site) en utilisant les biopolymères protéiniques par lavage dans une technologie cyclique.

Les objectifs de traitement du lavage in situ visent à garantir la conformité des lixiviats et des conditions sanitaires, conformément aux objectifs d'un Plan de Gestion et des CMA (Concentrations Admissibles Maximales) d'une EQRS ou d'une ARR préventive ou prédictive, afin d'assurer la conformité sanitaire, pour une utilisation future du site.

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Removal of short- and long-chain PFAS compounds using a multi-regenerable ion-exchange resin with charge-switching technology

Speaker:
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Abstract:

The contamination of drinking water and groundwater sources by per- and polyfluoroalkyl substances (PFAS) has received increasing attention in recent years. In several regions worldwide, PFAS concentrations significantly exceed the limits established by international regulations. Although more than 15,000 types of PFAS have been identified, the most extensively studied compounds such as PFOA (perfluorooctanoic acid) and PFOS (perfluorooctane sulfonic acid) have been linked to serious health issues, including liver damage, cancer, and thyroid disease. This environmental problem has reached alarming levels because PFAS compounds have been used for decades in thousands of industrial and consumer products without prior regulations.

The growing effort to develop PFAS remediation technologies highlights the urgent need for effective removal approaches. Currently, the most widely used technologies for PFAS removal include granular activated carbon (GAC), nanofiltration membranes, foam fractionation, and ion-exchange (IX) resins. Although IX resins are among the most effective methods for removing various types of PFAS, several challenges remain, such as their single-use nature, the reliance on organic solvents or high salt concentrations for regeneration, and their limited effectiveness in removing short- and ultra-short-chain PFAS.

In this context, this study presents a potential alternative to address these challenges by evaluating the performance of AmphoRes™, a multi-regenerable, charge-switchable ion-exchange resin. This work is presented as a case study assessing the feasibility of using AmphoRes™ through rapid small-scale column tests (RSSCTs) conducted under simulated conditions with real groundwater provided by the Orange County Water District (OCWD, California, USA) and other cases.

The groundwater provided by OCWD was fully characterized using liquid chromatography–tandem mass spectrometry (LC-MS/MS) to determine the concentrations of four main PFAS compounds considered in this study: perfluorooctanoic acid (PFOA), perfluoropentanoic acid (PFPeA), perfluorobutane sulfonic acid (PFBS), and perfluorobutyric acid (PFBA). In addition, total organic carbon (TOC), dissolved organic carbon (DOC), and both heavy and non-heavy metals were analyzed.

The RSSCT results demonstrated successful PFAS adsorption after six regeneration cycles using acidic and basic regenerants HCl adjusted to pH ≈ 2 and NaOH adjusted to pH ≈ 11 to promote PFAS desorption and resin cleaning. The 50 % breakthrough of cumulative bed volumes (BV_{50}) reached approximately 473,000 BV_{50} for PFOA (long-chain), 443,000 BV_{50} for PFBS, 256,000 BV_{50} for PFBA, and 273,000 BV_{50} for PFPeA (short-chain). Moreover, AmphoRes™ exhibited strong affinity for certain heavy metals, including Fe, Mn, Al, Cr, and Co, but low affinity for monovalent and divalent ions such as Na^+, K^+, Ca^{2+}, and Mg^{2+}. The

regeneration solution contains around 0.1-10 ppm PFAS at pH 11. This is a great match with PFAS destruction technologies.

These findings and the current pilot studies highlight the effectiveness of charge-switching technology in achieving controlled cycles of PFAS adsorption and desorption. The regeneration strategy relies on limited volumes of dilute alkaline or acidic solutions, avoiding the use of organic solvents and highly concentrated salt brines. Furthermore, AmphoRes™ demonstrated promising suitability for combined PFAS and heavy metal removal, supporting its consideration for future groundwater treatment applications, while underscoring the need for additional pilot-scale evaluations under varied water quality conditions.

PFAS Treatment with Ion Exchange: Worldwide compliance to Everchanging Regulations

Summary:

PFAS maximum contamination levels have been in place in the US for over a year now though the implementation timeline has stretched out. The EU Drinking Water Directive has only recently come into its enforceable time period. The regulatory strategies have been different around the world. In this talk, we will discuss how the US has embraced single use ion exchange resin for treatment of the US regulated PFAS compounds. We will discuss our work on short chain PFAS treatment to meet these slightly different regulations in Europe.

Keywords:

Regulations, Ion Exchange Treatment, Compliance, Short Chain, TFA

Abstract:

Per- and polyfluoroalkyl substances (PFAS) are persistent environmental contaminants that pose significant challenges for water treatment, particularly due to the mobility and resistance to degradation exhibited by short-chain PFAS compounds. Ion exchange (IX) technology has emerged as an effective and economical approach for PFAS remediation, offering high selectivity and the advantage of media regeneration.

We will start with how the United States has been implementing IX for compliance to the Federal US EPA maximum contaminant levels with single-use resin. Next, to meet European regulations, we will pivot to how the combination of single-use and regenerable resin reduces the cost of treatment while improving the efficacy.

This work presents recent advances in the application of regenerable ion exchange resins specifically designed for the removal of short-chain PFAS from contaminated water sources. We will focus on evaluating the performance and regeneration efficiency of IX resins, comparing their adsorption capacities, kinetics, and selectivity for various short-chain PFAS under environmentally relevant conditions.

Through modeling and pilot-scale experiments, we demonstrate that the selected regenerable IX resins achieve removal of PFAS, with protocols that minimize secondary waste generation. These findings highlight the potential for scalable, cost-effective, and sustainable PFAS management strategies that address both long- and short-chain compounds, advancing the practical implementation of ion exchange technologies in drinking water and wastewater treatment applications.

Presenter

Cathy Swanson, Director of Business Development, Emerging Markets with Purolite™ Resins, Ecolab

Biography

Based in Southern California, Cathy has specialized in treatment with ion exchange for 18 years. She serves as Vice Chair of the AWWA Ion Exchange Committee Meeting and co-chair of its Subcommittee standard for single-use resins including PFAS, perchlorate, and chrome VI which was published Feb 2025, and a regenerable resins standard to be that is in the works. Her project portfolio includes both remediation and drinking water sites. She received her BS in Chemical Engineering at Northwestern University in the Chicago area and her MBA from UNC Chapel Hill.

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MODULAR TREATMENT SOLUTIONS FOR THE ELIMINATION OF SHORT- AND ULTRA-SHORT-CHAIN PFAS FROM INDUSTRIAL WASTEWATER AND GROUNDWATER

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Per- and polyfluoroalkyl substances (PFAS) are persistent man-made fluorinated chemicals valued for their heat-, water-, grease-, and oil-resistant properties, making them widely used in industrial processes and consumer products[1]. Their strong carbon-fluorine bond resists natural degradation, leading to widespread environmental accumulation[2,3]. Human exposure to some PFAS is linked to health impacts on the thyroid, immune system, and more[4]. Short- and ultra-short-chain PFAS (≤C7) present a particular treatment challenge: their small size, high mobility, and weak sorption affinity allow them to migrate far from contamination sources and evade conventional removal technologies[5]. Compounds such as Trifluoroacetic acid (TFA) are now being detected at high environmental concentrations[6,7], and expanding regulatory frameworks are creating an urgent need for effective treatment solutions.

The aim of this study was to design a treatment approach that proves to efficiently degrade and defluorinate short- and ultra-short-chain PFAS from industrial wastewater and contaminated groundwater.

To achieve this, a modular treatment approach has been created, which combines separation and destruction. The destructive step employs photochemical reduction, in which mediator chemicals are activated by UV light to permanently degrade and defluorinate target PFAS. Where applicable, upstream separation technologies such as nanofiltration are integrated to concentrate the PFAS stream, improve treatment performance, and reduce overall energy demand.

Laboratory results demonstrate >99% degradation of TFA in industrial wastewater and >99% removal of PFBA in contaminated groundwater using the combined nanofiltration and photochemical reduction system. In addition, an on-site pilot demonstrated degradation and defluorination of an ultra-short-chain C3 PFAS under real industrial conditions. These findings offer a promising pathway to close a critical and growing treatment gap for short- and ultra-short-chain PFAS.

Keywords: Environmental compliance, groundwater remediation, industrial water treatment, PFAS, wastewater treatment

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Surfactant Enhanced PFAS Aquifer Remediation and Decontamination of AFFF Fire Suppression Systems

Dr. David Holmes (Geosyntec Consultants Ltd, UK), Dr. Cecilia Macleod (University of Greenwich, UK), Scott Poynor (Geologic Science and Technology), and George A. Ivey (Ivey International Inc.)

ABSTRACT

PFAS removal from aquifers typically relies on groundwater pump and treat (P&T) methods, using filtration, granular activated carbon, or ion-exchange resins. P&T is often slow and less effective due to contaminant sorption, low hydraulic conductivity, and low PFAS concentrations. While in-situ injections of granular sorbents shows potential, they are stoichiometrically limited by the physical restrictive volumes that can be injected into the subsurface, relative to the PFAS mass requiring containment.

Surfactant enhanced recovery (SER) removes PFAS from source zones more rapidly and cost-effectively than P&T or sorbent products alone. This observation was based on a multi-year University study that examined specialized surfactants that were improving PFAS mass removal efficiency. The study involved a series of large soil-column (75cm heigh by 14cm diameter) tests to evaluate the efficacy of novel-surfactants to enhance PFOS and PFAS (C4 to C12) concentrations in aqueous phases, during simulated soil-aquifer flushing. These experiments were performed at the University of Greenwich, UK~~.~~ Following each test, the columns were deconstructed for moisture profiling, and soil sampling to assess residual PFAS retention.

The experiments also evaluated the impact of solvent-enhanced extraction and surfactant-enhanced recovery, as well as the mass of PFOA and PFOS retained by the column soils after drainage tests. The inclusion of surfactants was shown to reduce the soil moisture content, thereby facilitating increased water drainage, and greater PFAS mass removal in the affected soil layers.

Comparatively, recent surfactant-enhanced decontamination of AFFF fire suppression systems indicated significantly greater PFAS mass reductions compared to conventional Federal Aviation Administration (FAA) water or solvent flushing methods alone. This approach could lower the risk of residual PFAS cross-contamination of new non-PFAS replacement products.

During the decontamination of AFFF fire suppression systems, using conventional FAA water flushing, this removed >90% of PFAS, but left significant residue PFAS. While the use of dilute surfactant (1% to ≤5%) was then circulated, under pressure (60 psi) and temperature (40°C), to achieve significantly higher PFAS mass removal, as verified by surface swab tests and time-based effluent sampling. Further, the laboratory EPA Method 1633 analyses was enhanced with carbon-13 labeled standards for improved sensitivity and reliability of the PFAS (C4 to C12) results.

SER consistently increased PFAS mass removal for aquifer soils by over 200% to 600% per flushing compared to water alone, providing a reliable a cost-effective method for in-situ soil and aquifer remediation.

Ex-situ surfactant-enhanced decontamination of the AFFF fire suppression system removed 99.99998% of PFAS, preventing expensive system disposal and risk of residual PFAS cross-contaminating of new fire suppression products introduced, providing a more reliable cost-effective option to the FAA method.

From concentration to flux: integrated analytical, monitoring and remediation strategies for sustainable PFAS management in soil and groundwater

De la concentration au flux : stratégies intégrées d'analyse, de suivi et de remédiation pour une gestion durable des PFAS dans les sols et les eaux souterraines

Authors : Erik Bosmans (iFLUX), Marjan Joris (iFLUX), Pieter Joos (SGS), Jan De Vos (ABO-group)

Innovative nature of the proposed topic

The proposed contribution results from the LIFE project CAPTURE PFAS (https://www.life-capture-pfas.com), a collaboration of 8 partners, funded by the European LIFE program. It presents an integrated and operational framework for PFAS management that moves beyond conventional concentration-based assessment. Its novelty lies in the combination of a tiered analytical protocol, flux-based groundwater monitoring, innovative remediation technology trains and a pragmatic risk assessment approach that explicitly addresses PFAS mixtures and unknown compounds. By linking characterisation, exposure and mitigation, the approach improves decision-making efficiency and supports more sustainable remediation strategies compared with current practice.

Keywords

PFAS, soil and groundwater, flux-based monitoring, passive samplers, remediation technologies, risk assessment, LIFE project

Objectives

The main objective is to demonstrate, through concrete use cases, how integrated analytical protocols, flux measurements and innovative remediation technologies can improve the sustainable management of PFAS-contaminated soil and groundwater. Specific objectives are to

- broaden PFAS characterisation beyond target lists,
- improve exposure and risk assessment through flux-based monitoring,
- optimise remediation efficiency using tailored technology trains, and
- support regulators and site owners with pragmatic, science-based decision tools.

Novelty and improvement over existing practice

A key innovation is the development of a robust, tiered analytical protocol, called PFASafe® that starts with total PFAS screening (AOF/EOF), progresses to expanded LC-MS/MS target analysis including short- and ultra-short-chain PFAS, and integrates suspect screening to identify unknown or emerging compounds. PFASafe® is like a menu chart, where the customer can choose which analyses are appropriate to his/her problem. This approach significantly improves upon current analytical practices that focus on a narrow PFAS subset.

In parallel, the project introduces flux-based monitoring using passive groundwater samplers, known as iFLUX Samplers, with new resins, achieving detection limits an order of magnitude lower than existing systems. Flux measurements provide direct insight into PFAS mass transport, enabling better exposure assessment and more targeted remediation design than concentration-only data.

Technical, economic, environmental and social context

From a technical perspective, the project combines advanced analytics, monitoring and remediation technologies into coherent workflows applicable at contaminated sites. Economically, flux-based monitoring and improved source characterisation reduce uncertainty and help avoid over- or under-design of remediation systems, thereby lowering long-term costs. Environmentally, the focus on sustainable treatment trains, such as foam fractionation for soils and advanced oxidation processes for water, aims to minimise secondary waste and energy use. Socially and regulatorily, the project addresses growing public concern and tightening EU standards by providing transparent, defensible tools for risk-based decision-making.

Prospects and justification

Laboratory validation and pilot-site preparation demonstrate that the proposed methods are technically feasible and scalable. Field demonstrations are implemented and will further substantiate performance under real conditions. The strong involvement of industrial and consultancy partners ensures a clear pathway towards replication and market uptake. The integrated framework therefore offers a justified and realistic prospect for improving PFAS management across Europe, supporting regulators, site owners and communities with more reliable data and more sustainable solutions.

Anticipation strategies for drinking water authorities facing PFAS risks

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Technical abstract

The management of PFAS in drinking water supply in France is taking place in a context of highly variable water resources—approximately 33,000 abstraction points—and strict public service continuity requirements. The regulatory framework is evolving rapidly, with a threshold of 100 ng/L for the sum of 20 PFAS and a target value of 20 ng/L for 4 PFAS, supplemented by guideline values for TFA and 6:2 FTSA. Beyond 2027, monitoring is expected to rely on a combination of long-term, exploratory, and localized schemes, within a regulatory framework likely to evolve through regular updates of the list of monitored substances.

National exploratory monitoring campaigns conducted between 2023 and 2025 identified around fifty local authorities with significant PFAS concentrations in distributed water, mainly in the Grand Est and Auvergne-Rhône-Alpes regions. The extension of monitoring since 2026 suggests a likely increase in the number of affected territories. Detailed analysis of two water sources also highlights strong temporal variability in concentrations, a distribution between intermediate-, short-, and ultra-short-chain PFAS, and the presence of TFA at concentrations in the range of 0.5 to 1 µg/L.

The current state of the art highlights mature technologies (TRL 9)—including activated carbon adsorption, membrane filtration, and ion exchange resins—as well as emerging processes. Activated carbon shows good overall performance, except for ultra-short-chain PFAS and TFA. Membrane processes achieve high removal efficiencies for all PFAS, including TFA, but generate significant concentrate streams and involve high energy consumption. Ion exchange resins also provide effective removal, provided that compatibility with the raw water matrix is ensured.

The operational strategy is based on a three-horizon approach. In the short term, priority is given to resource characterization (regulated and non-regulated PFAS, water matrix) and the implementation of hydraulic solutions (substitution, blending, hydraulic barriers). While these solutions may achieve compliance targets, they remain temporary due to their impact on the robustness of the drinking water supply system. In parallel, temporary treatment solutions—particularly granular activated carbon using mobile filtration units—are deployed. A methodology for assessing PFAS removal performance, based on extrapolation of data from existing full-scale installations or pilot studies, supports the sizing and treatment rates of these temporary systems.

Pilot testing is a key step to consolidate performance data, compare treatment options (GAC, µGAC, resins, membranes, or combinations thereof), and secure the design of permanent facilities.

In the medium term, the implementation of permanent treatment facilities relies on the development of scenarios incorporating several key parameters: average and peak flows, raw water quality (acceptable concentration levels), regulatory targets, and operational time

constraints. The main options considered include activated carbon (granular or micro-granular), ion exchange resins, and membrane processes.

In the long term, the objective is to anticipate stricter regulatory requirements by designing adaptable facilities: sizing based on more stringent criteria, allowing for future integration of additional treatment steps, securing land availability, and maintaining capacity margins. The example of SEDIF illustrates this approach, with the deployment of a membrane-based treatment train combining nanofiltration and low-pressure reverse osmosis, supported by long-term pilot operations.

All these elements lead to a progressive and structured strategy combining hydraulic adaptation, temporary treatment, pilot testing, and the deployment of scalable long-term solutions.

Removal and Complete Destruction of PFAS on Activated Carbon: Results from Measurement Campaigns and Industrial Validation

Élimination et destruction complète des PFAS sur charbon actif: Résultats des campagnes de mesure et validation industrielle

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Innovative Nature of the Proposed Topic:

- A pioneering analytical method for determining PFAS adsorbed on activated carbon
- An industrial-scale approach for complete PFAS destruction (>99.97% DRE) through thermal reactivation and flue gas treatment.
- Confirmation across multiple measurement campaigns on different furnace types, ensuring robustness and reproducibility.
- Regulatory integration aligned with POP requirements and upcoming European standards.

