Time-Dependent Partitioning of PFAS between Soil and Water Phases After Land Application of Biosolids and Compost

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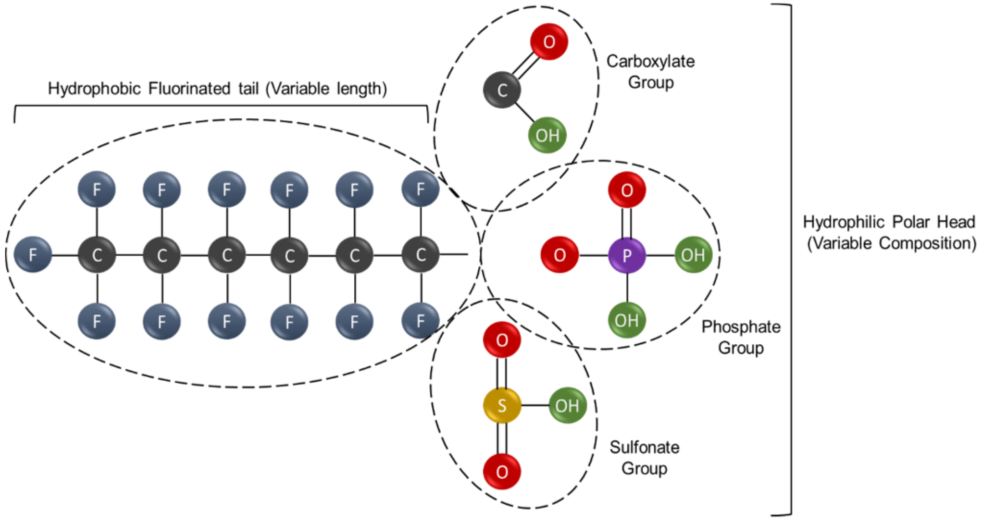
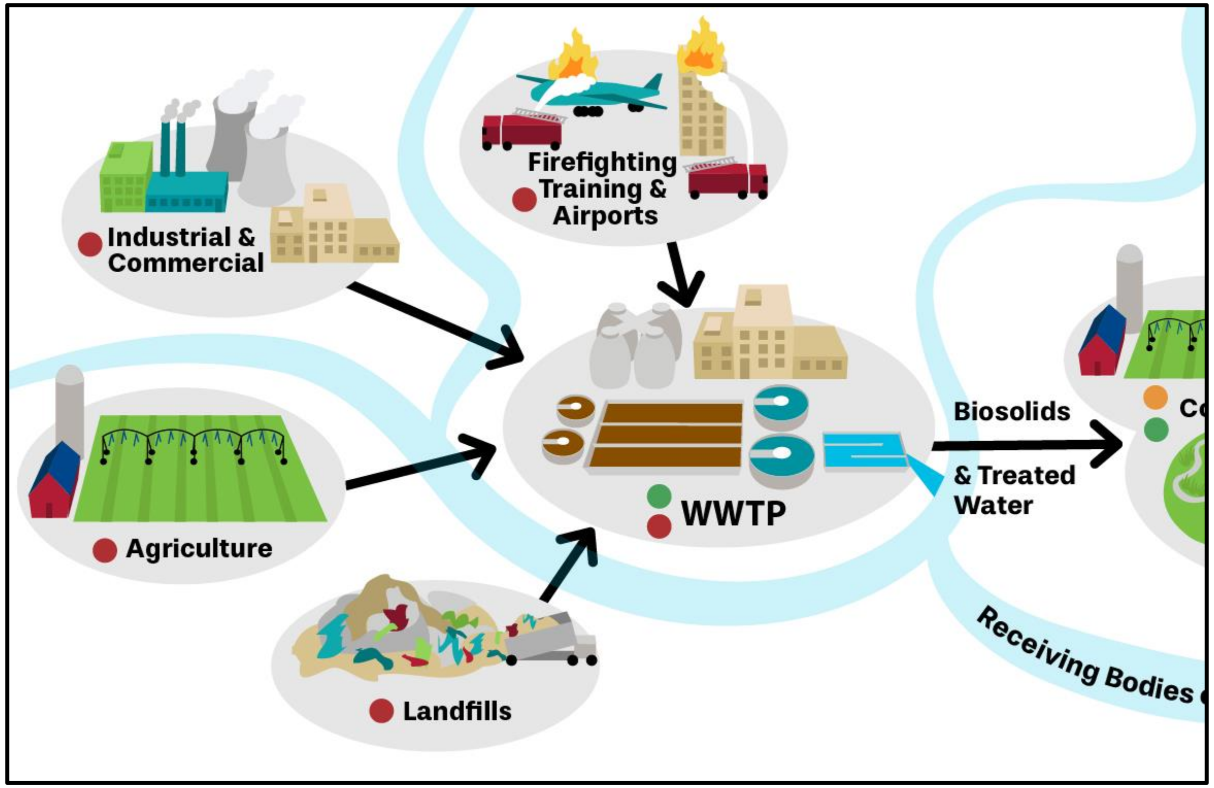
What are PFAS?

- Synthetic chemicals, widely used in industrial and consumer products.
- Strong C–F bonds (~130 kcal/mol), persist heat, oil, stains, grease, and water;
- Known as "forever chemicals" due to their persistence in the environment and resistance to natural degradation.
- Shown to have adverse health effects in animals and humans, and potential carcinogenicity.

Source: Pinellas.gov/pfas



Sources of PFAS in Biosolids



- Biosolid produced at WWTPs:

  ~ 7.18 million tons per year

  (~6.51 million kg/year)
- 60% land-applied
- 20% landfilled
- 20% incinerated
- Land application of biosolids can result in uptake of perfluoroalkyl acids into edible crops

