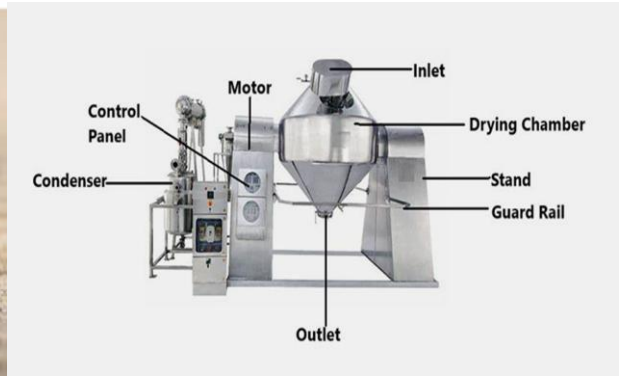
NJWEA 111th Annual Conference
Session: Air Pollution & GHG
Atlantic City, NJ May 12, 2026

SoPE PROCESS CLEANS UP PFAS FROM BIOSOLIDS: GAS EMISSIONS IMPLICATIONS

By: Edward Weinberg, P.E., President, ESSRE Consulting, Inc.



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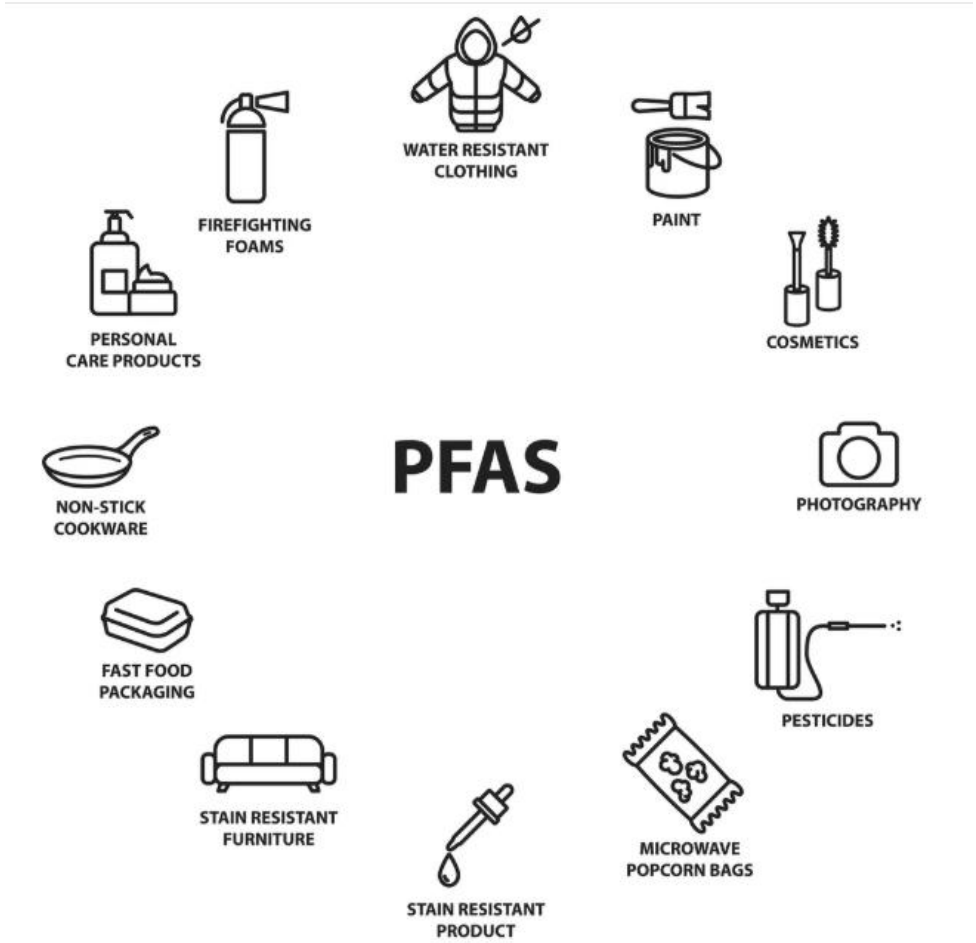
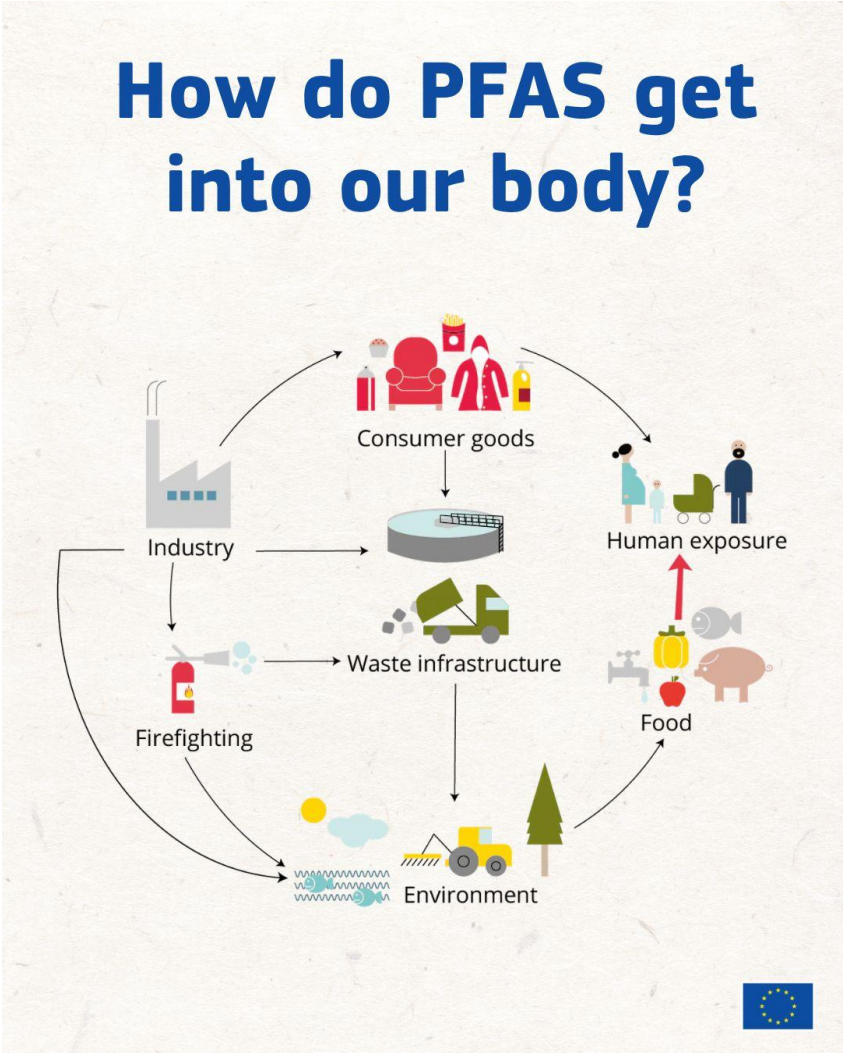
PFAS Many Uses Perpetuates the PFAS Cycle





