An Overview of PFAS Treatment Technologies

Peter R. Jaffé
Department of Civil and Environmental Engineering
Princeton University

NERC PFAS Webinar

March 24, 2026

Major Sources of PFAS

- **Atmospheric deposition.** Sorption to colloids or partitioning into the vapor phase (e.g., from PFAS production facilities).
- **Aqueous Film Forming Foam (AFFF) application.** Since the early 60's, AFFF's primary ingredient was PFOS in addition to other PFAS.
- **Landfill leachate.**
- **Land applications of biosolids from wastewater treatment plants.**

Media Contaminated Requiring Treatment

- Water, especially drinking water
- Soil

  Highly contaminated, but smaller locations (i.e., airports, DoD sites, industrial sites).

  Larger tracks of land (e.g., contaminated farmland).
- Groundwater
- Biosolids
- Landfill leachate

Required Timeframe for Treatment

- **Drinking water plants.** When treating several millions of gallons per day, treatment needs to be **fast**. Unit operation process on the order of 10's of minutes, typically removal via sorption.
- **Soil, contaminated sites.** Once source has been isolated, treatment can be **slower** (~ years if needed), allowing for more cost-effective technologies.

Physical Processes

- **Sorption.** Carbon, biochar, nanomaterials, ion exchangers. Greater sorption for longer-chain PFAS than shorter ones.
- **Reverse Osmosis/Nanofiltration.** Effective, specially in removing colloids that can contain PFAS.
- **Foam Fractionation.** Bubbling to induce the adsorption of surfactant molecules to the air-liquid interface.

- Destruction of PFAS is not achieved in these processes and spent sorbent or concentrate need treatment/disposal.

Chemical Processes

- **Incineration.** 1100^{o}C for more than 2 seconds (Brunn et al., 2023).
- **Pyrolysis.** Heated to between 400^{o}C and 900 ^{o}C anaerobically (still lots of unknowns).
- **Photolysis.**
- **Oxidation/Reduction.**

Biological Processes

- **Biodegradation/biotransformation**

polyfluorinated substances – many aerobic and anaerobic organisms have been reported that can at least partially degrade them. In many cases polyfluorinated compounds (precursors) get transformed to perfluorinated compounds.

perfluorinated substances – much harder to degrade.

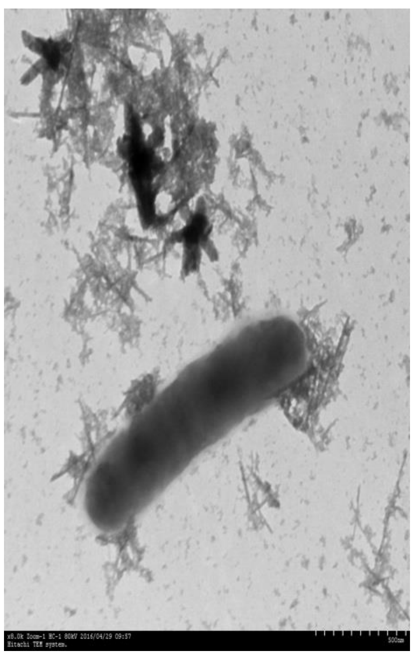
- **Phytoremediation**

We might be now at a point where we were 40 years ago with biological remediation for chlorinated compounds.

Oxidation of NH_4^+ under Fe reducing conditions

$$3Fe_2O_3 \cdot 0.5H_2O + 10H^+ + NH_4^+ \rightarrow 6Fe^{2+} + 8.5H_2O + NO_2^-$$

$$\Delta G_r \leq -145.08 kJ\ mol^{-1}$$



***Acidimicrobium* sp. strain A6**

(ATCC, PTA-122488)