- MCL in drinking water for PFOA and PFOS: 4 ppt, but no MCL for soil/biosolids

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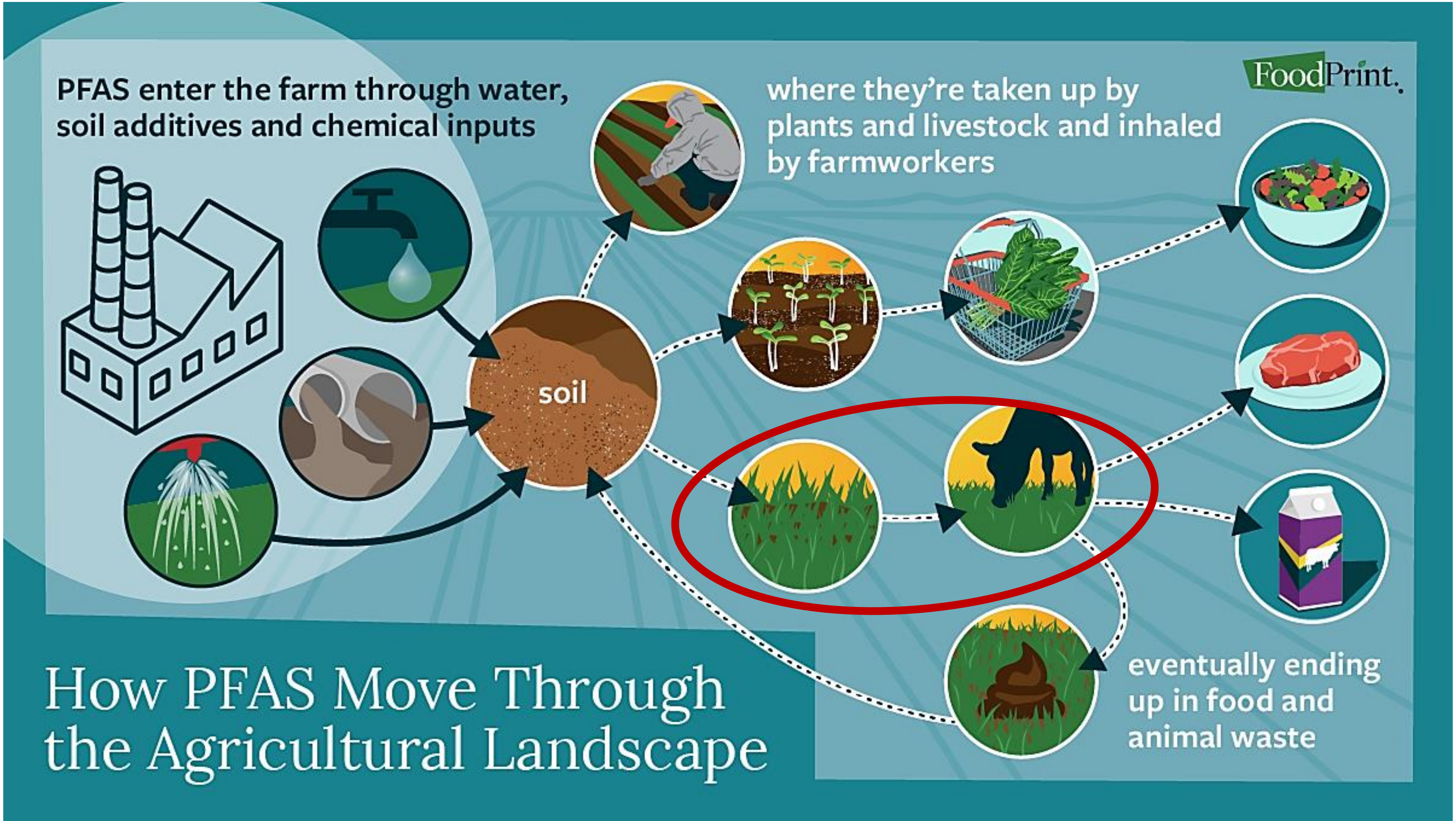
Recent Developments

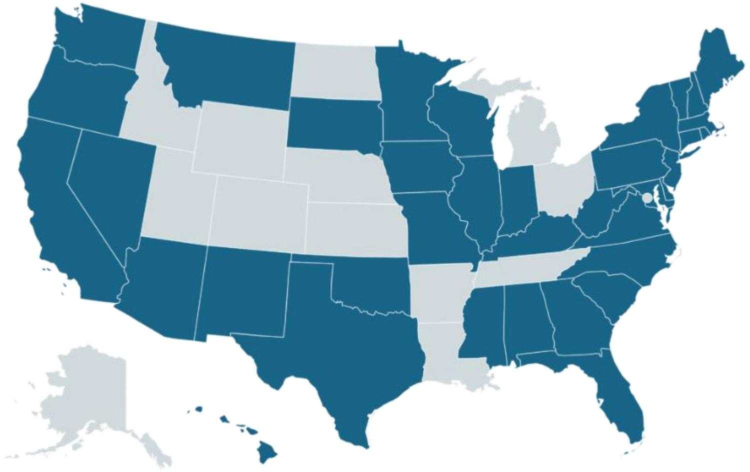


PFAS regulation landscape is changing

Some states are regulating biosolids for land application to address PFAS.

States are increasingly addressing the use of PFAS-contaminated biosolids for various land uses, with **Oklahoma** seeking to prohibit the land application of biosolids containing PFAS, **Washington** seeking to improve testing for PFAS in biosolids, and **Iowa** seeking to allow landowners the right to refuse the application of biosolids on their land if PFAS are detected.

States that actively regulate PFAS on land application:
CO, **CT**, **MA**, **MD**, **ME**, **MI**, **MN**, **NH**, **NY**, **WI**.



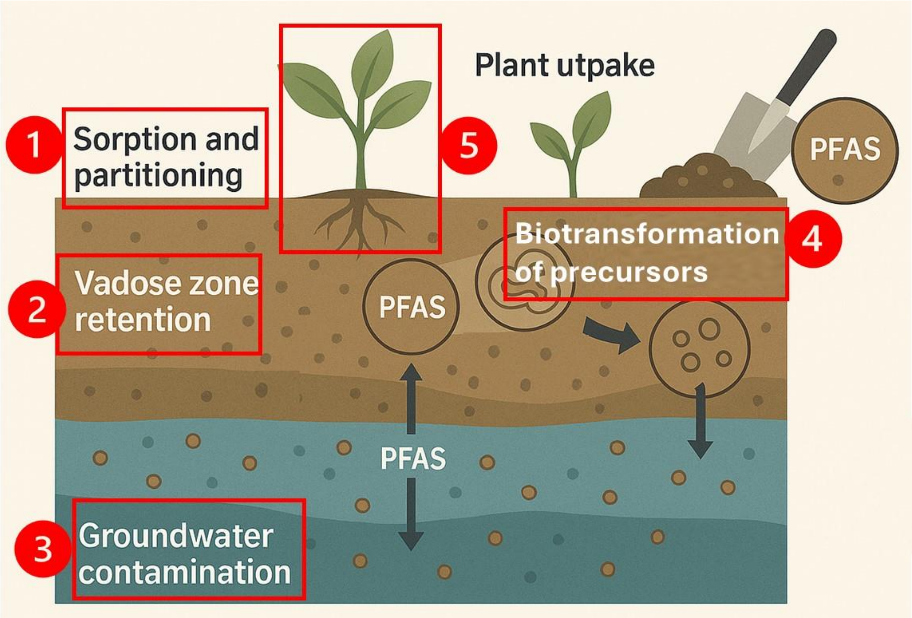
At least 37 states (in blue) are considering legislation to limit PFAS use and exposure.

Strategies implemented by states on PFAS regulation of land-applied biosolids based on concentration.

State	PFAS used as indicator	Tier 4 (µg/kg)	Tier 3 (µg/kg)	Tier 2 (µg/kg)	Tier 1 (µg/kg)
CO	PFOS	≥ 50	NA*	≤50	NA*
MD	PFOS or PFOA	≥ 100	50 - 99	20 - 49	≤20
MI	PFOS or PFOA	≥ 100	20 - 99	NA*	≤20
MN	PFOS or PFOA	≥125	50 - 24	20 - 49	≤20
NY	PFOS or PFOA	≥ 50	NA*	21- 49	≤20
WI	PFOS or PFOA	≥150	50 - 149	21- 49	≤20

Study Focus Areas

- What type of PFAS **partition to biosolids** during wastewater treatment?
- Is there any difference in the PFAS composition in the samples collected **before and after dewatering**, and **composting**?
- Does the presence of divalent metals like Ca^{2+} or Mg^{2+}, soil type, and soil acidity affect PFAS dissolution behavior from biosolids and compost?
- Partitioning between liquid/solid phases: Can PFAS in biosolids and compost migrate to groundwater, in surface waters, like drainage ditches and retention ponds?



Study Objectives and Focus

Year 1

- Biosolids
- Effect of metals
- Analytical methods for 40 PFAS

Year 2

- Compost
- pH effects
- Partitioning on the vegetative fraction
- Precursors

Objectives – Year 1

- Conduct sampling of biosolids after dewatering and drying processes at two Miami-Dade wastewater treatment plants (South District and Central District Wastewater Treatment Plants).

- Analyze biosolids samples for PFAS content and component profile; determine the prevalent PFAS compounds.

- Conduct leaching experiments to evaluate the release of PFAS from biosolids under site-specific conditions.