Objectives:

- Demonstrate the effectiveness of thermal reactivation in removing and destroying PFAS adsorbed on activated carbon.
- Validate compliance with POP regulation and future European requirements.
- Present results from measurement campaigns across different furnace types and process streams.
- Explain the innovative methodology for PFAS analysis on activated carbon and the construction of PFAS and fluorine mass balances.
- Confirm the robustness of the process and its positive environmental impact.

Keywords: PFAS, activated carbon, thermal reactivation, complete destruction, DRE, POP, mineralization, fluorine, flue gas treatment, regulatory compliance.

Speaker: Ir. Lowie Bolle, R&D Project Lead, DESOTEC

Abstract:

PFAS are found in wastewater, exhaust gases, and solid waste of many industry sectors like chemical manufacturing and waste treatment. Although EU regulations such as the Industrial Emissions Directive (IED) and the Waste Framework Directive address PFAS, standardized emission limits are still under development. DESOTEC, a Belgium-based environmental services company, has developed relevant expertise in PFAS removal and destruction through its mobile activated carbon systems and industrial reactivation processes.

Once PFAS are adsorbed onto activated carbon, the spent carbon is thermally re-activated at 850 °C whereby PFAS oxidise and mineralise into CO_2, HF, SO_2 etc. In this context, Desotec wanted to understand the fate of PFAS in its reactivation process and has done a series of measurements to understand:

- Removal efficiency: the percentage to which the process removes PFAS from the waste stream.
- Destruction efficiency: the percentage to which the process and flue gas treatment effectively eliminates or destroys PFAS introduced into the system via the waste stream.

- Mineralization efficiency: the percentage to which the reactivation process and flue gas treatment converts PFAS in general to inorganic fluorine

The destruction and removal efficiency (DRE) is calculated based on mass flow and concentration data from various points in the industrial system. In the study, a DRE of over 99.97 % was achieved. No HF was detected in the stack emissions, but fluoride was found in the scrubber water, indicating successful mineralisation. A fluorine mass balance confirmed 96 % closure, validating the effectiveness of the process and measurement methodology.

Importantly, the extended study was confirmed during multiple distributed measurement campaigns across different reactivation furnace types, carbon types and process parameters, further demonstrating the robustness and reproducibility of the process.

In conclusion, mobile activated carbon systems combined with industrial-scale reactivation offer a robust, cost-effective, and environmentally sound solution for PFAS removal and destruction. This approach aligns with emerging regulatory requirements and provides a scalable method for managing PFAS emissions across various industrial sectors.

Evaluation of the efficiency of a two-stage reverse osmosis (RO) system for trifluoroacetic acid retention applied to industrial wastewater treatment

Semi-industrial scale case study

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Often called “perpetual pollutants,” per- and polyfluoroalkyl substances (PFAS) are persistent compounds, and their removal by conventional technologies (biological processes and adsorption onto activated carbon) remains limited.
Reverse osmosis (RO), is a proven technology in the surface water and groundwater treatment sectors, appears promising for PFAS retention. Among these, trifluoroacetic acid (TFA), an ultra-short-chain PFAS, presents a particular challenge due to its low molar mass, high hydrophilicity, and sometimes significant concentration in industrial effluents.

During the summer of 2025, Veolia Hazardous Waste Europe conducted semi-industrial-scale trials at the SOTREMO hazardous waste treatment site in Le Mans (France), to evaluate the effectiveness of reverse osmosis (RO) in retaining TFA.
The build-up of the unit includes 3 reverse osmosis stages in series. During the tests only two of them were used. The installation was fed with the site's general effluent supplemented with increasing amounts of TFA at concentrations ranging from 10 to 65,900 µg/L. The unit was equipped with FilmTec™ SW30HRLE-370/34i membranes and operated in feed-and-bleed mode with a feed rate of 3.0 m^3/h and an overall recovery rate of 84%.

The results obtained show excellent retention capacity of the RO unit with an average overall removal rate of 99.2 ± 0.7%. The transmission rate to the first stage of 1.4 ± 0.2%, confirms the independence of the retention mechanism from the TFA content at the RO inlet. The use of a third stage would allow a removal rate up to 99.9% or higher.

This study confirmS the potential of the RO technology for the treatment of effluents with high or even very high TFA concentrations. The results demonstrate the RO’s capacities for treating TFA contaminated hazardous waste, whether in a direct treatment stream or as a finishing treatment.

PFAS: Significant progress in industrial wastewater and sludge management in response to the global environmental challenge

Delphine Steinmann, Research and Development Engineer - Suez (France)

Delphine Steinmann[1], Naike Noyon[1], Olivier Danel [1], Anne Lise Ravaud[1], Priscilla Pareuil[2], Cléa Barbier[2], Marina Moura Lima[2], Anne Réguer[2], Mélanie Lemunier[2], Pierre Emmanuel Pardo[3], Safwan Al Ayoubi[3], Sid Ahmed Kessas[3], Hugues Vanden Bossche[3]

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KEYWORDS: PFAS, industrial water treatment, sludge, separation processes, destruction processes

CONTEXT AND OBJECTIVES

PFAS are persistent chemicals that accumulate in the environment and pose growing health risks, leading to stricter global regulations. Industrial wastewater is a key concern, acting both as a pollution source and a treatment opportunity. In this context, SUEZ is conducting innovative projects aimed at developing matrix-specific analytical methods, validating the effectiveness of existing hazardous waste and urban sludge treatment processes, and investigating new separation and destruction technologies.

METHODS AND RESULTS

Analytical Methods Development

Method development focused on matrix-specific optimization of extraction procedures, including solvent selection, sample-to-solvent ratio, stirring techniques (vortex or ultrasonic), pH adjustment, extraction time, number of extraction cycles, and dilution strategies before or after extraction. Up to 30 PFAS are routinely analyzed in waste, effluent, and sludge matrices using internal methods validated through interlaboratory comparisons, with limits of quantification down to 40 ng/L depending on the matrix and PFAS load. For gaseous emissions, up to 49 PFAS are measured by an independent accredited laboratory following the XP X43-126 standard.

Separation Processes

Foam fractionation has been tested at pilot scale on industrial wastewater treatment plants to reduce contaminated volumes prior to final destruction. Operating parameters such as air-water ratio, water residence time, and surfactant addition were assessed to optimize PFAS separation and minimize the volume of contaminated foam. Foam fractionation experiments achieved PFAS extraction efficiencies greater than 96%, with volume reduction factors of several tens. Ongoing tests using two-stage treatment configurations aim to further reduce foam volumes. These results highlight the potential of foam fractionation as a promising pre-treatment step for diluting PFAS-contaminated wastewater.

Stabilization and Solidification

Stabilization/Solidification (S/S) is evaluated as a containment solution for PFAS-contaminated mineral waste. More than 70 formulations were tested using various hydraulic binders, mineral waste types, mixing liquids, and additives. PFAS loads ranged up to several mg/kg, with different maturation times applied for consolidation. Leaching behavior was assessed according to the French standard NF X31-211.

Among the tested S/S formulations, optimized recipes achieved PFAS immobilization efficiencies exceeding 97% within the stabilized waste matrix. Leaching tests confirmed significant reductions in PFAS release. This approach provides a viable management option for mineral wastes unsuitable for thermal treatment.

High-Temperature Thermal Destruction

High-temperature incineration is applied for the destruction of highly concentrated PFAS aqueous waste. Tests were conducted on hazardous waste incineration plants operating at temperatures above 1100°C (typically 1150–1400°C) with residence times exceeding 2 seconds, in compliance with European regulations for halogenated hazardous waste. Various waste types containing PFAS concentrations ranging from hundreds of µg/L to tens of g/L were treated, including carboxylic, sulfonic, telomer-based PFAS, and ultra-short-chain compounds. High-temperature incineration demonstrated excellent performance, with destruction and removal efficiencies (DRE) greater than 99.9999% and destruction efficiencies (DE) exceeding 99.99%, in line with the recommendations of the Stockholm Convention for Persistent Organic Pollutants (POP). Comprehensive monitoring confirmed the absence of significant PFAS emissions in flue gases, effluents, and residues, validating the effectiveness of this technology for highly concentrated PFAS waste.

Hydrothermal gasification (GH)

Our study evaluated the degradation of PFAS by hydrothermal gasification. Experiments were conducted on a continuous pilot plant at high pressure (up to 30 MPa) and temperatures between 400 and 600 °C with solutions containing up to 17 PFAS (C1 to C9). Two complex matrices (organic and mineral) were studied with concentrations ranging from 500 to 12,000 µg/L. Analysis of 41 PFAS, fluoride and adsorbable organic fluorine (AOF) were carried out. Beyond achieving high PFAS degradation efficiency exceeding 99.99% for most PFAS species, including ultra-short chains, the process demonstrated a strong capacity for resource recovery. These results position hydrothermal gasification as a promising technology for both resource recovery and micropollutant treatment.

Sludge pyrocarbonisation

The destruction performance of per- and polyfluoroalkyl substances (PFAS) was evaluated at full-scale pyrocarbonisation unit of a municipal wastewater treatment plant. The PYREG pyrocarbonisation system receives sludge dried to 90% solids and pyrolyzes it at 600 °C in a twin-screw reactor in very poor O_2 atmosphere, producing a biochar and a pyrolysis gas stream that is subsequently oxidized in a combustion chamber operated at almost 1000 °C. Analytical results identified 16 PFAS compounds in the dried sludge feedstock. No PFAS were detected in the resulting biochar nor in the siloxane dust fractions (50 species analyzed). Gas-phase PFAS were further investigated for pyrolysis gas and fumes according to OTM-45 for semi-volatile PFAS (55 species) and OTM-50 for volatile PFAS (30 species), along with analysis of trifluoroacetic acid (TFA). Seven semi-volatile PFAS species were detected in the raw pyrolysis gas prior to oxidation. After high-temperature oxidation, only PFHxDA was detected, and solely at concentrations below quantification limits. Considering all investigated PFAS species, the overall destruction efficiency achieved within the pyrocarbonisation process reached 99.99%. Beyond demonstrating near-complete PFAS elimination, the process produces a PFAS-free biochar that functions as a carbon-negative fertilizer, enabling safe nutrient recycling while contributing to long-term carbon sequestration.

CONCLUSIONS AND PERSPECTIVES

Effective PFAS waste management relies on combining analytical expertise with treatment solutions tailored to the specific characteristics of each waste type. In parallel, SUEZ is evaluating alternative destruction technologies which will have to demonstrate their benefits compared to existing solutions in terms of range of molecules destroyed, cost and environmental impact.

PFAS Enhanced Retention using Colloidal Activated Carbon: Proven, Low-Cost Remediation of Groundwater and Soil

Rétention améliorée des PFAS grâce au charbon actif colloïdal : une méthode éprouvée et économique de dépollution des eaux souterraines et des sols

Scott Wilson, President & CEO, REGENESIS
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Background

PFAS remediation, the elimination of risk posed by per- and polyfluoroalkyl substances in soil and groundwater, is advancing rapidly. Regulatory agencies and practitioners are now embracing the use of colloidal activated carbon (CAC) to treat PFAS in situ, as performance data from over 75 completed site remediation projects world-wide have proven the effectiveness and longevity of the technology. Data from completed in situ PFAS remediation project sites show an overwhelming cost advantage to treating PFAS in situ compared to any other technology, with typical projects completed at 25-40% of the cost associated with installing and maintaining a pumping and treating PFAS impacted groundwater.

PFAS Enhanced Retention

The proven approach of treating a PFAS plume in-situ is referred to as PFAS Enhanced Retention (PER). Akin to Enhanced Natural Attenuation, an in-situ remediation approach widely practiced when treating chlorinated solvent contamination, PER focuses on boosting the ability of the aquifer to passively bind and restrict the flux of PFAS contamination. The implementation of PFAS enhanced retention employing CAC, unlike traditional pump & treat approaches, does not generate a PFAS waste, does not risk the spread of PFAS contamination, and does not spread potential PFAS liability.

Recent work funded by the US Government (ESTCP/SERDP) provides additional confidence in the performance longevity of PER designs employing CAC through a modeling and database tool that estimates PFAS retention lifespans based on site-specific hydrogeologic settings, PFAS chemistry, and sorbent loading. Modeling suggests a single in situ treatment with CAC will offer median performance lifetimes of approximately 870 years for PFOS, 150 years for PFOA and 180 years for PFHxS, underscoring the long-term reliability of CAC as an in situ PER strategy.

Comparing the performance of PER employing CAC to the decades of experience with long term pump-and-treat operations illustrate the limitation of extraction-based systems. A salient example is the PFAS treatment system currently operating at Wurtsmith US Air Force Base. Performance and cost analyses at this site show the existing pumping and treating system will fail to achieve regulatory standards even after 100 years of operating. In contrast, a passive PER system employing CAC would immobilize the PFAS within the subsurface at this project site immediately, achieving and maintaining regulatory requirements for >100 years, at cost savings of over 60%.

The implementation of PFAS enhanced retention employing colloidal activated carbon will be discussed along with performance results and cost analyses of full-scale remediation projects in USA and Europe.

Scalable UV Destruction of PFAS in Foam-Fractionated Minnesota Groundwater

Authors:
Joseph Tirado; Elizabeth McCumber; James McKone, PhD; Zekun Liu, PhD; Claros Technologies Inc.

Keywords: PFAS, PFAS destruction, UV, groundwater remediation, mineralization

Framing and Objectives

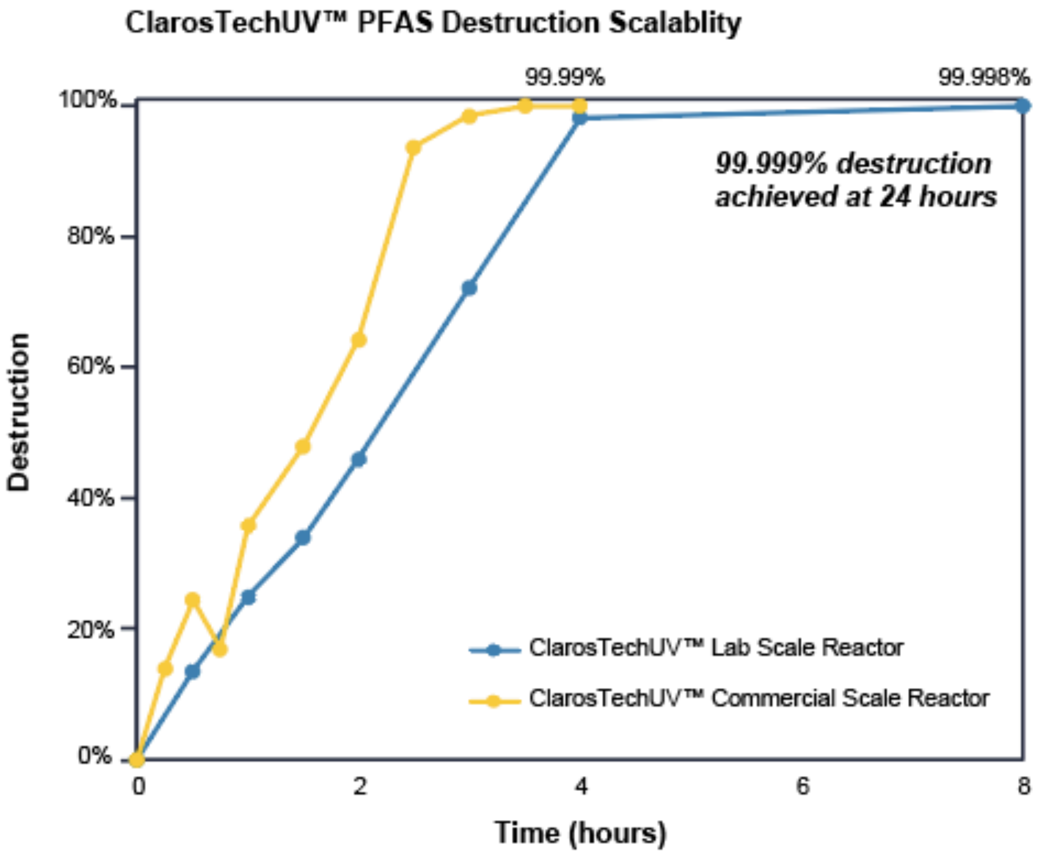
Introduction and Objective. Per and polyfluoroalkyl substances (PFAS) represent a significant and persistent challenge to water quality due to their widespread occurrence and chemical resilience. Filtration-based techniques are not a viable final solution as they primarily transfer PFAS to secondary waste streams. This study evaluates a proprietary UV-based technology designed for the complete mineralization of long, short, and ultra-short chain PFAS compounds. Minnesota Pollution Control Agency (MPCA) conducted a pilot study to test foam fractionation on groundwater and surface water that is known to be contaminated with PFAS. Claros performed PFAS destruction in wastewater collected from a groundwater remediation site and treated with foam fractionation to pre-concentrate the PFAS species. The objective was to demonstrate and critically compare destruction performance across reactor systems from laboratory to commercial scale.

Methods. A quantity of wastewater was obtained from MPCA and characterized by ClarosLabs™ ISO- and ASTM-certified analytical facility with respect to its chemical composition and physicochemical properties of relevance to UV-based destruction. PFAS species identified and targeted for destruction included perfluorooctane sulfonic acid (PFOS) and perfluorooctanoic acid (PFOA), as well as several short and ultra-short chain species in lower quantities, with a total mass concentration in the range of 30–35 ppm of total organofluorine (TOF). Notably, optical transparency was reduced due to the presence of suspended particulates; this turbidity was addressed with gravity-based filtration, which mimics the behavior of large-scale sedimentation operations. PFAS destruction was carried out in a liter-scale laboratory tubular reactor in a static condition without solution agitation to establish a performance baseline. Further destruction experiments were carried out in a commercial-scale reactor running with 30 gallons of gravity-filtered wastewater under a recirculating flow condition with intermittent sample collection to monitor for PFAS destruction. PFAS content was monitored via LC-MS analysis.

