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ITN PERFORCE3

PER and polyfluorinated alkyl substances towards the **F**uture **O**f **R**esearch and its **C**ommunication in **E**urope

Policy input: Comments on the EU PFAS Annex XV Restriction report

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1. Introduction to PERFORCE3

The ITN (Innovative Training Network) PERFORCE3 (PER and polyfluorinated alkyl substances (PFASs) towards the Future Of Research and its Communication in Europe 3) is a Europe-wide multi-partner doctoral research training programme in the field of PFASs contaminants coordinated by Stockholm University and funded by the European Union's Horizon 2020 research and innovation programme under its Marie Skłodowska-Curie Actions.

Website for further information: https://perforce3-itn.eu/

This document is provided with the PERFORCE3 comments on the EU PFAS Annex XV restriction report.

2. Additional information from recent literature

2.1. Degradation potential of specific PFAS sub-groups

Licul-Kucera, V.; Frömel, T.; Kruså, M.; van Wezel, A. P.; Knepper, T. P. Finding a Way out? Comprehensive Biotransformation Study of Novel Fluorinated Surfactants. Chemosphere 2023, 339, 139563. https://doi.org/https://doi.org/10.1016/j.chemosphere.2023.139563.

Brief summary and explanation of its importance: In a new study, the environmental fate of two trifluoromethoxy-substituted surfactants was investigated. Degradability was tested in aerobic activated sludge over 126 days. No mineralisation was observed. The main transformation products were carboxylic acids with ≤3 fluorinated carbon atoms.

2.2. Analytical techniques

Cioni, L.; Nikiforov, V.; Coêlho, A. C. M. F.; Sandanger, T. M.; Herzke, D. Total Oxidizable Precursors Assay for PFAS in Human Serum. Environ. Int. 2022, 170, 107656. https://doi.org/https://doi.org/10.1016/j.envint.2022.107656.

Abstract: Per- and polyfluoroalkyl substances (PFAS) are a class of chemicals including over 4700 substances. As a limited number of PFAS is routinely analyzed in human serum, complementary analytical methods are required to characterize the overlooked fraction. A promising tool is the total oxidizable precursors (TOP) assay to look for precursors by oxidation to perfluoroalkyl acids (PFAA). The TOP assay was originally developed for large volumes of water and had to be adapted for 250 µL of human serum. Optimization of the method was performed on serum samples spiked with model precursors. Oxidative conditions similar to previous TOP assay methods were not sufficient for complete oxidation of model precursors. Prolonged heating time (24 h) and higher oxidant amount (95 mg of Na2S2O8 per 225 µL of serum) were needed for complete conversion of the model precursors and accomplishing PFAA yields of 35–100 %. As some precursors are not fully converted to PFAA, the TOP assay can only provide semi-quantitative estimates of oxidizable precursors in human serum. However, the TOP assay can be used to give indications about the identity of unknown precursors by evaluating the oxidation products, including perfluoroalkyl sulfonic acids (PFSA) and perfluoroalkyl ether carboxylic acids (PFECA). The optimized TOP assay for human serum opens the possibility for high-throughput screening of human serum for undetected PFAA precursors.

Haque, F.; Soerensen, A. L.; Sköld, M.; Awad, R.; Spaan, K. M.; Lauria, M. Z.; Plassmann, M. M.; Benskin, J. P. Per-and Polyfluoroalkyl Substances (PFAS) in White-Tailed Sea Eagle Eggs from Sweden: Temporal Trends (1969--2021), Spatial Variations, Fluorine Mass Balance, and Suspect Screening. Environ. Sci. Process. \& Impacts 2023.

Abstract: Temporal and spatial trends of 15 per- and polyfluoroalkyl substances (PFAS) were determined in white-tailed sea eagle (WTSE) eggs (Haliaeetus albicilla) from two inland and two coastal regions of Sweden between 1969 and 2021. PFAS concentrations generally increased from ~1969 to ~1990s–2010 (depending on target and site) and thereafter plateaued or declined, with perfluorooctane sulfonamide (FOSA) and perfluorooctane sulfonate (PFOS) declining faster than most perfluoroalkyl carboxylic acids (PFCAs). The net result was a shift in the PFAS profile from PFOS-dominant in 1969–2010 to an increased prevalence of PFCAs over the last decade. Further, during the entire period higher PFAS concentrations were generally observed in coastal populations, possibly due to differences in diet and/or proximity to more densely populated areas. Fluorine mass balance determination in pooled samples from three of the regions (2019–2021) indicated that target PFAS accounted for the vast majority (i.e. 81–100%) of extractable organic fluorine (EOF). Nevertheless, high resolution mass-spectrometry-based suspect screening identified 55 suspects (31 at a confidence level