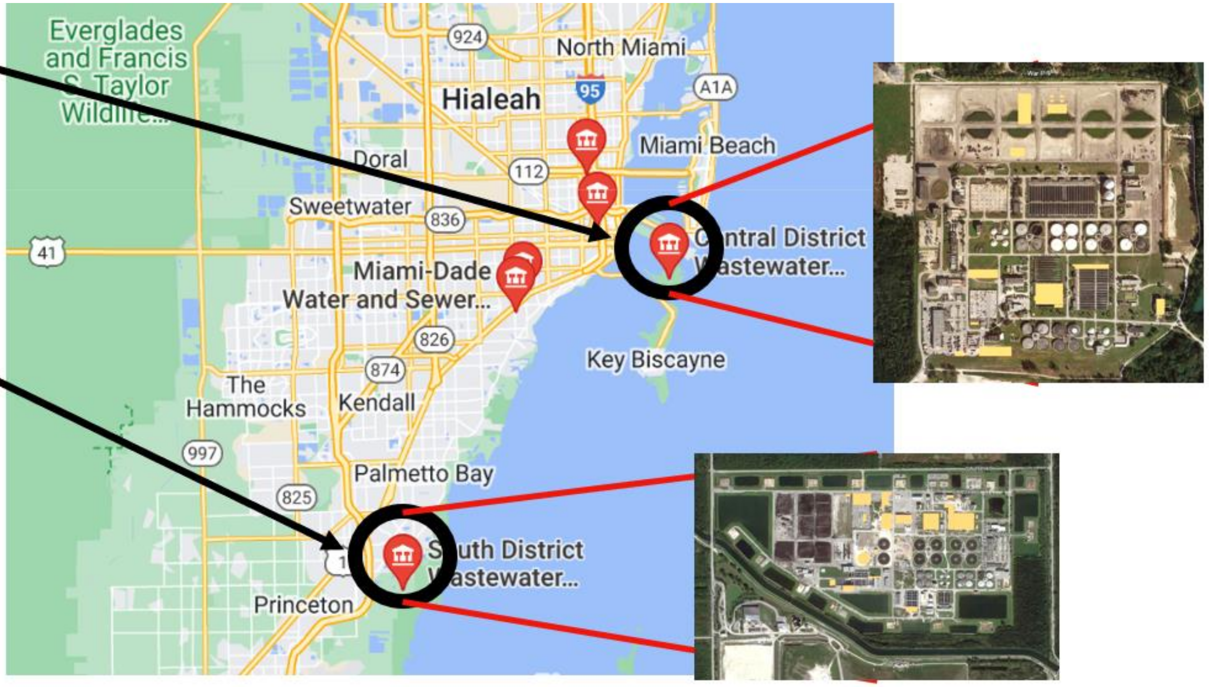
- Estimate time-dependent solubilization and the release characteristics of the PFAS homologues from biosolids.

- Further scientific understanding of PFAS originating from biosolids as a source in the environment, potential exposure pathways for human health and ecological effects.

Sampling Biosolids at WWTPs

- **Central District Wastewater Treatment Plant**
  - MDWASD's oldest and largest plant with a treatment
  - Capacity: 143 million gallons per day (MGD)
  - Ave daily flow: 101 MGD
  - Effluent discharged via outfalls

- **South District Wastewater Treatment Plant**
  - Wastewater Treatment Water Reclamation plant
  - Receives leachate from South Dade Landfill
  - Capacity: of 112.5 MGD
  - Ave daily flow: 93.2 MGD
  - Effluent discharged via injection wells



1 Thickened Sludge ➡ 2 Digested Sludge ➡ 3 Dewatered Sludge ➡ 4 Biosolids for Land Application

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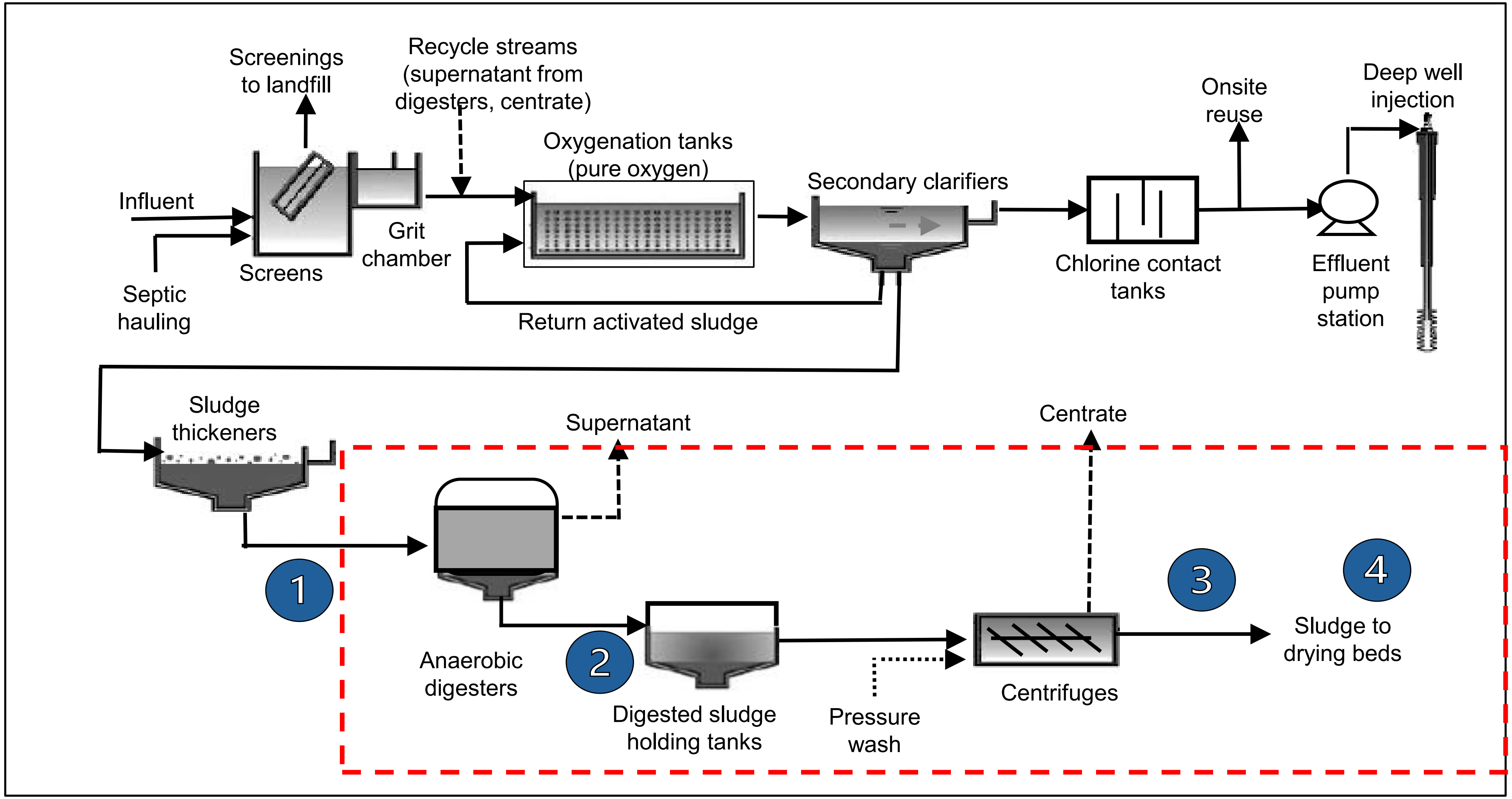
Sampling Biosolids at WWTPs