Thousands of PFAS Compounds

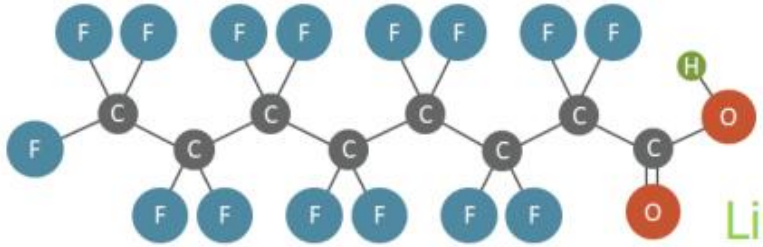
PFAS Chemistry

Perfluoroalkyls: Chain of only C and F atoms

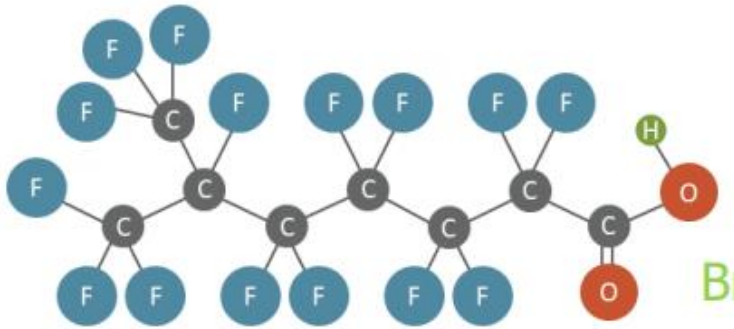
PFCAs (perfluoroalkyl carboxylates)

- Carbon
- Hydrogen
- Oxygen
- Chlorine
- Fluorine
- Single bond
- Double bond

PFOA (perfluorooctanoic acid)

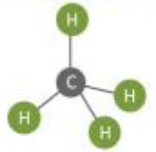


Linear isomer



Branched isomer
(1 example)

Methane

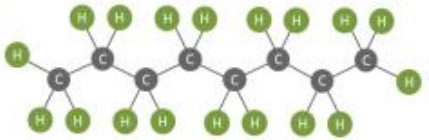


Alkyl: only C and H atoms

TCE (trichloroethene)

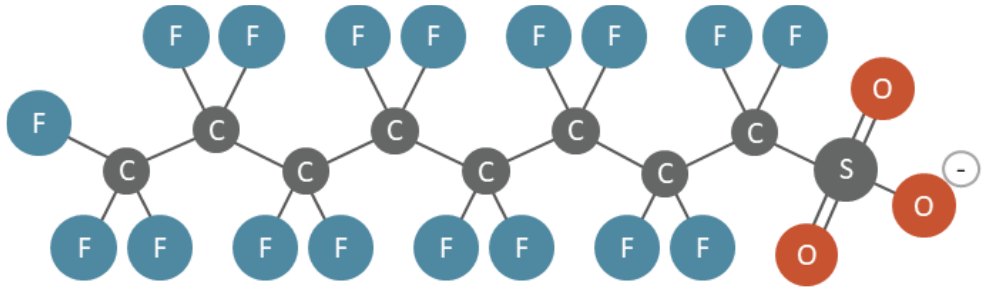
Benzene

Octane



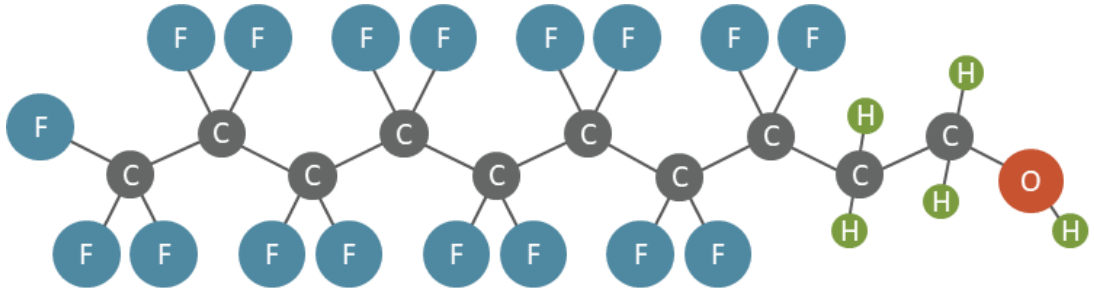
Thousands of PFAS Compounds

PFSAs (perfluoroalkane sulfonates)



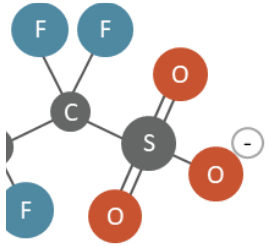
PFOS (perfluorooctane sulfonate)

<u>Poly</u>fluoroalkly Substances

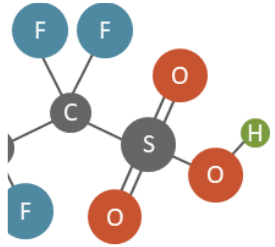


Partially fluorinated, at least one Carbon has a non-fluorine atom. Example, 8:2 Fluorotelomer alcohol (8:2 FTOH)

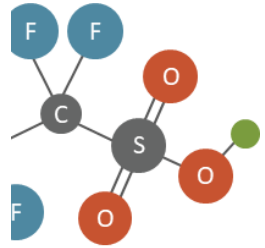
PFAS Compounds Exist in Various States



Anion



Acid



Salt

PFAS "Forever" – Enormous Liabilities

- **EPA** has finalized maximum contaminant levels for six PFAS compounds
- **EPA**'s Superfund designation of PFOA and PFOS as hazardous substances under CERCLA
- Top 12 PFAS Producers: 3M, AGC, Archroma, Arkema, BASF, Bayer, Chemours, Daikin, Honeywell, Merck, and Solvay
  - Cummulative Annual Profits: **$4B**
  - 3M's settlement case **$12.5 B** (drinking water)
- UK Environment Agency estimates remediation costs for between 2,900 and 10,200 high-risk sites in England at between **£31 billion and £121 billion**
- **PFAS Destruction TAM Estimates: Global $400B; US Biosolids $36.4 (23,900 WWTP)**