[CL] of 1–3 and 24 at a CL of 4–5), of which 43 were substances not included in the targeted analysis. Semi-quantification of CL ≤ 2 suspects increased the identified EOF to >90% in coastal samples. In addition to showing the impact of PFAS regulation and phase-out initiatives, this study demonstrates that most extractable organofluorine in WTSE eggs is made up of known (legacy) PFAS, albeit with low levels of novel substances.

2.3. Scope

Rehnstam S., Czeschka M.B. and Ahrens L., 2023. Suspect screening and total oxidizable precursor (TOP) assay as tools for characterization of per- and polyfluoroalkyl substance (PFAS)-contaminated groundwater and treated landfill leachate. Chemosphere, 334, 138925.

Brief summary and explanation of its importance: In this study, landfill leachate treated in a conventional wastewater treatment plant and PFAS-contaminated groundwater were subjected to suspect screening analysis and semi-quantification using total oxidizable precursor (TOP) assay and liquid chromatography coupled to high-resolution mass spectrometry (LCHRMS). Suspect screening identified a total of 28 PFAS, of which six were not included in the targeted method and were identified with confidence level (CL) ≥3. This study supports the group approach for regulation of PFAS.

Joerss H., Menger F., Tang J., Ebinghaus R. and Ahrens L., 2022. Beyond the Tip of the Iceberg: Suspect Screening Reveals Point Source-Specific Patterns of Emerging and Novel Per- and Polyfluoroalkyl Substances in German and Chinese Rivers. Environ. Sci. Technol., 56**,** 5456–5465.

Brief summary and explanation of its importance: In total, 86 PFAS were identified and grouped into 18 structure categories. Homologue patterns revealed distinct differences between fluoropolymer production sites in China and Germany. In the Chinese Xiaoqing River Basin, the C8 homologue was the most prevalent compound of the emerging series of chlorinated perfluoroalkyl carboxylic acids (Cl-PFCAs) and perfluoroalkylether carboxylic acids (PFECAs). In contrast, C6 and shorter homologues were dominant in the German Alz River. The large number of identified unregulated PFAS underlines the importance of a grouping approach on a regulatory level, whereas the revealed contamination patterns can be used to estimate, prioritize, and minimize contributions of specific sources.

2.4. Emissions

Gobelius L., Glimstedt L., Olsson J., Wiberg K. and Ahrens L., 2023. Mass flow of per- and polyfluoroalkyl substances (PFAS) in a Swedish municipal wastewater network and wastewater treatment plant. Chemosphere, 336, 139182.

Brief summary and explanation of its importance: This study assessed mass flows of 26 PFAS in a wastewater network and WWTP, to provide new insights into their sources, transport, and fate in different treatment steps. Wastewater and sludge samples were collected from pumping stations and the main WWTP in Uppsala, Sweden. Overall, PFAS were not efficiently removed in the WWTP, with mean removal efficiency of 10 ± 68% for individual PFAS, resulting in discharge of 7000 mg/d for Σ26PFAS into the recipient. This shows that conventional WWTPs are inefficient in removing PFAS from wastewater and sludge, so advanced treatment techniques are needed.

2.5. Exposure

Ragnarsdóttir, O.; Abdallah, M. A.-E.; Harrad, S. Dermal Uptake: An Important Pathway of Human Exposure to Perfluoroalkyl Substances? Environ. Pollut. 2022, 307, 119478. https://doi.org/https://doi.org/10.1016/j.envpol.2022.119478.

