Thermal desorption as a high removal remediation technique for soils contaminated with per- and polyfluoroalkyl substances (PFASs)

M. Sörenård*, A-S. Lindh, L. Ahrens

Department of Aquatic Sciences and Assessment, Swedish University of Agricultural Sciences (SLU), Uppsala, Sweden

* mattias.sorengard@slu.se

Abstract

Soils contaminated with per- and polyfluoroalkyl substances (PFASs) are an important source for impacting drinking water delivery systems and surface water bodies world-wide, posing an urgent risk to human health and environmental quality. However, few treatment techniques have been tested for PFAS-contaminated soil hotspots. This study investigated the possibility of thermal desorption as a possible technique to remediate soils contaminated with multiple PFASs. Two fortified soils ($\sum_9$PFAS $\approx 4$ mg kg$^{-1}$) and one field-contaminated soil ($\sum_9$PFAS $\approx 0.025$ mg kg$^{-1}$) were subjected to a 75-min thermal treatment at temperatures ranging from 150 to 550°C. Soil concentrations of PFASs showed a significant decrease at 350°C, with the $\sum_9$PFAS concentration decreasing by, on average, 43% and 79% in the fortified and field contaminated soils, respectively. At 450°C, >99% of PFASs were removed from the fortified soils, while at 550°C the fraction removed ranged between 71 and 99% for the field contaminated soil. In the field contaminated soil, PFAS classes with functional groups of sulfonates (PFSAs) and sulfonamides (FOSAs) showed higher removal than the perfluoroalkyl carboxylates (PFCAs). Thus thermal desorption has the potential to remove a wide variety of PFASs from soil, although more studies are needed to investigate the cost-effectiveness, creation of transformation products, and air-phase vacuum filtration techniques.

1. Introduction

Per- and polyfluoroalkyl substances (PFASs) are a large group of partially or completely fluorinated organic compounds that vary in structure and chemical properties and are generally persistent to thermal, chemical, and biological degradation [1, 2]. Concerns have been raised because of their ubiquitous distribution in the environment, high persistency, bioaccumulation potential, and adverse effects on humans and biota [3–8]. A common point source is the unregulated usage of PFAS-containing aqueous film-forming foams (AFFFs) at firefighter
training facilities [9–11]. Although the use of PFAS-containing AFFFs is now restricted, the PFASs still present in contaminated soil are unsolicitedly leaching to the environment [12–14] and potentially polluting drinking water sources, e.g., in Japan [15], Germany [16], and Sweden [17]. Thus, there is an urgent need to remediate PFAS-contaminated hotspot areas and although a few soil guideline values have been set for PFASs, for example in Australia and New Zealand (i.e. 0.009, 2 and 20 mg kg\(^{-1}\), depending on soil usage [18]). However, several countries have set drinking water guideline values for PFASs, for example in USA (i.e. 70 ng L\(^{-1}\) for PFOS and PFOA) and Sweden 90 ng L\(^{-1}\) for \(\sum_{11}\)PFASs), which are forcing problem owners to remediate their PFAS-contaminated soil [19].

The extreme challenges of PFAS-contaminated soil remediation has been acknowledged [20, 21] and multiple technologies have been reviewed. Suggested remediation methods for PFAS-contaminated soil are stabilization technologies [22–26], electrodialytical remediation [27] and phytoremediation [28]. However, soil stabilization methods do not provide a long-term solution and phytoremediation is a slow and long-term approach [20]. In a recent review article, Mahinroosta and Senevirathna [21] showed that there is a lack of laboratory-scale and field-scale studies of soil remediation for PFASs.

A conventional treatment method for soil is incineration, a costly but efficient ex situ treatment regarding high removal in which PFASs are destroyed by combusting the contaminated soil [29]. Fluorotelomer-based acrylic polymer waste and PFAS-contaminated sewage sludge have been reported to degrade PFASs successfully at 725˚C [30–33], although others have found that complete degradation of PFASs requires temperatures of 900–1100˚C [33–35]. Another viable thermal treatment method for contaminated solids is thermal desorption [36], where the solid is heated ex situ or in situ [29] and the vaporized contaminants partition to the air phase, from which they can be removed by air filters [37]. The technique is considered to be less energy-demanding than incineration, can achieve high removal [29], and is generally applicable for organic contaminants [38]. Thermal desorption has previously been shown to successfully remove persistent soil organic pollutants such as polyaromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs) at 500˚C [39], and PFAS thermal desorption from the soil phase has been observed at 350˚C after 10 days\[40\].

The aim of this study was therefore to further evaluate, whether thermal desorption is a viable remediation method for removal of PFASs in contaminated soil and to identify critical variables such as optimal temperature, soil texture, treatment times and fortified vs. natural aged contaminated soil. Specific objectives were to: i) evaluate whether thermal desorption can be used to remove PFASs from contaminated soil, ii) determine the removal for 9 commonly found and regulated PFASs, and iii) identify the temperatures required for thermal desorption of PFASs from different types of soils with different PFAS contamination levels.