Results. PFAS destruction dynamics were observed to be similar across laboratory and commercial-scale systems: final destruction of PFOS and PFOA reached 99.99% (4 log) after 4 hours of continuous treatment and 99.999% (5 log) after extended treatment for 24 hours, with total defluorination approaching 90%. Notably, when accounting for PFAS separation and concentration associated with the foam fractionation pretreatment, these destruction timescales correspond to groundwater remediation at several million gallons per day. Moreover, using the power requirements of the recirculating reactor, the total electrical energy required for 4 log destruction of PFOA and PFOS was estimated as 0.6 kWh/gal, which is dramatically lower than the fuel energy required for thermal treatments that achieve similar levels of PFAS destruction.

Significance and Outlook. Current remediation strategies primarily convert PFAS pollution into concentrated waste streams. This study validates a scalable, energy-efficient pathway to integrate PFAS capture and concentration with chemical destruction via C-F bond cleavage. By demonstrating consistent destruction levels exceeding 99.99% from bench to commercial scale, these results support practical implementation of proprietary UV-based destruction on high-turbidity, foam-fractionated groundwaters—thereby offering a permanent end-of-life solution for "forever chemicals" at a fraction of the energy cost of thermal destruction.

(see graphic next page)



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Vendredi 19 juin 2026

08h30
Accueil des participants

Technologies de traitement pour l'eau, les sols, les sédiments et l'air (Part. 2)
Recherche et développement (R&D)

Présidents :
- *Sylvie Traverse, Département Air, Procédés technologiques et ICPE - Ginger Burgeap, France*
- *Dr. Christophe Rousselle, Agence Nationale de Sécurité Environnementale et Sanitaire (ANSES) - Société Francophone de la Santé et de l'Environnement (SFSE) & Association pour la Recherche en Environnement (ARET), France*
- *Dr. Frank Karg, SFSE & ARET, Directeur scientifique Ginger Group - HPC (Inogen), Président d'Atlantis Développement & Expert Judiciaire, France*

09h00
Défluoration des PFAS et du TFA par un procédé innovant utilisant un plasma froid
Christophe Louvigné, Directeur général - Holowaves (France)

09h30
Capturer ce que les autres manquent – Résines échangeuses d'ions innovantes pour l'élimination des PFAS à chaîne courte et ultra-courte dans l'eau
Bjoern Dinges, Directeur du développement commercial et des technologies d'application – Lanxess (Allemagne)

10h00
Études de cas des différences très significatives de la lixiviabilité des PFAS per- & poly-fluorés dans les sols et leur solubilisation vers les eaux souterraines
Dr. Frank Karg, SFSE & ARET, Directeur scientifique Ginger Group - HPC (Inogen), Président d'Atlantis Développement & Expert Judiciaire (France)

10h30
Pause-café & thé

11h00
Benchmark Européen des technologies de remediation des sols et des eaux souterraines polluées au PFAS
Boris Devic-Bassaget, Directeur technique - SARPI Remediation (France)

11h30
À l'avant-garde de la gestion responsable des fluoropolymères : l'engagement de FPG en faveur de la réduction des émissions et des pratiques durables
Takayuki Nakamura, Conseiller technique principal, Département RSE, Affaires publiques - Daikin Chemical Europe (Allemagne)

12h00
Capturer et concentrer les PFAS à l'aide de nanoparticules magnétiques recyclables
Géraldine Gouhier, Directrice commerciale CARNOT i2C & Professeur - Institut CARMeN (France)

12h30
Déjeuner

14h00
Destruction des PFAS par plasma non thermique dans les eaux (usées). Focus sur les PFAS ultracourts et les matrices difficiles
Wouter De Weirdt, Président-directeur général - Tectero (Belgique)

14h30
Retours d'expérience des techniques de remédiation in-situ : (1) immobilisaiton et (2) soil flushing accompagnée par foam fractionation
Loïc Ruiz, Ingénieur Projets - Jan de Nul (Belgique)

15h00
Décontamination et destruction des effluents et des émulseurs contenant des PFAS grâce à un réacteur d'oxydation hydrothermale supercritique (SCWO)
Thibault Derode, Ingénieur en chef ELIXIR - ArianeGroup (France)

15h30
Pause-café & thé

16h00
Nanoparticules de fer encapsulées en biomasse microalguale comme nouveaux adsorbants pour l'élimination des PFAS : emploi de colorants comme proxies de composés cibles
Emilio Brivio Sforza, Chercheur doctorant - Université de Milan-Bicocca (Italie)

16h30
Démonstration à l'échelle pilote de l'immobilisation des PFAS dans le sol et les eaux souterraines (projet PIGGS)
- *Wim Vansina, Conseiller principal - Antea Group (Belgique)*
- *Loïc Ruiz, Ingénieur Projets - Jan de Nul (Belgique)*

17h00
Traitement des PFAS dans les effluents industriels par osmose inverse couplée à une électro-oxydation
Guillaume Deruy, Ingénieur R&D - Séché Environnement (France)

17h30
Fin de la quatrième journée
Fin de la conférence

Friday June 19, 2026

08h30
Welcoming participants

Treatment Technologies for Water, Soils, Sediments and Air (Part. 2)
Research & Development (R&D)

Presidents:
- *Sylvie Traverse, Department of Air, Process Technologies and ICPE - Ginger Burgeap, France*
- *Dr. Christophe Rousselle, French Agency for Environmental and Health Safety (ANSES) - Francophone Society for Health and the Environment (SFSE) & Association for Environmental Research (ARET), France*
- *Dr. Frank Karg, SFSE & ARET, Scientific Director of Ginger Group - HPC (Inogen), CEO of Atlantis Développement & Court Expert, France*

09h00
Defluorination of PFAS and TFA by an innovative process using cold plasma
Christophe Louvigné, Managing Director - Holowaves (France)

09h30
Capturing What Others Miss – Innovative Ion Exchange resins for Short- and Ultra-Short-Chain PFAS Removal in Water
Björn Dinges, Business Development & Application Technology Manager – Lanxess (Germany)

10h00
Case studies of very large Leachability Differences concerning per- & poly-fluorinated PFAS in soils and their Solubilization in Groundwaters
Dr. Frank Karg, SFSE & ARET, Scientific Director of Ginger Group - HPC (Inogen), CEO of Atlantis Développement & Court Expert (France)

10h30
Coffee & Tea break

11h00
European Benchmark of remediation technologies for soil and groundwater polluted by PFAS
Boris Devic-Bassaget, Technical Director - SARPI Remediation (France)

11h30
Leading the way in responsible fluoropolymer management: FPG's commitment to emission reduction and sustainable practices
Takayuki Nakamura, Senior Technical Advisor, CSR Department, Public Affairs - Daikin Chemical Europe (Germany)

12h00
Capture and concentrate PFAS with recyclable magnetic nanoparticules
Géraldine Gouhier, CARNOT i2C Sales Director & Professor - CARMeN Institute (France)

12h30
Lunch

14h00
PFAS destruction via nonthermal plasma in (waste)water. Focus on ultrashort PFAS and difficult matrices
Wouter De Weirdt, Chief Executive Officer - Tectero (Belgium)

14h30
Field experience and evaluation of in situ remediation techniques: (1) immobilzation and (2) soil flushing coupled with foam fractionation
Loïc Ruiz, Project Engineer - Jan de Nul (Belgium)

15h00
Decontamination and destruction of firefighting foams and rinse water containing PFAS through SuperCritical Water Oxidation (SCWO)
Thibault Derode, Chief Engineer ELIXIR - ArianeGroup (France)

15h30
Coffee & Tea break

16h00
Microalgal-based carbon encapsulated iron nanoparticles as novel adsorbents for PFAS removal: From dye proxies to target compounds
Emilio Brivio Sforza, PhD Researcher - University of Milan-Bicocca (Italy)

16h30
Pilot-Scale Demonstration of PFAS Immobilization in Soil and Groundwater (PIGGS Project)
- *Wim Vansina, Principal Advisor - Antea Group (Belgium)*
- *Loïc Ruiz, Project Engineer - Jan de Nul (Belgium)*

17h00
Treatment of PFAS in industrial effluents by reverse osmosis coupled with electro-oxidation
Guillaume Deruy, R&D Engineer - Séché Environnement (France)

17h30
End of the fourth day
End of conference

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Good Soil

Des sols pollués à la santé des sols : pollutions, fonctions et résilience

Van verontreinigde bodems naar bodembiodiversiteit en -gezondheid: verontreiniging, functies en veerkracht

From contaminated soils to soil health: pollution, functions and resilience

3 & 4/12/2026
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3. Surveillance, diagnostic et santé des sols / Monitoring, diagnose en bodemgezondheid / Soil monitoring, diagnosis and health
4. Gestion durable des sols en milieu urbain / Duurzaam bodembeheer in stedelijk gebied / Sustainable soil management in urban areas
5. Prévention et restauration des sols dégradés / Preventie en herstel van aangetaste bodems / Prevention and restoration of degraded soils

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HOLOWAVES
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Destruction de PFAS

Défluoration des PFAS et du TFA par un procédé innovant utilisant un plasma froid

Christophe Louvigné, Directeur général – Holowaves (France)

Nous développons une chaîne de valeur intégrée, modulaire et réplicable dédiée au traitement des lixiviats contaminés par les substances per- et polyfluoroalkylées (PFAS), avec une capacité cible de 2 m³/h. Cette approche repose sur la coordination de partenaires spécialisés couvrant l'ensemble de la chaîne de traitement, depuis la caractérisation des sites pollués jusqu'à la destruction finale des concentrats. Le dispositif débute par une phase de diagnostic visant à qualifier les matrices contaminées, évaluer les niveaux de pollution et définir un périmètre d'intervention optimisé sur les plans technique et économique. En amont de l'étape destructive, la technologie développée par CHROMAFORA constitue un levier stratégique grâce à sa capacité à concentrer les effluents contaminés jusqu'à un facteur 1/1000, permettant la production de concentrats à haute teneur en PFAS adaptés à un traitement ciblé.

Ces concentrats sont ensuite traités par un procédé électrochimique continu basé sur une technologie de plasma froid, opérant avec une consommation énergétique de 6 kWh pour un débit de 2 m³/h. L'un des principaux avantages compétitifs de cette technologie réside dans l'absence de consommables et de réactifs additionnels, limitant la dépendance aux intrants, renforçant la robustesse opérationnelle du procédé et contribuant à la compétitivité économique du traitement à l'échelle industrielle. Les premiers essais réalisés sur des matrices industrielles concentrées issues du secteur pharmaceutique, présentant des concentrations de l'ordre de 2 g/L en PFAS, ont démontré une efficacité de destruction atteignant 99 % des liaisons carbone–fluor, au cœur de la persistance environnementale de ces composés.

La combinaison d'une étape de concentration amont, d'un procédé de destruction ciblée et d'une faible intensité en intrants positionne cette solution comme une réponse technologique différenciante dans un contexte de renforcement rapide des exigences réglementaires et environnementales liées aux PFAS.

Le projet entre désormais dans une phase décisive d'industrialisation visant à convertir cette validation technologique en solution opérationnelle de marché. Cette étape comprend la montée en échelle du procédé, l'évaluation de sa robustesse en conditions réelles d'exploitation, la sécurisation des paramètres de performance et la préparation de son déploiement sur des territoires confrontés à des pollutions diffuses ou concentrées par les PFAS. L'objectif est de proposer à court terme une solution industrielle capable de répondre aux attentes croissantes des acteurs publics et privés en matière de dépollution, de conformité réglementaire et de maîtrise des coûts de traitement.

HOLOWAVES
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Destruction de PFAS

Defluorination of PFAS and TFA by an innovative process using cold plasma

Christophe Louvigné, Managing Director - Holowaves (France)

English abstract :

We are developing an integrated, modular, and scalable value chain dedicated to the treatment of leachates contaminated with per- and polyfluoroalkyl substances (PFAS), with a target processing capacity of 2 m^3/h. This approach relies on the coordination of specialized partners covering the entire treatment sequence, from contaminated site characterization to the final destruction of concentrated streams. The process begins with a diagnostic phase aimed at characterizing contaminated matrices, assessing pollution levels, and defining a technically and economically optimized intervention scope. Upstream of the destruction stage, the technology developed by CHROMAFORA provides a strategic advantage through its ability to concentrate contaminated effluents by up to a factor of 1,000, enabling the production of high-strength PFAS concentrates suitable for targeted treatment.

These concentrates are subsequently treated using a continuous electrochemical process based on cold plasma technology, operating with an energy consumption of 6 kWh at a flow rate of 2 m^3/h. One of the key competitive advantages of this technology lies in the absence of consumables and additional chemical reagents, thereby reducing dependency on inputs, enhancing operational robustness, and improving the economic competitiveness of large-scale treatment operations. Initial trials conducted on concentrated industrial matrices from the pharmaceutical sector, with PFAS concentrations in the range of 2 g/L, demonstrated destruction efficiencies reaching 99% of carbon–fluorine bonds, which are responsible for the exceptional environmental persistence of these compounds.

The combination of an upstream concentration step, a targeted destruction process, and low input intensity positions this solution as a differentiated technological response in a context of rapidly strengthening regulatory and environmental requirements related to PFAS management.

The project is now entering a decisive industrialization phase aimed at transforming this technological validation into a market-ready operational solution. This stage includes process scale-up, assessment of robustness under real operating conditions, validation of performance parameters, and preparation for deployment in territories affected by diffuse or concentrated PFAS contamination. The objective is to deliver, in the short term, an industrial solution capable of meeting the growing expectations of both public and private stakeholders in terms of remediation efficiency, regulatory compliance, and treatment cost control.

Capturing What Others Miss – Innovative Ion Exchange resins for Short- and Ultra-Short-Chain PFAS Removal in Water

Björn Dinges, Business Development & Application Technology Manager – Lanxess (Germany)

Innovative technologies and materials are needed to comply with increasingly stringent regulatory requirements regarding PFAS emissions into the environment.
Removing short- and ultra-short-chain per- and polyfluoroalkyl substances (PFAS) from wastewater is a particular challenge because they often bind only poorly to adsorbent materials. Here we highlight our case study at Chemours in Dordrecht, in which a novel selective ion exchange (IEX) resin with groundbreaking performance is used.
Lewatit® MDS TP 108 used to remove short-chain PFAS is significantly superior to conventional selective resins, which is reflected in a 4-6 times longer service life and thus lower resin consumption. The disposal costs for the loaded resin and the carbon footprint from thermal utilization are correspondingly lower. In addition, a very compact design of ion exchange filter is possible. More than 99.9% of all fluorinated organic compounds from the wastewater remain on the adsorbent materials.

International PFAS Congress
Paris 16 - 19 June 2026

Etudes des cas des différences très significatives de la lixiviabilité des PFAS per- & poly-fluorés dans les sols et leur solubilisation vers les eaux souterraines.

Case studies of very large Leachability Differences concerning per- & poly-fluorinated PFAS in soils and their Solubilization in Groundwaters

Frank KARG (Dr. rer. nat. / es. Sc. / PhD)
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1. Introduction

Le lessivage (ou la lixiviabilité) et l'impact des substances perfluoro-alkylées et polyfluoro-alkylées (PFAS) sur l'eau dans les sols, les aquifères et même les matériaux de construction (comme le béton) varient considérablement selon le type de molécule. Ces phénomènes sont essentiels pour :

- Étudier et **modéliser les différents profils de migration des PFAS et leurs effets chromatographiques** dans les sols et les aquifères,
- **Évaluer les risques associés à la migration différenciée es PFAS**, et
- **Évaluer l'efficacité de diverses méthodes de dépollution et de traitement, telles que le lavage et l'élution des sols, et différentes techniques d'immobilisation.**

La lixiviation des PFAS des sols est liée à la longueur de leur chaîne carbonée et à leurs groupements fonctionnels. Alors que les PFAS à chaîne courte ($CF_2 \leq 5$) sont facilement désorbés et lixiviés, les PFAS à chaîne longue sont plus difficiles à désorber. Les PFAS possédant un groupement carboxylate sont lixiviés plus facilement et en plus grande quantité que ceux possédant un groupement sulfonate ou sulfonamide.

La lixiviation des PFAS à chaîne longue est plus dépendante du pH : elle augmentait à pH élevé (pH > 7,5 - 8, tandis que celle des PFAS à chaîne courte estt moins sensible au pH. **Aucune propriété (simplifiée) du sol, prise isolément, ne permettait de décrire adéquatement la lixiviation des PFAS.** Globalement, la structure chimique des PFAS semblait avoir un impact plus important sur leur lixiviation que les propriétés physico-chimiques des sols (26).

Actuellement, très peux des technologies de dépollution in-situ sont applicables aux pollutions par les PFAS dans les zones saturées et non saturées, à part du lavage via l'utilisation des ingrédients spécifiques comme les bio-polymères protéiniques ou les Béta-cyclodextrines. Les stratégies de dépollution mises en œuvre appliquent principalement des méthodes très coûteuses telles que l'excavation des sols pollués (& mise en décharge, lavage hors site et traitement thermique) ou le P&T (pump-and-treat) très coûteux en tant que technologie de dépollution hydraulique des eaux souterraines.

En raison de leur grande solubilité, de leur stabilité chimique, de leur mobilité dans l'environnement et de leur bioaccumulation, les substances alkylées poly- et perfluorées (PFAS) représentent une préoccupation importante en ce qui concerne leur impact potentiel sur l'environnement et la santé. Dans toute l'Europe (Belgique, France, Allemagne, Suisse, Italie et autres pays), de nombreux sites contaminés par des PFAS dans le sol, les eaux souterraines, les eaux de surface, etc. ont été identifiés, dont certains couvrent de vastes zones, comme la contamination de la couche arable de plus de 800 hectares dans la région de Rastatt (Baden-Württemberg, Allemagne), où des boues de compostage de papier et de stations d'épuration contenant des PFAS ont été utilisées comme fertilisants.