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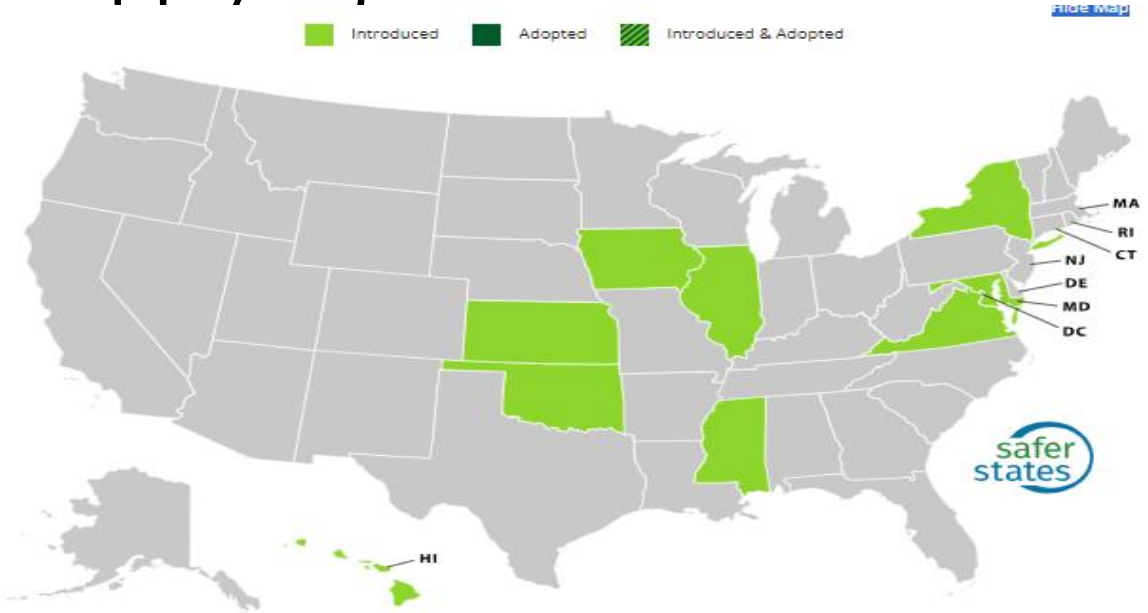
Foreseeing the PFAS Biosolids Future: Banning Land Applications

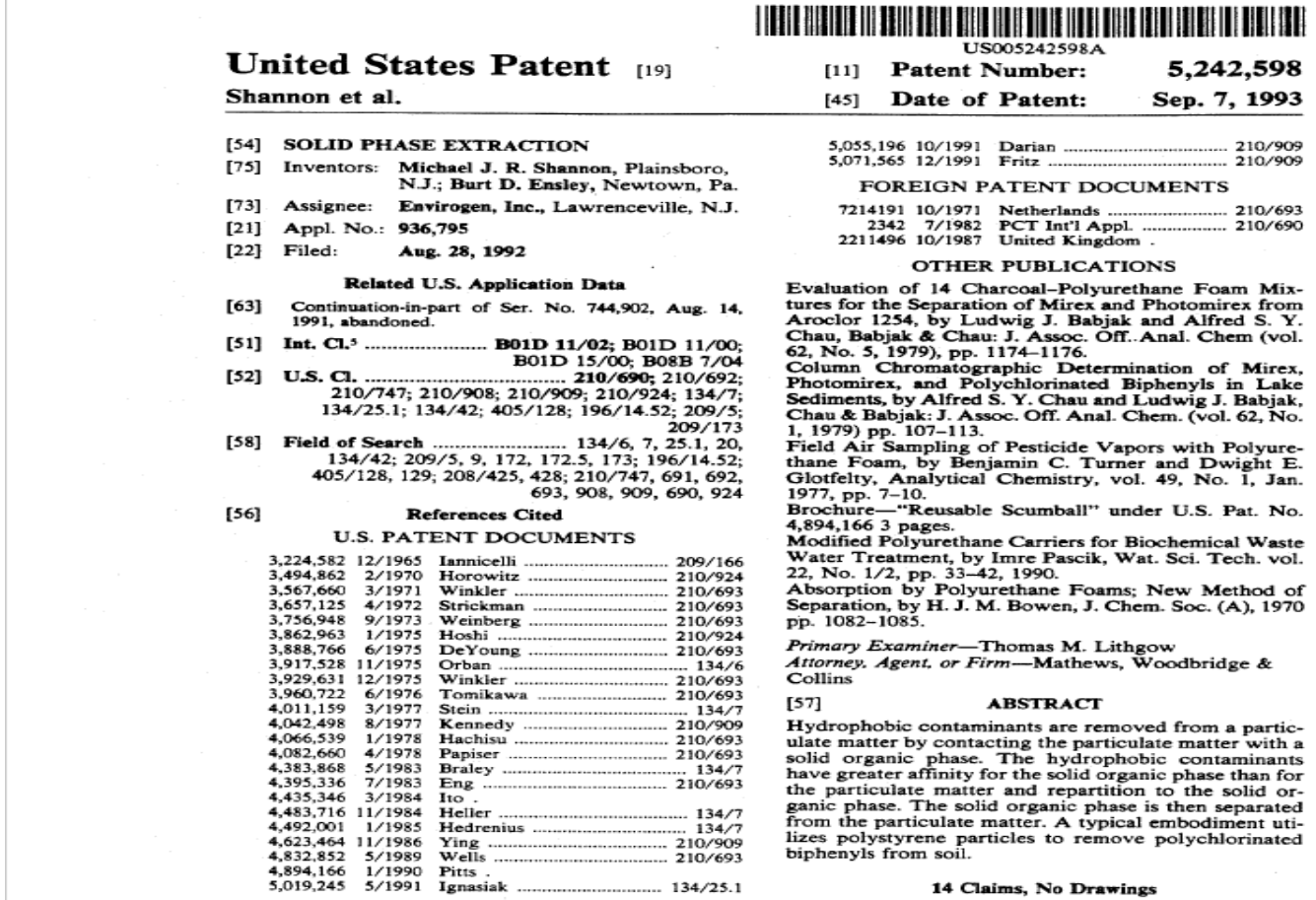
- ME, CT, MI have fully banned or restricted land application
- MI, NH, MA require biosolids testing
- Several states are applying restrictions as of 1Q 2026:



SoPE Patent –Solid Organic Phase Extraction

- The SoPE process repartitions hydrophobic compounds (PCBs, Hg, PFAS) from solids, soils, sediments, biosolids or spent GAC/IXR onto another more hydrophobic solid phase material

- Why is PFAS hydrophobic?
  - Strong Carbon-Fluorine (C-F) Bond
  - F makes it highly Electronegative
  - Resistant to dissolving in water
  - Caused by the fluorinated "tail"



US005242598A

United States Patent [19]
Shannon et al.

[11] **Patent Number: 5,242,598**
[45] **Date of Patent: Sep. 7, 1993**

[54] **SOLID PHASE EXTRACTION**
[75] Inventors: **Michael J. R. Shannon**, Plainsboro, N.J.; **Burt D. Ensley**, Newtown, Pa.
[73] Assignee: **Envirogen, Inc.**, Lawrenceville, N.J.
[21] Appl. No.: **936,795**
[22] Filed: **Aug. 28, 1992**

Related U.S. Application Data

[63] Continuation-in-part of Ser. No. 744,902, Aug. 14, 1991, abandoned.