Abstract: Per- and polyfluoroalkyl substances (PFAS) have been produced and used in a broad range of products since the 1950s. This class, comprising of thousands of chemicals, have been used in many different products ranging from

firefighting foam to personal care products and clothes. Even at relatively low levels of exposure, PFAS have been linked to various health effects in humans such as lower birth weight, increased serum cholesterol levels, and reduced antibody response to vaccination. Human biomonitoring data demonstrates ubiquitous exposure to PFAS across all age groups. This has been attributed to PFAS-contaminated water and dietary intake, as well as inadvertent ingestion of indoor dust for adults and toddlers. In utero exposure and breast milk have been indicated as important exposure pathways for foetuses and nursing infants. More recently, PFAS have been identified in a wide range of products, many of which come in contact with skin (e.g., cosmetics and fabrics). Despite this, few studies have evaluated dermal uptake as a possible route for human exposure and little is known about the dermal absorption potential of different PFAS. This article critically investigates the current state-of-knowledge on human exposure to PFAS, highlighting the lack of dermal exposure data. Additionally, the different approaches for dermal uptake assessment studies are discussed and the available literature on human dermal absorption of PFAS is critically reviewed and compared to other halogenated contaminants, e.g., brominated flame retardants and its implications for dermal exposure to PFAS. Finally, the urgent need for dermal permeation and uptake studies for a wide range of PFAS and their precursors is highlighted and recommendations for future research to advance the current understanding of human dermal exposure to PFAS are discussed.

M F Coêlho, A. C.; Cioni, L.; Van Dreunen, W.; Berg, V.; Rylander, C.; Urbarova, I.; Herzke, D.; Sandanger, T. M. Legacy Perfluoroalkyl Acids and Their Oxidizable Precursors in Plasma Samples of Norwegian Women. Environ. Int. 2023, 178, 108026. https://doi.org/https://doi.org/10.1016/j.envint.2023.108026.

Abstract: Humans are exposed to perfluoroalkyl acids (PFAA) mainly through direct pathways, such as diet and drinking water, but indirect exposure also occurs when PFAA precursors break down to form legacy PFAA. Exposure to PFAA precursors raises particular concern, as neither the exposure nor the precursors themselves have been well described. In the present study, we aimed to assess the indirect contribution of oxidizable PFAA precursors to the total per- and polyfluoroalkyl substances (PFAS) burden in human plasma following the voluntary phase-out of production of long-chain PFAS. In addition, multiple logistic regression was used to explore associations between selected lifestyle and dietary factors and the oxidizable PFAA precursors fraction. This study included 302 cancer-free participants of the Norwegian Women and Cancer postgenome cohort. PFAS analyses were performed in plasma samples to determine PFAS concentrations before and after oxidation with the Total Oxidizable Precursor (TOP) assay. In pre-TOP analyses, perfluorooctane sulfonic acid (PFOS) was the dominant compound, followed by perfluorooctanoic acid (PFOA).The vast majority (98%) of the study population had increased post-TOP concentrations for at least one PFAA. The formation of PFAA accounted for 12% of the total PFAS burden, with seven PFAA observed post-TOP in at least 30% of study participants. PFHpA, br- PFOA, and PFDA were only detected in post-TOP analyses and showed the highest increase in concentrations. Of the PFAA with increased concentrations, we noted significant associations for year of birth, parity, BMI, and some dietary factors, although they were not consistent between the different PFAA. These results indicate that while the TOP assay might not provide a complete assessment of total PFAS burden in humans, it offers comprehensive assessment of unknown PFAA precursors that might be present in plasma, and it could therefore be implemented as an auxiliary tool in this regard.

Sadia, M.; Kunz, M.; ter Laak, T.; De Jonge, M.; Schriks, M.; van Wezel, A. P. Forever Legacies? Profiling Historical PFAS Contamination and Current Influence on Groundwater Used for Drinking Water. Sci. Total Environ. 2023, 890, 164420. https://doi.org/https://doi.org/10.1016/j.scitotenv.2023.164420.

Abstract: A wide range of PFAS residues were studied in an aquifer used for drinking water production which was affected by historical PFAS contamination from a landfill and military camp. Samples were taken at three monitoring and four pumping wells at different depths ranging from 33 to 147 m below the land surface and analysed for a series of 53 PFAS (C2-C14) and PFAS precursors (C4-C24). A comparison of results to earlier research from 2013, with a more limited range of PFAS, showed decreasing concentrations and migration of PFAS with increasing depth and distance from the contamination source. The PFAS profile and branched/linear isomer ratio are used as source characterization tools. The landfill was confirmed to contaminate the groundwater in both monitoring wells, while the military camp was indicated as a probable source for PFAS observed in the deep sampling points of one of the monitoring wells. Pumping wells used to produce drinking water are not yet affected by these two PFAS sources. In one of the four sampled pumping wells, a different PFAS profile and isomer pattern was observed, which indicated a different but yet unknown source. This work shows the necessity of implementing regular screening to identify potential (historical) PFAS sources to be able to prevent future contaminant migration nearby and towards drinking water abstraction wells.