Des expériences montrent que certains PFAS, et notamment leurs précurseurs (PFAS polyfluorés) des types sulfobétaïnes et sulfonates, tels que le (N-)EtFOSA, le (N-EtFOSAA), les Capstones comme le 6:2-FTNO et le 6:2-FTAB, ou encore le 6:2-FTS (ou H4PFOS), sont très difficiles à lessiver des sols. En effet, sans l'application d'un pH fortement alcalin (pH > 9), la présence de minéraux argileux et de sesquioxydes empêche la désorption de ces PFAS. Cette situation change radicalement lors de la biotransformation ou de l'oxydation de ces molécules en PFAS per-fluorées finaux, tels que les acides perfluoro-sulfoniques et carboxyliques beaucoup plus solubles.

Afin de clarifier les différences très importantes dans la lixiviation des PFAS per- et polyfluorés dans les sols et leur solubilisation dans les eaux souterraines, une étude plus détaillée a été réalisée sur un grand site pollué par les PFAS pour clarifier la lixiviation des différents PFAS poly- et perfluorés dans différentes matrices, ce qui nous amène à étudier également les effets chromatographiques dans les sols et les aquifères des différentes fractions de PFAS.

Plusieurs paramètres influencent la lixiviation des PFAS (cf. Fig. 1) :

Paramètres des substances :

A. La polarité des molécules,
B. La taille des molécules,
C. La solubilité des molécules,
D. Volatilisation des PFAS de type FTOH (voir la constante de Henry, etc.),

Paramètres des substratums :

E. Le type de substrats (sols, remblais, roches, matériaux de construction tels que le béton, etc.) en fonction de leur perméabilité et de la granulométrie, de leur composition minéralogique (argiles, sels, sesquioxydes, etc.), de leur composition organique (matières organiques, COT, tourbe, acides humiques et fulviques, etc.),
F. Les capacités d'adsorption (Kd) et de désorption, qui dépendent de la matrice d'adsorption (sols, aquifères, matériaux de construction (béton, etc.),

Paramètres environnementaux :

G. Le pH (et notamment l'alcalinité) et le potentiel redox (en mV),
H. La température,
I. L'activité microbiologique, en particulier en conditions aérobies, et la biotransformation des substances PFAS,
J. La présence de métaux ayant un effet catalytique sur les processus de biotransformation microbiologique des substances PFAS,
K. La présence d'intermédiaires de solubilisation. Autres substances ou autres polluants,
L. Débit et quantités d'eau de lixiviation et d'élution par unité de temps.
M. Utilisation ou non d'agents de lavage, par exemple des biopolymères protéiques, des bêta-cyclodextrines, des amines tertiaires, etc.

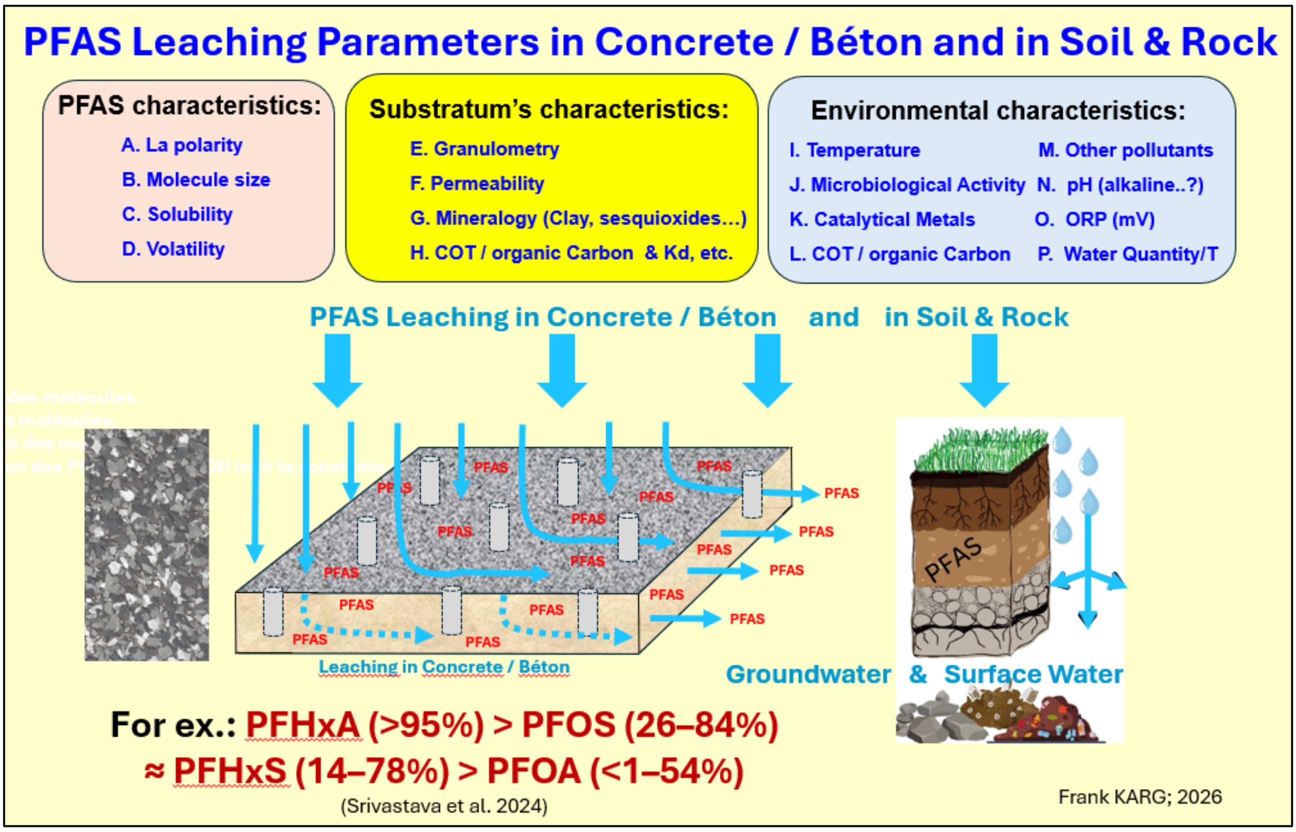

Fig. 1 : Paramètres de lixiviation & élution des PFAS dans les sols, aquifères et bétons

La polarité des molécules de PFAS est cruciale, car il en existe :

- **Non ioniques** (p. ex., polyéthylène glycols, oligomères d'acrylamide).
- **Anioniques** (p. ex., sulfonates, sulfates, carboxylates et phosphates).
- **Cationiques** (p. ex., composés d'ammonium quaternaire : bétaïnes et sulfobétaïnes) et
- **Zwitterions.**

La Fig. 2 montre des Zwitterions du type Capstone A & B (6 :2 FTNO et 6 :2 FTAB), typiquement présent dans les anciens mousses anti-incendie (AFFF) et leur solubilité en dépendance du pH.

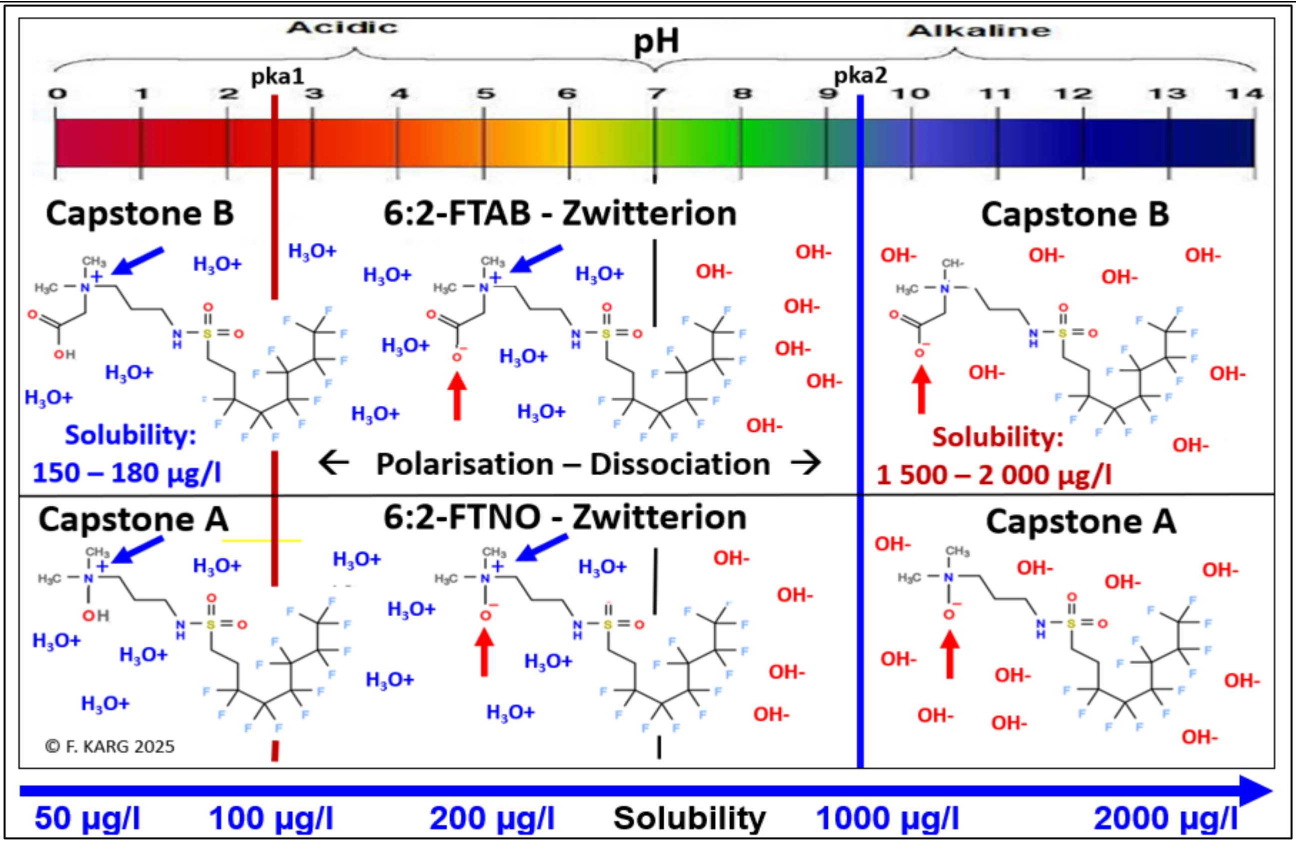

Fig. 2 : Zwitterions du type Sulfobétaines Capstone A & B (6 :2 FTNO et 6 :2 FTAB), typiques pour les anciens mousses antiincendie (AFFF) et leur solubilité en dépendance du pH.

Le pH est un paramètre crucial pour la lixiviation, car la solubilité de nombreux PFAS augmente avec l'alcalinité (pH > 7,5). **Il en va de même pour la taille des molécules de PFAS** : plus la molécule est petite, plus sa solubilité est élevée. Solubilité : PFAS-C1 ultracourt > PFAS C2-4 court > PFAS C5-X long.

Certains PFAS, en fonction de leur **spéciation de polarité**, possèdent un pouvoir de lixiviation extrêmement difficile, de telle sorte que même l'extraction et les analyses en laboratoire deviennent presque impossibles, comme c'est le cas pour le PFECHS, une molécule PFAS typique des huiles hydrauliques d'aviation (voir Fig. 3).

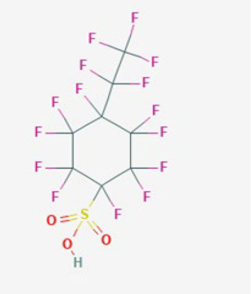	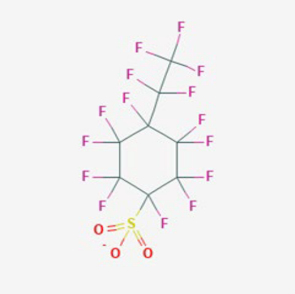	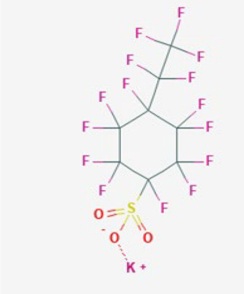
$C_8HF_{15}O_3S$	$C_8F_{15}O_3S^-$	$C_8F_{15}KO_3S$

Fig. 3 : Spéciations ioniques du PFECHS (PFAS des huiles d'aviation) selon les pH.

Les Fig. 4a & b montrent la dépendance de lixiviation et d'élution des PFAS selon le pH et la granulométrie des substratums (selon 24).

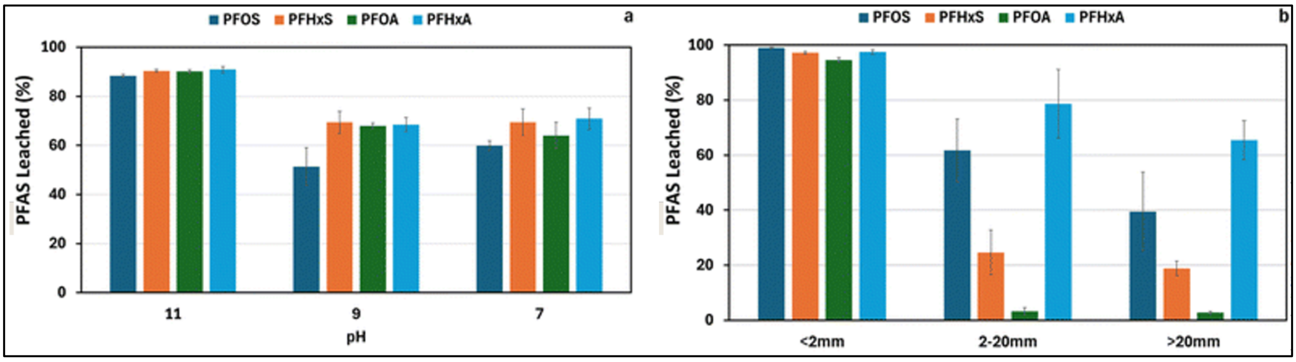

Fig. 4a & b : Dépendance de lixiviation et d'élution des PFAS selon le pH et la granulométrie des substratums (selon 24). Il est à constater que (contrairement aux attentes) une granulométrie fine augmente la capacité de lixiviation, car l'emmagasinement (adsorption) des PFAS est supérieur. Les lixiviations & élutions en pH alcalin sont supérieurs

Au contraire, les acides perfluoro-carboxyliques (PFCA) et acides perfluoro-sulfoniques (PFSA) sont très solubles et lixiviables. Ce phénomène est utilisable d'une façon que pour les dépollutions par lavages in-situ ou ex-situ une pré-oxidation par bio-transformation ou par un peroxyde (persulfate etc.) des précurseurs des PFCA et des PFSA, par ex. les Capstones 6 :2 FTAB, 6 :2 FTNO, 6 :2 FTS, (N-)EtFOSA, (N-)EtFOSAA etc. au préalable pourra faciliter et accélérer la dépollution.

À l'inverse, les acides perfluoro-carboxyliques (PFCA) et les acides perfluoro-sulfoniques (PFSA) sont très solubles et lessivables. Ce phénomène peut être exploité de manière à faciliter et accélérer le processus de dépollution par lavage in situ ou ex situ, soit par pré-oxydation (via une biotransformation ou par un peroxyde (persulfate, etc.) des précurseurs (PFAS poly-fluorés) des PFCA et des PFSA, tels que les Capstones 6:2 FTAB, 6:2 FTNO, 6:2 FTS, (N-)EtFOSA, (N-)EtFOSAA, etc. envers les PFCA et PFSA. Ce principe est par exemple appliqué aussi par le Top-Assay (cf. Fig. 6).

La lixiviabilité selon la longueur de la chaine (xC) des molécules PFAS est montre en Fig. 5 (selon 25).

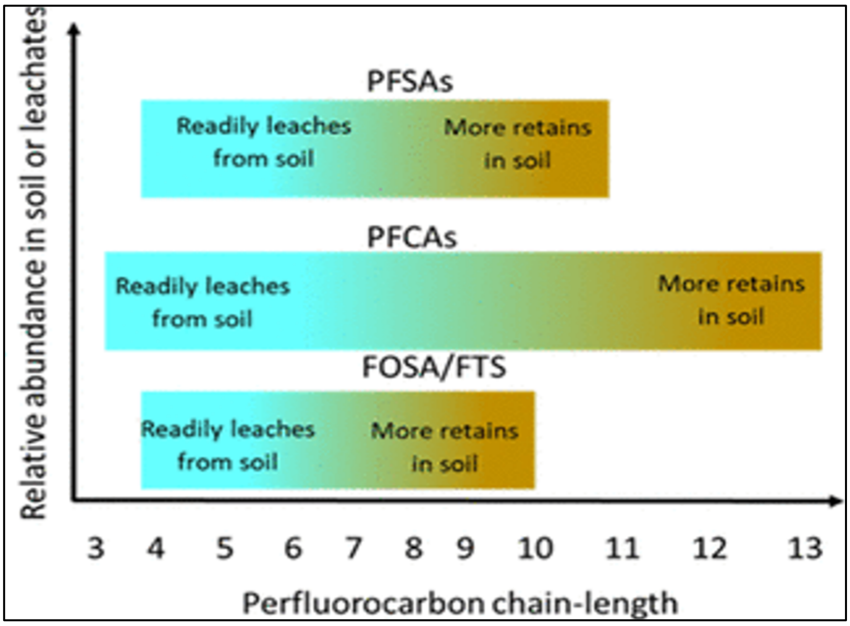

Fig. 5 : Lixiviabilité selon la longueur de la chaine (xC) des molécules PFAS (selon 25).