[51] **Int. Cl.**[5] **B01D 11/02**; B01D 11/00; B01D 15/00; B08B 7/04
[52] **U.S. Cl.** **210/690**; 210/692; 210/747; 210/908; 210/909; 210/924; 134/7; 134/25.1; 134/42; 405/128; 196/14.52; 209/5; 209/173
[58] **Field of Search** 134/6, 7, 25.1, 20, 134/42; 209/5, 9, 172, 172.5, 173; 196/14.52; 405/128, 129; 208/425, 428; 210/747, 691, 692, 693, 908, 909, 690, 924

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Column Chromatographic Determination of Mirex, Photomirex, and Polychlorinated Biphenyls in Lake Sediments, by Alfred S. Y. Chau and Ludwig J. Babjak, Chau & Babjak: J. Assoc. Off. Anal. Chem. (vol. 62, No. 1, 1979) pp. 107–113.
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Primary Examiner—Thomas M. Lithgow
Attorney, Agent, or Firm—Mathews, Woodbridge & Collins

[57] **ABSTRACT**

Hydrophobic contaminants are removed from a particulate matter by contacting the particulate matter with a solid organic phase. The hydrophobic contaminants have greater affinity for the solid organic phase than for the particulate matter and repartition to the solid organic phase. The solid organic phase is then separated from the particulate matter. A typical embodiment utilizes polystyrene particles to remove polychlorinated biphenyls from soil.

14 Claims, No Drawings

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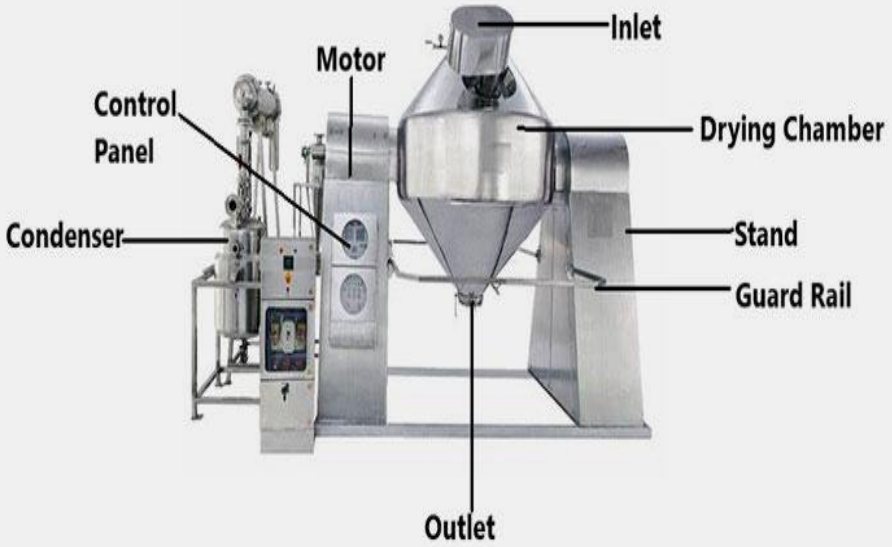
SoPE Process Steps and Materials



Simple Batch Operation:

- Add ingredients thru INLET
  1) Biosolids + Solvent (mix)
  2) Water (mix)
  3) Extractant Material
- Mix all for designated time and recover solvent
- Discharge thru OUTLET
- Separate Extractant Material from Biosolids (not shown)

Two **S**olid **O**rganic **P**hase **E**xtractants: **Expanded Polystyrene Beads & Rubber Crumb/Tire Tread**

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SoPE PCB Soil Results

Solvent	PCB REMOVAL (%)	
	Process #1	Process #2
Methanol	54.8	58.1
Acetone	65.8	97.5
Dioxane	89.5	96.2
Ether/methanol	56.2	93.7
Ether/acetone	55.6	80.7

Process #2 follows steps shown in previous slide

Source: US Patent No. 5,242,598

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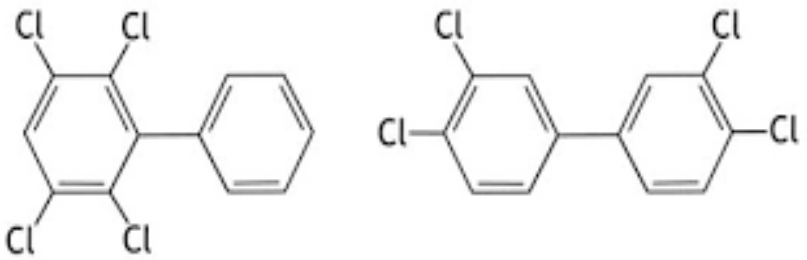
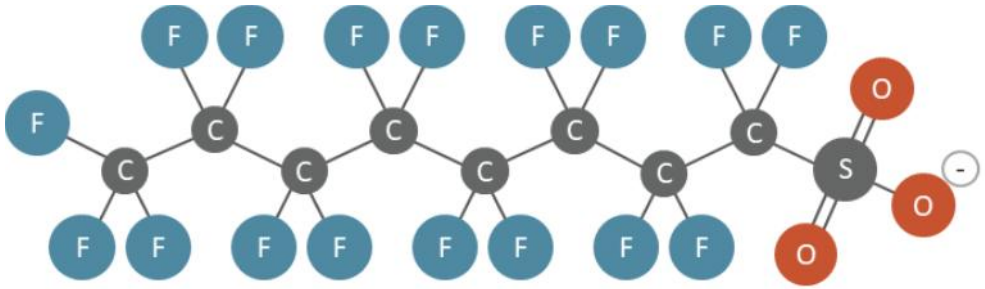
PFAS vs Polychlorinated Biphenyls (PCBs)





PCBs: Highly chlorinated the more hydrophobic

PFAS: Longer C chain the more hydrophobic

Only Cl and H atoms = 209 PCB Congeners

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PFAS Hydrophobic Repartioning Challenges

- PFAS Compared to PCBs
  - Hydrophilic Tail
  - PPT vs. PPM Concentrations (lower driving force & probabilistic contact upon mixing)
  - PFAS lower partitioning coefficients (K_d)
  - Remediation of mix of PFAS compounds
  - Biosolids co-contaminants vs. PCB contaminated soils

