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Degradation of Per- and Polyfluoroalkyl Substances in Stormwater and Secondary Concentrated Liquid from AFFF-impacted Sources

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ABSTRACT

The widespread use of per- and polyfluoroalkyl substances (PFAS) has led to global contamination requiring innovative treatment needs to address the recalcitrant nature of PFAS. Traditional treatment techniques fail to degrade PFAS; separation and sequestration from the environment has been the main treatment, which produce a secondary waste stream requiring disposal. However, a concerted push from industry and the United States Department of Defense has focused on the development of destructive technologies. UV/SGM is a destructive treatment technology developed to degrade PFAS in concentrated liquid wastes. In this study, UV/SGM is challenged to treat synthetic ion exchange still bottoms, which consists of high concentrations of PFAS, salts, and total organic carbon. Two reactor configurations which were designed to combine photocatalytic and photolysis treatments in one system were assessed in this study. Total PFAS were degraded 81-91% from each reactor configuration and defluorination recovery varied from 72-92%. In addition, nitrate degradation and subsequent nitrite production during treatment were tracked over treatment time, and ultimately completely removed from the system. Dilute AFFF-impacted stormwater was also evaluated and yielded significant PFAS degradation and defluorination; however, full scale implementation is hindered by degradation rates. Results indicate that dilute wastewaters require longer contact time for PFAS degradation, making UV/SGM treatment impractical due to the sheer volume of dilute wastestreams requiring treatment. Concentrated wastestreams are the most practical field scale application of UV/SGM technology. Results further support the need for a sequestration and concentration technology followed by destruction treatment in a systems approach for PFAS.

Keywords: PFAS, Concentrated liquid, Photocatalysis, Emerging Contaminants

1 INTRODUCTION

Per- and polyfluoralkyl substances (PFAS) are ubiquitous in the environment and have become a growing global environmental and health concern (Cousins et al., 2022). PFAS are bioaccumulative in nature, believed to be responsible for numerous health effects, and are known to be very recalcitrant to remediation (ITRC, 2020). Manufacturing and application of aqueous film-forming foam (AFFF) has led to the widespread occurrence of PFAS in a variety of media including, soils, sediments, groundwater, surface water, drinking water, and receiving waters (Leeson et al., 2020). Treatment of PFAS impacted liquids can be separated into sequestration (field-implemented) and destructive technologies (limited-application). Sequestration technologies for liquids include but are not limited to: sorption technologies (ion exchange [Singh et al., 2020; Linang et al., 2022] and granular activated carbon [USEPA, 2018]), reverse osmosis (Kanchanapiva and Tantisattayakul 2022), and filtration (Boo et al., 2018). Field implemented treatment of solids consists of sorption and stabilization, or excavation and disposal (ITRC 2020). Incineration, a common PFAS treatment avenue, is under temporary prohibition through a memorandum issued as there are questions regarding the production of volatile byproducts produced during the process (DoD, 2022).

Sequestration technologies remove PFAS from the bulk solution, however, do not destroy the PFAS, thus creating a secondary waste. Secondary wastes can include solids (spent ion exchange resin, GAC, membranes, and filters) and/or liquids (reject streams, regenerative solutions, and ion exchange still bottoms) which require disposal. Alternatively, secondary concentrated wastes can be treated by destructive technologies ultimately resulting in the breakdown of PFAS into inorganic species. Destructive technologies are limited application technologies, designed to optimally treat specific sets

of PFAS wastestreams. Developing destructive technologies include but are not limited to hydrothermal alkaline treatment (Wu et al., 2019), UV/sulfite (Ren et al., 2021), plasme (Singh et al., 2020), photocatalysis (Cates, 2018), ozone (Boving and Ball 2020), sonolysis (Kulkarni et al., 2022), and electron beam (Feng et al., 2021). Many developing technologies and in the beginning stages, requiring more robust assessments of the technology's capabilities and limitation, ability to degrade a variety of PFAS, and energy and cost assessments/comparisons. Additionally, the ability to effective scale-up some destructive technologies has been identified as a possible limitation to the efficiency and effectiveness in the field.