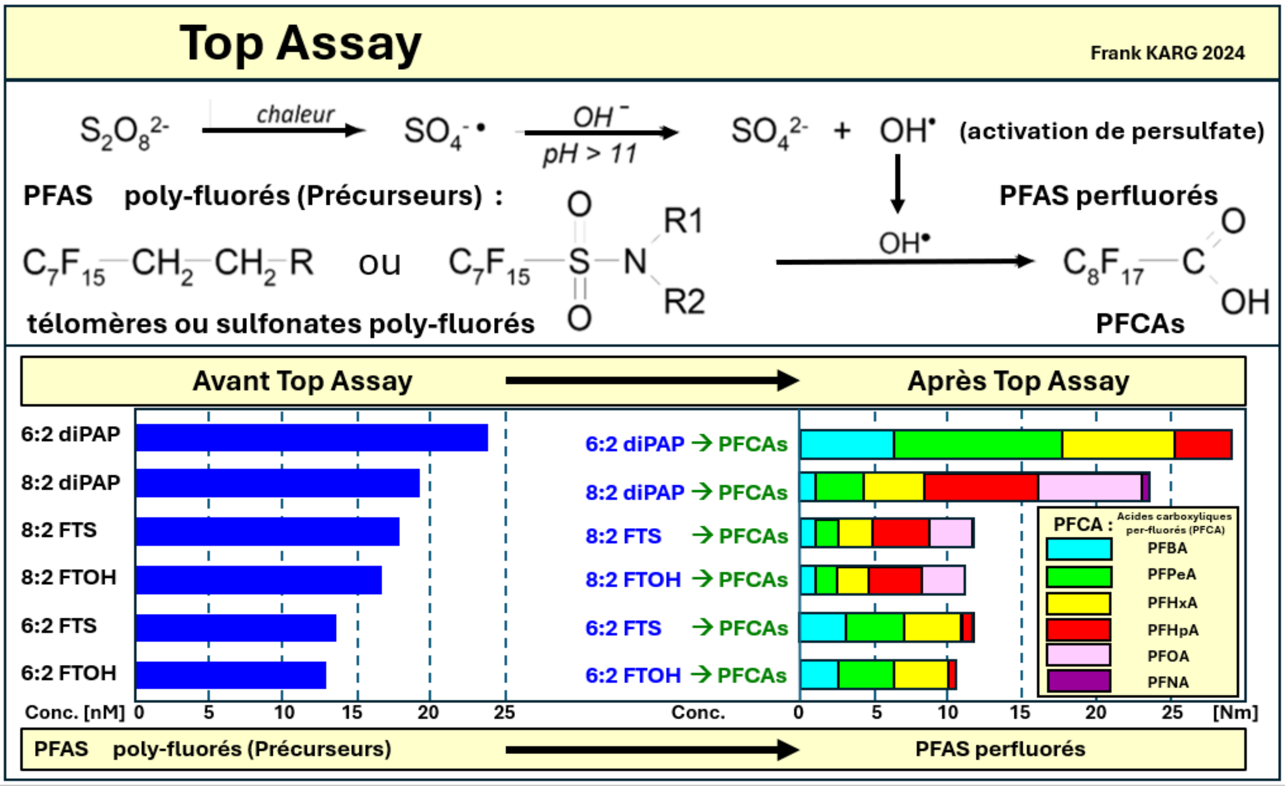

Fig. 6 : Top Assay : Oxydation par le persulfate des précurseurs (PFAS poly-fluorés) envers les PFCA et PFSA.

L'oxydation des substances polyfluoroalkylées (PFAS) est possible par voie chimique, par exemple au persulfate (F. KARG, 2024-2025), ou par prétraitement microbiologique utilisant des consortiums bactériens et les injections de l'air afin de garantir un environnement aérobie dans le sous-sol (sols et aquifères). L'avantage de la pré-oxydation chimique au persulfate réside dans sa rapidité d'application, mais son utilisation est parfois interdite en raison de risques de toxicité. La pré-oxydation microbiologique présente l'avantage d'une mise en œuvre relativement simple par percolation ou injection d'un consortium bactérien associé à une injection d'air, le Bio-Air-Sparging (BAS). Son inconvénient est sa durée, d'environ 6 à 12 semaines lorsque la teneur en argile est inférieure à 50 %. Par la suite, un lavage utilisant des biopolymères protéiques, des PFAS perfluorés crées, beaucoup plus solubles, est possible dans un circuit de régénération des lixiviats de lavage pour la séparation et l'élimination des PFAS (F. KARG, 2024-2025).

2. La Lixiviation au service de la dépollution par lavages in-situ et ex-situ des sols et matériaux

Des expériences montrent qu'en l'absence de dégradation microbiologique aérobie, des précurseurs tels que le 6:2-FTAB, l'EtFOSAA, le 6:2-FTS, etc., peuvent persister à plus de 70 % des concentrations de PFAS dans les sols et les eaux souterraines pendant plus de 35 ans (F. Karg, 2024-2025). Pour cette raison une pré-oxydation préalable vers les PFAS per-fluorés plus solubles est nécessaire (cf. Fig. 7 – 11).

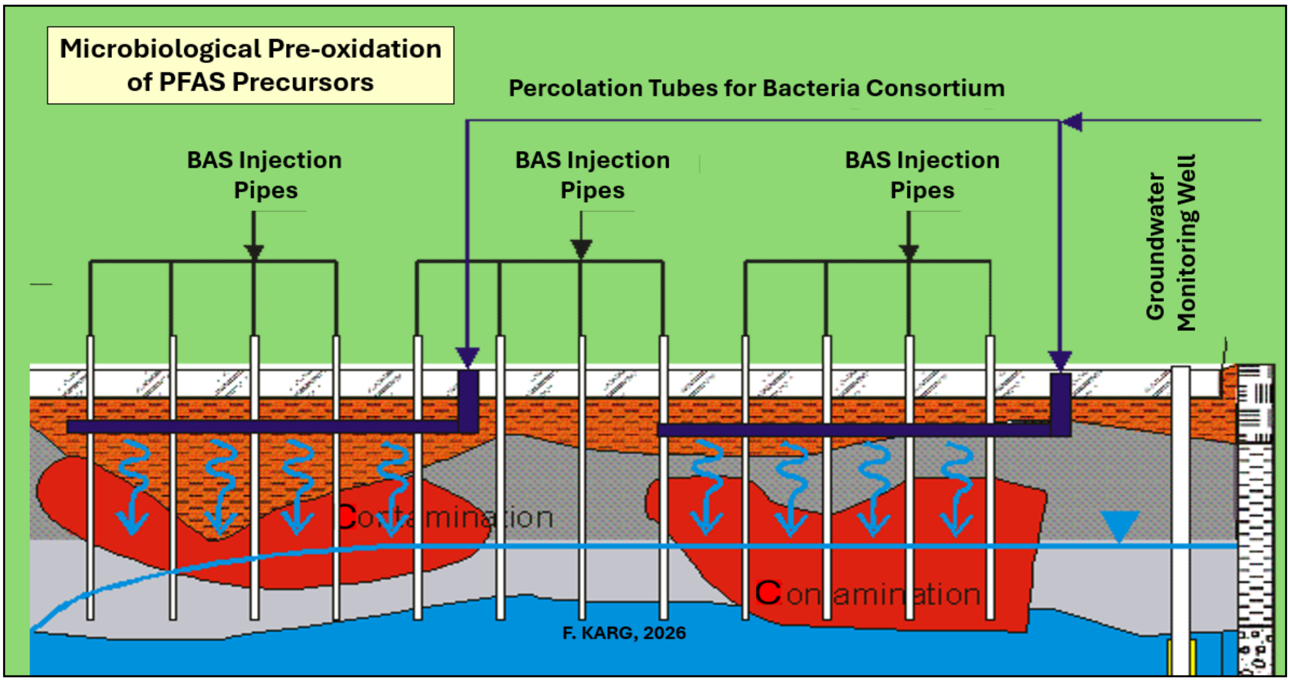

Fig. 7. Pré-oxydation Microbiologique des Précurseurs PFAS du type 6 :2-FTAB, 6 :2-FTS, EtFOSA

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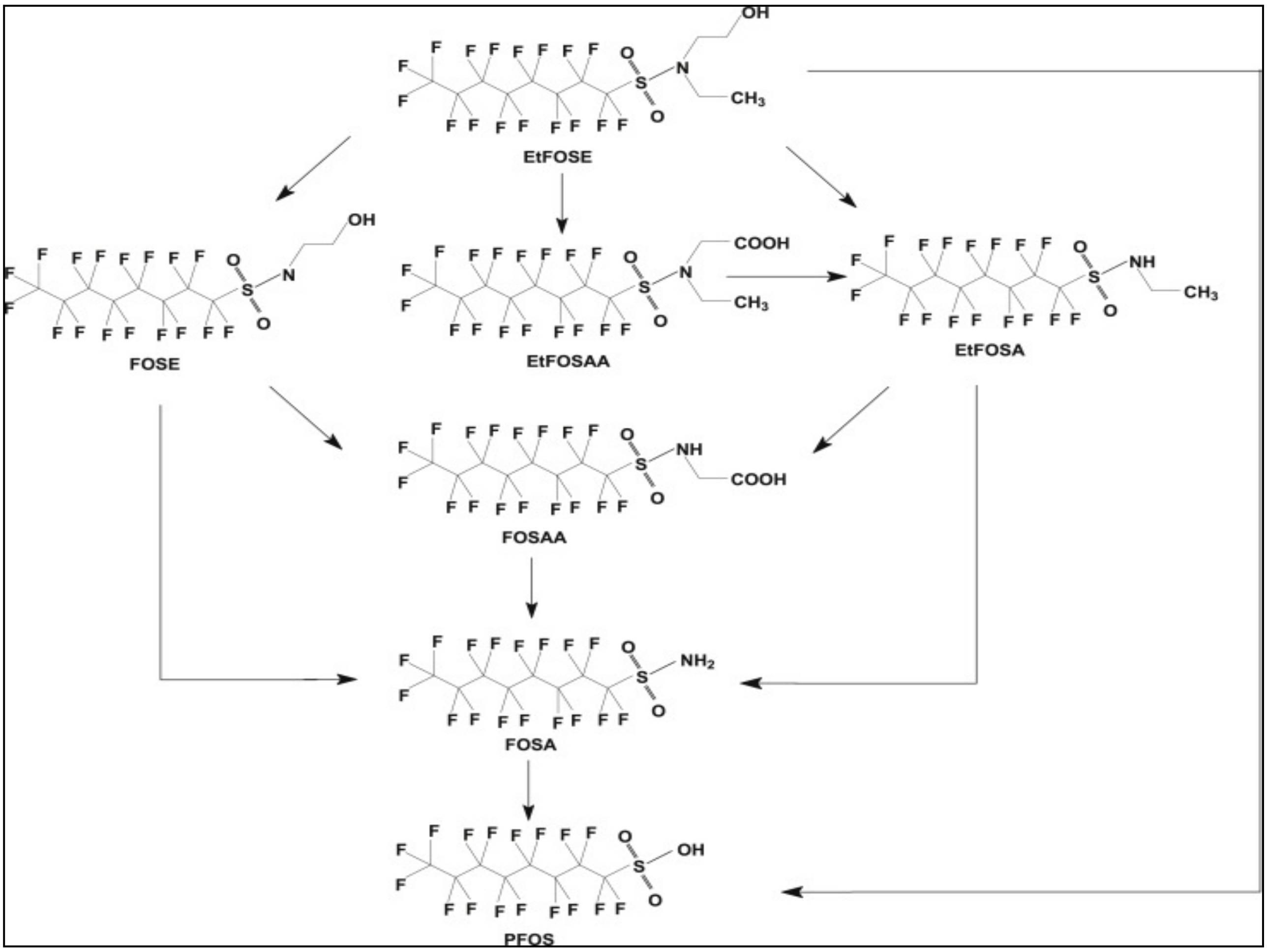


Fig. 8 : Biotransformation des Précurseurs poly-fluorés EtFOSE, EtFOSAA, FOSE, EtFOSA et FOSAA er FOSA vers le PFOS (S. Chen et al. 2021).

Après la pré-oxydation microbiologique des PFAS poly-fluorés (précurseurs), voir figures 2 et 3, par exemple le 6:2-FTAB, le 6:2-FTS et le 6:2-FTOH, en PFBA, PFPrA, PFPeA et PFHxA, beaucoup plus solubles, ou de l'EtFOSAA en PFOS, le lavage in situ (ou ex situ) des sols contaminés par les PFAS est parfaitement possible, par ex. via des consortiums des bactéries : Acidimicrobium sp. Strain A6, Acidimicrobium sp. Strain A6 et/ou Pseudomonas strain SYC ou Rhodococcus jostii RHA1 et Pseudomonas oleovorans, etc.

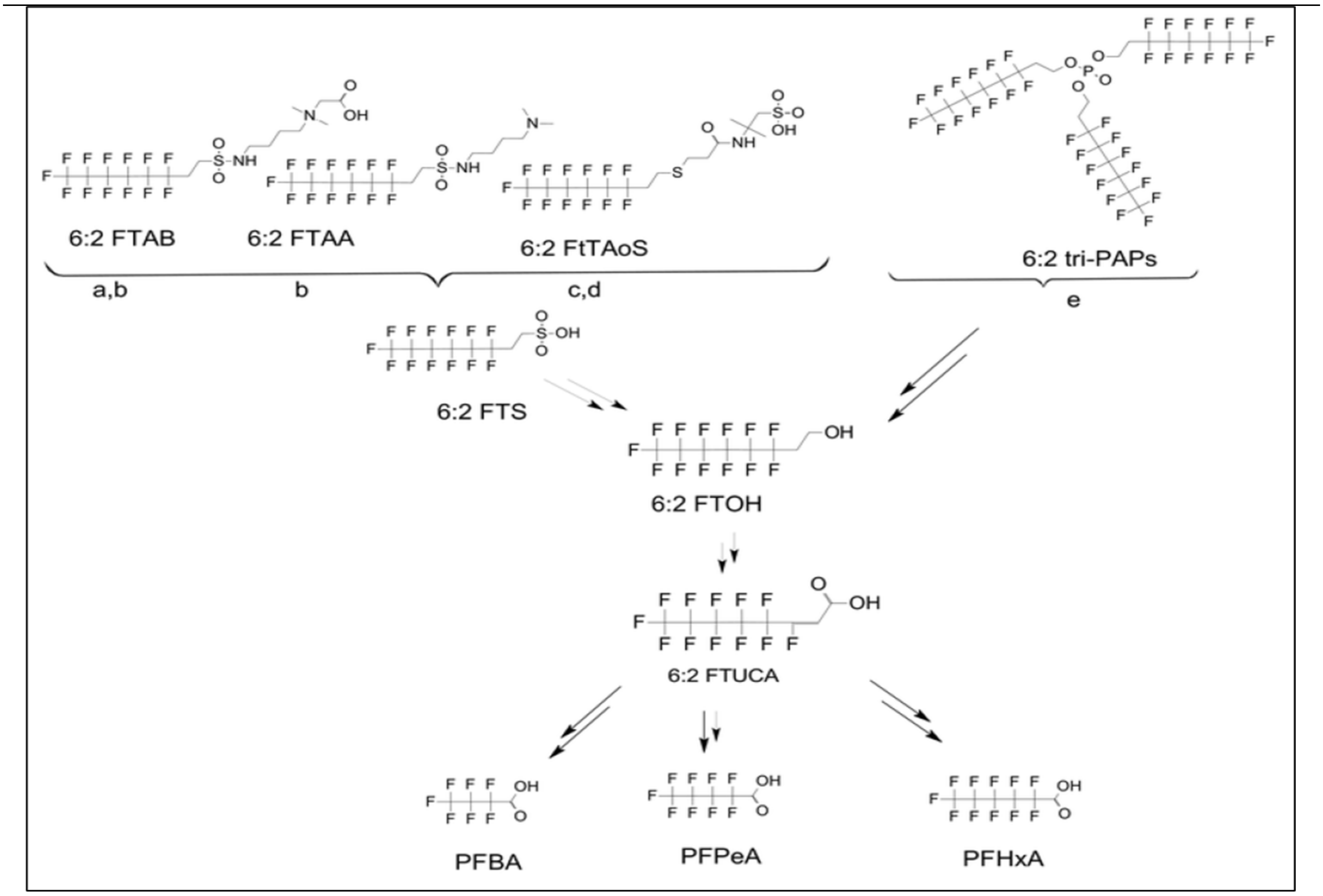
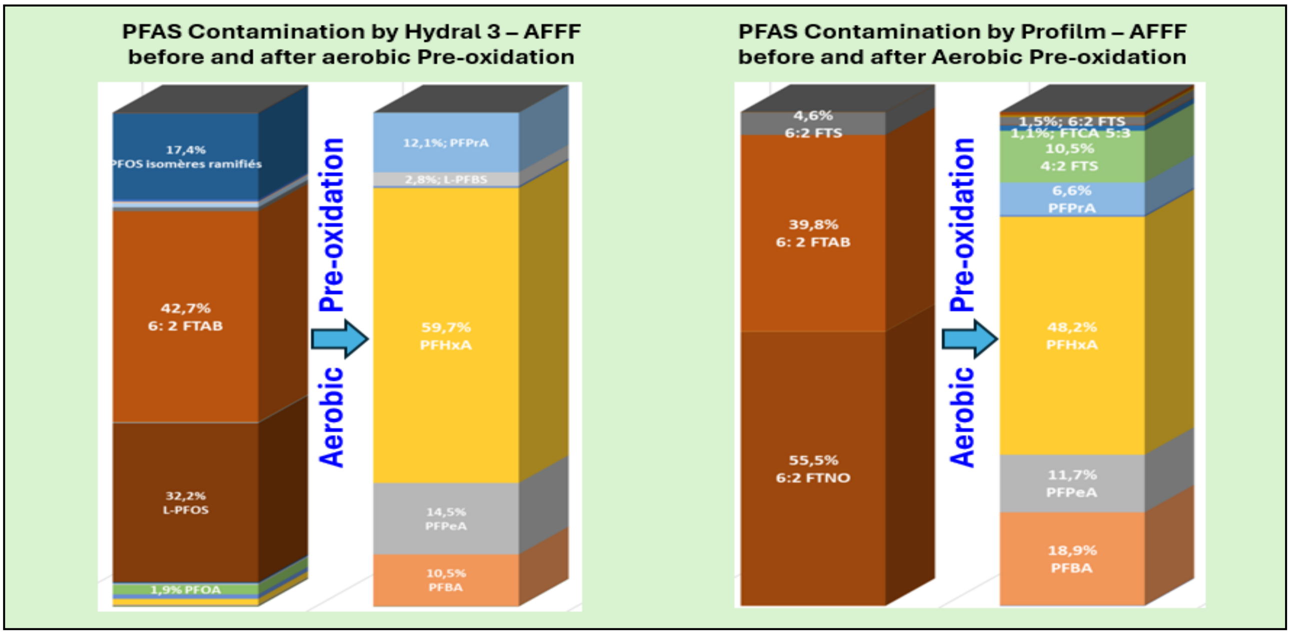


Fig. 9 : Biotransformation des précurseurs poly-fluorés 6 :2-FTAB, 6 :2-FTS, 6:2-FTOH ves les PFCA plus solubles ; PFBA, PFPeA et PFHxA (LaFond et al. 2023, D.M.J. Shaw et al. 2019 ,Ying Shi, 2018 et V. Mendeza et. al. 2022).