2. Material and methods

2.1 Target compounds

The target PFASs comprised: six perfluoroalkyl carboxylates (PFCAs), namely perfluorobutanoate (PFBA), perfluorohexanoate (PFHxA), perfluorooctanoate (PFOA), perfluorononanoate (PFNA), perfluorodecanoate (PFDA), and perfluoroundecanoate (PFUnDA); two perfluoroalkyl sulfonates (PFSAs), namely perfluorohexane sulfonates (PFHxS) and perfluorooctane sulfonates (PFOS); and one perfluorooctanesulfonamide (FOSA) (purity >99%, Wellington Laboratories, Guelph, ON). A total of nine isotopically labeled internal standards (IS) were used: \(^{13}\)C\(_4\)-PFBA, \(^{13}\)C\(_2\)-PFHxA, \(^{13}\)C\(_4\)-PFOA, \(^{13}\)C\(_5\)-PFNA, \(^{13}\)C\(_2\)-PFDA, \(^{13}\)C\(_2\)-PFUnDA, \(^{18}\)O\(_2\)-PFHxS, \(^{13}\)C\(_4\)-PFOS, and \(^{13}\)C\(_8\)-FOSA (purity >99%, Wellington Laboratories, Guelph, ON).
2.2 Experimental design

The thermal desorption technique was assessed on bench-scale using two Swedish soils, a loamy sand soil from Högsåsa and a clay soil from Vreta Kloster, both sampled at 0.35–0.45 m depth (for soil characterization, see [41] and laboratory-fortified with PFASs. In addition, a silty clay soil at a fire-fighter training facility known to be contaminated with PFAS-containing AFFFs, located at Stockholm Arlanda Airport, Sweden [28], was sampled at 0.10–0.30 m depth. The PFAS-fortified soils were separately fortified with a mixture of 11 PFASs, which resulted in a concentration of 600 μg kg⁻¹ for individual PFASs, and then aged for two months before the start of the experiment. The aging was performed by shaking (end-over-end, 100 rpm) a slurry of 0.5 kg fortified soil and 1 L of Millipore water for two weeks, freeze-drying the slurry for one week, and then shaking (end-over-end, 100 rpm) the dry soil for two weeks and storing it at 25˚C until use in the experiment.

The soils were separately freeze-dried (7 days) and homogenized with a mortar, and 4 g per sample were placed in amber glass bottles (40 mL, diameter 95 mm x height 27.5 mm; GENE-TEC, Sweden). Each soil was treated in experimental triplicates at 150˚C, 250˚C, 350˚C, 450˚C, or 550˚C (n = 3 in each case) for 15, 45 and 75 min, respectively, using a high-temperature furnace (ThermoLyne™ 62700 Furnace, 19 cm x 22 cm x 33 cm). Previous studies have used treatment times ranging between 20 and 60 min for PCBs and PAHs [42–44]. Negative controls (soil samples treated, but not fortified with PFASs) (n = 3) and positive controls (soil samples fortified with PFASs, but not treated) were included as reference and quality controls for each contaminated soil (n = 9). All samples were stored air-tight at 4˚C before further analysis.

2.3 Sample preparation, analysis, and quality control

The soil samples were analyzed for PFASs according to a validated method, as described elsewhere [45]. In brief, liquid-solid extraction was used with 3.0 ± 0.2 g of freeze-dried (7 days) solid sample and 30 mL of methanol fortified with 100 μL of an IS mixture (c = 0.010 μg mL⁻¹). The eluent was concentrated by a nitrogen gas stream to 500 μL and the aliquot was fortified with 500 μL Millipore water (Millipore, Germany) and transferred to an Eppendorf tube (Eppendorf, Germany) for clean-up using 25 mg ENVICarb 120/400 (Supelco, USA) and glacial acetic acid (Merck, Germany). The tubes were then vortexed and centrifuged at 15000 rpm for 15 min. All samples were filtered with recycled cellulose syringe filters (Sartorius, 0.45 μm) into 1.5 mL auto-injector brown glass vials (Eppendorf, Germany).