While some destructive technologies can treat more dilute wastestreams (Nau-Hix et al., 2021), many focus on concentrate wastestreams due to the low volume of production, allowing for extended processing time between concentrate production. However, liquids with elevated PFAS concentrations often have elevated levels of salt, total organic carbon (TOC), metals, or other additional constituents, which can impact or impair treatment (Cates, 2018). Ion exchange resins are regenerated by washing with an alcohol/salt solution and then distilled, resulting in a highly concentrated PFAS brine (Singh et al., 2020). Resins also adsorb additional ions such as nitrate, organic content, and metals, which are also extracted from the resin during the regeneration process. Foam fractionation, an innovative separation technology, targets the PFAS surfactant nature, creating a less complex matrix in the concentrated foam (Smith et al., 2022). Destructive technologies are in various stages of development; however, initial validation is primarily performed with clean PFAS matrices such as PFAS spiked deionized water. Impacts of various water quality parameters, co-solvents, and/or co-contaminants has been demonstrated to negatively impact technologies (Cates, 2018; Ren et al., 2021), requiring more robust laboratory research studies to aid in successful transition into the field. It is also important to understand how matrix effects, PFAS concentrations, and additional factors effect degradation kinetics in order to determine where sequestration technologies and destructive technologies are the most cost effective and energy efficient.

In this study AFFF-impacted stormwater and ion exchange still bottoms are treated using ultraviolet activated silica-based granular media (UV/SGM), an innovative photocatalytic destructive technology. Using these wastestreams this study aims to elucidate the differences between treating a dilute and concentrated PFAS wastestream and begin to assess where destructive technologies belong within a treatment process. Additionally, two reactor configurations, coupling photocatalytic and photolysis treatment will be assessed, demonstrating possible paths for future scale up and pilot scale implementation. Insights on destructive treatment, specifically UV/SGM, and future work will be assessed based on the results of the study.

2 METHODS AND MATERIALS

2.1 Chemicals, sample preparation, and analysis

All chemical reagents were purchased from Fisher Scientific or Sigma Aldrich. Stormwater from a facility were AFFF was utilized during an active fire-fighting event was collected and shipped from a confidential site by a third-party consultant. Previous studies with mini-column reactors present stormwater PFAS concentrations and additional water quality parameters (McIntyre et al., 2022). A summary of total PFAS is listed in Table 1. Synthetic still bottoms were prepared by combining perfluorooctane sulfonate (PFOS), perfluorononanoic acid (PFNA), 6:2 fluorotelomer sulfonate (6:2 FTS), perfluorooctanoic acid (PFOA), perfluorohexane sulfonate (PFHxS), perfluoroheptanoic acid (PFHpA), perfluorohexanoic acid (PFHxA), perfluoropentanoic acid (PFPeA), perfluorobutanoic acid (PFBA), Chemguard AFFF, sodium chloride (NaCl), sodium sulfate (Na_2SO_4), sodium nitrate ($NaNO_3$), sodium bicarbonate ($NaHCO_3$), iron (II) sulfate ($FeSO_4$), methanol, and municipal leachate. Concentrations of PFAS and additional components were advised by a third-party vendor which develops regenerable ion exchange resins for PFAS treatment. Concentrations of PFAS and additional analytes are listed in Table 2. Only PFAS in EPA Method 537 were analyzed, although additional perfluoroalkyl acid (PFAA) precursors could be present in the synthetic still bottoms due to the addition of the Chemguard AFFF.

Table 1. *Stormwater total PFAS and theoretical fluoride*

Analyte	Total PFAS (ppb)	Theoretical Fluoride (ppb)
Target and suspect screening (QTOF)	1,684	861
TOP Assay (post-treatment)	1,550	1,025

Table 2. *Synthetic still bottoms analytes*

Analyte	Concentration (ppm)
PFAS	
Perfluorooctane sulfonate	48.4
Perfluorononanoic acid	8.95
6:2 Fluorotelomer sulfonate	19.8
Perfluorooctanoic acid	92.7
Perfluorohexane sulfonate	90.0
Perfluoroheptanoic acid	10.4
Perfluorohexanoic acid	20.9
Perfluoropentanoic acid	17.1
Perfluorobutanoic acid	87.0
Total PFAS	**395.25**
Additional Analytes	
Fluoride	<0.1
Chloride	44,641
Sulfate	6,643
Nitrate	1,346
Iron	6.75
TOC	4,020

Sample analysis for PFAS was performed through analyte separation on a Shimadzu Nexera XR ultra-high pressure liquid chromatographer followed by mass detection on a Shimadzu 9030 Quadrupole Time-of-flight Mass Spectrometer. Sample preparation and analysis were performed analogous to previous studies (McIntyre et al., 2022; McIntyre et al., 2021) with the exception of using an Agilent InfinityLab Poroshell 120 ED-C18 analytical column for this study.