PFAS Contamination by Hydral 3 – AFFF before and after aerobic Pre-oxidation

PFAS Contamination by Profilm – AFFF before and after Aerobic Pre-oxidation

Fig. 10. : Biotransformation des précurseurs poly-fluorés 6 :2-FTAB et 6 :2-FTNO ves les PFCA plus solubles ; PFBA, PFPrA, PFPeA et PFHxA via 6 semaines d'oxydation microbiologique aérobie.

L'objectif des traitements par lavage in-situ des zones non-saturées et saturés (aquifères) après la pré-oxydation microbiologique (ou chimique) est d'appliquer un traitement alternatif de réhabilitation in-situ et sur site des PFAS des zones saturées et non saturées et des sols excavés, en utilisant un processus de lavage avec des composés de bio-polymères protéiniques biodégradables et des bêta-cyclodextrines (cf. Fig. 11). Les ingrédients biopolymères tensioactifs spécialement développés sont utilisés pour séparer correctement les PFAS du sol.

Le lixiviat de lavage a également une action positive sur les eaux souterraines et est ensuite pompé de l'aquifère au moyen d'un système de lavage hydraulique

Cette technologie permet l'extraction in-situ et/ou sur place et l'élimination ultérieure des PFAS monomères dans les sols superficiels et profonds sans recourir à des méthodes destructrices telles que l'excavation. Cette approche ne nécessite pas la séparation des différentes fractions granulométriques du sol.

Au cours de la mise au point du processus, l'efficacité de cette approche technique de dépollution est d'abord testée par une étude de faisabilité en laboratoire, puis par une application pilote sur le terrain, suite à la pré-oxydation. La première étape consiste à effectuer des essais à petite échelle sur des colonnes bio-lysimètres de percolation de sol, puis dans les colonnes d'élution de sol et, après quelques semaines (3 à 4), dans le cadre d'une application pilote sur le terrain.

Les acides carboxyliques perfluorés à chaîne courte (comme le PFBA, le PFPeA, etc.) peuvent être lessivés de des sols en utilisant simplement de l'eau comme ingrédient de lavage. Les acides carboxyliques à chaîne plus longue > C8 (PFOA, PFNA, PFDA, PFUnDA, etc.) et les acides sulfoniques (PFOS, PFNS, etc.) sont moins mobiles. La technologie de lavage avec des bio-polymères protéiniques prouve clairement que ces composés peuvent être mobilisés au moyen des biotensides spécialement développés. Des tests lysimétriques ont montré qu'une réduction de 99,9 % de la concentration en PFAS dans le sol est obtenue en appliquant la nouvelle technologie développée. Des applications sur le terrain ont permis de réduire les concentrations de PFAS de plus de 80 % en l'espace de trois semaines.

En comparaison avec l'analyse coût-avantage, les traitements de lavage in situ sont environ 30 fois moins chers que les excavations ou le P&T : Pump and Treat. La technologie est également applicable aux PFAS volatiles, comme les FTOH (alcools fluorotélomères, etc.).

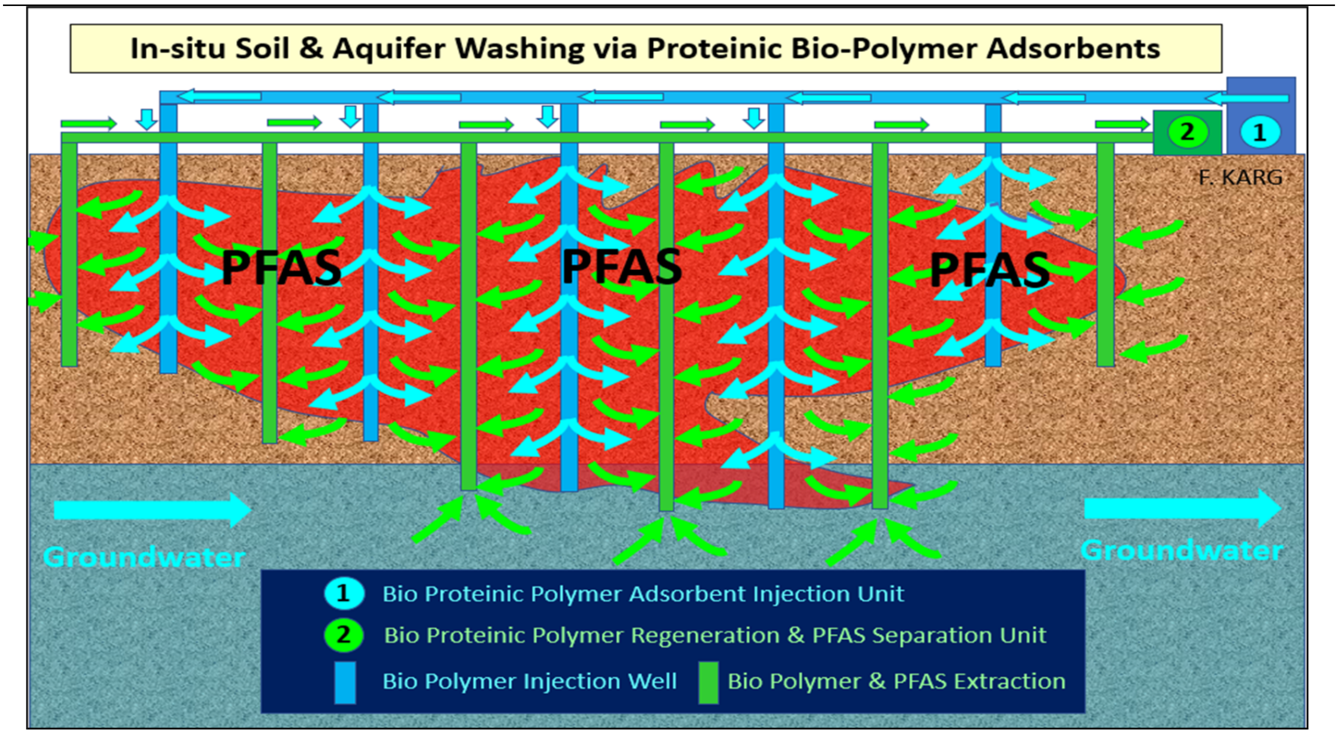


Fig. 11 : Lavage du sol in situ pour la décontamination des PFAS avec des bio-polymères protéiques ou les bêta-cyclodextrines (F. KARG 2024 – 2026).

Le processus offre la possibilité de traiter les sols contenant des PFAS in situ dans la zone saturée et non saturée en mobilisant les PFAS et en traitant ensuite les eaux souterraines à l'aide d'une technologie de pointe. Une autre application possible de la méthode développée qui est actuellement appliquée sur le terrain est le traitement ex-situ des sols excavés contenant des PFAS (sur site et hors site) en utilisant les biopolymères protéiniques par lavage dans une technologie cyclique. A titre réprésentativ

3. Lixiviation des PFAS dans les bétons

Les ‘anciens bétons (< 2024) contient couramment des Adjuvants à la base des PFAS pou leurs effets hydrofuges et plastifiants. Les PFAS les plus lixiviés à partir des bétons sont par ex (selon 24) les PFHxA (>95%) > PFOS (26–84%) ≈ PFHxS (14–78%) > PFOA (<1–54%), cf. Fig. 1). Certain chantiers et sites des bétons anciens (routiers) etc. montrent des pollutions par les PFAS dans les eaux souterraines très significatives. Une graphique (Fig. 12 montre de façon représentative la cinétique de désorption et de lixiviation du PFHxA fortement présent dans les (anciens) adjuvants du béton (selon 24).

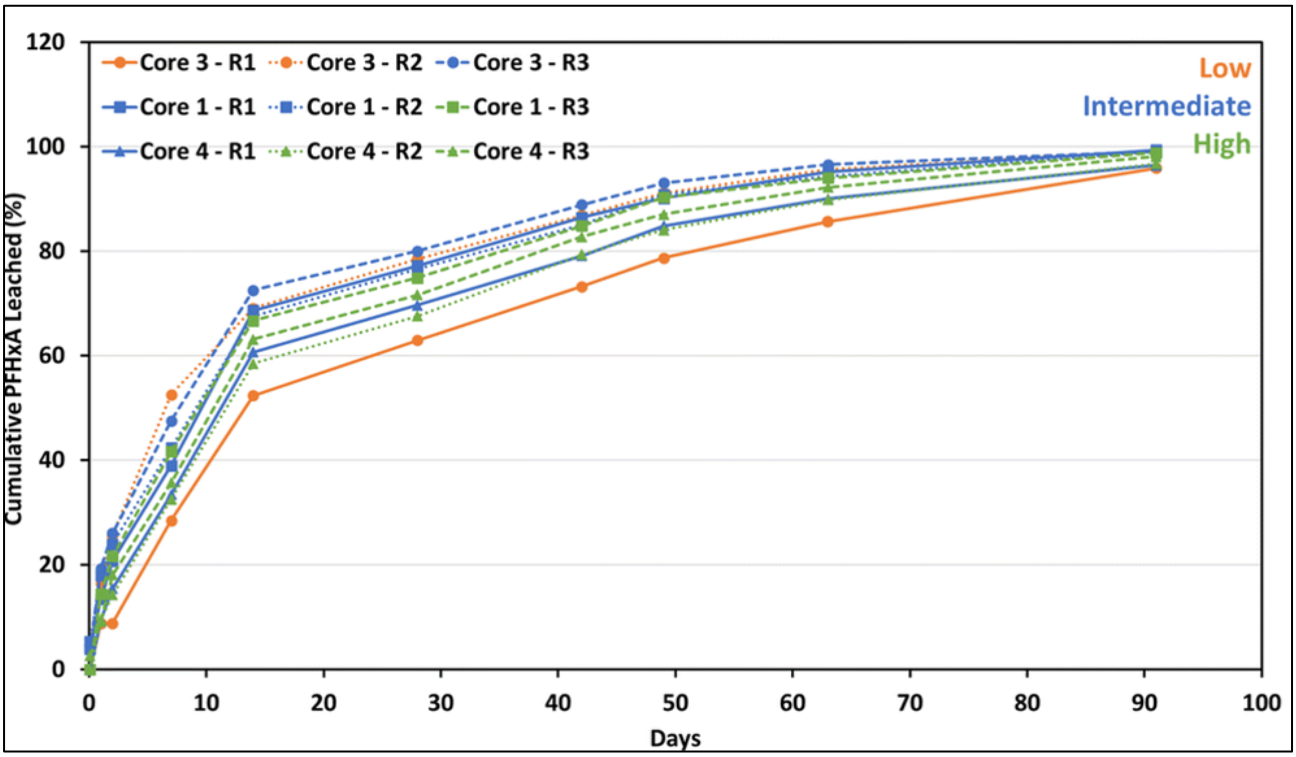


Fig. 12 : Cinétique de désorption et de lixiviation du PFHxA fortement présent dans les (anciens) adjuvants du béton (selon 24).

4. Conclusion

Les évaluations des risques (EQRS et ARR) d'un plan de gestion d'un site pollué aux PFAS doivent tenir compte de la lixiviation des PFAS et de leurs fronts de migration (qui pourraient être modélisés). Les études de faisabilité technico-économiques des stratégies de réhabilitation, notamment par le lavage in-situ ou ex-situ (on-site et off-site) ou par Immobilisation, doivent prendre en compte les capacités de lixiviation et d'élution des différents PFAS.

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European Benchmark of remediation technologies for soil and groundwater polluted by PFAS

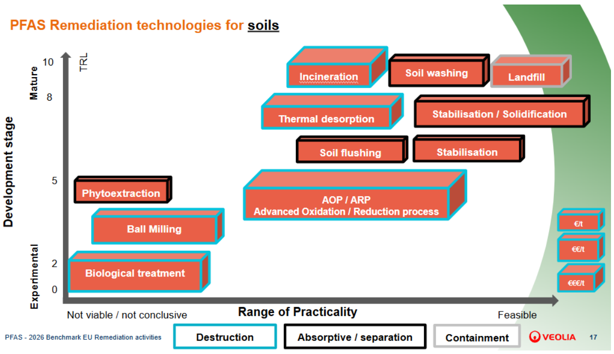
Speaker: Boris Devic-Bassaget, Sarpi Remediation France

VEOLIA |Remediation France, 17, Rue du Périgord - 69330 MEYZIEU - Membre UPDS

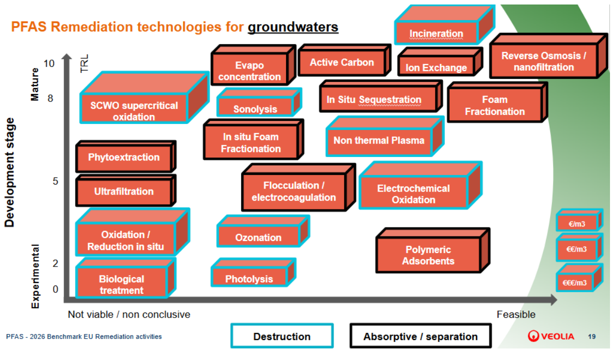
In the management of contaminated sites and soils, interventions remain rare in countries without soil threshold values. This is particularly true in France and Spain, which differ from other European countries.

The existence of regulatory values for soil recovery, as in Belgium and the Netherlands, allows for the regulation of treatment methods for soils contaminated with PFAS by washing, defining an acceptable technical entry threshold to ensure their treatment and final disposal or reuse. For the soil-washing process, PFAS are largely transferred into water, and their treatment is carried out by concentration on filter media (activated carbon, resins). These widely used techniques remain quite expensive in terms of filter media, which do not have very high loading rates, especially for short chains, and are practically ineffective for ultrashort chains.

Following a critical review of the maturity of various PFAS treatment technologies in both soil and water matrices, initial field feedback will be presented: foam fractionation, in-situ thermal desorption or solidification stabilization will be discussed. Finally, future technologies such as Non Thermal Plasma, Sonolysis and those being considered for groundwater management using reactive permeable barriers, with and without pollutant extraction, will be addressed.



PFAS Remediation technologies for **soils**



PFAS Remediation technologies for **groundwaters**

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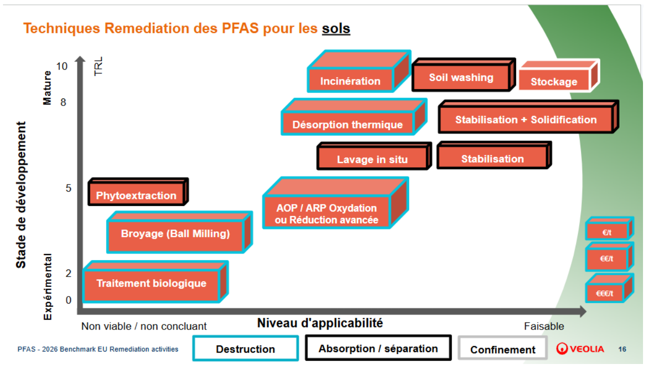
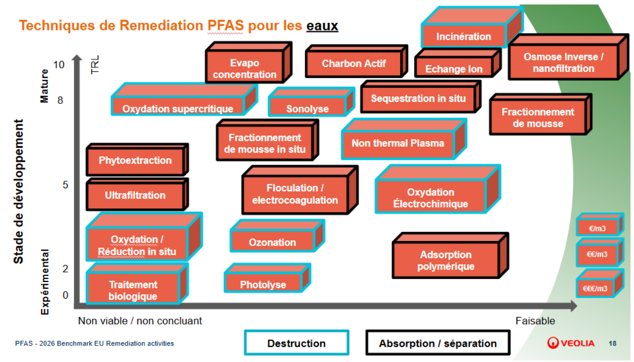
Dans la gestion des sites et sols pollués, les interventions restent encore rares dans les pays qui n'ont pas de valeurs seuil. C'est particulièrement le cas en France et en Espagne qui se différencient des autres pays européens.
L'existence de seuils libératoires réglementaires, comme en Belgique et aux Pays-Bas, permet d'encadrer les modalités de traitement par lavage des terres polluées aux PFAS en définissant un seuil technique d'entrée acceptable pour assurer leur traitement et leur exutoire final. Pour ces sites, les PFAS sont en grande partie transférés dans les eaux de process et leur traitement est réalisé par concentration sur média filtrant (charbon actif, résines). Ces techniques largement répandues restent assez coûteuses en termes de média filtrant qui n'ont pas de taux de chargement très élevés, notamment pour les chaînes courtes, et pratiquement inefficaces pour les chaînes ultracourtes.
Suite à une étude critique des maturités des différentes technologies de traitement des PFAS sur les 2 matrices sol et eaux, des premiers retours terrain seront présentés : la Foam Fractionation, la désorption thermique sur situ ou par stabilisation solidification. Enfin il sera évoqué celles d'avenir, telles que la sonolyse, le non thermal plasma, et celles envisagées pour la gestion des nappes phréatiques par barrières perméables réactives avec et sans extraction des polluants.