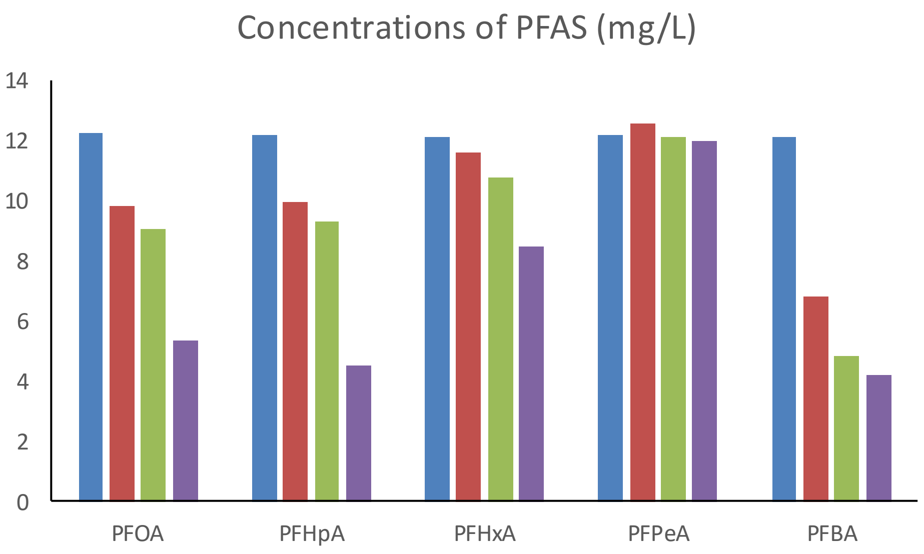
A6 is an autotroph that can use NH_4^+ and H_2 as electron donor, and Fe(III) as electron acceptor.

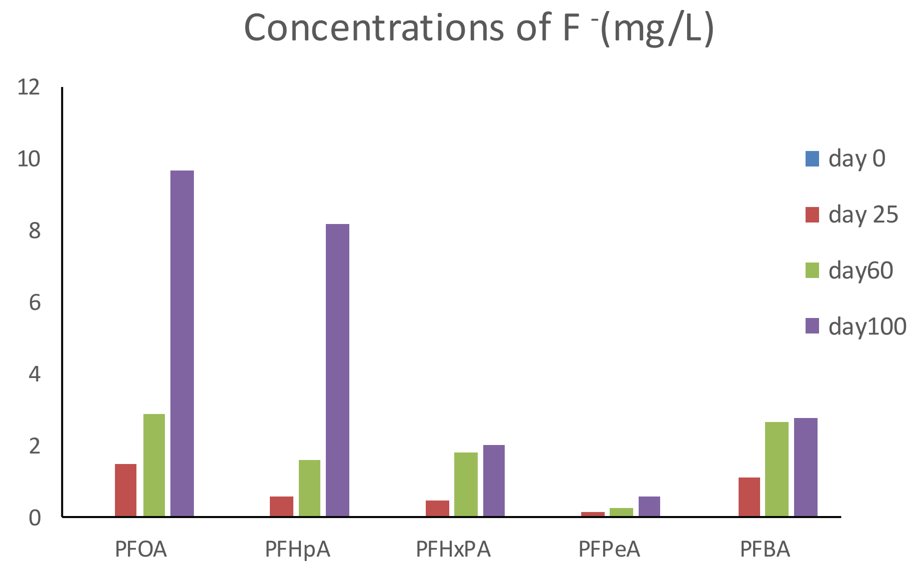
A6's doubling time ~ 10 – 14 days.

A6's genome contains multiple dehalogenase genes (GenBank accession numbers MK358459-MK358462), and two fluoride ion transporter genes (***CrcB***, PROKKA_02975, and PROKKA_02977.