Ultra-high performance liquid chromatography-tandem mass spectroscopy (UHPLC-MS/MS) (Quantiva TSQ; Thermo Fisher, MA, USA) was used for the chemical analysis. The injection volume was 10 μL separated on a BEH-C18 column (1.7 μm, 50 mm, Waters), with a run time of 12 min using methanol and Millipore water with 5 mM ammonium acetate (purity >99.99%, Sigma-Aldrich) as eluents. An eight-point calibration curve ranging between 0.01 and 100 ng mL⁻¹ with a linear fit (R² >0.99) was used for quantification. The data were evaluated using TraceFinder™ software (Thermo Fisher, MA, USA). Since no PFASs were present in the laboratory blanks (n = 3), the limit of detection (LOD) was set to the lowest quantifiable calibration point with a signal to noise ratio >3. No PFASs were detected in laboratory blanks above LOD, and therefore, method detection limits (MDL) were set to LOD. The MDLs ranged between 0.003 (PFHxA and PFNA) and 0.2 (PFOS) μg kg⁻¹ dry weight (dw). The internal standard dilution method was used to compensate for losses or matrix effects. The relative recoveries were calculated as the measured concentration in fortified clay and sand reference samples compared with the theoretical fortification concentration (600 μg kg dw). The values obtained ranged between 48% (PFUnDA) and 130% (FOSA) (average 78%). The average
relative standard deviation (all samples were performed in experimental triplicates \((n = 3)\) for the individual PFASs was 15 ± 8% and 11 ± 4.5% in the field contaminated soil and fortified soils, respectively. As a positive control, a non-fortified sandy soil was treated together with the contaminated samples at all temperatures \((n = 3)\). It was found that only PFBA displayed a concentration >0.1% of the concentration in the treated fortified soils, foremost at the lower treatment temperatures \((5.0 \pm 0.92\% \text{ and } 0.16 \pm 0.016\% \text{ difference compared with the PFBA concentrations at } 150˚C \text{ and } 550˚C, \text{ respectively})\) (Table S1 in S1 Appendix).

### 3 Results and discussion

The fraction removed PFASs from the soil generally increased with the treatment temperature, but was dependent on the soil type, soil initial concentration, and PFAS characteristics (Fig 1). Comparing the fortified clay and loamy sand soils, at 350˚C PFCAs and FOSA were removed to >99%, while the PFSAs showed removal ranging between 51% (PFHxS) and 66% (PFOS). At 450˚C, the removal was >99% for all PFASs in both PFAS-fortified soils. This indicates that the functional group is an important parameter influencing the desorption potential of PFASs. However, the difference between PFSAs and PFCAs cannot be explained by the vapor pressure, since the vapor pressure constants \((\log P_L [\log Pa])\) were similar for the two groups (range 0.83–2.9 for the C4–C8 PFSAs and 0.82–3.1 for the C3-C10 PFCAs) [46]. However, these vapor pressure constants were estimated using the COSMOtherm model for chemical properties and can be biased due to the analysis being limited to non-ionized neutral forms of the PFASs. The PFCAs and PFSAs included in this study generally have an acid dissociation constant \((pK_a) < 2\) [47], with the exception of FOSA, which has \(pK_a = 6.2–6.5\) [48], meaning that they are predominantly protonated anions at the pHs in the tested soils. On the other hand, previous studies have shown that PFSAs are more strongly sorbed than PFCAs to soil and sediments [49–51], which might result in lower desorption potential for PFSAs. However, PFOS and PFOA are reported to show similar desorption behavior in soil [52]. In contrast to the two fortified soils, the fraction removed PFASs from the field contaminated soil were lower at all treatment temperatures tested. At 350˚C, \(\Sigma_9\)PFAS removal was 43%, compared with 71% and 87% for the fortified clay and sand soil, respectively. At 450˚C, 99% of PFSAs (PFHxS, PFOS) were removed from the field contaminated soil, similarly to the fortified soils. At 550˚C, PFPeA was removed to >97%, but other PFCAs were only removed to 71–93%, from the field contaminated soil. The lower desorption potential of PFASs in the field contaminated soil compared with the fortified soils could be explained by the lower concentration of PFASs or/ and stronger sorption of PFASs in the naturally aged soil than in the fortified soils [53]. The shorter-chained PFCA (PFBA) even showed negative removal for the field contaminated soil at 150–450˚C, which might be explained by the presence of unidentified precursor compounds that degraded into PFBA [54, 55]. This is a particular concern, as the use of shorter-chain PFASs has increased since the ban on C8-based PFASs in AFFF [56]. Except of PFBA, no degradation products could be observed throughout the experiment, i.e. increase of shorter chain homologues as a product of longer chain PFASs, which has been observed in other PFAS degradation studies [57, 58]. This indicates that the main removal mechanism observed in this study is thermal desorption and not degradation.

When comparing the treatment times at 15, 45 and 75 min the desorption behavior was similar between the three soils (Tables S2-4 in SI). The PFAS concentrations in the soil decreased with increasing treatment time for almost all temperatures (except for 550˚C), Fig 2. This experiment showed that the optimal temperature and treatment time for thermal desorption of PFASs is between 350˚C and 450˚C, and between 15 and 45 min, which is in agreement with a previous study using 350˚C but 10 days treatment time [40]. In addition, a treatment
time of over 45 min for thermal desorption of PFASs is not necessary to minimize the energy demand of this treatment option.

