Techniques and Technologies to Remove Per- and Polyfluoroalkyl Substances (PFAS) From Contaminated Soil and Water – A Literature Review on PFAS Remediation Options

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PFAS, An Emerging Threat To Environment and Human Health

Emerging Threat: Per- and poly-fluoroalkyl substances (PFAS) are associated with adverse health outcomes, including cancer, reduced fetal growth, and liver injury. Human exposures occur through contaminated water, soil, air, and food. Remediation strategies will be critical to reducing PFAS exposures in people and the environment.

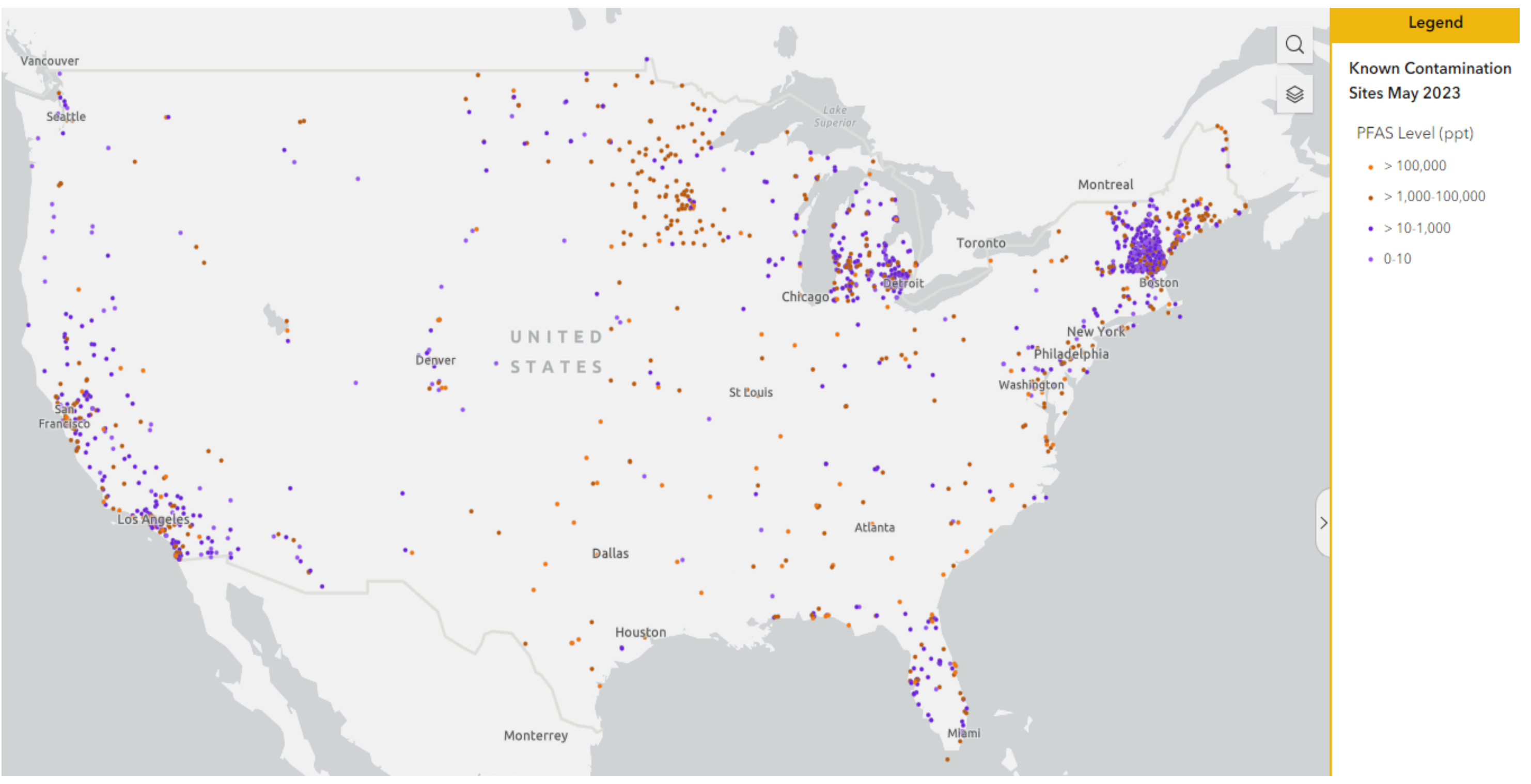
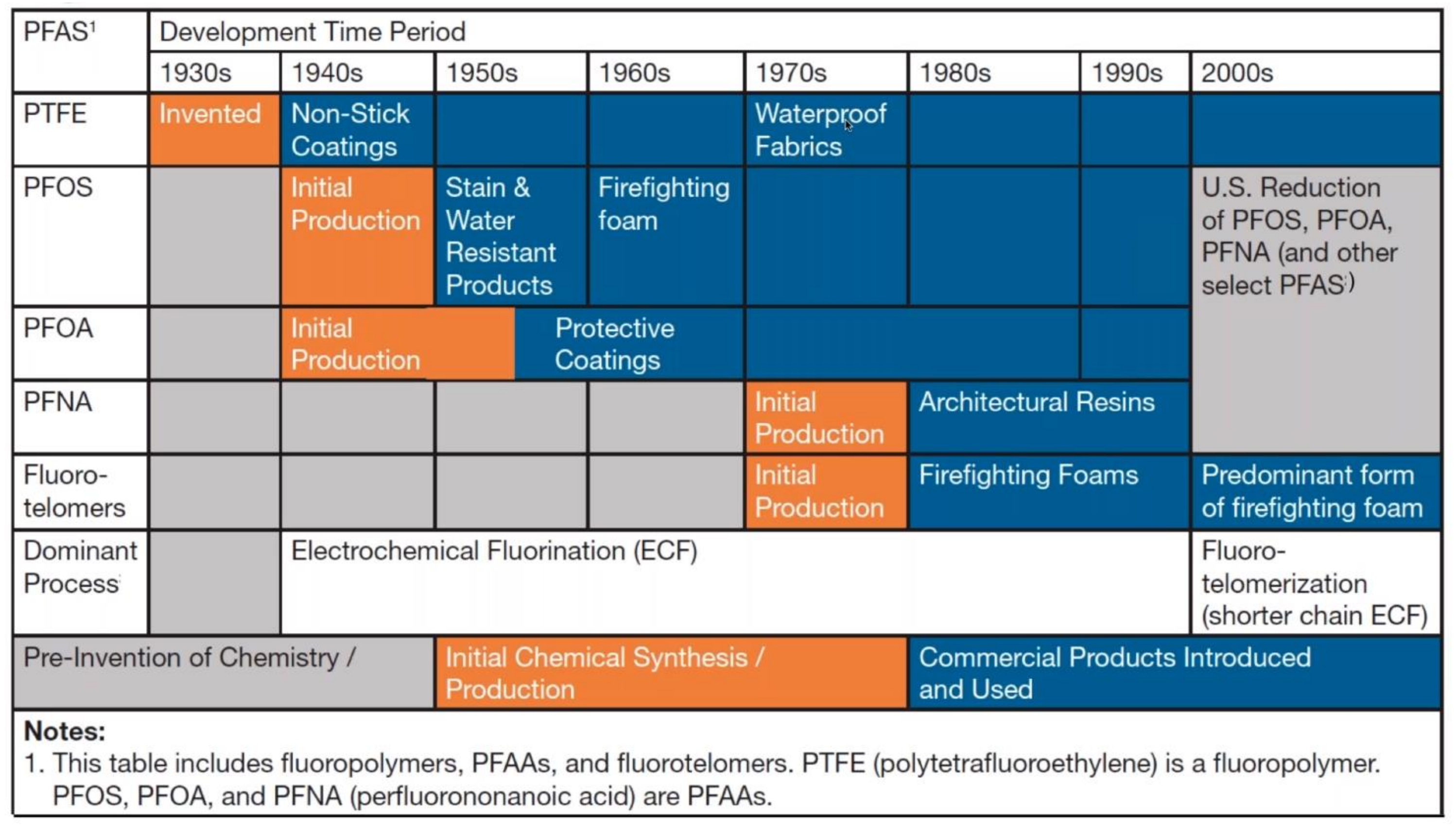