Analysis of anionic inorganics was performed on a Metrohm 940 Professional Ion Chromatographer series Vario. Still bottom samples were diluted 10x, 100x, and 1000x, based upon the suspected concentration of the analyte of interest. This in part is due to high salt concentrations within the still bottoms and the proximity of the chloride peak with the fluoride peak during analysis, as well as to protect the detector. Stormwater samples were analyzed undiluted as this solution lacked the high concentrations of salt. Standard Metrohm A Supp 7 eluent concentrate was utilized, which was diluted automatically 20x by an 800 Dosino. 0.5 M sulfuric acid was injected at a rate of 0.1 mL/min as a suppression solution. A seven-calibration standard was developed for the analytes of interest and analyzed with each batch, producing a reproducible linear calibration curve with an R^2 value of 0.99. Sample and standard preparation and analysis, along with quality control samples, were consistent with EPA Method 300.0 (USEPA, 1993).

2.2 UV/SGM Experiments

UV/SGM is a photocatalytic destructive treatment technology developed in previous studiesfor organic contaminant treatment (McIntyre and Hart 2021). The porous media is designed to operate as a packed granular bed surrounding a UV light submerged in the center, allowing for the system to operate as a flow through or recirculation reactor. A packed bed allows for photocatalysis without the need to filter the photocatalyst from a slurry after treatment is completed. UV/SGM has been validated to degrade a variety of PFAS in stormwater and PFAS spiked deionized water solutions (McIntyre et al., 2022; McIntyre et al., 2021). Laboratory system scale-up towards field demonstration is being assessed in additional studies.

PFAS degradation experiments were performed with two different reactor configurations, designed to couple photocatalysis and photolysis treatment. Each reactor was configured from 18 inches of 2.5 inch diameter pipe with threaded ends. The entire reactor was approximately 1 liter in empty bed contact. Figure 1 depicts the design of both reactors. Figure 1A is a two-column configuration, where one column is fully packed with SGM to create photocatalysis treatment, while the second column only contains a submerged UV lamp, creating a photolysis treatment. Figure 1B consists of one column with a quartz coil packed with SGM integrated into the column. Solution flows first through the coil (photocatalysis) and then proceeds through the interior reactor space in the column body (photolysis) before being recirculated. The quartz coil consists of natural quartz, which is unable to transmit 185 nm. In both reactor configurations, solution is recirculated through the reactors at a flowrate of 0.5 gallons per minute (gpm). All columns utilized 85-watt VUV lamps with an irradiance of 230 µW/cm^2 at 254 nm and 60

µW/cm^2 at 185 nm. The photocatalysis packed-bed reactor consists of approximately 400 grams of SGM and the coil consists of approximately 150 grams of SGM. Sodium hydroxide (NaOH) was added at 5% (v/v) of 1 Molar, equating to a 0.05 Molar final solution. Synthetic still bottom solution was diluted 5x from the original solution shown in Table 2 for all experiments to prevent fouling of the quartz sleeves by the salts. Stormwater was treated as it was received in the lab, with only NaOH added as an amendment. Five liters of solution were treated during each experiment and, experiments were conducted with respect to hours of reactive contact time.

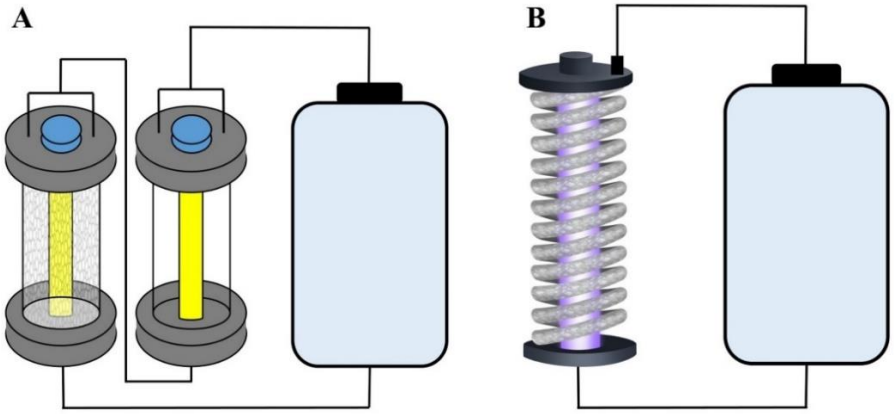


Figure 1. *UV/SGM reactor configurations with A) packed-bed configuration and B) coil configuration*

3 RESULTS AND DISCUSSION

3.1 AFFF-impacted stormwater

AFFF-impacted stormwater experiments were performed in the packed-bed reactor (Figure 1A) over 72 hours at a flowrate of 0.5 gpm and then compared to previous studies (McIntyre et al., 2022) using smaller scale column reactors, flowing at a rate of 35 mL/hr. Figure 2 presents total PFAS degradation versus defluorination for both treatments. The larger scaled system (Figure 2B) was not performed in duplicate, due to the limited available volume of solution. Significant differences in results can be observed, with slower degradation rates presented in the 0.5 gpm reactor. Theoretically this could be due to slower adsorption of the contaminant on to the photocatalysts and subsequent degradation caused by the higher flowrate. However, a higher concentration of fluoride is recovered in the 0.5 gpm reactor, despite having a similar removal of total parent PFAS. The data presented in Figure 2 begins to address why destructive treatment technologies are more focused on treating concentrated liquids, rather than groundwater or surface water, which require higher flowrates to treat the large volumes of feedwater.