Ultimately, the results indicate that soils polluted with mixtures of PFASs can be treated with high removal using thermal desorption at temperatures above 450°C. This is a higher temperature than for other organic pollutants such as PCBs and PAHs, which showed high removal at 400°C [43, 44]. The high removal using thermal desorption can be compared to stabilization techniques where the leaching of PFASs to the aqueous phase can be reduced by >99% [59, 26], but comparably higher than using granulated activated carbon or anion exchange for PFAS removal in drinking water [60]. Although soil stabilization techniques have shown high removal from leachate water, their long-term performance is still unknown, while thermal desorption removes PFASs from the soil and thereby reducing the risks of leaching into the aquatic environment. In addition, the treatment of contaminated soil using thermal

---

**Fig 1.** Individual PFAS concentrations after thermal desorption for 75 min at different treatment temperatures of A) naturally PFAS-contaminated soil from Stockholm Arlanda Airport, Sweden, B) fortified clay soil, and C) fortified loamy sand soil.

https://doi.org/10.1371/journal.pone.0234476.g001

**Fig 2.** Individual PFAS concentrations after thermal desorption for 15, 45 and 75 min at different treatment temperatures of fortified loamy sand soil.

https://doi.org/10.1371/journal.pone.0234476.g002
desorption has the advantage of also treating other co-contaminants often associated with PFAS-contaminated sites, e.g., non-aqueous phase liquid (NAPL), nonfluorinated AFFF surfactants, polyhalogenated compounds (PHCs), volatile organic compounds (VOCs), PCBs, PAHs, and metals [61, 43, 62], although heavy metals are not known to be affected by thermal desorption [63]. Further studies are required to test the thermal treatment methodology at field scale and assess possible degradation compounds, determine removal, and evaluate air-phase vacuum extraction and air filtration. Measurement of PFASs in the air phase is also needed, in order to enable mass balance calculations post-treatment to identify PFAS degradation or formation of PFAS degradation products. As a concluding remark, it should be noted that the treatment temperatures of 450–550˚C is not of insignificant magnitude and energy costs will ultimately be a limiting factor for problem owners to consider when comparing thermal desorption with other remediation methods for PFASs in soil or other solid materials.

Supporting information
S1 Appendix.

Author Contributions
Conceptualization: M. Sörengård, L. Ahrens.
Formal analysis: A-S. Lindh.
Investigation: M. Sörengård, A-S. Lindh.
Methodology: M. Sörengård, L. Ahrens.
Project administration: L. Ahrens.
Resources: L. Ahrens.
Supervision: M. Sörengård, L. Ahrens.
Validation: L. Ahrens.
Visualization: M. Sörengård, L. Ahrens.
Writing – original draft: M. Sörengård.
Writing – review & editing: M. Sörengård, A-S. Lindh, L. Ahrens.

References
1. Buck R.C., Franklin J., Berger U., Conder J.M., Cousins I.T., de Voogt P., et al, 2011. Perfluoroalkyl and polyfluoroalkyl substances in the environment: Terminology, classification, and origins. Integr. Environ. Assess. Manag. 7, 513–541. https://doi.org/10.1002/ieam.258 PMID: 21793199
2. Krafft M.P., Riess J.G., 2015. Selected physicochemical aspects of poly- and perfluoroalkylated substances relevant to performance, environment and sustainability-Part one. Chemosphere 129, 4–19. https://doi.org/10.1016/j.chemosphere.2014.08.039 PMID: 25245564
3. Borg D., Lund B.-O., Lindquist N.-G., Häkansson H., 2013. Cumulative health risk assessment of 17 perfluoroalkylated and polyfluoroalkylated substances (PFASs) in the Swedish population. Environ. Int. 59, 112–123. https://doi.org/10.1016/j.envint.2013.05.009 PMID: 23792420
4. Rahman, A., Haque, M.M., Haddad, K., Rahman, A.S., Kuczera, G., Weinmann, E., 2014. Assessment of the impacts of rating curve uncertainty on at-site flood frequency analysis: A case study for new South Wales, Australia. Presented at the Hydrology and Water Resources Symposium 2014, HWRS 2014—Conference Proceedings, pp. 962–969.
5. Chu S., Wang J., Leong G., Woodward L.A., Letcher R.J., Li Q.X., 2015. Perfluoroalkyl sulfonates and carboxylic acids in liver, muscle and adipose tissues of black-footed albatross (Phoebastria nigripes)
from Midway Island, North Pacific Ocean. Chemosphere 138, 60–66. https://doi.org/10.1016/j.chemosphere.2015.05.043 PMID: 26037817