- Potential Answer:  SoPE

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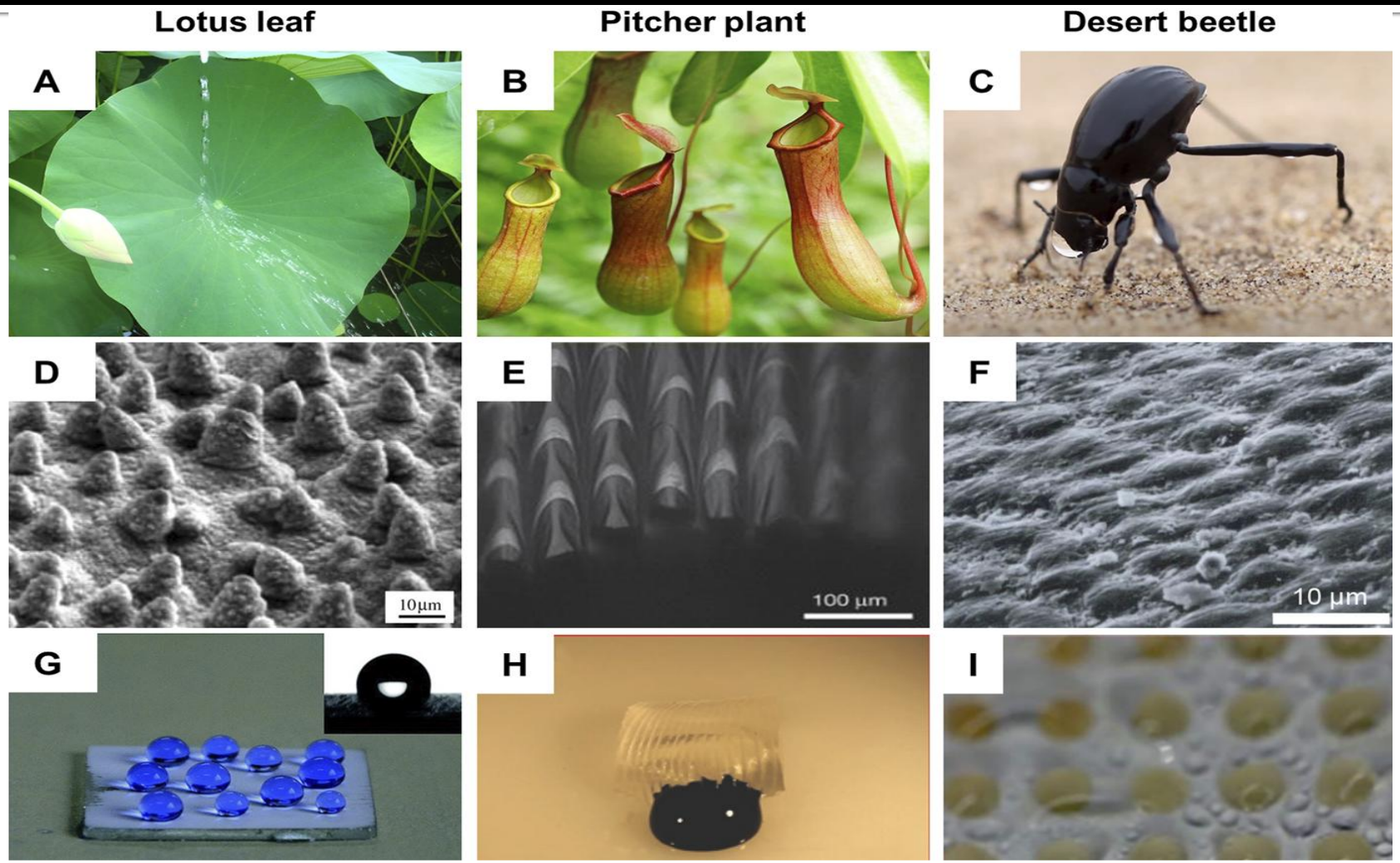
Superhydrophobic Biomimicry



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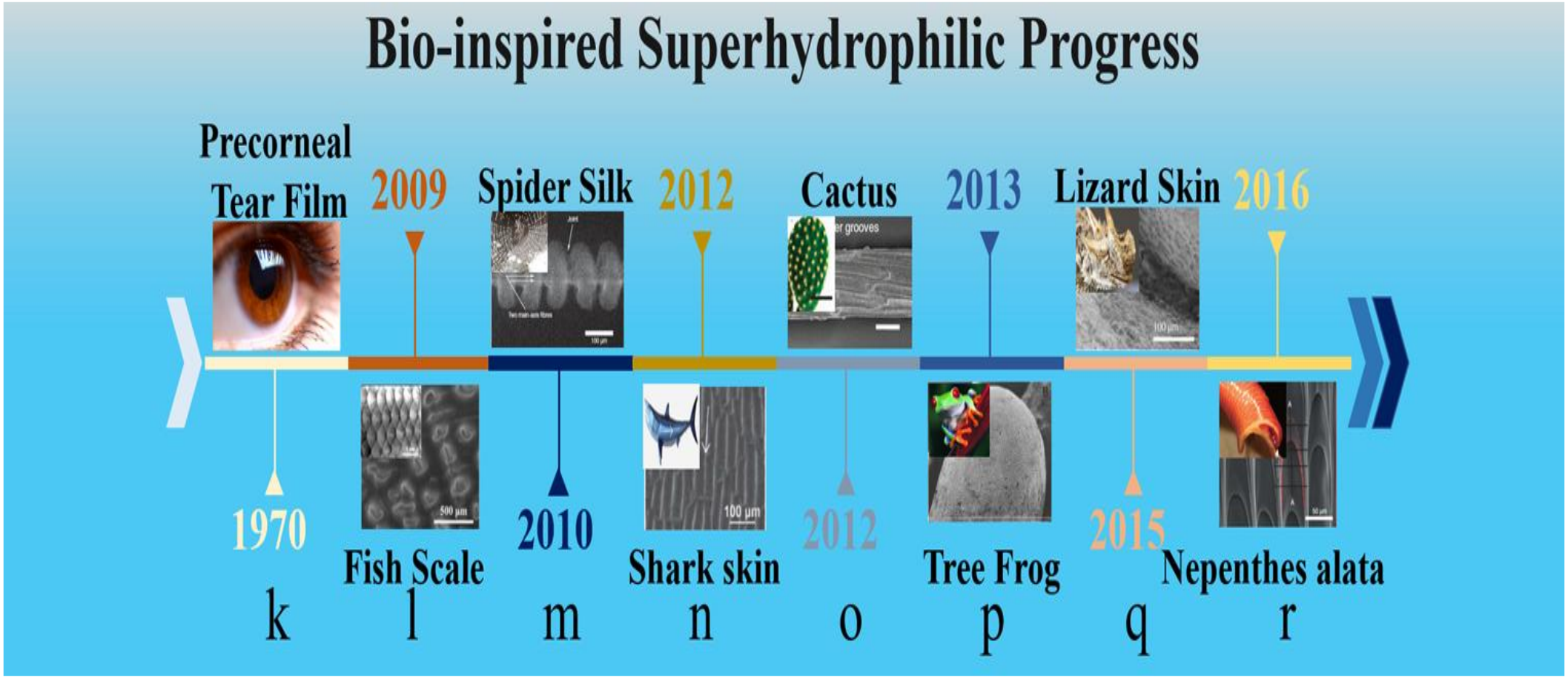
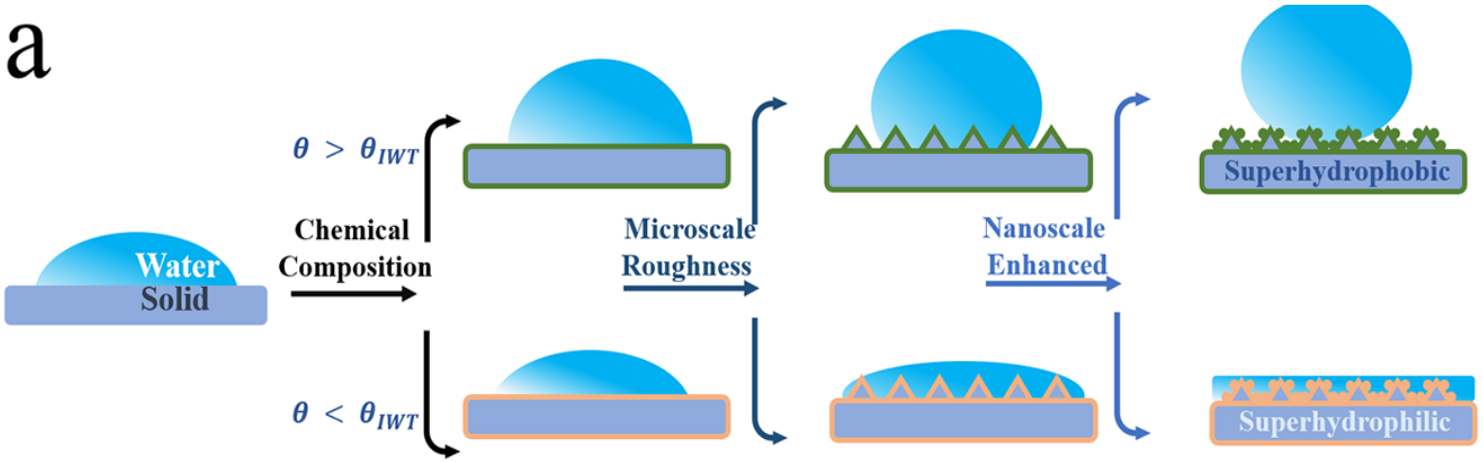
Superhydrophilic Biomimicry