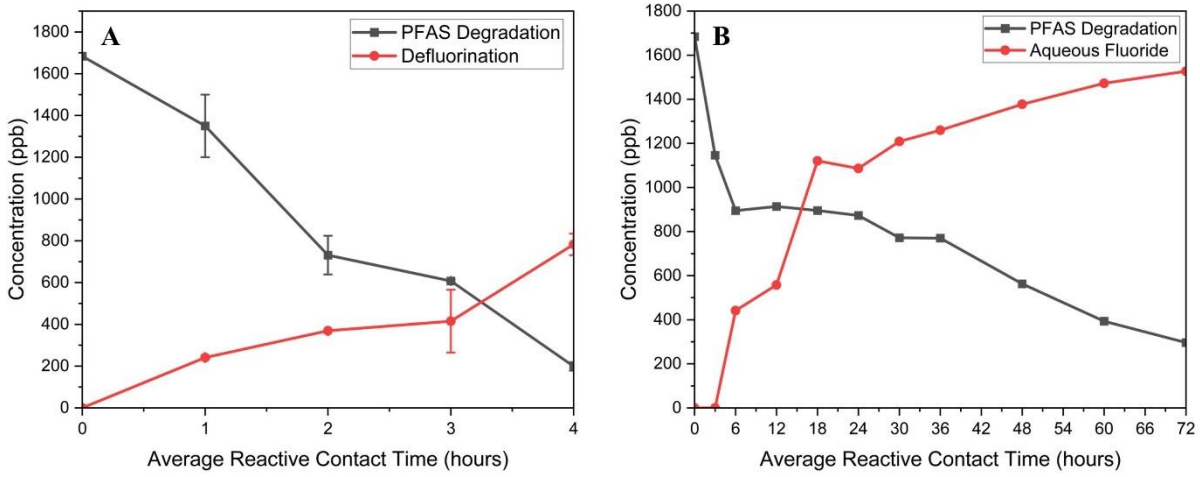


Figure 2. *AFFF-impacted stormwater results with A) previous study results (McIntyre et al., 2022) at a 35 mL/hr flowrate and B) current study results at a 0.5 gallon per minute flowrate*

PFAA precursors associated with AFFF formulations were identified in the stormwater solution. Five 6:2 fluorotelomers are presented in Figure 3. Total organic precursors (TOP) assay results presented in Table 1 point to the presence of other PFAA precursors, not identified, in the stormwater solution. Figure 3 shows degradation of 6:2 $FtSO_2AoS$, 6:2 FtSOAoS, 6:2 FTSA-PrB, and 6:2 $FTSO_2PA$ within 24 hours of treatment. Degradation products of these PFAA precursors is speculated to contribute to the concentration of 6:2 FTS which increases within the first 24 hours of treatment, before beginning to degrade.