6. Ashley-Martin J., Dodds L., Arbuckle T.E., Bouchard M.F., Fisher M., Morisset A.-S., et al, 2017. Maternal Concentrations of Perfluoroalkyl Substances and Fetal Markers of Metabolic Function and Birth Weight. Am. J. Epidemiol. 185, 185–193. https://doi.org/10.1093/aje/kwx213 PMID: 28172036

7. Wang Z., DeWitt J.C., Higgins C.P., Cousins I.T., 2017. A Never-Ending Story of Per- and Polyfluoroalkyl Substances (PFASs)? Environ. Sci. Technol. 51, 2508–2518. https://doi.org/10.1021/acs.est.6b04806 PMID: 28224793

8. Nguyen M.A., Wiberg K., Ribel E., Jossefsson S., Futter M., Gustavsson J., Ahrens L., 2017. Spatial distribution and source tracing of per- and polyfluoroalkyl substances (PFASs) in surface water in Northern Europe. Environ. Pollut. 220, 1438–1446. https://doi.org/10.1016/j.envpol.2016.10.089 PMID: 27839995

9. Anderson R.H., Long G.C., Porter R.C., Anderson J.K., 2016. Occurrence of select perfluoroalkyl substances at U.S. Air Force aqueous film-forming foam release sites other than fire-training areas: Field-validation of critical fate and transport properties. Chemosphere 150, 678–685. https://doi.org/10.1016/j.chemosphere.2016.01.014 PMID: 26786021

10. Barzen-Hanson K.A., Roberts S.C., Choyke S., Oetjen K., McAlees A., Riddell N., et al, 2017. Discovery of 40 Classes of Per- and Polyfluoroalkyl Substances in Historical Aqueous Film-Forming Foams (AFFFs) and AFFF-Impacted Groundwater. Environ. Sci. Technol. 51, 2047–2057. https://doi.org/10.1021/acs.est.6b03843 PMID: 28098889

11. Mejia-Avendano S., Munoz G., Sauve S., Liu J., 2017. Assessment of the Influence of Soil Characteristics and Hydrocarbon Fuel Cocontamination on the Solvent Extraction of Perfluoroalkyl and Polyfluoroalkyl Substances. Anal. Chem. 89, 2539–2546. https://doi.org/10.1021/acs.analchem.6b04746 PMID: 28192932

12. Ahrens L., Norstrom K., Viktor T., Cousins A.P., Jossefsson S., 2015. Stockholm Arlanda Airport as a source of per- and polyfluoroalkyl substances to water, sediment and fish. Chemosphere, Per- and Polyfluorinated Alkyl substances (PFASs) in materials, humans and the environment—current knowledge and scientific gaps. 129, 33–38. https://doi.org/10.1016/j.chemosphere.2014.03.136

13. Baduel C., Paxman C.J., Mueller J.F., 2015. Perfluoroalkyl substances in a firefighting training ground (FTG), distribution and potential future release. J. Hazard. Mater. 296, 46–53. https://doi.org/10.1016/j.jhazmat.2015.03.007 PMID: 25966923

14. Filipovic M., Woldegiorgis A., Norstrom K., Bibi M., Lindberg M., Österås A.-H., 2015. Historical usage of aqueous film forming foam: A case study of the widespread distribution of perfluoroalkyl acids from a military airport to groundwater, lakes, soils and fish. Chemosphere 129, 39–45. https://doi.org/10.1016/j.chemosphere.2014.09.005 PMID: 25262531

15. Murakami M., Kuroda K., Sato N., Fukushima T., Takizawa S., Takada H., 2009. Groundwater Pollution by Perfluorinated Surfactants in Tokyo. Environ. Sci. Technol. 43, 3480–3486. https://doi.org/10.1021/es03556w PMID: 19544843

16. Gellrich V., Brunn H., Stahl T., 2013. Perfluoroalkyl and polyfluoroalkyl substances (PFASs) in mineral water and tap water. J. Environ. Sci. Health—Part ToxicHazardous Subst. Environ. Eng. 48, 129–135. https://doi.org/10.1080/10934529.2013.719431

17. Li Y., Fletcher T., Mucs D., Scott K., Lindh C.H., Tallving P., et al, 2018. Half-lives of PFOS, PFHxS and PFOA after end of exposure to contaminated drinking water. Occup. Environ. Med. 75, 46–51. https://doi.org/10.1136/oemed-2017-104651 PMID: 29133598

18. Heads of EPAs Australia and New Zealand (HEPA), 2018. PFAS National Environmental Management Plan.

19. Gobelius L., Hedlund J., Dürig W., Tröger R., Lilja K., Wiberg K., et al, 2018. Per- and Polyfluoroalkyl Substances in Swedish Groundwater and Surface Water: Implications for Environmental Quality Standards and Drinking Water Guidelines. Environ. Sci. Technol. https://doi.org/10.1021/acs.est.7b05718