Fluoropolymers
Product Group of Plastics Europe

Leading the Way in Responsible Fluoropolymer Management:
FPG's Commitment to Emission Reduction and Sustainable Practices

Conference Abstract
The Fluoropolymers Product Group (FPG) of Plastics Europe represents the leading European manufacturers and importers of fluoropolymers. Fluoropolymers are a specific class of high-performance PFAS that are essential for critical applications e.g., in energy, healthcare and advanced technologies.

FPG members acknowledge their responsibility to address environmental concerns associated with PFAS and have collectively invested in achieving highly ambitious objectives for the reduction of emissions to air and water via an own-initiative Manufacturing Programme. The fluoropolymer industry is at the forefront of emission abatement, implementing state-of the-art technologies and continuously improving operational performance well beyond baseline regulatory requirements.

The FPG Manufacturing Programme is a three-pillar industry commitment covering emissions reduction targets (by end 2024 and 2030), technology sharing, and downstream user guidance. It reflects the fluoropolymer industry's collective commitment to transparency and continuous improvement with the dual aim of demonstrating advanced emission control capabilities and fostering constructive regulatory engagement in support of science-based, proportionate PFAS policy.

Pillar 1 – Emissions Reduction Commitments (Manufacturers in EU+UK)
Binding average emission factor targets for non-polymeric PFAS residues from polymerisation aids technology: 0.009% to air and 0.001% to water by end 2024, tightening to 0.003% and 0.0006% respectively by end 2030. Members also commit to R&D into substitution of PFAS-based polymerisation aids if technically and commercially feasible, engagement with national competent authorities, and improved analytical monitoring of residual emissions.

Pillar 2 – State of the Art Technologies Platform
A shared industry platform to promote uptake of commercially available best practices across emissions control (air and water), industrial hygiene, fugitive emission management, and raw material recovery updated on an ongoing basis, with implementation at each company's discretion.

Pillar 3 – Downstream User Guidance
Members commit to providing downstream fluoropolymer users with updated guidance on safe processing and prevention of environmental release. This is delivered through the Guide for the Safe Handling of Fluoropolymer Resins, complemented by dedicated guidance documents on TFE and on fluoropolymers more broadly, covering the responsible use and handling of these materials throughout the value chain.

Looking ahead, members, who have manufacturing sites in EU+ UK, are exploring a range of potential programme enhancements, including technically feasible and monitorable emission factors for air and water covering the full manufacturing process. A broader technology exchange, a dedicated analytical techniques platform, best practice sharing on solid PFAS waste destruction, and an expanded Safe Handling Guide covering fluoroelastomers and specialty polymers are also under consideration.

FPG - Fluoropolymers Product Group, https://fluoropolymers.eu/
Plastics Europe AISBL, Rue Belliard 40, box 16, 1040 Brussels, Belgium
Transparency Register: 454264611835 56

Keywords:

PFAS management, fluoropolymer, manufacturing Programme, emission control, the guide for safe handling of fluoropolymers, science-based sustainable policies, and transparency & cooperation.

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About Fluoropolymers Product Group (FPG):
The FPG is part of Plastics Europe, the industry association representing European polymer producers. It operates in accordance with the Plastics Europe governance rules, including Competition Compliance Rules. Plastics Europe covers the EU, plus UK, Norway, Turkey and Switzerland.

About Fluoropolymers:
Fluoropolymers are advanced materials that provide unmatched durability, chemical and thermal resistance, and stability in extreme environments. Their unique set of properties makes them essential in many industries, from healthcare and renewable energy to transportation, aerospace and semiconductors

Capture and concentrate PFAS
with recyclable magnetic nanoparticles

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Nowadays, the reprocessing of water is an emergency for our societies. Indeed, more and more organic pollutants like PFAS contaminants are reported and no ideal treatments already exist in waste water plants. Accordingly, we aim to develop a suitable alternative method to achieve PFAS removal from water in respect with the circular economy principles. Thus, we decided to use recycled magnetic iron oxide nanoparticles (MNPs) from steel industries wastes as remediation support. MNPs have recently received a considerable attention because of their potential application for water remediation and their easy magnetic extraction. To improve the stability and the capture efficiency of our support, we coated the MNPs and immobilized covalently β-cyclodextrins on the support by click chemistry (MNP@CD). Recently, β-cyclodextrins (β-CDs) have become a hot topic as potential PFAS adsorbent. It turns out that CDs forms inclusion complexes by host-guest interactions with many perfluoroalkyl substances with high association constants ($K_{PFOA}=5.10^5$ M^{-1}; $K_{PFOS}=7.10^5$ M^{-1}). We will present a new design of MNP@βCD remediation agent to capture PFAS in few minutes using a low energy-consuming magnetic process, an instantly release of the pollutant under its concentrate form and a regeneration of the support for many another cycles (Figure 1).

Figure 1: Capture, extraction, concentration of pollutants, and recycling of the MNP@βCD support

This new extraction process is extremely simple to implement, avoiding synthetic polymer, pyrolyze, and incineration of the support. PFAS are obtained in highly concentrated form allowing their analysis, quantification and degradation.

Patent: Nanoparticules magnétiques fonctionnalisées - procédé d’extraction d’un polluant de type PFAS associé
Gouhier, G.; Gouriou, L.; Rouvière, L., WO2026068905 - PCT/FR2025/050701

PFAS destruction via nonthermal plasma in (waste)water
Focus on ultrashort PFAS and difficult matrices

Wouter De Weirdt, Chief Executive Officer - Tectero (Belgium)

Tectero is a privately owned SME established in 2013 and based in Ghent (Belgium). Tectero BV is ISO 9001 certified since 2021. The main goal and activities of Tectero BV are the development of nonthemal plasma technology for the conversion of liquids and gases and carrying out contract research and development for third parties in the field of green chemistry, renewable energy and environment.

PFAS substances are synthetic compounds with unique properties including high chemical and thermal stability which are very persistent in the environment.

Since the 1940s PFAS have been used in numerous consumer products and industrial applications. PFAS are and have been used in firefighting foams, paints, coatings, textiles, paper, pesticides, pharmaceuticals, etc. PFAS is an omnipresent collection of over 12 000 compounds. The main problem for the environment is attributed to the fact that the carbon-fluorine bond in PFAS is thermodynamically very robust and provides persistence, inertness and stability to PFAS substances.

By applying a nonthermal plasma Tectero BV is able to destroy the carbon-fluorine bond in PFAS. Tectero's nonthermal plasma technology focusses on a continuous flow process and a full destruction and mineralisation of PFAS present in (waste)water. Tectero's process is able to degrade PFAS (both ultrashort, shor, medium and long chain) in many different types of water such as drinking and groundwater with a relative low PFAS load (hundreds of ng/L to tens of µg/L), process water with medium PFAS load (hundred µg/L to mg/L) and leachate water with a combined high PFAS load (mg/l to 5 mg/L) and high salt content. Also emergency response water (for example from fire fighting incidents) can be treated in a similar way. No pre-treatment is required except sand filtration. The process can be integrated as a first bulk remover, a final polishing or stand-alone wastewater treatment step. The process main driver is powered by electricity. When the electricity used is sourced from alternative energy production facilities the complete process if fully sustainable.
In this presentation Tectero BV will provide insight in the practical application results of nonthermal plasma destruction of PFAS in various types of (waste)water with a focus on the destruction of ultrashort PFAS and difficult matrices.

Field experience and evaluation of in situ remediation techniques: (1) immobilization and (2) soil flushing coupled with foam fractionation.

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Objectives

The objective of this presentation is to provide an overview of two innovative remediation techniques developed for the management of PFAS-contaminated soils and groundwater:

- Demonstrate the effectiveness of PFAS immobilization using injection and soil mixing technologies.
- Present laboratory and pilot-scale validation results obtained under different contamination and soil conditions.
- Explain the integration of soil flushing and foam fractionation for active PFAS removal and concentration.
- Discuss the applicability, scalability, and long-term performance of these remediation approaches.
- Introduce the upcoming pilot-scale demonstration within the European LIFE PFASTER project.

Technical Summary

PFAS Immobilization in Contaminated Soil

Immobilization of PFAS in contaminated soil is a promising remediation technique that addresses several limitations associated with conventional soil and groundwater treatment methods. The approach involves the introduction of specific additives into contaminated soil matrices. These additives interact with PFAS molecules through electrostatic and hydrophobic interactions, significantly reducing PFAS mobility and limiting their transfer toward groundwater. Compared with traditional remediation methods such as soil washing, immobilization offers a more practical and economically feasible solution, particularly for large industrial areas where excavation or ex-situ treatment may not be realistic.

The technology has been validated on a laboratory scale, where leachate testing demonstrated PFAS reductions of up to 99.9%, resulting in concentrations below 50 ng/L. Lab scale durability tests further confirmed the longevity of the immobilization effect. Although some decrease in immobilization efficiency may occur over time, PFAS leaching remains significantly reduced compared with untreated conditions.

A pilot-scale application using soil mixing technology was successfully conducted at the Port of Antwerp. Following immobilization treatment, a reduction of 99.1% in PFAS leaching was observed. The field results confirmed the scalability and practical applicability of the technique under real environmental conditions. More details will be shared in the PIGGS-presentation (by Antea and Jan De Nul).

Both injection and soil mixing configurations are possible as implementation methods for in-situ immobilization. These techniques provide flexible deployment options depending on site-specific geological and contamination conditions.

Overall, PFAS immobilization represents a robust and scalable remediation strategy capable of substantially reducing environmental risks associated with PFAS-contaminated sites.

Soil Flushing Combined with Foam Fractionation

Soil flushing combined with foam fractionation is an integrated remediation approach developed to actively remove PFAS from contaminated soil and groundwater systems. The technique relies on the injection of surfactants into the soil to enhance the desorption of PFAS from soil particles and promote their transfer into the aqueous phase. Once mobilized, the contaminated groundwater is extracted, treated, and subsequently re-injected into the soil, creating a controlled recirculation process that improves contaminant recovery efficiency.

Different surfactant injection strategies have been evaluated during the development of the technology. These include: (1) inline dosing using recirculated groundwater as well as (2) the direct injection of surfactant solutions into the soil through DeepFlow technology integrated within the recirculation grid. The extracted groundwater is then treated using foam fractionation, a water treatment process that concentrates PFAS into a significantly reduced waste stream known as foamate. This concentration mechanism is particularly effective for long-chain PFAS compounds (>C7), although process optimization has also demonstrated improved removal of short- and medium-chain PFAS.

Laboratory-scale investigations demonstrated strong remediation performance, with soil flushing achieving PFAS removal efficiencies of up to 95% under optimal conditions, while foam fractionation achieved concentration and removal efficiencies approaching 90%.

Pilot-scale investigations confirmed the scalability and operational feasibility of the combined treatment approach. Soil flushing achieved removal efficiencies of up to 84% in passive ex-situ configurations, while foam fractionation consistently demonstrated PFAS removal efficiencies close to 90%. The addition of co-surfactants significantly enhanced the removal of short- and medium-chain PFAS compounds. For example, removal efficiencies for PFHxA increased from approximately 20% to more than 90%, PFPeA from nearly 0% to more than 80%, and PFBA from nearly 0% to more than 50%.

A further pilot-scale demonstration combining soil flushing and foam fractionation will be conducted during the summer of 2026 as part of the PFASTER project, supported by the European Union LIFE Programme. During this demonstration, multiple operational configurations and different biosurfactants will be evaluated to further optimize treatment efficiency and support the transition toward full-scale implementation.

Overall, the combination of soil flushing and foam fractionation represents a promising and scalable remediation strategy for PFAS-contaminated sites, particularly where active contaminant removal and sustainable groundwater treatment are required.

Decontamination of firefighting foaming agent storage and dosing systems and effluent destruction through SuperCritical Water Oxidation (SCWO)

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The European regulation 2024/2462 of 19 September 2024, which comes into effect in 2026, prohibits the use of fluorinated aqueous film-forming foams (AFFF) which contain PFAS, used by firefighters and fuel depots for decades. With respect to this regulation, it is crucial to understand the technical and environmental aspects of effectively decontaminating equipment, piping, and tanks before transitioning to non-fluorinated foaming agents.

ArianeGroup's Pilot Decontamination Campaign

In this context, ArianeGroup has undertaken a pilot campaign to decontaminate fire-fighting vehicles for French fire-fighters and fuel depots, followed by the destruction of generated effluents. The developed decontamination protocol aims at minimizing vehicle downtime, reducing decontamination effluents, and optimizing process performance.

Innovative Decontamination Solution: SDPerf

Water alone is insufficient for recovering PFAS, which can hardly stick on tank surfaces often stored outdoors for years. ArianeGroup’s chemical formulation teams have developed SDPerf, a PFAS-specific solution that chemically dissolves solidified PFAS layers. Post-decontamination analysis, conducted in an in-house laboratory, ensure fast results within 2 days, reducing vehicle downtime. The use of SDPerf also limits rinse water volumes, thereby minimizing transportation and treatment costs as well as environmental impacts.

Environmentally Friendly PFAS Destruction: ELIXIR® SCWO Technology

Since 2017, ArianeGroup has been exploring more environmentally friendly alternatives to dispose its energetic material wastes. In partnership with Aquarden Technologies, ArianeGroup demonstrated the industrial-scale performance of the ELIXIR® SuperCritical Water Oxidation (SCWO) technology for the destruction for organic substances destruction. Supercritical water (> 221 bar and > 374°C) successfully mineralize PFAS, including short chains, by breaking the carbon-fluorine bond. ELIXIR® enables efficient treatment of PFAS-polluted tank and piping decontamination water.

Pilot Campaign learnings

Learnings from this pilot campaign will be presented, including PFAS destruction performance, along with information about the environmental and energetic characteristics of the implemented solutions. Additionally, we will share destruction results obtained with more concentrated wastes, such as pure AFFF and TFA.

Microalgal-Based Carbon Encapsulated Iron Nanoparticles as Novel Adsorbents for PFAS Removal: From Dye Proxies to Target Compounds

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This study evaluates the performance of microalgal-based carbon-encapsulated iron nanoparticles (ME-nFe), containing iron oxides and zero-valent iron, for the adsorption of PFAS from aqueous solution and the use of synthetic dyes as cost-effective proxies during adsorbent optimization. ME-nFe were produced by hydrothermal carbonization of microalgae grown in the liquid fraction of municipal digestate.

The encapsulation of iron makes the material more stable in water and magnetically recoverable. ME-nFe have already been successfully employed, at laboratory scale, for the removal of heavy metals (Mantovani et al., 2023) and pharmaceuticals compounds (Mantovani et al., 2024), showing promising results.

A preliminary removal study was conducted using dyes selected as proxies, since their adsorption kinetics are similar to those of PFAS (Sörengård et al., 2020): based on their log Kd, Procion Red, 3B Red, Methyl Orange and Sudan Black are held to closely reproduce the adsorption behaviour of medium- and long-chain PFAS on ME-nFe. While PFAS analysis rely on costly HPLC-MS detection and quantification, the dyes can be easily quantified by UV-vis spectrophotometry. Removal experiments were carried out at a constant temperature of 25 °C, varying pH values (3, 4, 6, and 7,4) and contact times (2, 5, 20 and 200 minutes) to identify the most favorable operational conditions for the application of the method. Experimental results showed that dye removal by ME-nFe nanoparticles was influenced by both contact time and solution pH. For all dyes, removal efficiency increased with contact time, reaching equilibrium after approximately 20 minutes. However, the effect of pH varied depending on the properties of each dye. The best removal of cationic dyes (Methylene Blue, Crystal Violet and Malachite Green) was obtained under neutral conditions (pH 6–7.4), and was over 95%. Conversely, anionic dyes (Procion Red MX-5B, Cibacron Brilliant Red 3B-A and Methyl Orange) were more efficiently adsorbed under acidic conditions (pH 3–4), with removal efficiencies between 70% and 95%. The hydrophobic dye Sudan Black B was more effectively removed (84–87%) at acidic pH (3–4) too. Dye adsorption is affected by electrostatic interactions with the ME-nFe nanoparticles, whose point of zero charge occurs at pH ≈ 6.4 (M. Mantovani et al., 2023), as well as by the ionic form of the dye, which depends on the ratio between its pKa and the solution pH (Saha et al., 2011), and by its molecular structure.

After determining the optimal conditions using the dye proxies, the PFAS removal tests were performed using a standard solution of known concentration containing various length PFAS. The results of the PFAS tests confirmed the initial hypothesis regarding the importance of pH in determining the effectiveness of their adsorption (Figure 1). The different doses of nanoparticles yielded comparable results, suggesting that the treatment is effective even at the lowest dose. In particular, the best results were obtained at pH 3 with of 2 g ME-nFe /L, with removal efficiencies over 92% for PFOS, PFDA, PFUnDA, and PFDoDA, and 62% for PFOA. Conversely, short-chain PFAS were not effectively removed at pH 3. PFPeA (5 carbon atoms) was more effectively removed at pH 6, with a final efficiency of 54%. Statistical analyses confirmed the initial hypothesis regarding the use of dyes to predict the behavior of nanoparticles toward PFAS. Specifically: at pH 3, Procion Red MX-5B acts as a proxy for PFOS and PFDA; Cibacron Brilliant Red 3B-A and Sudan Black are proxies for PFNA, as is Methyl Orange, although to a lesser extent; Malachite Green and Methylene Blue can also be considered proxies for PFOA. At pH 6, Methyl Orange and Cibacron Brilliant Red 3B-A serve as proxies for PFHxA, PFHpA, PFOA, PFNA, PFDA, PFUnDA, PFDoDA, and PFBS; Sudan Black is a proxy for PFUnDA. The differing effectiveness of the nanoparticles against these compounds may be due to interaction and adsorption mechanisms other than electrostatic ones.