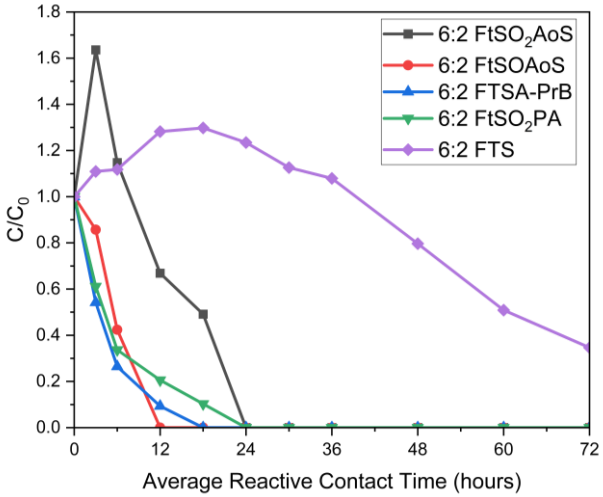


Figure 3. *PFAA precursor degradation in AFFF-impacted stormwater*

3.2 Synthetic ion exchange still bottoms

Treatment of synthetic still bottoms was studied to better understand the matrix effects of complex concentrated wastestreams and assess the effects of PFAS concentration on degradation. Synthetic still bottom solution was treated in both the packed-bed and coil reactor configurations. 9 PFAS were tracked throughout the treatment period as depicted in Figure 4. Both reactor configurations yielded significant degradation of all PFAS, with slower degradation rates for PFHxS and 6:2 FTS. While similar trends are shown in both configurations, degradation rates of PFSAs and PFAA precursors are substantially slower in the coil configuration. Degradation rates of PFCAs are nearly identical between the two reactor configurations. Results further validate, under alkaline conditions, SGM is solely responsible for the degradation of PFSAs and PFAA precursors, while PFCAs can be degraded by photolysis. The pack-bed reactor contained more SGM than the coiled configuration, thus greater degradation occurs. Final PFAS concentrations, along with percent removal, are presented in Table 3.

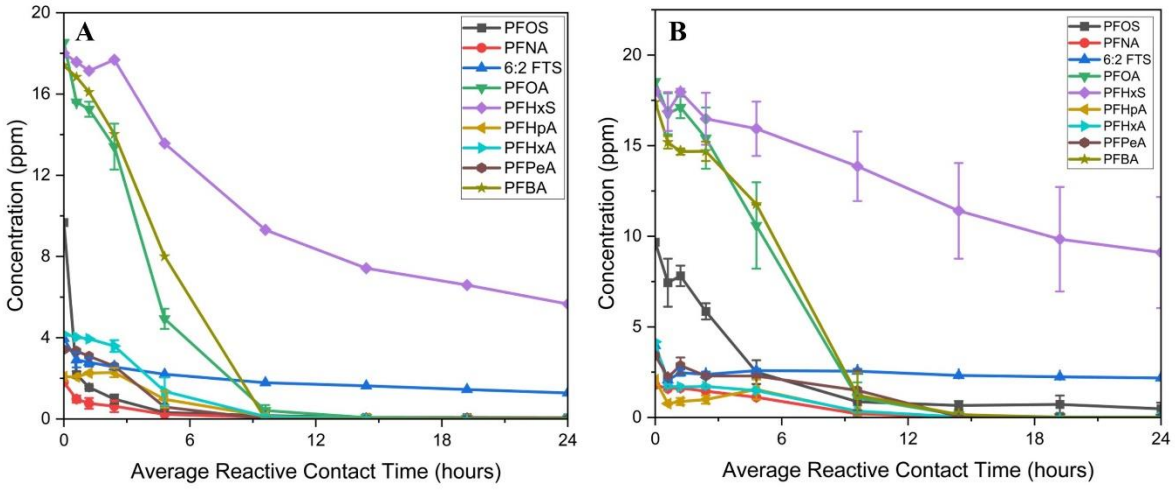


Figure 4. *Individual PFAS degradation with A) packed-bed configuration and B) coil configuration*

Table 3. *Synthetic still bottoms average results*

Analyte	Initial Concentration (ppm)	24-hour Treatment Concentration (ppm)	Percent Removal (%)
Packed-bed Reactor			
PFOS	9.67	0.058	99
PFNA	1.79	<LOD[a]	>99.99
6:2 FTS	3.96	1.3	67
PFOA	18.54	0.013	99.9
PFHxS	18.00	5.7	68
PFHpA	2.08	0.0087	99
PFHxA	4.18	0.0046	99.9
PFPeA	3.42	0.063	98
PFBA	17.40	0.040	99
Coiled Reactor			
PFOS	9.67	0.48	95
PFNA	1.79	<LOD[a]	>99.99
6:2 FTS	3.96	2.2	44
PFOA	18.54	0.018	99.9
PFHxS	18.00	9.1	49
PFHpA	2.08	0.0061	99
PFHxA	4.18	0.0084	99
PFPeA	3.42	0.097	97
PFBA	17.40	0.31	98

[a] LOD – limit of detection

Total PFAS degradation and subsequent aqueous fluoride recovery are presented in Figure 5. The packed-bed configuration resulted in 10% more degradation than the coil configuration after 24 hours of contact time (Figure 5a). However, Figure 5B depicts over 15% more defluorination for the coil configuration, despite degrading less PFAS. This is hypothesized to be from more fluoride precipitating within the pore space of SGM (McIntyre et al. 2022). Fluorine mass balances for both configurations were calculated using starting and ending concentrations from Table 3. The packed-bed reactor resulted in an 84 ± 6% total fluorine mass balance, while the coiled reactor resulted in a fluorine mass balance of 106 ± 3%. Considering only PFAS in EPA Method 537 were analyzed, PFAA precursors present in the still bottoms solution due to AFFF addition could be defluorinating, resulting in unaccounted fluorine in the mass balance calculation. Degradation rates of PFAS within the synthetic still bottoms were significantly faster compared to the AFFF-impacted stormwater, despite having substantially greater matrix effects. This is theorized to be from the lower concentration of PFAS in the AFFF-impacted stormwater, requiring longer contact time to adsorb and degrade the PFAS. Similar conclusions have been presented in other studies of photocatalytic PFAS degradation in literature (Cates, 2018).