20. Ross I., McDonough J., Miles J., Storch P., The lakkat Kochun arayanan P., Kalve E., et al, 2018. A review of emerging technologies for remediation of PFASs. Remediat. J. 28, 101–126. https://doi.org/10.1002/rem.21553

21. Mahinroosta R., Seneviratna L., 2020. A review of the emerging treatment technologies for PFAS contaminated soils. J. Environ. Manage. 255, 109896. https://doi.org/10.1016/j.jenvman.2019.109896 PMID: 32063301

22. Das P., Arias E., Kambala V., Mallavarapu M., Naidu R., 2013. Remediation of perfluorooctane sulfonate in contaminated soils by modified clay adsorbent—A risk-based approach topical collection on remediation of site contamination. Water. Air. Soil Pollut. 224. https://doi.org/10.1007/s11270-013-1714-y
23. Hale S.E., Arp H.P.H., Slinde G.A., Wade E.J., Bjerseth K., Breedveld G.D., et al, 2017. Sorbent amendment as a remediation strategy to reduce PFAS mobility and leaching in a contaminated sandy soil from a Norwegian firefighting training facility. Chemosphere 171, 9–18. https://doi.org/10.1016/j.chemosphere.2016.12.057 PMID: 28002769

24. Kupryianchyk D., Hale S.E., Breedveld G.D., Cornelissen G., 2016a. Treatment of sites contaminated with perfluorinated compounds using biochar amendment. Chemosphere, Biochars multifunctional role as a novel technology in the agricultural, environmental, and industrial sectors 142, 35–40. https://doi.org/10.1016/j.chemosphere.2015.04.085

25. McGregor R., 2018. In Situ treatment of PFAS-impacted groundwater using colloidal activated Carbon. Remediation 28, 33–41. https://doi.org/10.1002/rem.21558

26. Sören gland M., Kleja D.B., Ahrens L., 2019a. Stabilization and solidification remediation of soil contaminated with poly- and perfluoroalkyl substances (PFASs). J. Hazard. Mater. 367, 639–646. https://doi.org/10.1016/j.jhazmat.2019.01.005

27. Sören gland M., Niarchos G., Jensen P.E., Ahrens L., 2019b. Electro dialytic per- and polyfluoroalkyl substances (PFASs) removal mechanism for contaminated soil. Chemosphere 232, 224–231. https://doi.org/10.1016/j.chemosphere.2019.05.088

28. Gobelius L., Lewis J., Ahrens L., 2017. Plant Uptake of Per- and Polyfluoralkyl Substances at a Contaminated Fire Training Facility to Evaluate the Phytoremediation Potential of Various Plant Species. Environ. Sci. Technol. 51, 12602–12610. https://doi.org/10.1021/acs.est.7b02926 PMID: 28972370

29. Vidonish J.E., Zygourakis K., Masiello C.A., Sabadell G., Alvarez P.J.J., 2016. Thermal Treatment of Hydrocarbon-Impacted Soils: A Review of Technology Innovation for Sustainable Remediation, Engineering 2, 426–437. https://doi.org/10.1016/J.ENG.2016.04.005

30. Loganathan B.G., Sajwan K.S., Sinclair E., Senthil K., Kannan K., 2007. Perfluoroalkyl sulfonates and perfluorocarboxylates in two wastewater treatment facilities in Kentucky and Georgia. Water Res. 41, 4611–4620. https://doi.org/10.1016/j.watres.2007.06.045 PMID: 17632203

31. Vecitis C.D., Park H., Cheng J., Mader B.T., Hoffmann M.R., 2009. Treatment technologies for aqueous perfluorooctanesulfonate (PFOS) and perfluorooctanoate (PFOA). Front. Environ. Sci. Eng. China 3, 129–151. https://doi.org/10.1007/s11783-009-0022-7

32. Wang F., Shih K., Lu X., Liu C., 2013. Mineralization Behavior of Fluorine in Perfluorooctanesulfonate (PFOS) during Thermal Treatment of Lime-Conditioned Sludge. Environ. Sci. Technol. 47, 2621–2627. https://doi.org/10.1021/es305352p PMID: 23360134

33. Yamada T., Taylor P.H., Buck R.C., Kaiser M.A., Giraud R.J., 2005. Thermal degradation of fluorotelomer treated articles and related materials. Chemosphere 61, 974–984. https://doi.org/10.1016/j.chemosphere.2005.03.025 PMID: 16257319

34. Wang F., Lu X., Li X., Shih K., 2015. Effectiveness and Mechanisms of Defluorination of Perfluorinated Alkyl Substances by Calcium Compounds during Waste Thermal Treatment. Environ. Sci. Technol. 49, 5672–5680. https://doi.org/10.1021/es506234b PMID: 25850557