1 Thickened Sludge → 2 Digested Sludge → 3 Dewatered Sludge → 4 Biosolids for Land Application

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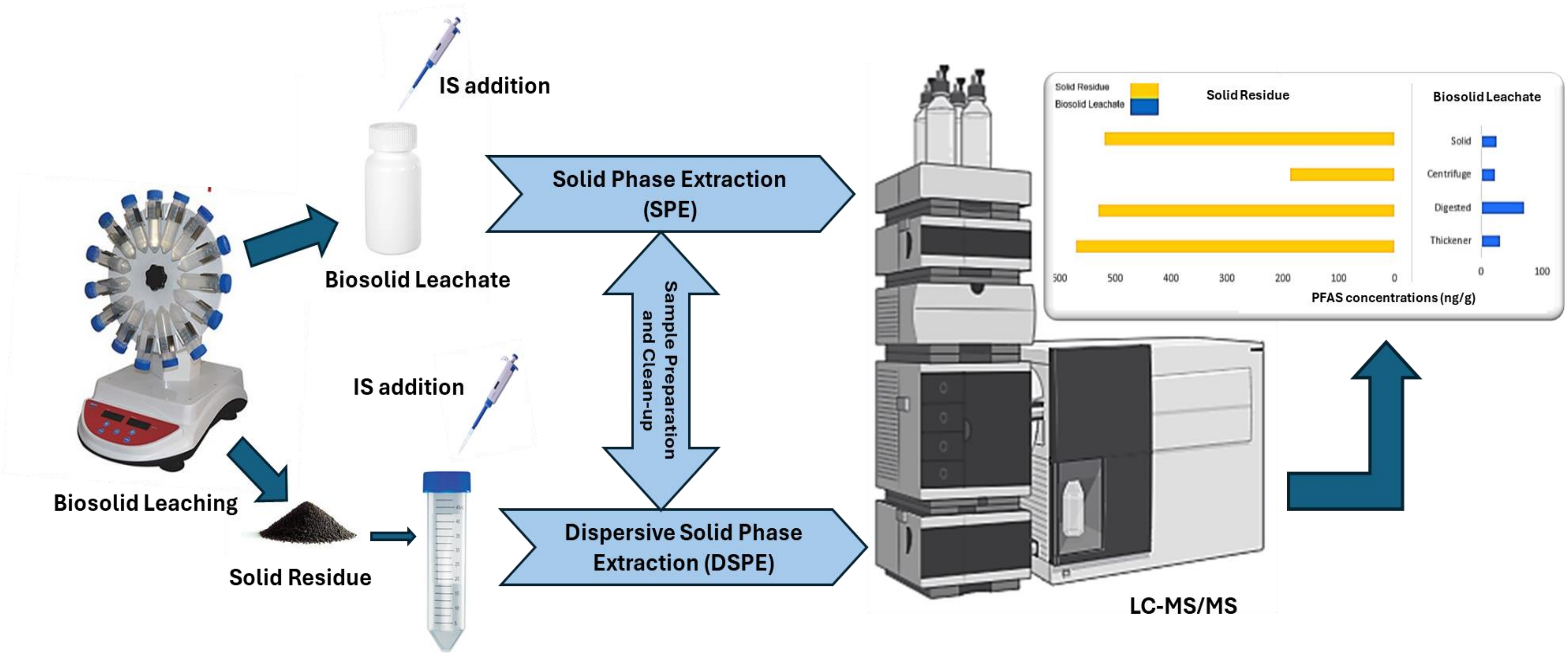
Methodology- PFAS leaching and analysis



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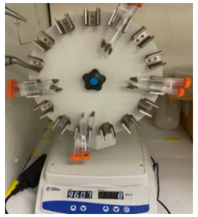
Year 1
Technical Approach

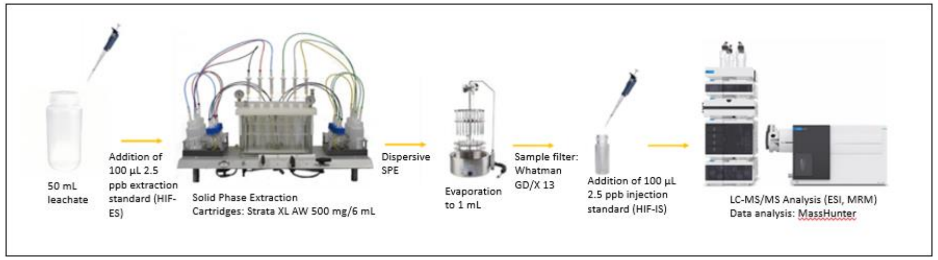
Chemical analyses of PFAS content in biosolids and leachates