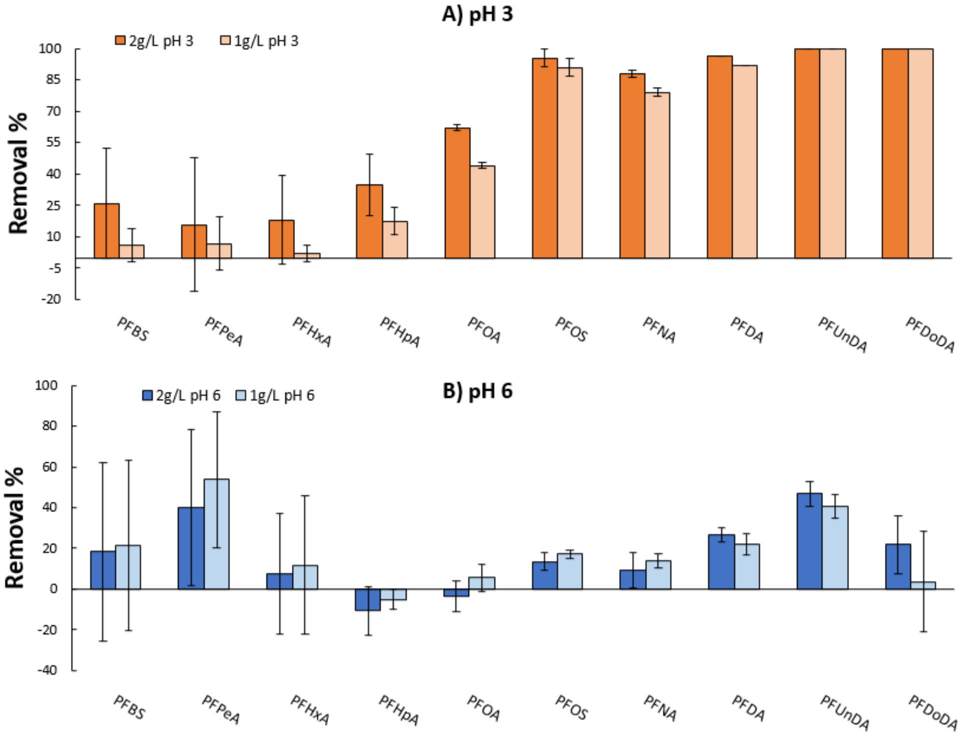

Figure 1. Percent removal of PFBS, PFPeA, PFHxA, PFHpA, PFOA, PFOS, PFNA, PFDA, PFuNDA, PFDoDA. Figure A) shows result at pH 3 for both Me-nFe dosages; Figure B) shows result at pH 6. Data are presented as average and st.dev (n=4).

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Pilot-Scale Demonstration of PFAS Immobilization in Soil and Groundwater (PIGGS Project)

Presenters

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Innovative Nature

This study presents an integrated pilot-scale demonstrations combining PFAS immobilization, rapid total-PFAS field screening, and dual-depth application techniques (soil mixing and subsurface injection). The project evaluates a newly developed immobilization additive (JDN).

Keywords

PFAS, immobilization, soil remediation, groundwater, soil mixing, injection, pilot study, field screening

Objectives

- To demonstrate the feasibility and effectiveness of PFAS immobilization using the JDN additive.
- To assess the performance of soil mixing and injection as delivery techniques for the immobilization reagent.
- To quantify PFAS leachate reduction under field conditions and compare results with laboratory-scale tests.
- To evaluate long-term stability.

Summary

In the framework of KIS VZW (Knowledge centre for Innovative Remediation Solutions), a pilot-scale demonstration of PFAS immobilization was carried out in Flanders (Belgium). The pilot test was executed by Soetaert (Jan De Nul foundations) on a site made available by Port of Antwerp-Bruges. For performance monitoring, an innovative rapid PFAS screening technique developed by Ghent University was applied, enabling detection of total PFAS concentrations within hours. The JDN additive used for immobilization was specifically developed by Envisan (Jan De Nul site remediation). The immobilisation will be monitored by Antea Group for a period of eighteen months.

The objective of the PIGGS project is to evaluate the feasibility and effectiveness of PFAS immobilization using the JDN additive for both shallow contamination (via soil mixing in the unsaturated zone) and deeper contamination (via Deepflow^{TM} injection into the saturated zone). Two PFAS contaminated test zones were selected. Initial leachate concentrations ranged from 12,000–27,000 ng/L in the injection zone and 8,900 ng/L in the soil-mixing zone, with PFOS as the dominant compound (92%). Short-chain PFAS represented only 4% of the eluted fraction.

Preceding the field test, laboratory experiments were conducted on site-specific soils to optimize design and dosing. A 1% additive dosage yielded an average PFAS leachate reduction of 98%. After treatment, PFAS leaching decreased to 224–503 ng/L in the injection zone and to 166 ng/L in the soil-mixing zone. For reference, the EU limit for drinking water is the sum of 20 PFAS ≤ 100 ng/l and the sum of measured PFAS ≤ 500 ng/l. PFOS immobilization efficiency reached 99.9%, while short-chain PFAS removal averaged 73%. Increasing the additive dosage provided only marginal additional benefit; therefore, a 1% dosage was selected for both test zones.

Soil mixing, based on deep soil mixing foundation techniques, ensured homogeneous additive distribution and proceeded without operational issues. Injection results were impacted by challenging geological conditions at the test site, particularly the presence of very fine and compacted sand. Despite several optimisation efforts and repeated adjustments, the injection performance remained limited under these site-specific conditions.

Monitoring during the first six months after immobilization showed a stable immobilization efficiency of 98-99%. Similar performance was achieved for short-chain PFHxSA (91% efficiency). The interpretation of the results is influenced by background PFAS concentrations present in the surrounding soil and groundwater. In particular, treated soils below the groundwater table show some variability in leaching behaviour. Additional long-term monitoring over one more year will allow further validation of the treatment performance and stability over time.

On a laboratory scale, the durability of the immobilization is subjected to cycles of freezing/thawing and wetting/drying. The immobilized samples reacted differently to each test. Therefore, it is not just the dosage and the immobilization additive that determine the success of the immobilization. More data needs to be collected to predict the parameters of a successful immobilization.

The PIGGS project provides an extensive evaluation of PFAS immobilization performance, operational considerations, and monitoring approaches. Based on the lessons learned, the technique can be further developed for full-scale application across a range of PFAS-impacted environments.

Treatment of PFAS in industrial effluents by reverse osmosis coupled to electro-oxidation of membrane concentrate

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1. Introduction

Per- and polyfluoroalkyl substances (better known by the acronym PFAS) are organo-fluorinated molecules characterized by the presence of an alkyl group of carbon atoms that are either fully per- or partially polyfluoroalkylated at one end, while the other end is a diverse functional group (carboxylic, sulfonic, sulfonamide, alcohol, iodide, alkene) [1, 2]. Their chemical and thermal inertness, combined with their harmful effects on health, their ubiquity, and the need for new treatment standards, explain the interest in developing treatment processes [2, 3, 4]. The objective of this study is to investigate an innovative treatment process for concentrate and destroy PFAS in industrial effluents in situ. Reverse osmosis is first used to concentrate the PFAS, and the concentrate is then subjected to destructive treatment by electro-oxidation. Membrane permeates and electro-oxidation-treated concentrates are PFAS-depleted streams that can be mixed before discharge. In this context, the treatment of real and synthetic effluents with high PFAS concentrations (several mg.L^{-1}) by reverse osmosis and electro-oxidation was carried out.

2. Materials and methods

A reverse osmosis pilot (Osmonics SG) equipped with a flat-plate membrane was used to filter TFA, PFBA, PFPeA, or PFOA and a mixture of 9 PFAS (PFBA, PFPeA, PFHxA, PFHpA, PFOA, PFNA, PFuNDA, PFBS, Gen-X) at concentrations between 7 and 60 mg.L^{-1} in ultrapure water. Water permeability measurements were performed between filtrations to validate membrane fouling. Two real wastewater samples contaminated with PFAS present in firefighting foams were then treated: runoff water (Σ_{21}PFAS = 136 µg.L^{-1}, including 128 µg.L^{-1} of TFA) and groundwater (Σ_{21}PFAS = 90 µg.L^{-1}, including 69 µg.L^{-1} of TFA) from an industrial area. The retention of trifluoroacetic acid (TFA) by reverse osmosis will be specifically investigated.

An electro-oxidation pilot plant with a boron-doped diamond anode (anodic surface area of 160 cm^2) and two steel cathodes was used to degrade PFAS in solution in ultrapure water, at concentrations close to reverse osmosis concentrates (between 24 and 360 mg.L^{-1}). Two real effluents, namely firefighting water (Σ_{35}PFAS=1.15 mg.L^{-1}, predominantly 6:2 FTAB at 1.03 mg.L^{-1} and 6:2 FTS at 0.11 mg.L^{-1}, TOC=218.8 mg.L^{-1}) and a synthesis reactor purge (PFHxA=5638 mg.L^{-1}), were also treated. To directly and indirectly assess retention by membrane processes and degradation by electro-oxidation, PFAS were analyzed by LC-MS/MS chromatography, and measurements of total organic carbon (TOC) and conductivity were performed.

3. Results

In the case of reverse osmosis, due to a concentration phase upstream of the membrane, TFA exhibits an initial rejection of 90.8 %, which increases and stabilizes at 95 %. PFBA also shows increasing rejections, from 95 % to 98 %. The other PFAS exhibit constant rejections, ranging from 98 % to 99.99 %. The nine PFAS in cocktail showed rejection rates ranging from 96.7 % to 99.9 % for all PFAS. PFAS were slightly better retained in cocktails than alone, due to potential pore blockage by long-chain PFAS

[5]. In real wastewater, reverse osmosis achieved retention rates of 97 % (runoff water) and 99.7 % (groundwater) for the 15 PFAS analyzed. TFA was retained at 99.6 % and 99.7 % for runoff and groundwater, respectively. The lower PFAS retention in runoff may be related to the high conductivity of the effluent (14.29 $mS \cdot cm^{-1}$). However, PFAS retention by reverse osmosis was minimally affected by the type of water treated.

Regarding PFAS treatment by electro-oxidation, C_2-C_{11} carboxylic acid PFAS were degraded between 75 % and 99.99 % and defluorinated between 22 % and 99.99 % after 4 hours of electrolysis. Short-chain (PFBA, PFPeA, PFHxA, Gen-X) and ultrashort-chain (TFA, PFPrA) PFAS were more degraded and defluorinated than long-chain (PFHpA, PFOA, PFNA, PFuNDA) PFAS. C_6 sulfonic acid PFAS (PFBS) was less degraded than its carboxylic acid equivalent (PFHxA), with 12 % degradation and 10 % defluorination, compared to 97 % degradation and 75 % defluorination for PFHxA. This difference has been observed in other studies and could be related to a more stable sulfonate group [6]. It is observed that in most cases, PFAS degradation is greater than TOC degradation and defluorination, indicating that PFAS is more frequently degraded into byproducts than mineralized. Short- and ultra-short-chain PFAS are rapidly mineralized, and byproduct formation increases with increasing perfluorinated chain length.

Regarding the treatment of real effluents, PFHxA in the blowdown was degraded by 96.8 % after 3 hours of electrolysis (residual of 40.8 $mg.L^{-1}$) and by 99.6 % (residual of 2.7 $mg.L^{-1}$) after 7 hours of treatment. For fire suppression water, electrochemical treatment resulted in rapid degradation of 6:2 FTAB, which was degraded by 95.15 % in just 30 minutes and by more than 98.16 % after 4 hours of treatment. The formation of 6:2 FTS and short-chain PFAS (PFHxA, PFPeA, and PFBA) at concentrations higher than their initial levels was observed after 1 hour of treatment. Their formation reflects the 6:2 FTAB degradation mechanism, which is first degraded to 6:2 FTS, then to PFHxA, PFPeA and PFBA [7]. All of these PFAS also underwent significant degradation, and after 4 hours of treatment, all PFAS were degraded below their limits of quantification, resulting in an overall degradation of over 98.46 %. A TOP essay of the effluent after 4 hours of treatment did not lead to the formation of additional PFAS, indicating that all PFAS were degraded by the process. TOC was linearly degraded up to 3 hours of electrolysis, at which point it was almost completely degraded (89.72 %). Extending electrolysis to 6 hours resulted in 92 % TOC degradation.

4. Conclusion

Reverse osmosis demonstrated very high retention rates, even for smaller PFAS. These results confirm the value of reverse osmosis for concentrating PFAS prior to oxidation. Whether applied to synthetic solutions or actual effluents, PFAS retention by reverse osmosis was only slightly affected. Electro-oxidation effectively degraded all PFAS, with the best mineralization performance achieved for short- and ultra-short-chain PFAS. This process combination also proved effective for treating real effluents.

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ADDITIONAL SUMMARIES

Puratech – Reducing the cost of PFAS treatment

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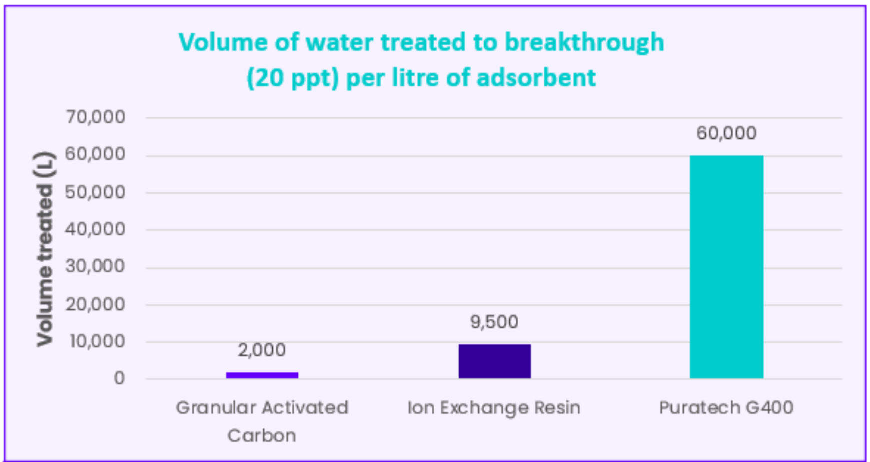
Introduction

Puraffinity is a London based developer, manufacturer and supplier of novel adsorbent medias for PFAS treatment. In 2025 we commercialized our first product, Puratech, which is an Alumina Based Surface Functionalized Media. Puratech operates at Empty-Bed-Contact-Times as low as 30 seconds which provides significant OPEX, CAPEX and sustainability benefits compared to traditional PFAS removal technologies such as Granular Activated Carbon (GAC). Puratech can be installed as the standalone technology for PFAS removal or as part of a treatment train for more complex waters such as landfill leachate.

Puratech is specifically designed for PFAS capture which enables a significantly greater volume of water to be treated per litre of adsorbent media (Fig.1 below). This in turn results in reduced total cost of treatment via; reduced adsorbent media volumes (up to 40x less than GAC), reduced disposal costs, reduced CAPEX through smaller installations and reduced OPEX through longer media lifespan and less frequent changeouts.



PFAS Species	PFOS	PFOA	GenX	PFHpA	PFNA	PFHxS
Conc (ppt)	1000	500	900	40	50	300

Figure 1: Volume of water treated per litre of three adsorbent medias

Our first full-scale application was installed in Sweden in June 2025 with our customer, Envytech AB. We deployed our product at 20 m3/hr for remediation of contaminated groundwater from a large infrastructure project. The site has been undergoing long-term remediation due to the leaching of historic Aqueous Film Forming Foam (AFFF). After a successful pilot, the client decided to switch from GAC to Puratech due to its increased performance and total treatment cost reduction.

As a result, the client replaced 4,000 L of GAC with 200 L of Puratech (see Fig. 2 for comparison), whilst also benefiting from an estimated 50% increase in adsorbent lifespan. This significant reduction in media volume and replacement frequency highlights the ability of Puratech to reduce both CAPEX and OPEX, ultimately lowering the total cost of treatment with a 40-fold reduction in material volume and a 95% lower carbon dioxide equivalent (CO2e) footprint.

Figure 2: Puraffinity PFAS system (200L of media) which replaced a 4,000L GAC system.

In addition to remediation projects, we are operating across potable water, landfill leachate, industrial effluent and more. Puratech is a genuinely novel and commercially available technology that is being applied today to contain PFAS from water in real world applications. We can support from lab trials through to full-scale service offering with a strong Engineering Team to support our clients in the field and a dedicated Product Development team iterating further next generation products.

Challenges and opportunities of PFAS removal by adsorption with granular activated carbon (GAC) using mobile filters and industrial reactivation of PFAS-loaded activated carbon

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Per- and polyfluoroalkyl substances (PFAS) represent one of the most pressing challenges in environmental and water protection due to their persistence, mobility, and potential toxicity. Increasing regulatory restrictions at national and European levels are driving the demand for technically robust, scalable, and sustainable remediation solutions for already contaminated environmental media. Adsorptive treatment using granular activated carbon (GAC) is a well-established approach, that can be optimized and adapted to a wide range of PFAS profiles and application scenarios.

This contribution addresses current challenges and opportunities in PFAS removal using GAC and presents experimental results on the adsorption performance of activated carbons derived from different raw materials toward short- and long-chain PFAS. The materials are systematically compared and classified according to their suitability for specific treatment applications. In addition, mobile GAC filtration systems are introduced as flexible, practice-oriented solutions for soil, drinking water, and wastewater treatment, including operational concepts, service models, and logistical advantages.

Further focus of this work is the subsequent industrial thermal reactivation of PFAS-loaded GAC. The results demonstrate that complete mineralization of adsorbed PFAS can be achieved under controlled process conditions, thereby preventing the formation and release of secondary or degradation products. By integrating adsorption performance, mobile treatment concepts, and safe end-of-life management of activated carbon, this contribution provides a comprehensive and application-oriented approach to advancing sustainable PFAS remediation strategies.

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