Incubation experiments with Acidimicrobium sp. Strain A6

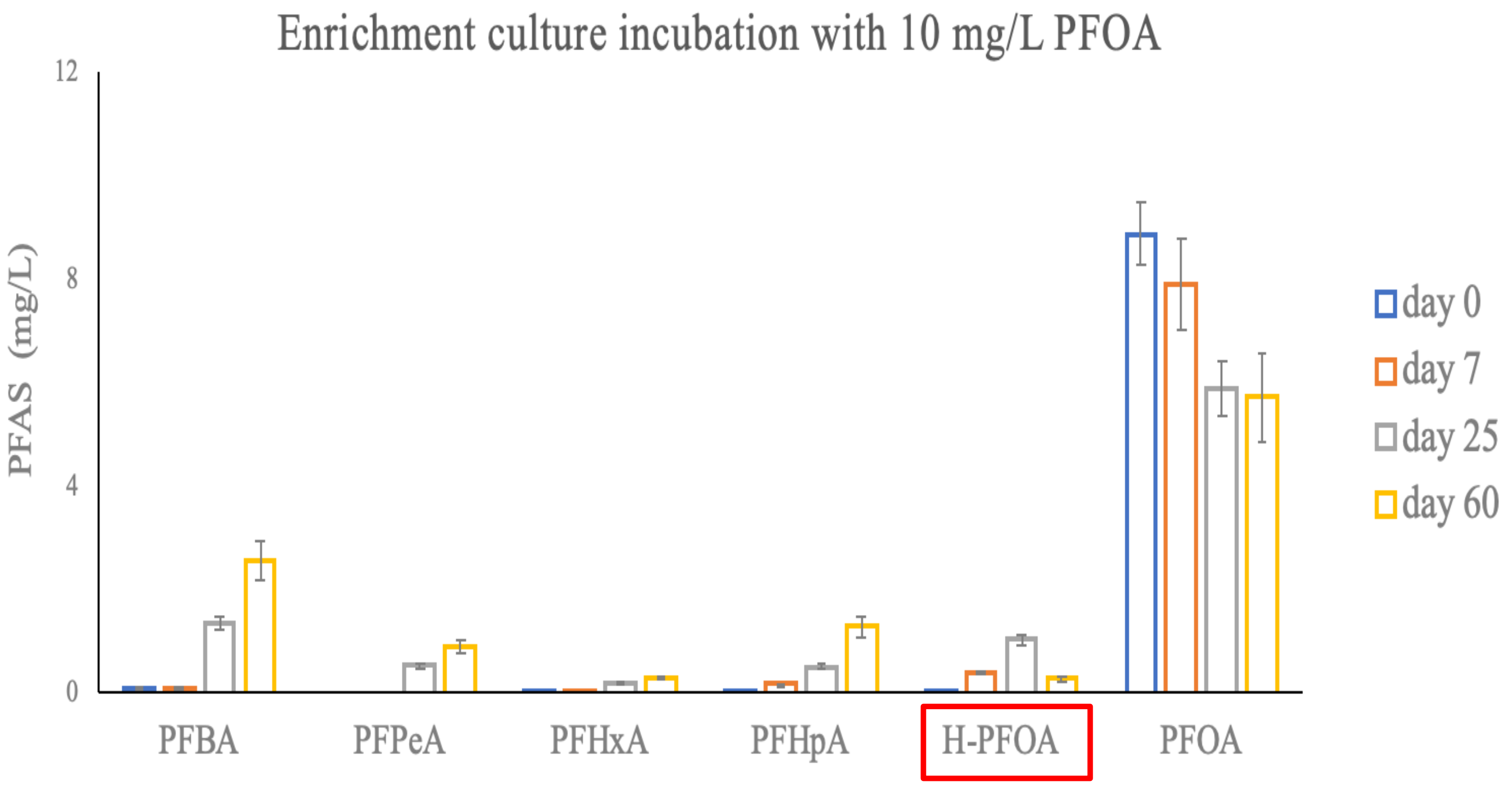
Degradation of perfluoro carboxylic acids (PFCAs) of various carbon chain lengths and production of F^-