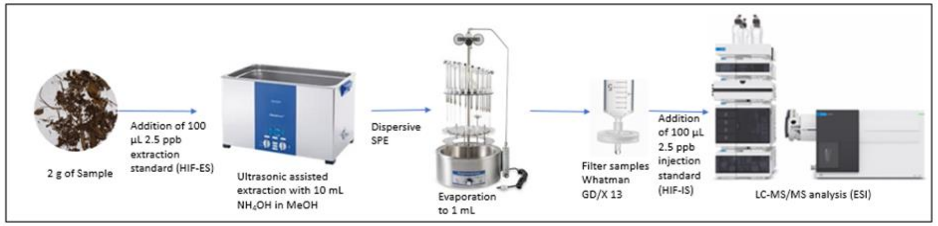
40 PFAS analyzed

Detected 24 different PFAS



Leachate





Solids

Abbreviation	Compound Name	Formula	Mol Weight
Perfluoroalkyl carboxylic acids			
PFBA	Perfluorobutanoic acid	$C_4HF_7O_2$	214.04
PFPeA	Perfluoropentanoic acid	$C_5HF_9O_2$	264.05
PFHxA	Perfluorohexanoic acid	$C_6HF_{11}O_2$	314.05
PFHpA	Perfluoroheptanoic acid	$C_7HF_{13}O_2$	364.06
PFOA	Perfluorooctanoic acid	$C_8HF_{15}O_2$	414.07
PFNA	Perfluorononanoic acid	$C_9HF_{17}O_2$	464.08
PFDA	Perfluorodecanoic acid	$C_{10}HF_{19}O_2$	514.08
PFUdA	Perfluoroundecanoic acid	$C_{11}HF_{21}O_2$	564.09
PFDoA	Perfluorododecanoic acid	$C_{12}HF_{23}O_2$	614.10
PFTrDA	Perfluorotridecanoic acid	$C_{13}HF_{25}O_2$	664.11
PFTeDA	Perfluorotetradecanoic acid	$C_{14}HF_{27}O_2$	714.11
Perfluoroalkyl sulfonic acids			
PFBS	Perfluorobutanesulfonate	$C_4HF_9O_3S$	300.10
PFPeS	Perfluoropentanesulfonate	$C_5HF_{11}O_3S$	350.11
PFHxS	Perfluorohexanesulfonate	$C_6HF_{13}O_3S$	400.11
PFHpS	Perfluoroheptanesulfonate	$C_7HF_{15}O_3S$	450.12
PFOS	Perfluorooctanesulfonate	$C_8HF_{17}O_3S$	500.13
PFNS	Perfluorononanesulfonate	$C_9HF_{19}O_3S$	550.14
PFDS	Perfluorodecanesulfonate	$C_{10}HF_{21}O_3S$	600.14
PFDoS	Perfluorododecanesulfonate	$C_{12}HF_5O_3S$	700.16
Fluorotelomer sulfonic acids			
4-2 FTS	1H,1H,2H,2H-perfluorohexanesulfonate	$C_6H_5F_9O_3S$	328.15
6-2FTS	1H,1H,2H,2H-perfluorooctanesulfonate	$C_8H_5F_{13}O_3S$	428.17
8-2 FTS	1H,1H,2H,2H-perfluorodecanesulfonate	$C_{10}H_5F_{17}O_3S$	528.18
Perfluorooctane sulfonamides			
FOSA	Perfluorooctanesulfonamide	$C_8H_2F_{17}NO_2S$	499.15
NMeFOSA	N-methyl perfluorooctanesulfonamide	$C_9H_4F_{17}NO_2S$	513.17
NEtFOSA	N-ethyl perfluorooctanesulfonamide	$C_{12}H_{10}F_{17}NO_3S$	571.25
Perfluorooctane sulfonamidoacetic acids			
N-MeFOSAA	N-methylperfluoro-1-octanesulfonamidoacetic acid	$C_{11}H_6F_{17}NO_4S$	571.21
N-EtFOSAA	N-ethylperfluoro-1-octanesulfonamidoacetic acid	$C_{12}H_8F_{17}NO_4S$	585.23
Perfluorooctane sulfonamide ethanols			
NMeFOSE	N-methyl perfluorooctanesulfonamidoethanol	$C_{11}H_4F_{21}NO_3S$	629.19
NEtFOSE	N-ethyl perfluorooctanesulfonamidoethanol	$C_{12}H_6F_{21}NO_3S$	643.21
Per- and Polyfluoroether carboxylic acids			
HFPO-DA	2,3,3,3-Tetrafluoro-2-(1,1,2,2,3,3,3-heptafluoropropoxy)-propanoic acid	$C_6HF_{11}O_3$	330.05
ADONA	4,8-Dioxa-3H-perfluorononanoic acid	$C_{10}H_{11}N_4NaO_5S$	322.27
PFMPA	Perfluoro-3-methoxypropanoic acid	$C_4HF_7O_3$	230.04
PFMBA	Perfluoro-4-methoxybutanoic acid	$C_5HF_9O_3$	280.04
NFDHA	Nonafluoro-3,6-dioxaheptanoic acid	$C_5HF_9O_4$	296.04
Ether sulfonic acids			
9Cl-PF3ONS	9-Chlorohexadecafluoro-3-oxanonane-1-sulfonic acid	$C_8HClF_{16}O_4S$	532.58
11Cl-PF3OUdS	11-Chloroeicosafluoro-3-oxaundecane-1-sulfonic acid	$C_{10}HClF_{20}O_4S$	632.60
PFEESA	Perfluoro(2-ethoxyethane)sulfonic acid	$C_4HF_9O_4S$	316.10
Fluorotelomer carboxylic acids			
FPrPA or 3:3FTCA	3-Perfluoropropyl propanoic acid	$C_6H_5F_7O_2$	242.09
FPePA or 5:3FTCA	3-Perfluoropentyl propanoic acid	$C_8H_5F_{11}O_2$	342.11
FHpPA or 7:3FTCA	3-Perfluoroheptyl propanoic acid	$C_{10}H_5F_{17}O_2$	478.10

What we learned during year 1 research

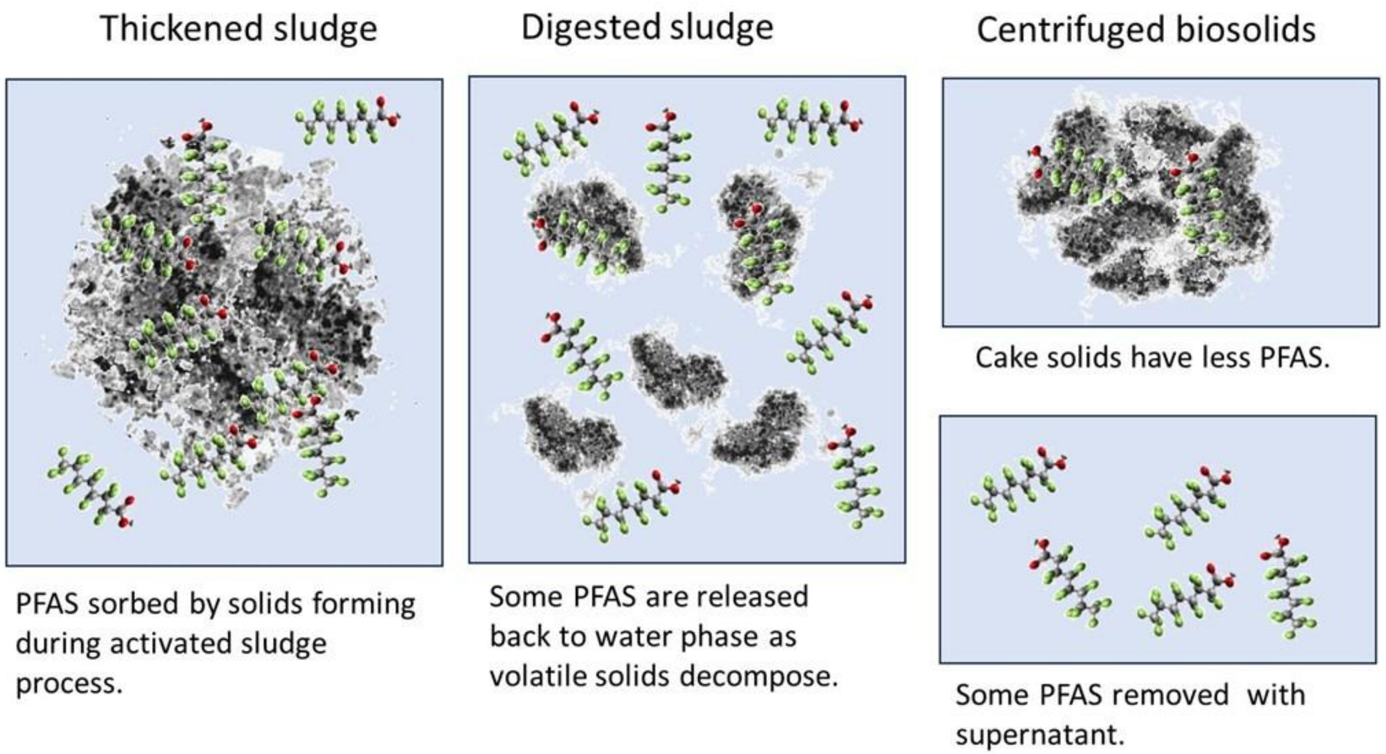
- Distinct differences in PFAS composition in biosolids between

  South District vs Central District plants

- Predominance of long-chain PFAS.

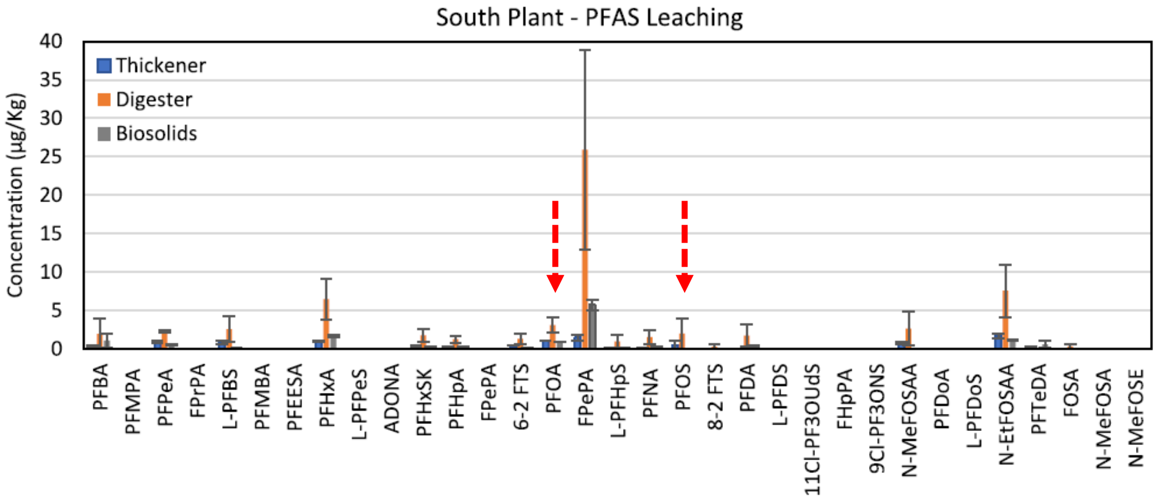
- PFAS in biosolids leach rapidly, after 1 day.