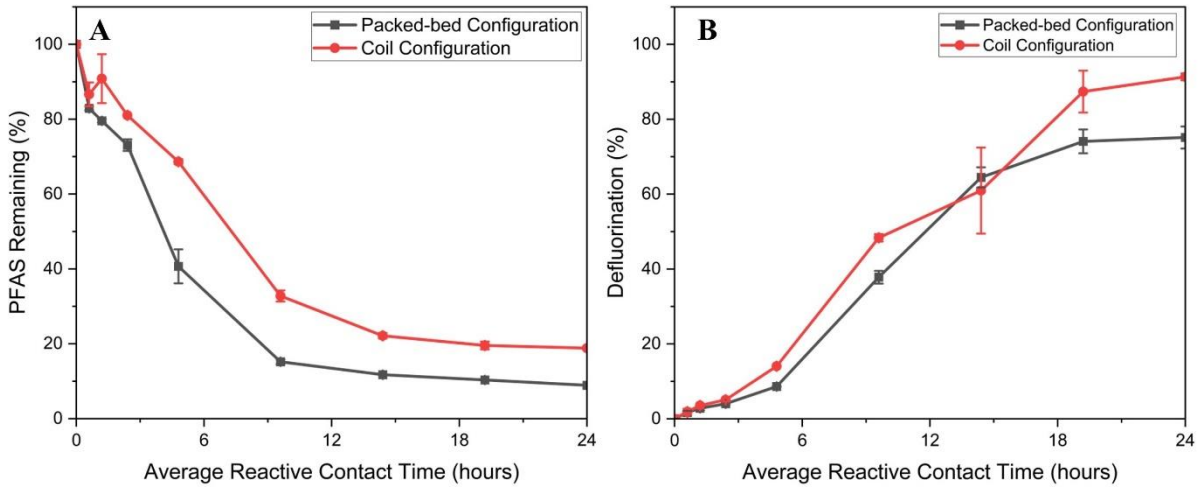


Figure 5. *Packed-bed versus coil reactor configuration with A) total PFAS degradation and B) aqueous fluoride recovered (defluorination)*

In addition to being a highly concentrated PFAS liquid waste, still bottoms contain high concentrations of salts, metals, and total organic carbon (TOC) which can impact PFAS degradation rates. While the impact of individual constituents on PFAS degradation kinetics was not assessed in this study, nitrate and nitrite were tracked over the treatment period (Figure 6). Nitrate is no longer present in effluent samples in both reactors after approximately 12 hours. Nitrite only appears after treatment commences, though there is a rapid peak followed by subsequent decrease. Figure 6 supports a denitrification process occurring due to the reactive radical species within the UV/SGM treatment. When evaluating the trends in the degradation curves impeding constituents, such as nitrate, could delay or slow the degradation of PFAS as they are preferentially sorbed. Impacts of chloride, TOC, sulfate, and iron were not assessed, but are hypothesized to also have some impact on PFAS degradation kinetics.