Sadia, M.; Nollen, I.; Helmus, R.; ter Laak, T. L.; Béen, F.; Praetorius, A.; van Wezel, A. P. Occurrence, Fate, and Related Health Risks of PFAS in Raw and Produced Drinking Water. Environ. Sci. Technol. 2023, 57 (8), 3062–3074. https://doi.org/10.1021/acs.est.2c06015.

Abstract : This study investigates human exposure to per- and polyfluoroalkyl substances (PFAS) via drinking water and evaluates human health risks. An analytical method for 56 target PFAS, including ultrashort-chain (C2–C3) and branched isomers, was developed. The limit of detection (LOD) ranged from 0.009 to 0.1 ng/L, except for trifluoroacetic-acid and perfluoropropanoic-acid with higher LODs of 35 and 0.24 ng/L, respectively. The method was applied to raw and produced drinking water from 18 Dutch locations, including groundwater or surface water as source, and applied various treatment processes. Ultrashort-chain (300 to 1100 ng/L) followed by the group of perfluoroalkyl-carboxylic-acids (PFCA, ≥C4) (0.4 to 95.1 ng/L) were dominant. PFCA and perfluoroalkyl-sulfonic-acid (≥C4), including precursors, showed significantly higher levels in drinking water produced from surface water. However, no significant difference was found for ultrashort PFAS, indicating the need for groundwater protection. Negative removal of PFAS occasionally observed for advanced treatment indicates desorption and/or degradation of precursors. The proportion of branched isomers was higher in raw and produced drinking water as compared to industrial production. Drinking water produced from surface water, except for a few locations, exceed non-binding provisional guideline values proposed; however, all produced drinking waters met the recent soon-to-be binding drinking-water-directive requirements.

Nguyen M.A., Norström K., Wiberg K., Gustavsson J., Josefsson S. and Ahrens L., 2022. Seasonal trends of per- and polyfluoroalkyl substances in river water affected by fire training sites and wastewater treatment plants. Chemosphere, 308**,** 136467.

Brief summary and explanation of its importance: Distinct different seasonal trends were observed in the two catchments in Sweden. This demonstrates that the pollution is mobilized during periods of high flow in the first catchment (Stockholm Arlanda Airport), while it is diluted during high flow in the second catchment (Uppsala). Average annual loads for ΣPFASs were estimated at ~5.2 and ~3.7 kg/yr for the catchment in Uppsala and Stockholm Arlanda Airport, Thus, both catchments add PFASs to Lake Mälaren, which is Sweden's most important source area for drinking water production (around 20% of the Swedish population).

Sörengård M., Bergström S., McCleaf P., Wiberg K. and Ahrens L., 2022. Long-distance transport of per- and polyfluoroalkyl substances (PFAS) in a Swedish drinking water aquifer. Environ. Pollut., 311, 119981.

Brief summary and explanation of its importance: Comprehensive analysis of PFAS concentrations in the Uppsala (Sweden) drinking water aquifer revealed that contamination was greatest in groundwater and was most likely caused by a military airport site with historical PFAS-based AFFF usage pre-1985 to 2005. This firefighting training site has used PFAS-containing AFFF in the past, and based on topography, drains to aquifer used for drinking water production. Quantification of PFAS levels showed that the esker-based drinking water aquifer had groundwater ΣPFAS concentrations of up to 1000 ng/L, dominated by PFHxS and PFOS. Thus, strategies for sustainable management of the contaminated aquifer should be based on continued monitoring of PFAS in both the aquifer and drinking water. This demonstrates the importance of monitoring PFAS concentrations throughout a groundwater aquifer, to better understand variations in transport from contamination sources and resulting impacts on PFAS concentrations in drinking water extraction areas.

Nyström-Kandola J., Ahrens L., Glynn A., Johanson G., Benskin J.P., Gyllenhammar I., Lignell S. and Vogs C., 2023. Low concentrations of perfluoroalkyl acids (PFAAs) in municipal drinking water associated with serum PFAA concentrations in Swedish adolescents. Environ. Intern., 180, 108166.