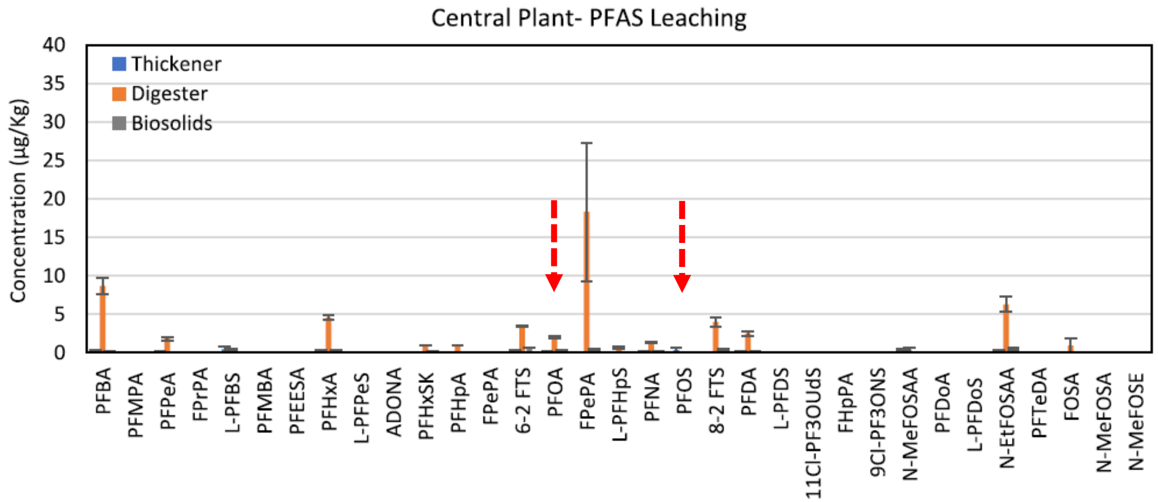
PFAS fate during biosolids handling



- Majority of PFAS is associated with the organic solids produced during aeration, ultimately ending up in the thickened sludge.
- As volatile solids decompose, some PFAS are released into the water phase and removed during dewatering by centrifugation.

Results – Leachate from biosolids





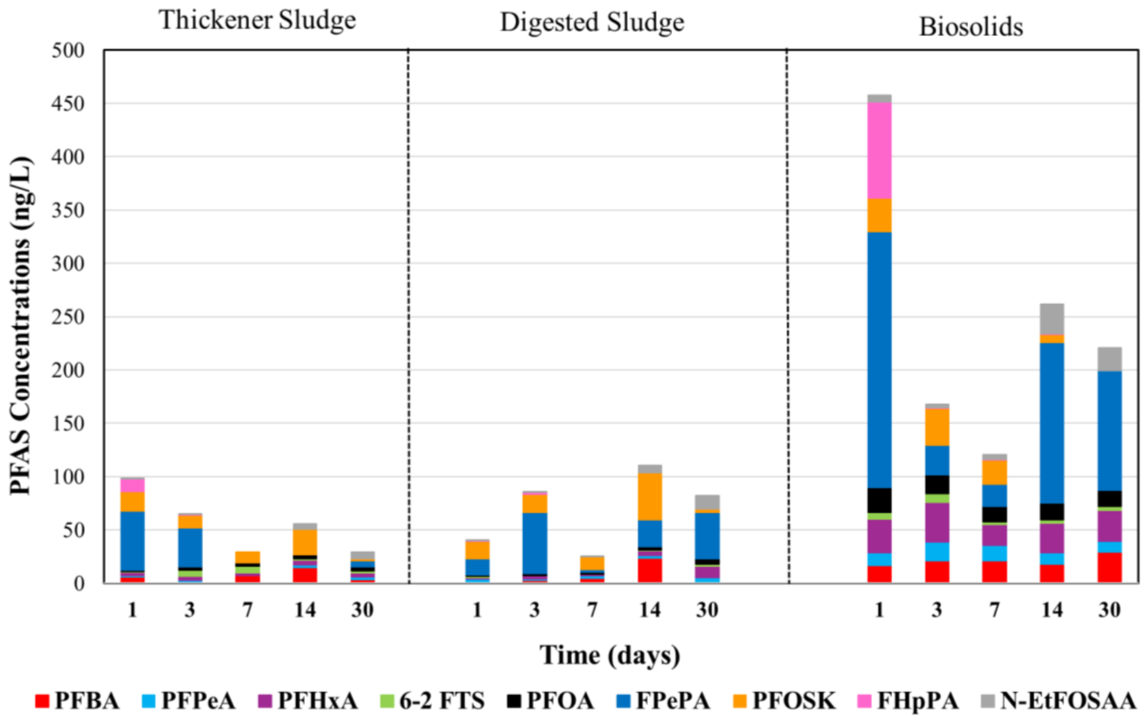
Concentration (µg/Kg) of PFAS in biosolid leachates from SDWWTP and CDWWTP

Predominant PFAS in biosolid leachates: PFBA, PFHxA, PFOA, FPePA, PFOS, and FHpPA