Figure 1. Over 1,930 confirmed U.S. PFAS contaminated sites identified by PFAS Project Lab[1]



PFAS[1]	Development Time Period							
	1930s	1940s	1950s	1960s	1970s	1980s	1990s	2000s
PTFE	Invented	Non-Stick Coatings			Waterproof Fabrics			
PFOS		Initial Production	Stain & Water Resistant Products	Firefighting foam				U.S. Reduction of PFOS, PFOA, PFNA (and other select PFAS)
PFOA		Initial Production	Protective Coatings					
PFNA					Initial Production	Architectural Resins		
Fluoro-telomers					Initial Production	Firefighting Foams		Predominant form of firefighting foam
Dominant Process		Electrochemical Fluorination (ECF)						Fluoro-telomerization (shorter chain ECF)
Pre-Invention of Chemistry /			Initial Chemical Synthesis / Production			Commercial Products Introduced and Used		

Notes:
1. This table includes fluoropolymers, PFAAs, and fluorotelomers. PTFE (polytetrafluoroethylene) is a fluoropolymer. PFOS, PFOA, and PFNA (perfluorononanoic acid) are PFAAs.

Figure 2. History of PFAS production and use according to ITRC[2]

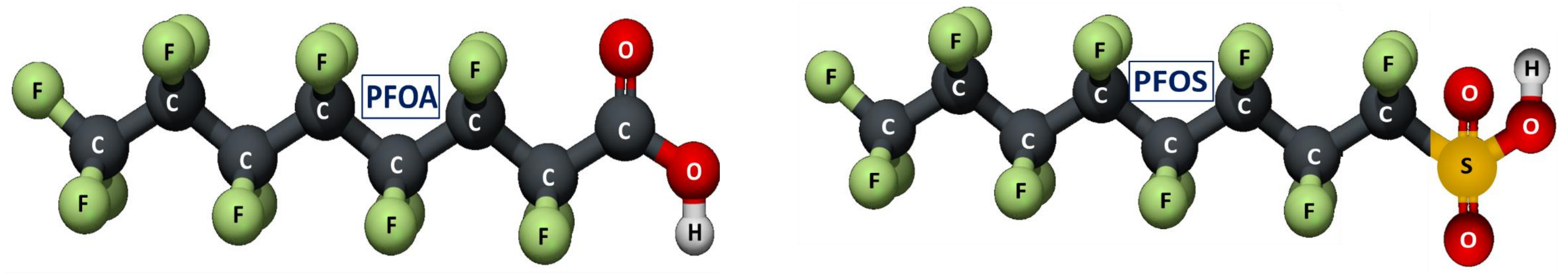
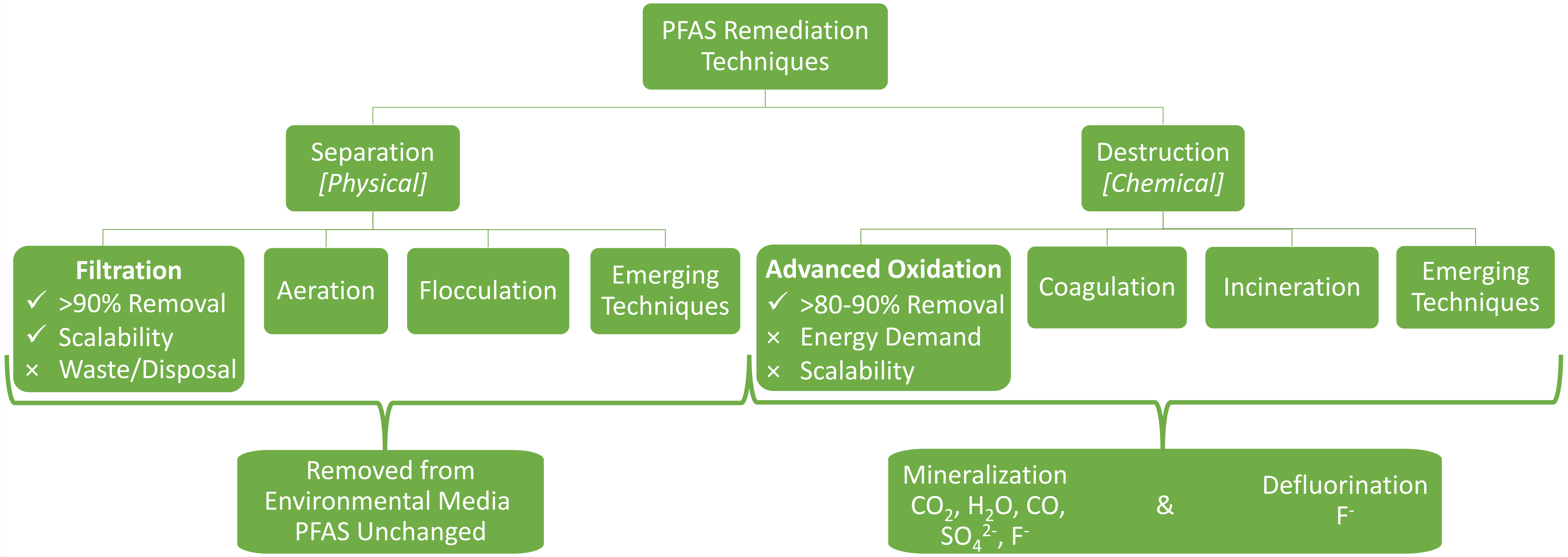