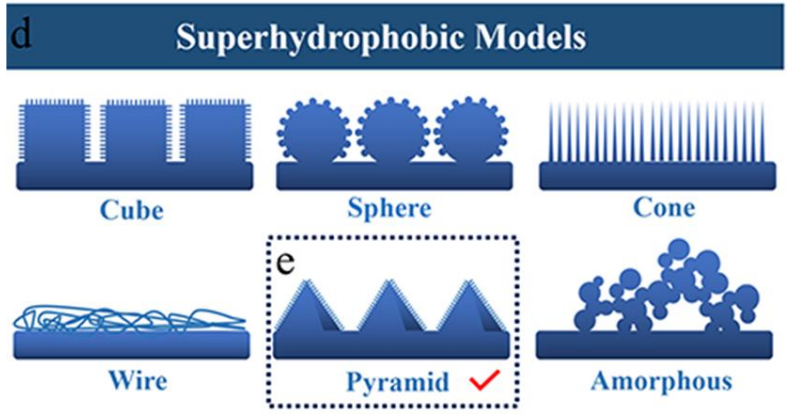
Y., Si, Z. Dong, L. Jiang, *Bioinspired Designs of Superhydrophobic and Superhydrophilic Materials*, ACS Cent. Sci. 2018, 4, 1102−1112

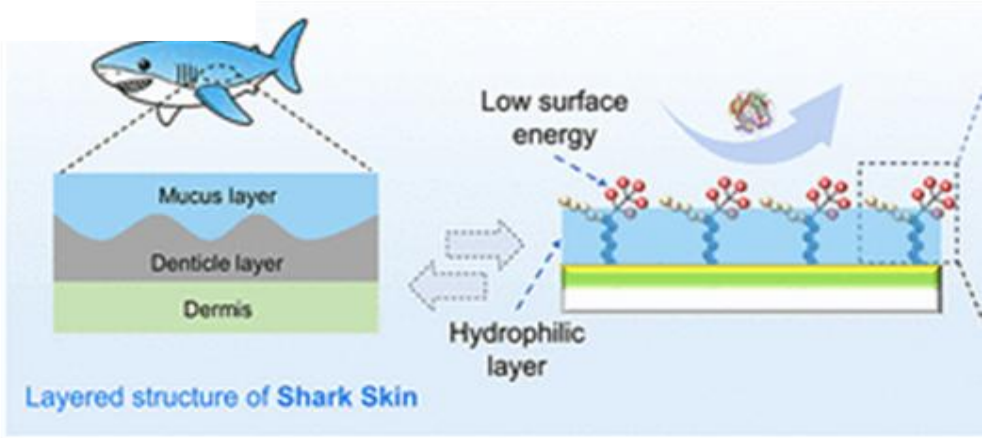
"Super" SoPE - Hydrophobic, Hydrophilic Surfaces



Wet Contact Angle > 150°

Wet Contact Angle < 10°





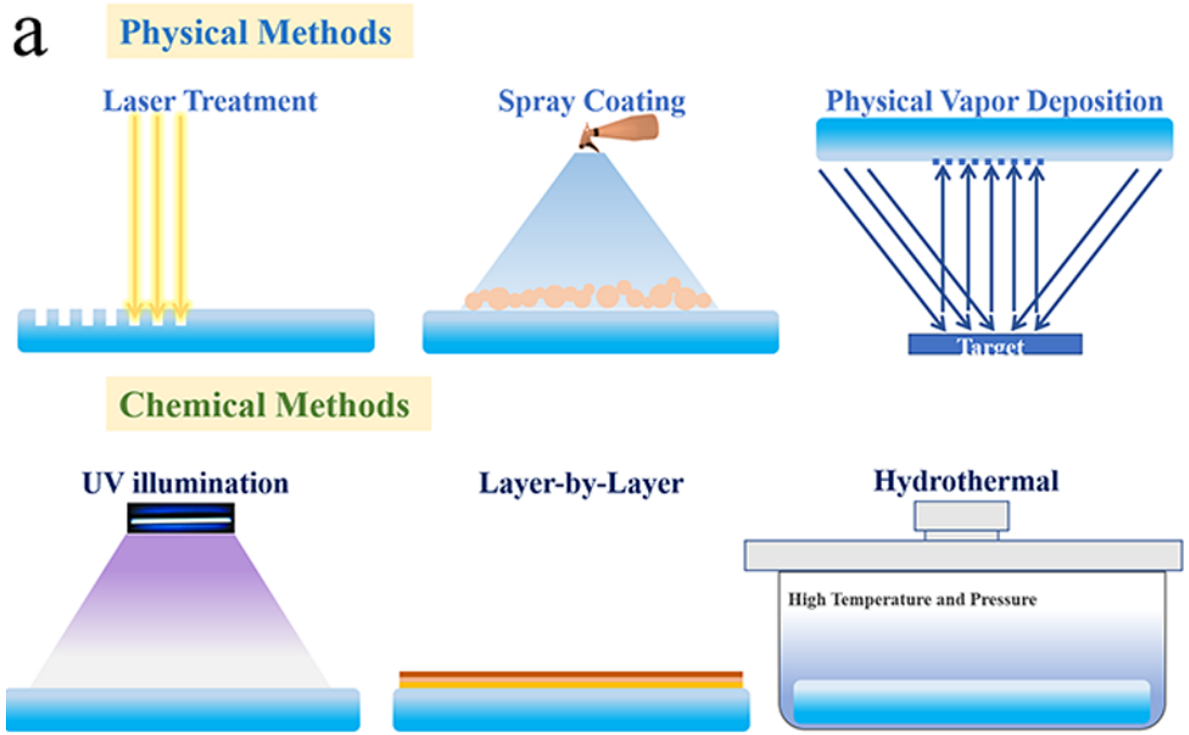
Source: Yifan Si, Zhichao Dong, and Lei Jiang, *Bioinspired Designs of Superhydrophobic and Superhydrophilic Materials*, ACS Cent. Sci. 2018, 4, 1102−1112