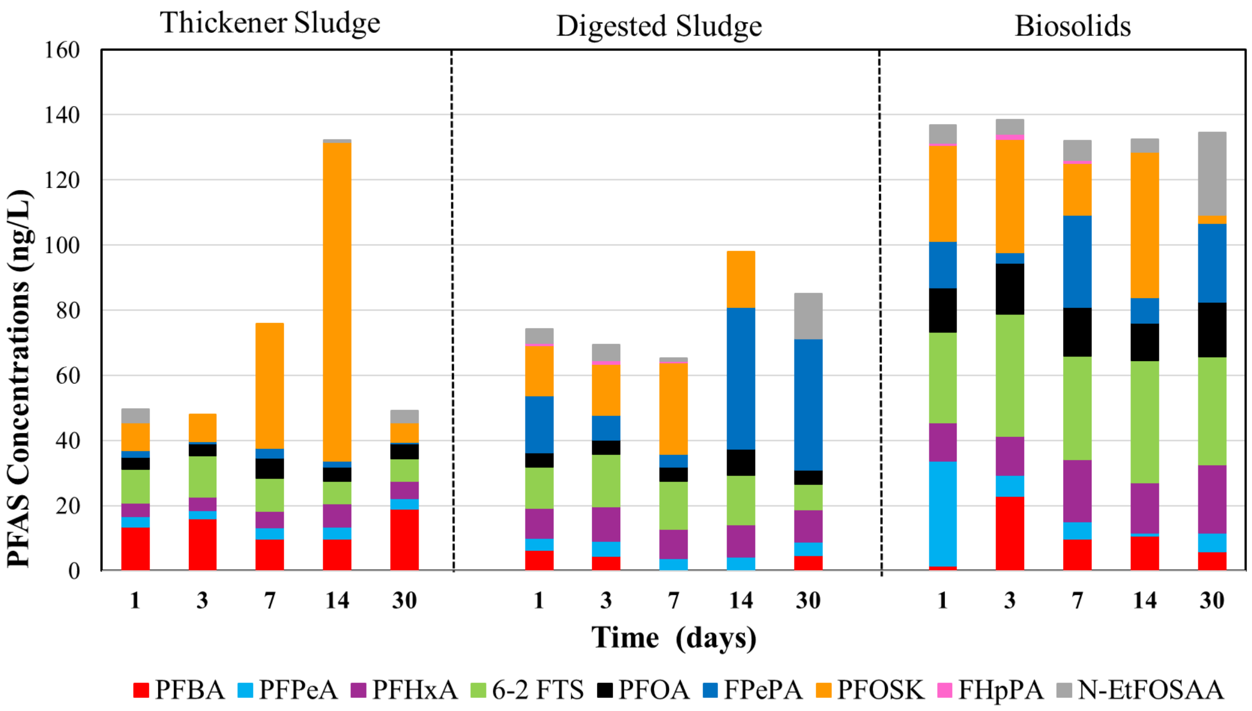
15-B

PFAS leaching from biosolids over time

South District



Central District



The highest FPePA leaching (239.8 ± 17.3 ng/L) occurred on day one of batch tests. The second-highest SDWWTP biosolids leachate concentration (90.5 ± 11.5 ng/L) after day 1 was attributed to FHpPA.

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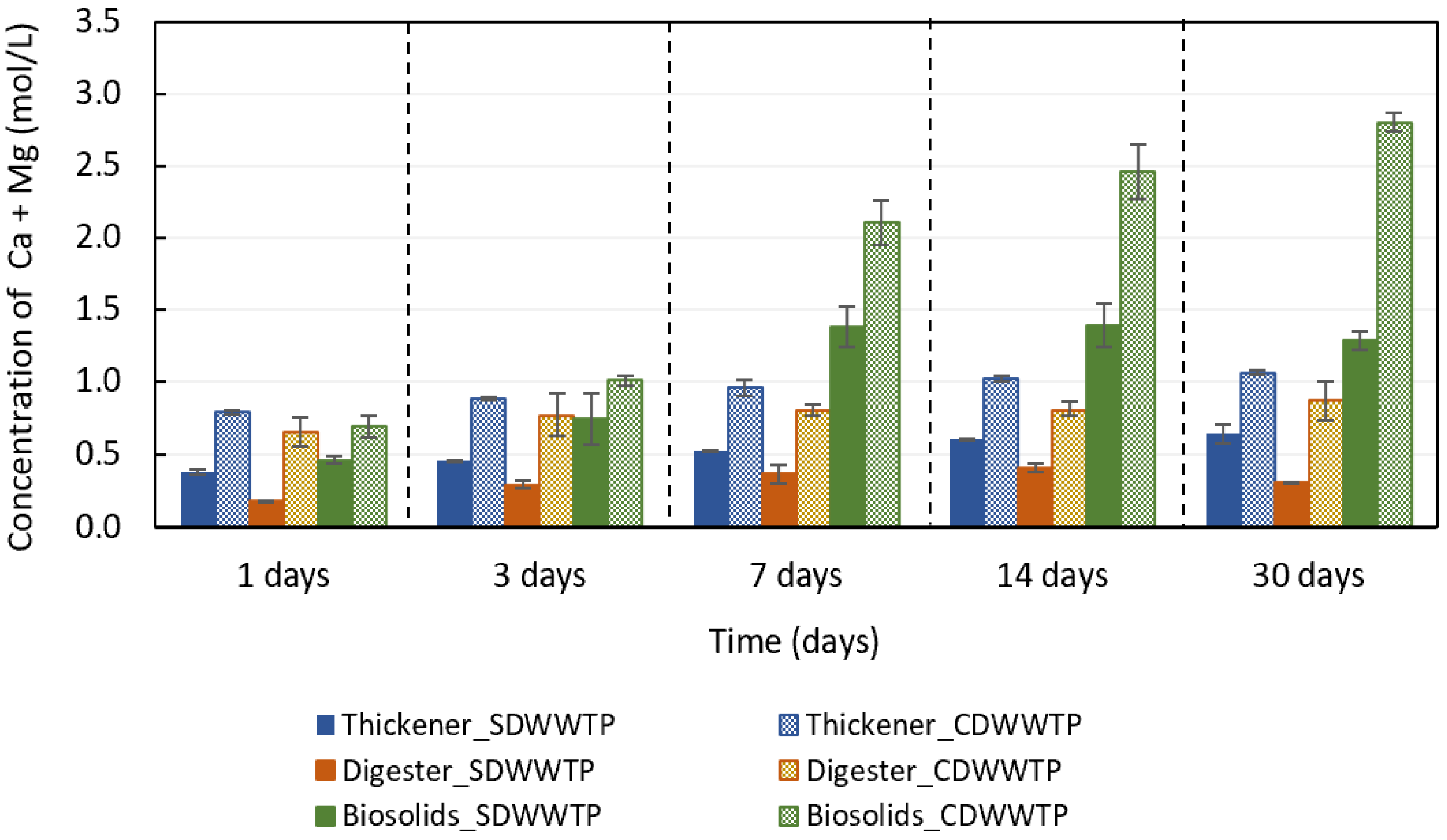
Combined concentrations of Ca and Mg

- The combined levels of Ca^{2+} and Mg^{2+} were consistently lower in SDWWTP leachate than in CDWWTP samples;

- Lower Ca^{2+} and Mg^{2+} levels in SDWWTP leachate compared to CDWWTP may explain the higher PFAS concentrations in SDWWTP leachate (Arvaniti et al., 2014)