Brief summary and explanation of its importance: In this study, the association between concentrations of perflurooctanoic acid (PFOA), perfluorononanoic acid (PFNA), perfluorohexane sulfonic acid (PFHxS) and perfluorooctane sulfonic acid (PFOS), and their sum (Σ4PFAAs) was evaluated in drinking water and serum in Swedish adolescents using weighted least squares regression. Serum PFAA concentrations was paired in adolescents (age 10–21 years, n = 790) from the dietary survey Riksmaten Adolescents 2016–17 (RMA) with mean PFAA concentrations in water samples collected in 2018 from waterworks (n = 45) supplying DW to the participant residential and school addresses. Significant positive

associations between PFAA concentrations in DW and serum were found for all four PFAAs and Σ4PFAAs, The European Food Safety Authority has determined a health concern concentration of 6.9 ng Σ4PFAAs/mL serum. This level was to a large degree exceeded by RMA participants with DW Σ4PFAA concentrations above the maximum limits implemented in Denmark (2 ng Σ4PFAAs/L) and Sweden (4 ng Σ4PFAAs/L) than by RMA participants with DW concentrations below the maximum limits. In conclusion, PFAA exposure from low-level contaminated DW must be considered in risk assessment for adolescents.

Sörengård M., Kikuchi J., Wiberg K. and Lutz A., 2022. Spatial distribution and load of per- and polyfluoroalkyl substances (PFAS) in background soils in Sweden. Chemosphere, 295, 133944.

Brief summary and explanation of its importance: This paper presents one of the first comprehensive studies investigating PFAS (n = 28) in background forest soils (n = 27) on national scale across Sweden. Partial least squares discriminant analysis (PLS-DA) showed regional clustering of PFAS compositional profiles, indicating that PFAS soil background concentrations are functions of spatial variations at local, regional, and countrywide scale. Such spatial trends have not been observed previously and it could not be deduced whether they are indicative of trends on a global scale, or country-specific and better explained by proximity to densely populated urban areas. An interpolation and extrapolation raster map created from the results was used to calculate the average total PFAS load on Swedish soils. Estimated total load in the top 10-cm soil layer was 2.7 ± 2.4 tons for PFOS and 16 ± 14 tons for ΣPFAS, indicating that soil carries a considerable legacy of past PFAS release.

Mussabek D., Söderman A., Imura T., Persson K.M., Nakagawa K., Ahrens L. and Berndtsson R., 2023. PFAS in the Drinking Water Source: Analysis of the Contamination Levels, Origin and Emission Rates. Water, 15, 137.

Brief summary and explanation of its importance: Groundwater contamination caused by the use of the aqueous film-forming foam (AFFF) containing per- and polyfluoroalkyl substances (PFAS) was investigated in southern Sweden. Sum PFAS concentrations in groundwater ranged between 20 and 20,000 ng/L; PFAS composition was primarily represented by PFOS and PFHxS.

2.6. Remediation

Hubert, M.; Arp, H. P. H.; Hansen, M. C.; Castro, G.; Meyn, T.; Asimakopoulos, A. G.; Hale, S. E. Influence of Grain Size, Organic Carbon and Organic Matter Residue Content on the Sorption of per- and Polyfluoroalkyl Substances in Aqueous Film Forming Foam Contaminated Soils - Implications for Remediation Using Soil Washing. Sci. Total Environ. 2023, 875, 162668. https://doi.org/https://doi.org/10.1016/j.scitotenv.2023.162668.

Abstract :A soil that was historically contaminated with Aqueous Film Forming Foam (AFFF) was dry sieved into size fractions representative of those produced during soil washing. Batch sorption tests were then conducted to investigate the effect of soil parameters on in situ per- and polyfluoroalkyl substances (PFAS) sorption of these different size fractions: < 0.063 mm, 0.063 to 0.5 mm, 0.5 to 2 mm, 2 to 4 mm, 4 to 8 mm, and soil organic matter residues (SOMR). PFOS (513 ng/g), 6:2 FTS (132 ng/g) and PFHxS (58 ng/g) were the most dominant PFAS in the AFFF contaminated soil. Non-spiked, in situ Kd values for 19 PFAS ranged from 0.2 to 138 L/Kg (log Kd −0.8 to 2.14) for the bulk soil and were dependant on the head group and perfluorinated chain length (spanning C4 to C13). The Kd values increased with decreasing grain size and increasing organic carbon content (OC), which were correlated to each other. For example, the PFOS Kd value for silt and clay (< 0.063 mm, 17.1 L/Kg, log Kd 1.23) were approximately 30 times higher compared to the gravel fraction (4 to 8 mm, 0.6 L/Kg, log Kd −0.25). The highest PFOS Kd value (116.6 L/Kg, log Kd 2.07) was found for the SOMR fraction, which had the highest OC content. Koc values for PFOS ranged from 6.9 L/Kg (log Koc 0.84) for the gravel fraction to 1906 L/Kg (log Koc 3.28) for the silt and clay, indicating that the mineral composition of the different size fractions also influenced sorption. The results here emphasize the need to separate coarse-grained fractions and fine-grained fractions, and in particular the SOMR, to optimize the soil washing process. Higher Kd values for the smaller size fractions indicate that coarser soils are better suited for soil washing.