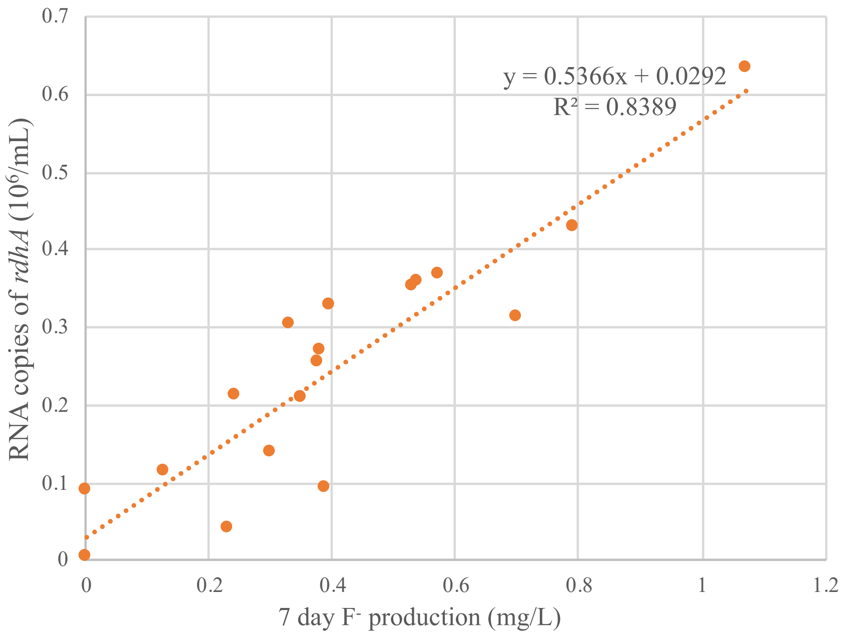


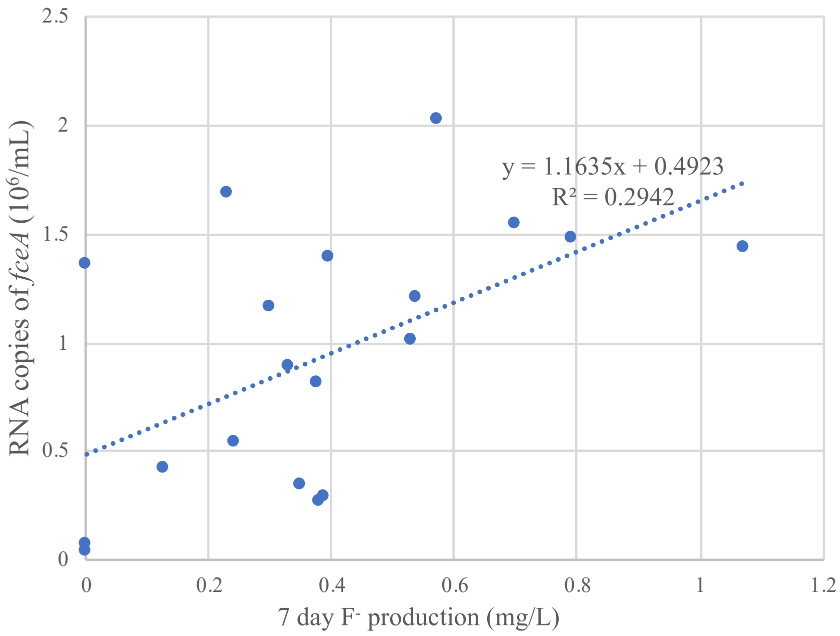
Similar results for perfluorosulfonic acids (PFSAs): PFDS, PFOS, PFHxS, PFBS

Shorter PFCAs produced during the degradation of PFOA by A6



Expression of rdhA genes and FceA gene vs. F^- production over 7 days in the pure A6 culture for PFOA, PFOS, and PFHxS incubations