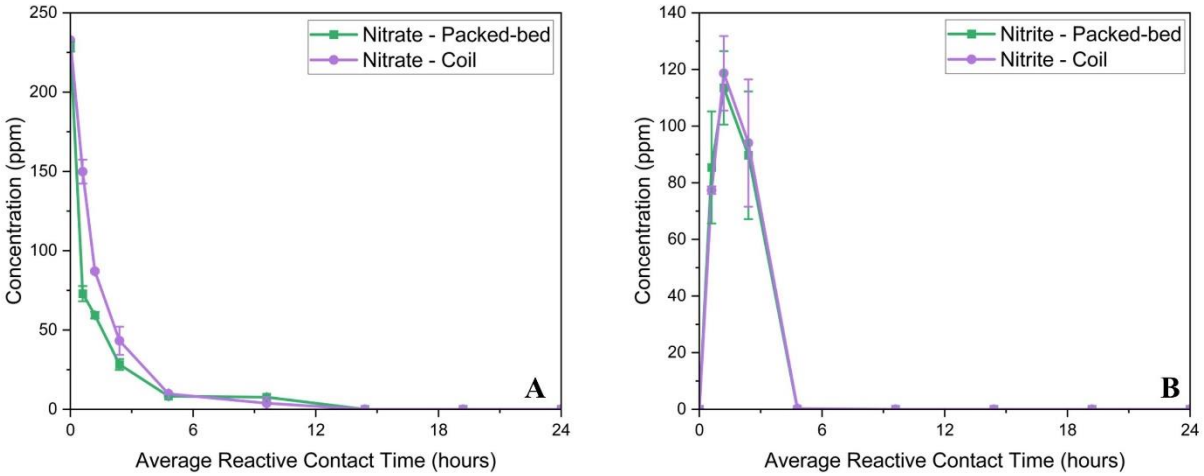


Figure 6. *Denitrification within UV/SGM treatment with A) nitrate and B) nitrite*

4 CONCLUSION, ENVIRONMENTAL IMPLICATIONS, AND FUTURE WORK

AFFF-impacted stormwater and synthetic still bottoms were treated during this study to determine the impact of PFAS concentrations in wastestreams on efficiency of UV/SGM treatment. Comparison of PFAS degradation within environmentally relevant wastestreams allowed for a better understanding of where UV/SGM and other destructive technologies are best utilized within the treatment process. While PFAS degradation and subsequent fluoride recovery occurred in both AFFF-impacted stormwater and synthetic still bottoms, synthetic still bottoms resulted in faster degradation rates. Secondary concentrated PFAS liquids are produced from some sequestration or separation technologies, allowing for a low volume of solution to be processed in destructive treatment systems. Some destructive technologies are greatly impacted by salts such as chloride, sulfate, or nitrate, TOC, or turbidity. While there are clear matrix effects presented in the synthetic still bottoms treatment, considerable PFAS degradation is observed, making UV/SGM a promising destructive technology which can be coupled with several different treatment processes in a train type system. In addition, reactor configuration was evaluated for UV/SGM usage. Both packed-bed and coil reactor configurations resulted in significant PFAS degradation in a complex concentrated liquid waste with 72-92% defluorination. Therefore, either system could be chosen for system scale-up. Future work with UV/SGM will further explore treatment of still bottoms using processed still bottoms produced on site, assess the effects of individual analytes or salts on PFAS treatment, and assess the treatment of other concentrated PFAS liquids compared to the synthetic still bottoms treated in this study.

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REFERENCES

Boo, C., Wang, Y., Zucker, I., Choo, Y., Osuji, C. O., & Elimelech, M. (2018). High Performance Nanofiltration Membrane for Effective Removal of Perfluoroalkyl Substances at High Water Recovery. Environmental Science and Technology, 52(13), 7279–7288. https://doi.org/10.1021/acs.est.8b01040

Boving, T., Ball, R. (2020). Enhanced Oxidative Destruction of PFAS in Investigation Derived Waste Soil and Water. *SERDP Project ER19-1545. Final Report. https://serdp-estcp-storage.s3.us-gov-west-1.amazonaws.com/s3fs-public/project_documents/ER18-1545%2BFinal%2BReport.pdf?VersionId=B.psJi.0EH71u96vMna8Q.iEzm3fFM2h*

Cates, E. (2018). Pilot Scale Assessment of a Deployable Photocatalytic Treatment System Modified with BiPO4 Catalyst Particles for PFAS Destruction in Investigation-Derived Wastewaters. SERDP Final Report ER18-1599.

Cousins, I. T., Johansson, J. H., Salter, M. E., Sha, B., & Scheringer, M. (2022). Outside the Safe Operating Space of a New Planetary Boundary for Per- and Polyfluoroalkyl Substances (PFAS). In *Environmental Science and Technology* (Vol. 56, Issue 16, pp. 11172–11179). American Chemical Society. https://doi.org/10.1021/acs.est.2c02765

DoD. (2022). Temporary Prohibition on Incineration of Materials Containing Per- and Polyfluoroalkyl Substances (PFAS). https://media.defense.gov/

Feng, M., Gao, R., Staack, D., Pillai, S. D., & Sharma, V. K. (2021). Degradation of perfluoroheptanoic acid in water by electron beam irradiation. *Environmental Chemistry Letters*, *19*(3), 2689–2694. https://doi.org/10.1007/s10311-021-01195-x

ITRC (Interstate Technology & Regulatory Council). 2020. *PFAS Technical and Regulatory Guidance Document and Fact Sheets* PFAS-1. Washington, D.C.: Interstate Technology & Regulatory Council, PFAS Team. https://pfas-1.itrcweb.org/.