Smith, S. J.; Keane, C.; Ahrens, L.; Wiberg, K. Integrated Treatment of Per- and Polyfluoroalkyl Substances in Existing Wastewater Treatment Plants—Scoping the Potential of Foam Partitioning. ACS ES&T Eng. 2023, 3 (9), 1276–1285. https://doi.org/10.1021/acsestengg.3c00091.

Abstract: Foam fractionation is becoming increasingly popular as a treatment technology for water contaminated with per- and polyfluoroalkyl substances (PFAS). At many existing wastewater treatment facilities, particularly in aerated treatment steps, foam formation is frequently observed. This study aimed to investigate if foam fractionation for the removal of PFAS could be integrated with such existing treatment processes. Influent, effluent, water under the foam, and foam were sampled from ten different wastewater treatment facilities where foam formation was observed. These samples were analyzed for the concentration of 29 PFAS, also after the total oxidizable precursor (TOP) assay. Enrichment factors were defined as the PFAS concentration in the foam divided by the PFAS concentration in the influent. Although foam partitioning did not lead to decreased ∑PFAS concentrations from influent to effluent in any of the plants, certain long-chain PFAS were removed with efficiencies up to 76%. Moreover, ∑PFAS enrichment factors in the foam ranged up to 105, and enrichment factors of individual PFAS ranged even up to 106. Moving bed biofilm reactors (MBBRs) were more effective at enriching PFAS in the foam than activated sludge processes. Altogether, these high enrichment factors demonstrate that foam partitioning in existing wastewater treatment plants is a promising option for integrated removal. Promoting foam formation and removing foam from the water surface with skimming devices may improve the removal efficiencies further. These findings have important implications for PFAS removal and sampling strategies at wastewater treatment plants.

Smith S.J., Lauria M., Ahrens L., McCleaf P., Hollman P., Bjälkefur Seroka S., Hamers T., Arp H.P.H. and Wiberg K., 2023. Electrochemical Oxidation for Treatment of PFAS in Contaminated Water and Fractionated Foam–A Pilot-Scale Study. ACS ES&T Water, 3, 1201–1211.

Brief summary and explanation of its importance: In this study, a practical treatment train that combines foam fractionation to concentrate PFAS from groundwater and landfill leachate was demonstrated, followed by an electrochemical oxidation (EO) step to degrade the PFAS. The study combined an up-scaled experimental approach with thorough characterization strategies, including target analysis, PFAS sum parameters, and toxicity testing. The mean total PFAS degradation over the designed treatment train reached 50%, with long- and short-chain PFAS degrading up to 86 and 31%, respectively. The treatment resulted in a decrease in the toxic potency of the water, as assessed by transthyretin binding and bacterial bioluminescence bioassays. Moreover, the extractable organofluorine concentration of the water decreased by up to 44%. Together, these findings provide an improved understanding of a promising and practical approach for on-site remediation of PFAS-contaminated water.

Smith S.J., Lewis J., Wiberg K., Wall E. and Ahrens L., 2023. Foam fractionation for removal of per- and polyfluoroalkyl substances: Towards closing the mass balance. Sci. Total Environ., 871, 162050.

Brief summary and explanation of its importance: This study verified the high treatment efficiency of a pilot-scale foam fractionation system for removal of PFAS from industrial water contaminated with aqueous film-forming foam. ΣPFAS removal reached up to 84 % and the removal of perfluorooctane sulfonic acid (PFOS) up to 97%, but the short-chain perfluorobutanoic acid (PFBA) was only removed with a mean efficiency of 1.5 %. In general, mobile short-chain PFAS were removed less efficiently when the perfluorocarbon chain length was below six for carboxylic acids and below five for sulfonic acids.