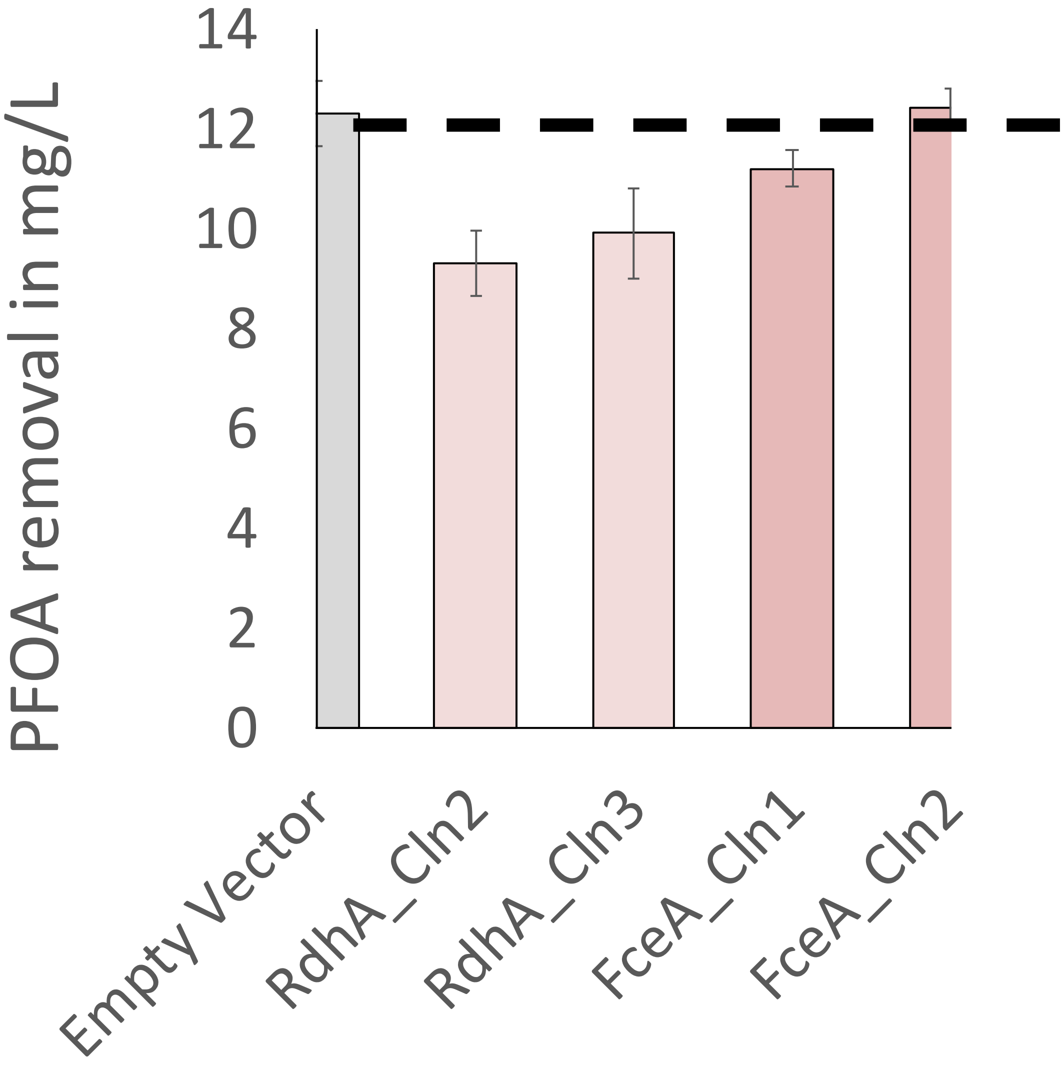
The haloacid dehalogenase genes (*dhl_1* and *dhl_2*) are not expressed during defluorination but are expressed during dichlorination (TCP).

The fluoride ion transporter genes (*CrcB*) are always expressed when defluorination is observed.

Altough the rdhA gene is key in the defluorination of PFAS by A6, it is unclear if

- The *rdhA* gene may be responsible for an enzyme that required to defluorinated PFAS.
- If so, can the *rdhA* gene be inserted into a plasmid and then the plasmid introduced into a fast-growing host?
- How about the *FceA*?
- If so, can the enzyme produced by that host degrade PFAS?

Effect of overexpression A6 dehalogenases in e-coli - 2 to 24-hour in vitro assays



Extremely promising results but need much more R&D.

Costs

- Effect of PFAS on health in the US ~ $37-59 billion/year (Cordner et al., 2021).
- Cleanup cost for PFAS contaminated sites in the US ~ $400 billion (Sansone and DiGiannantonio, 2023).
- Global cost of PFAA remediation ~ $20 to $7000 trillion/year (Ling, 2024). Global GDP ~ $106 trillion.

Conclusions

- Although technology for treating PFAS exist and have been shown to work well, cost estimates for PFAS remediation vary widely and are overwhelmingly steep.
- Therefore, we need to focus on the most harmful PFAS and sites/media contaminated with these compounds resulting in high exposure.
- Less costly treatment technology will need to be developed.

Selected References

- Cordner, A., Goldenman, G., Birnbaum, L. S., Brown, P., Miller, M. F. Mueller, R., Patton, S., Salvatore, D. H., Trasande, L. 2021. The true cost of PFAS and the benefits of acting now. Environ. Sci. Technol. 55:9630-9633.
- Ling, A. L. 2024. Estimated scale of costs to remove PFAS from the environment at current emission rates. Sci. Total Environ. 918, 170647.
- Sansone, K., DiGiannantonio, M. 2023. Easing the Financial Burden of Treating PFAS Contaminated Water. J. New England Water Works Association, 137(4):30-33.