Approaches to "Super" Surfaces

- **Two Solid Organic Phase Extractants for Consideration: Polystyrene** and **Rubber**

b Hierarchical Micro-Nano Structures

1. Template Replication
2. Photolithography
3. Electrospinning
4. Sol-Gel Processing
5. Other methods



SoPE Complements PFAS Destruction Technologies

- SoPE provides significant material volume reduction
  - EPBs up to 100:1 reduction, 1000 cy biosolids → 10 cy EPB for destruction
- Inversely provides significant PFAS concentration
- EPA guidance document (2024†) focuses on the effectiveness of the following emerging destruction technologies from available thermal and non-thermal treatments: mechanochemical degradation, electrochemical oxidation, gasification/**pyrolysis**, and supercritical water oxidation for the destruction of PFAS from solid materials

- Assumed most appropriate destruction technologycomplementary to SoPE : **PYROLYSIS**
- SoPE flips the pyrolysis script from **biosolids*** to **tire rubber** or **polystyrene**

*Thoma, E. D., Wright, R. S., George, I., Krause, M., Presezzi, D., Villa, V., Preston, W., Deshmukh, P., Kauppi, P., & Zemek, P. G. (2022). Pyrolysis processing of PFAS-impacted biosolids, a pilot study. Journal of the Air & Waste Management Association, 72(4), 309-318. https://doi.org/10.1080/10962247.2021.2009935

Auto Tire Management via Pyrolysis

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Commercial Waste Tire Pyrolysis Plant

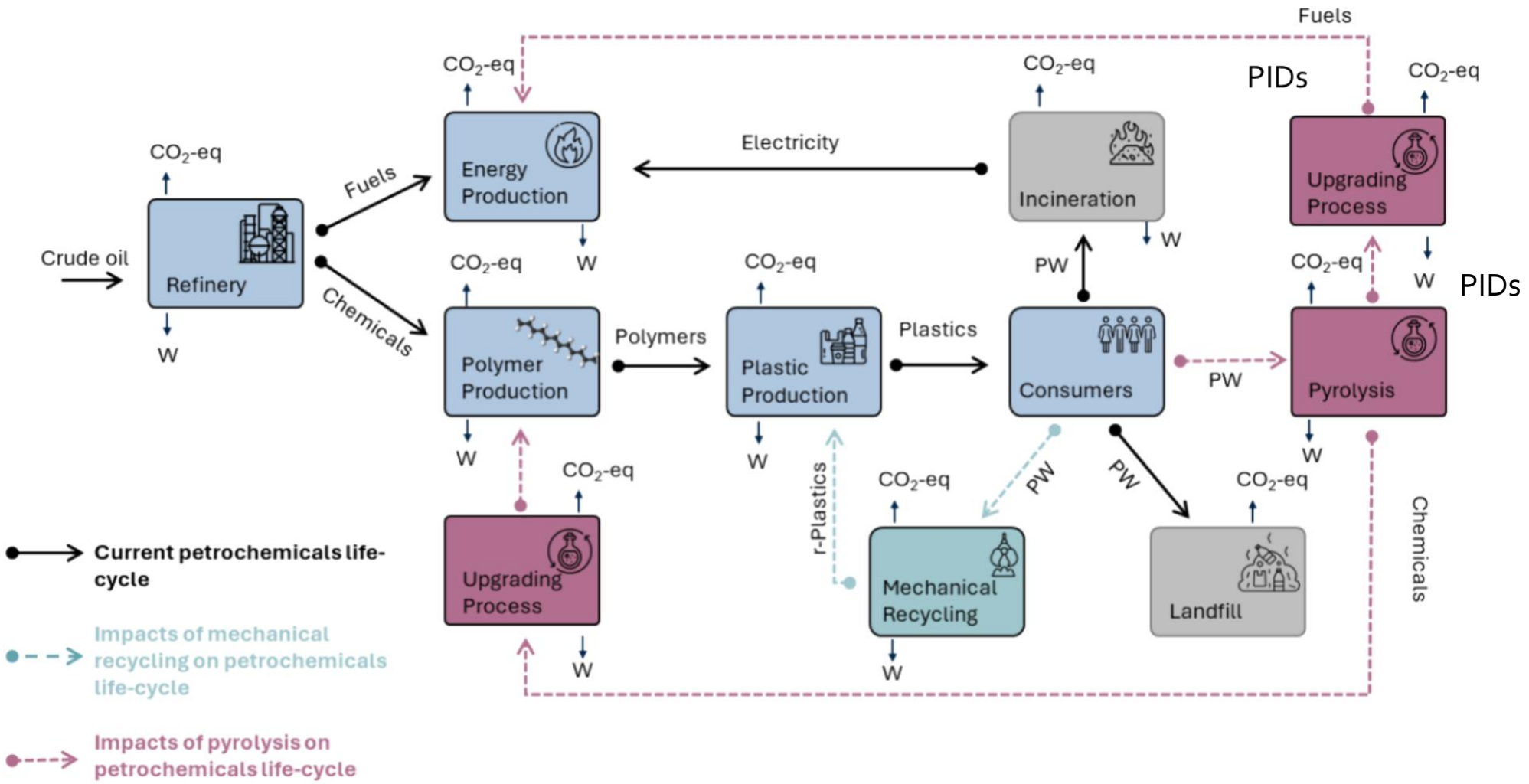
End Products:
Steel separated prior to Pyrolysis

Pyrolysis products: (Liq., Gas, Solid)
Pryo-oil, Syngas/non-condensable gases, carbon black

PFAS Products of Incomplete Combustion?? (PICs) Destruction?? (PIDs)