Niarchos G., Sörengård M., Fagerlund F. and Ahrens L., 2022. Electrokinetic remediation for removal of per- and polyfluoroalkyl substances (PFASs) from contaminated soil. Chemosphere, 291**,** 133041.

Brief summary and explanation of its importance: Two novel modifications to conventional electrokinetic remediation (EKR) were tested for the first time in a laboratory-scale study, to explore the capacity of EKR for PFAS removal. The results indicated up to 89% concentration and extraction of ΣPFASs for the two-compartment setup, with removal efficiency reaching 99% for individual short chain PFASs with C≤6. The single-compartment setup achieved 75% extraction and accumulation of ΣPFASs in granular activated carbon (GAC). This demonstrates, for the first time, good

effectiveness of coupling EKR with AC stabilisation for PFAS removal from soil. Perfluorocarbon chain length was a dominant factor affecting treatment efficiency in both setups, with very high removal rates for short-chain PFASs.

Niarchos G., Ahrens L., Kleja D.B. and Fagerlund F., 2022. Per- and polyfluoroalkyl substance (PFAS) retention by colloidal activated carbon (CAC) using dynamic column experiments. Environ. Pollut., 308**,** 119667.

Brief summary and explanation of its importance: In this study, dynamic soil column tests were used to assess the retardation of 10 classical perfluoroalkyl acids (PFAAs) as well as two alternative PFAS (6:2 and 8:2 fluorotelomer sulfonates) using CAC at 0.03% w/w, to investigate the fate and transport of PFAS under colloidal activated carbon (CAC) treatment applications. Results showed high retardation rates for long-chain PFAS and eight times higher retardation for the CAC-treated soil compared to the non-treated reference soil for the ΣPFAS. These findings are a step towards better understanding the extent of CAC's potential for remediation of PFAS-contaminated soil and groundwater and the limitations of its applications.

McCleaf P., Stefansson W. and Ahrens L., 2023. Drinking water nanofiltration with concentrate foam fractionation—A novel approach for removal of per- and polyfluoroalkyl substances (PFAS). Water Res., 232, 119688.

Brief summary and explanation of its importance: The present work examined a novel PFAS removal scheme for drinking water using nanofiltration (NF) filtration with treatment of the resulting NF concentrate via foam fractionation (FF) with and without co-surfactants. The NF-pilot removed 98% of PFAS from AFFF contaminated groundwater producing permeate with 1.4 ng/L total PFAS. Using FF resulted in ΣPFAS removal efficiency of 90% from the NF concentrate and with improved removal of 94% with addition of cationic co-surfactant.

Nassazzi W., Wu T.-C., Jass J., Lai F.Y. and Ahrens L., 2023. Phytoextraction of per- and polyfluoroalkyl substances (PFAS) and the influence of supplements on the performance of short–rotation crops. Environ. Pollut., 333, 122038.

Brief summary and explanation of its importance: This study assessed the PFAS phytoextraction potential of sunflower (Helianthus annuus), mustard (Brassica juncea), and industrial hemp (Cannabis sativa) in a greenhouse experiment, using inorganic fertilizer and a microbial mixture as supplements. In this study, the percentage of PFAS removal by plants was determined, and an estimation of the time required for PFAS phytoextraction was determined for the first time. This information is important for practical phytoremediation applications.

Niarchos G., Ahrens L., Kleja D.B., Leonard G., Forde J., Bergman J., Ribeli E., Schütz M. and Fagerlund F., 2023. In-situ application of colloidal activated carbon for PFAS-contaminated soil and groundwater: A Swedish case study. Remediation, 1– 10.

Brief summary and explanation of its importance: In this case study, the potential of colloidal activated carbon (CAC) for soil stabilization at the pilot scale was investigated, aiming to entrap PFAS and prevent their leaching from soil into groundwater. After CAC application, initial results indicated a 76% reduction of Σ11PFAS and high removal rates for long-chain PFAS, such as perfluorooctane sulfonic acid and perfluorooctanoic acid. A spike in concentrations was noticed 6 months after injection of CAC, showing a rebound of the plume and a reduction of treatment effectiveness. The results herein can serve as a guideline for treating similar sites and help avoid potential pitfalls of remedial efforts.