35. Watanabe N., Takemine S., Yamamoto K., Haga Y., Takata M., 2016. Residual organic fluorinated compounds from thermal treatment of PFOA, PFHxS and PFOS adsorbed onto granular activated carbon (GAC). J. Mater. Cycles Waste Manag. 18, 625–630. https://doi.org/10.1007/s11004-016-0532-x

36. Kuppusamy S., Thavamani P., Venkateswarlu K., Lee Y.B., Naidu R., Megharaj M., 2017. Remediation approaches for polycyclic aromatic hydrocarbons (PAHs) contaminated soils: Technological constraints, emerging trends and future directions. Chemosphere 168, 944–968. https://doi.org/10.1016/j.chemosphere.2016.11.015 PMID: 27823779

37. Lim M.W., Lau E.V., Poh P.E., 2016. A comprehensive guide of remediation technologies for oil contaminated soil—Present works and future directions. Mar. Pollut. Bull. 109, 14–45. https://doi.org/10.1016/j.marpolbul.2016.04.023 PMID: 27287117

38. Gilipour S., Farvash E.S., Keramati N., Yaghoozbadeh P., Rezaee M., 2015. Remediation of petroleum contaminated soils in urban areas using thermal desorption. J. Environ. Stud. 41, 643–652.

39. Zhao Z.-H., Li X.-D., Ni M.-J., Chen T., Yan J.-H., 2017. Remediation of PCB-contaminated soil using a combination of mechanochemical method and thermal desorption. Environ. Sci. Pollut. Res. 24, 11800–11806. https://doi.org/10.1007/s11356-017-8734-x

40. Crowmover E., Oberle D., Kluger M., Heron G., 2019. Perfluoroalkyl and polyfluoroalkyl substances thermal desorption evaluation. Remediat. J. 29, 77–81. https://doi.org/10.1002/rem.21623

41. Kirchmann H., Snåll S., Eriksson J., Mattsson L., 2005. Properties and classification of soils of the Swedish long-term fertility experiments: V. Sites at Vreta Kloster and Högåsa. Acta Agric. Scand. Sect. B Soil Plant Sci. 55, 98–110. https://doi.org/10.1080/09064710510008711
42. Mascolo G., Bagnuolo G., De T., Urriocho V., 2013. Direct analysis of polychlorinated biphenyls in heavily contaminated soils by thermal desorption/gas chromatography/mass spectrometry. Int. J. Environ. Anal. Chem. 93, 1030–1042. https://doi.org/10.1080/03067319.2012.708745

43. Qi Z., Chen T., Bai S., Yan M., Lu S., Buekens A., et al., 2014. Effect of temperature and particle size on the thermal desorption of PCBs from contaminated soil. Environ. Sci. Pollut. Res. 21, 4697–4704. https://doi.org/10.1007/s11356-013-2392-4

44. Liu J., Qi Z., Zhao Z., Li X., Buekens A., Yan J., et al., 2015. Thermal desorption of PCB-contaminated soil with sodium hydroxide. Environ. Sci. Pollut. Res. 22, 19538–19545. https://doi.org/10.1007/s11356-015-5136-9

45. Ahrens L., Taniyasu S., Yeung L.W.Y., Yamashita N., Lam P.K.S., Ebinghaus R., 2010. Distribution of polyfluoroalkyl compounds in water, suspended particulate matter and sediment from Tokyo Bay, Japan. Chemosphere 79, 266–272. https://doi.org/10.1016/j.chemosphere.2010.01.045 PMID: 20181376

46. Wang Z., MacLeod M., Cousins I.T., Scheringer M., Hungerbühler K., 2011. Using COSMOTHERM to predict physicochemical properties of poly- and perfluorinated alkyl substances (PFASs). Environ. Chem. 8, 389–398. https://doi.org/10.1071/EN10143

47. Rayne S., Forest K., Friesen K.J., 2009. Computational approaches may underestimate pKa values of longer-chain perfluorinated carboxylic acids: Implications for assessing environmental and biological effects. J. Environ. Sci. Health—Part Toxic/Hazardous Subst. Environ. Eng. 44, 317–326. https://doi.org/10.1080/10934520802659620

48. Rayne S., Forest K., 2009. A new class of perfluorinated acid contaminants: primary and secondary substituted perfluorooalkyl sulfonamides are acidic at environmentally and toxicologically relevant pH values. J. Environ. Sci. Health Part A Toxic/ Hazard. Subst. Environ. Eng. 44, 1388–1399. https://doi.org/10.1080/10934520903217278

49. Higgins C.P., Luthy R.G., 2006. Sorption of Perfluorinated Surfactants on Sediments. Environ. Sci. Technol. 40, 7251–7256. https://doi.org/10.1021/es061000h PMID: 17180974