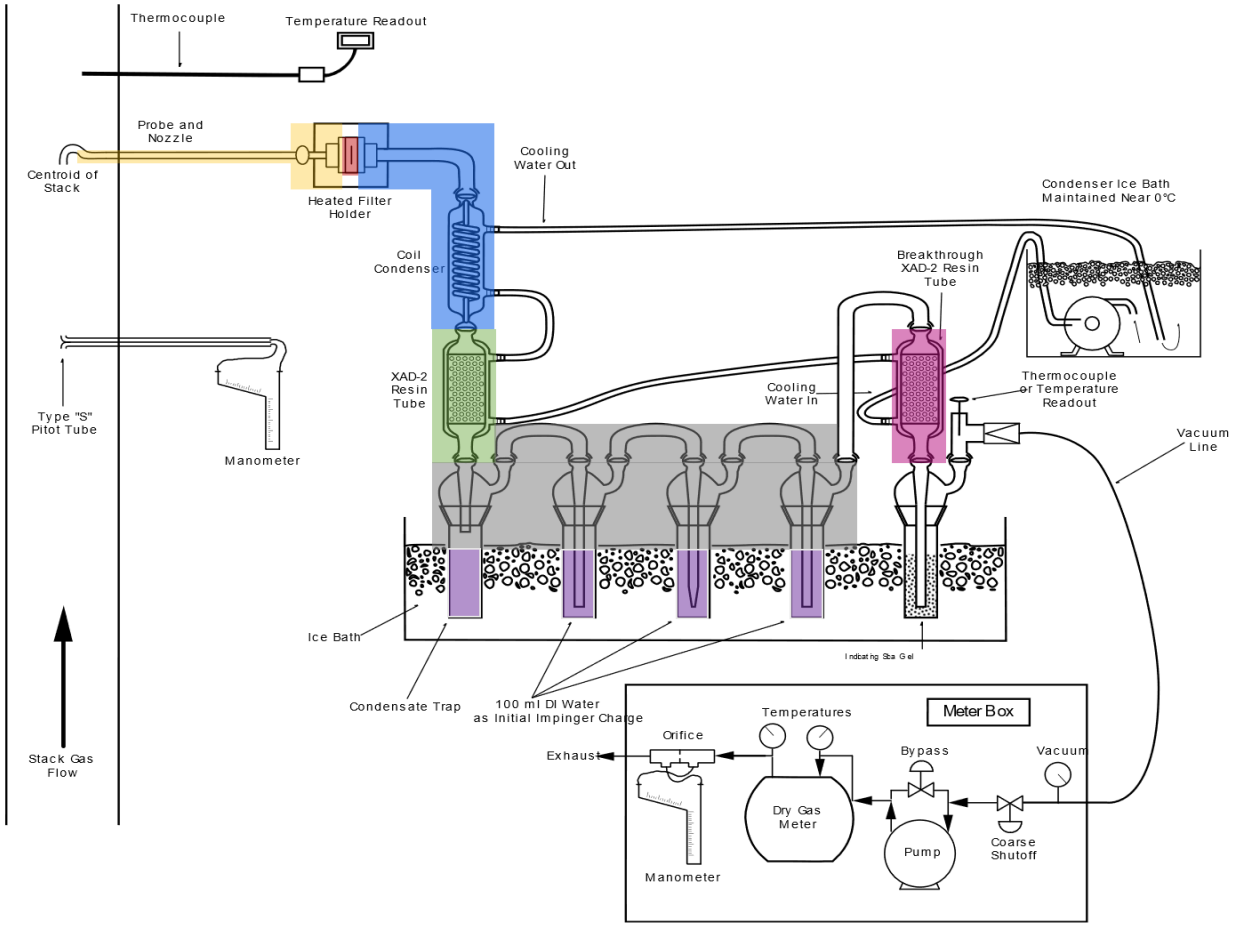
Alternative Source – Playground Tire Crumb???

Plastic Waste Management via Pyrolysis



Pyrolysis of SoPE PS provides styrene monomer **gas** a building block to make PS and other plastics. **Bio-oil** and **Biochar**

PFAS Gas Emissions Testing



EPA OTM-45: *Measurement of Selected Per- and Polyfluorinated Alkyl Substances from Stationary Sources*, U.S. EPA, January 2021

- List of 49 PFAS compounds are measured.

https://www.epa.gov/sites/default/files/2021-01/documents/otm_45_semivolatile_pfas_1-13-21.pdf

(Newer) EPA **OTM-50**: *Measurement of Selected Per- and Polyfluorinated Alkyl Substances from Stationary Sources*, U.S. EPA, January 2024, Rev 0 2025

- Collection in SS canistirs. Enables analysis of non-polar volatile PFAS thus better characterization of PICs

https://www.epa.gov/emc/emc-other-test-methods

SoPE PROCESS CLEANS UP PFAS FROM BIOSOLIDS: GAS EMISSIONS IMPLICATIONS

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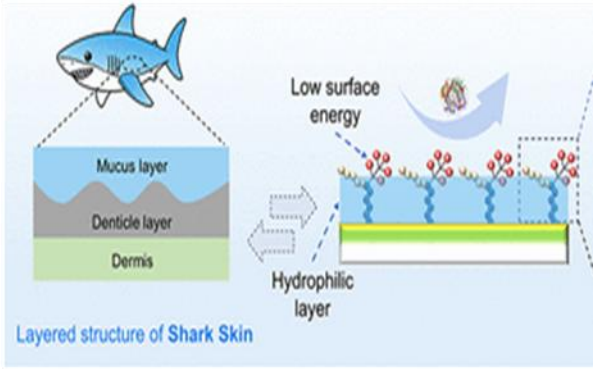
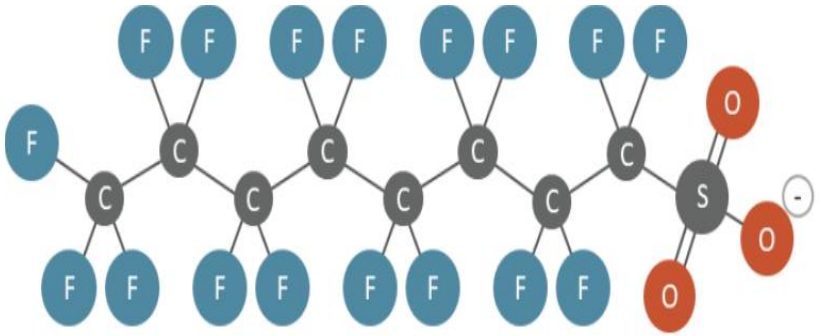
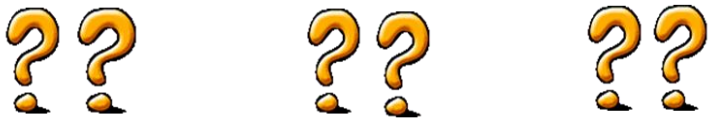




Questions



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