Kanchanapiya, P., & Tantisattayakul, T. (2022). Analysis of the additional cost of addressing per- and polyfluoroalkyl substance contamination from landfill leachate by reverse osmosis membranes in Thailand. Journal of Water Process Engineering, 45(September 2021), 102520. https://doi.org/10.1016/j.jwpe.2021.102520

Kulkarni, P. R., Richardson, S. D., Nzeribe, B. N., Adamson, D. T., Kalra, S. S., Mahendra, S., Blotevogel, J., Hanson, A., Dooley, G., Maraviov, S., & Popovic, J. (2022). Field Demonstration of a Sonolysis Reactor for Treatment of PFAS-Contaminated Groundwater. *Journal of Environmental Engineering*, *148*(11). https://doi.org/10.1061/(asce)ee.1943-7870.0002064

Leeson, A., Thompson, T., Stroo, H. F., Anderson, R. H., Speicher, J., Mills, M. A., Willey, J., Coyle, C., Ghosh, R., Lebrón, C., & Patton, C. (2021). Identifying and Managing Aqueous Film-Forming Foam-Derived Per- and Polyfluoroalkyl Substances in the Environment. *Environmental Toxicology and Chemistry*, *40*(1), 24–36. https://doi.org/10.1002/etc.4894

Linang S., Mora R., Huang Q., Casson R., Wang Y., Woodard S., & Anderson H. (2022). Field demonstration of coupling ion-exchange resin with electrochemical oxidation for enhanced treatment of per- and polyfluoroalkyl substances (PFAS) in groundwater. Chemical Engineering Journal Advances, 9. https://doi.org/10.1016/j.ceja.2021.100216

McIntyre, H. M., & Hart, M. L. (2021). Photocatalytic porous silica-based granular media for organic pollutant degradation in industrial waste-streams. *Catalysts*, *11*(2), 1–20. https://doi.org/10.3390/catal11020258

McIntyre, H. M., Minda, V., Gutheil, W., & Hart, M. L. (2021). Degradation and Defluorination of Aqueous Perfluorooctane Sulfonate by Silica-Based Granular Media Using Batch Reactors. *Journal of Environmental Engineering*, *147*(11). https://doi.org/10.1061/(asce)ee.1943-7870.0001922

McIntyre, H., Minda, V., Hawley, E., Deeb, R., & Hart, M. (2022). Coupled photocatalytic alkaline media as a destructive technology for per- and polyfluoroalkyl substances in aqueous film-forming foam impacted stormwater. *Chemosphere*, *291*, 132790. https://doi.org/10.1016/J.CHEMOSPHERE.2021.132790

Nau-Hix, C., Multari, N., Singh, R. K., Richardson, S., Kulkarni, P., Anderson, R. H., Holsen, T. M., & Thagard, S. M. (2021). Field Demonstration of a Pilot-Scale Plasma Reactor for the Rapid Removal of Poly- and Perfluoroalkyl Substances in Groundwater. *ACS ES and T Water*, *1*(3), 680–687. https://doi.org/10.1021/acsestwater.0c00170

Ren, Z., Bergmann, U., & Leiviskä, T. (2021). Reductive degradation of perfluorooctanoic acid in complex water matrices by using the UV/sulfite process. *Water Research*, *205*. https://doi.org/10.1016/j.watres.2021.117676

Smith, S. J., Wiberg, K., McCleaf, P., & Ahrens, L. (2022). Pilot-Scale Continuous Foam Fractionation for the Removal of Per- A nd Polyfluoroalkyl Substances (PFAS) from Landfill Leachate. *ACS Environmental Science and Technology Water*. https://doi.org/10.1021/acsestwater.2c00032

Singh, R. K., Multari, N., Nau-Hix, C., Woodard, S., Nickelsen, M., Mededovic Thagard, S., & Holsen, T. M. (2020). Removal of Poly- And Per-Fluorinated Compounds from Ion Exchange Regenerant Still Bottom Samples in a Plasma Reactor. Environmental Science and Technology, 54(21), 13973–13980. https://doi.org/10.1021/acs.est.0c02158

USEPA, 2018. Reducing PFAS in Drinking Water with Treatment Technologies (Fact Sheets). USEPA.

Wu, B., Hao, S., Choi, Y., Higgins, C. P., Deeb, R., & Strathmann, T. J. (2019). Rapid Destruction and Defluorination of Perfluorooctanesulfonate by Alkaline Hydrothermal Reaction. *Environmental Science and Technology Letters*, *6*(10), 630–636. https://doi.org/10.1021/acs.estlett.9b00506