50. Du Z., Deng S., Bei Y., Huang Q., Wang B., Huang J., et al., 2014. Adsorption behavior and mechanism of perfluorinated compounds on various adsorbents—A review. J. Hazard. Mater. 274, 443–454. https://doi.org/10.1016/j.jhazmat.2014.04.038 PMID: 24813664

51. Campos Pereira H., Ullberg M., Kleja D.B., Gustafsson J.P., Ahrens L., 2018. Sorption of perfluorooalkyl substances (PFASs) to an organic soil horizon—Effect of cation composition and pH. Chemosphere 207, 183–181. https://doi.org/10.1016/j.chemosphere.2018.05.012 PMID: 29730303

52. Zhi Y., Liu J., 2018. Sorption and desorption of anionic, cationic and zwitterionic polyfluoroalkyl substances by soil organic matter and pyrogenic carbonaceous materials. Chem. Eng. J. 346, 682–691. https://doi.org/10.1016/j.cej.2018.04.042

53. Li Yasong, Oliver D.P., Kookana R.S., 2018. A critical analysis of published data to discern the role of soil and sediment properties in determining sorption of per and polyfluorooalkyl substances (PFASs). Sci. Total Environ. 628–629, 110–120. https://doi.org/10.1016/j.scitotenv.2018.01.167 PMID: 29428853

54. Houtz E.F., Higgin C.P., Field J.A., Sedlak D.L., 2013. Persistence of perfluorooalkyl acid precursors in AFFF-impacted groundwater and soil. Environ. Sci. Technol. 47, 8187–8195. https://doi.org/10.1021/es4018877 PMID: 23865337

55. Weber A.K., Barber L.B., LeBlanc D.R., Sunderland E.M., Vecitis C.D., 2017. Geochemical and Hydrologic Factors Controlling Subsurface Transport of Poly- and Perfluorooalkyl Substances, Cape Cod, Massachusetts. Environ. Sci. Technol. 51, 4269–4279. https://doi.org/10.1021/acs.est.8b05573 PMID: 28285525

56. Brendel S., Fetter É., Staude C., Vieker L., Biegel-Engler A., 2018. Short-chain perfluorooalkyl acids: environmental concerns and a regulatory strategy under REACH. Environ. Sci. Eur. 30. https://doi.org/10.1186/s12302-018-0134-4

57. Liu Y., Chen S., Quan X., Yu H., Zhao H., Zhang Y., 2015. Efficient Mineralization of Perfluorooctanoate by Electro-Fenton with H2O2 Electro-generated on Hierarchically Porous Carbon. Environ. Sci. Technol. 49, 13528–13533. https://doi.org/10.1021/acs.est.5b03147 PMID: 26465252

58. Franke V., Schäfers M.D., Lindberg J.J., Ahrens L., 2019. Removal of per- and polyfluoroalkyl substances (PFASs) from tap water using heterogeneously catalyzed ozonation. Environ. Sci. Water Res. Technol. 5, 1887–1896. https://doi.org/10.1039/c9ew00339h

59. Kupynianchyck D., Hale S.E., Breedveld G.D., Cornelissen G., 2016b. Treatment of sites contaminated with perfluorinated compounds using biochar amendment. Chemosphere. Biochars multifunctional role as a novel technology in the agricultural, environmental, and industrial sectors 142, 35–40. https://doi.org/10.1016/j.chemosphere.2015.04.085
60. McCleaf P., Englund S., Östlund A., Lindegren K., Wiberg K., Ahrens L., 2017. Removal efficiency of multiple poly- and perfluoroalkyl substances (PFASs) in drinking water using granular activated carbon (GAC) and anion exchange (AE) column tests. Water Res. 120, 77–87. https://doi.org/10.1016/j.watres.2017.04.057 PMID: 28478297

61. Guelfo J.L., Higgins C.P., 2013. Subsurface Transport Potential of Perfluoroalkyl Acids at Aqueous Film-Forming Foam (AFFF)-Impacted Sites. Environ. Sci. Technol. 47, 4164–4171. https://doi.org/10.1021/es3048043 PMID: 23566120

62. Yao, Y., Volchek, K., Brown, C.E., 2015. Characterization of environmental samples from an aqueous film forming foam (AFFF)-impacted firefighting training area in Canada. Presented at the Proceedings of the 38th AMOP Technical Seminar on Environmental Contamination and Response, pp. 265–282.

63. Guemiza K., Coudert L., Metahni S., Mercier G., Besner S., Blais J.-F., 2017. Treatment technologies used for the removal of As, Cr, Cu, PCP and/or PCDD/F from contaminated soil: A review. J. Hazard. Mater. 333, 194–214. https://doi.org/10.1016/j.jhazmat.2017.03.021 PMID: 28359036