Figure 3. Molecular structures of perfluorooctanoic acid (PFOA) and perfluoroooctane sulfonic acid (PFOS)

Research Focus and Results

Objective: To understand **which** remediation strategies (techniques) are most **viable** for remediating PFAS contaminated soil and water. *Also*: What critical barriers exist for translation from bench scale/pilot research to real-world applications?

Methods: Literature review, with comparative analysis, of **329 remediation studies** (10 soil, 157 aqueous (laboratory-made), 162 water), of varying scales (bench, pilot, and industrial), from the PFAS-Tox Database[3] (https://pfastoxdatabase.org/), a publicly available systematic evidence map of over 1,000 PFAS health and toxicology studies.



PFAS Remediation Techniques

Separation *[Physical]*

Destruction *[Chemical]*

Filtration
- ✓ >90% Removal
- ✓ Scalability
- × Waste/Disposal

Aeration

Flocculation

Emerging Techniques

Advanced Oxidation
- ✓ >80-90% Removal
- × Energy Demand
- × Scalability

Coagulation

Incineration

Emerging Techniques

Removed from Environmental Media PFAS Unchanged

Mineralization CO$_2$, H$_2$O, CO, SO$_4^{2-}$, F$^-$ & Defluorination F$^-$

Figure 4. Summary of advantages, challenges, and product degradants of different PFAS remediation techniques

PFAS Chemistry

- Large class of human-made chemicals with hydrophobic *tail* and hydrophilic *head*
- Persistence from *tail's* strong carbon-fluorine (C-F) bonds; desirable remediation traits from functional group *head*
  - ⇒*Ex.* Dissociation (hydrogens from *head* break away) in water leads to anionic chemical (easier to remove than neutrally charged acid)

Common Challenges

- PFAS precursor transformations often result in toxic PFOA and PFOS as terminal degradants
- Different chemical structures may require unique remediation strategies

Future Directions

- What remediation techniques are best for:
  - ⇒Long versus Short Chain PFAS | Branched versus Linear
  - ⇒Carrying out Defluorination versus Mineralization
  - ⇒Destroying the PFAS *head* versus *tail*
- What are the specific technique/technology treatment train sequences to achieve high removal/destruction efficiencies (>90%)
- What are the main environmental health and engineering implications

References

1. PFAS Project Lab and PFAS Exchange: https://pfas-exchange.org/connecting-communities/
2. Interstate Technology and Regulatory Council (ITRC): itrcweb.org | https://pfas-1.itrcweb.org/fact-sheets/
3. PFAS-Tox Database Protocol Paper: https://pubmed.ncbi.nlm.nih.gov/35908389/
4. Environmental Working Group (EWG): ewg.org
5. Environmental Protection Agency (EPA): https://www.epa.gov/pfas
6. Agency for Toxic Substances and Disease Registry (ATSDR): https://www.atsdr.cdc.gov/pfas/health-effects/index.html

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