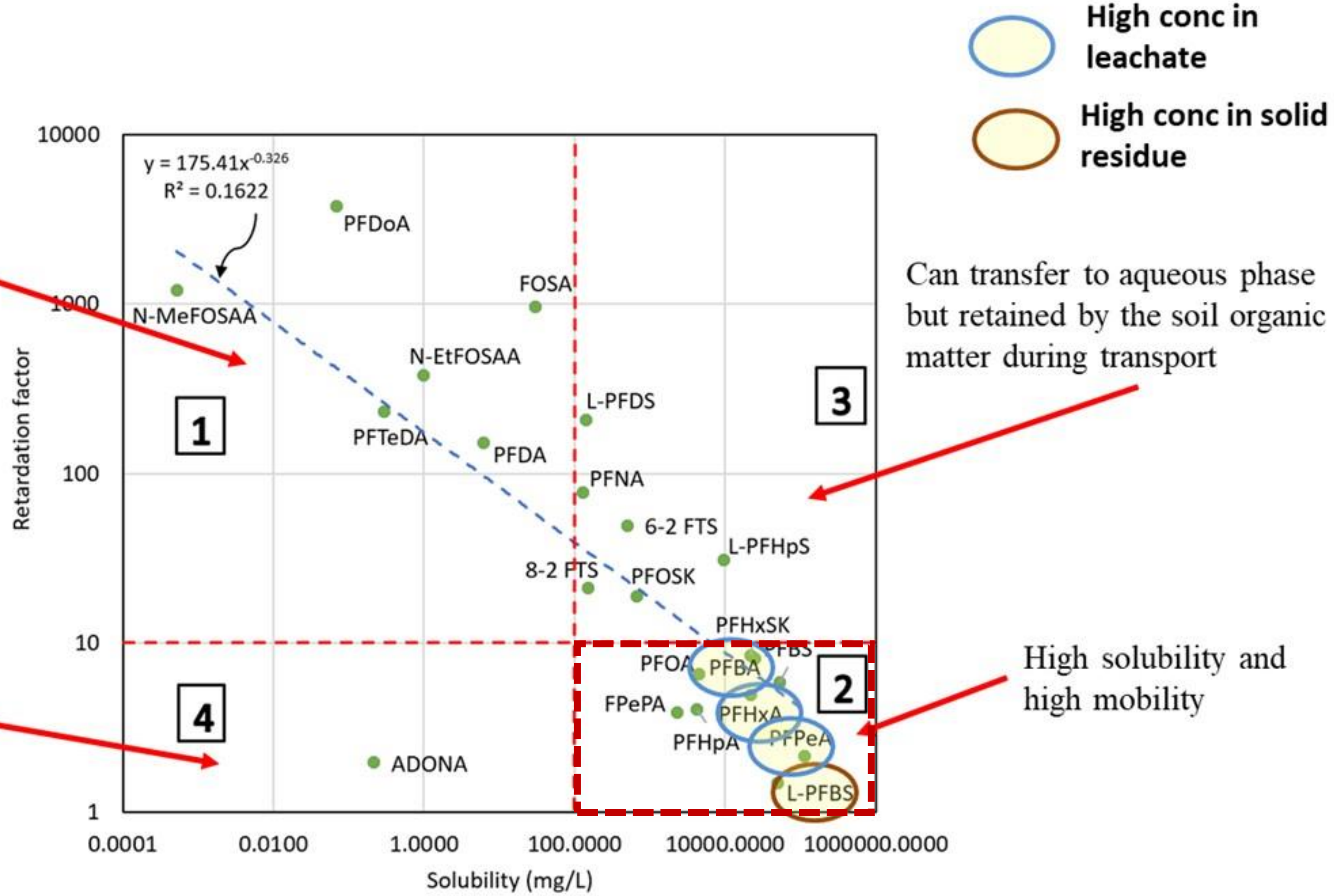


Batch test leachate of the samples from the South District and Central District wastewater treatment plants

Likely PFAS fate after land application

High accumulation tendency in soil

Slow transfer to aqueous phase



Can transfer to aqueous phase but retained by the soil organic matter during transport

High solubility and high mobility

What we learned

1. The leachate samples collected at different times indicate that PFAS would leach rapidly. The leaching tests led to the **highest PFAS concentrations after 1 day**.
2. The lower levels of PFAS in CDWWTP experimental samples correlated with higher concentrations of Ca and Mg in leachates from the tested wastewater processing stages.
3. The leaching of total PFAS (ng/kg) from biosolids was nearly six times higher at the South WWTP compared to the Central WWTP.
4. Leaching of P and Mg correlates with long-chain PFCAs, fluorotelomers, and emerging PFAS like 3,6-OPFHpA, suggesting they may indicate PFAS contamination from biosolids.

What we learned

1. **Distinct differences in PFAS composition** in biosolids between the South District (receives landfill leachate), and the Central District plants (domestic wastewater).
2. Biosolids from both plants have a predominance of **long-chain PFAS**, but biosolids collected from CDWWTP had a higher proportion of short-chain PFAS than SDWWTP.
3. Digested sludge exhibited higher concentrations of PFAS. As volatile solids decompose, some PFAS are released into the water phase and removed during dewatering by centrifugation.
4. The leachate from the samples collected at the **CDWWP has significantly lower** PFAS levels than those from the SDWWTP.

Objectives – Year 2

- Conduct additional sampling of (a) compost produced from biosolids, and (b) wood chips or vegetation used in compost (before and after screening)
- Expand the PFAS component profile by assessing the presence of other non-traditionally monitored PFAS by non-targeted analysis (NTA) of the original samples
- Conduct leaching experiments, following EPA method 1312, to evaluate PFAS releases from samples as received and after 24 h at variable pH conditions (pH 4.0, 5.5, 7.5).
- Further scientific understanding of PFAS originating from biosolids and compost as a source of environmental contamination, potential exposure pathways, and ecological effects.

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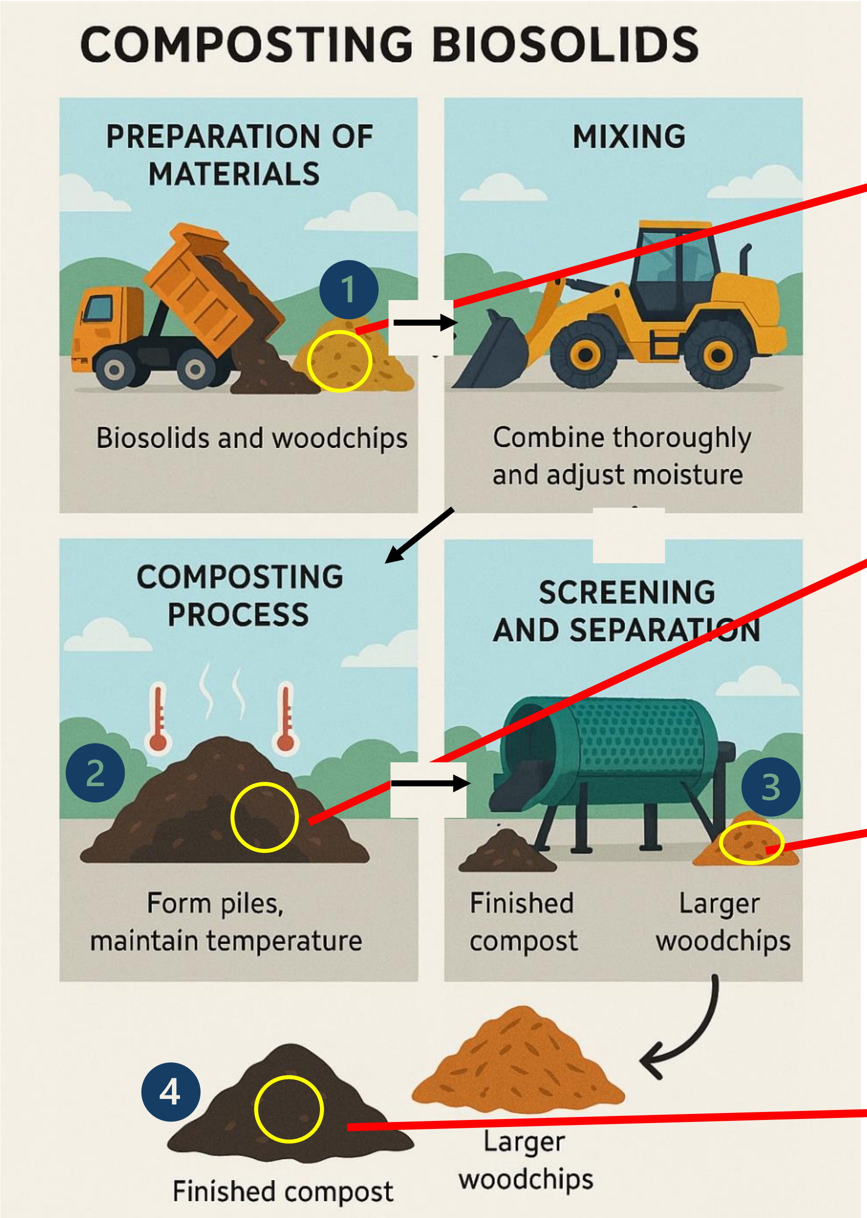
Biosolids composting process



FVW

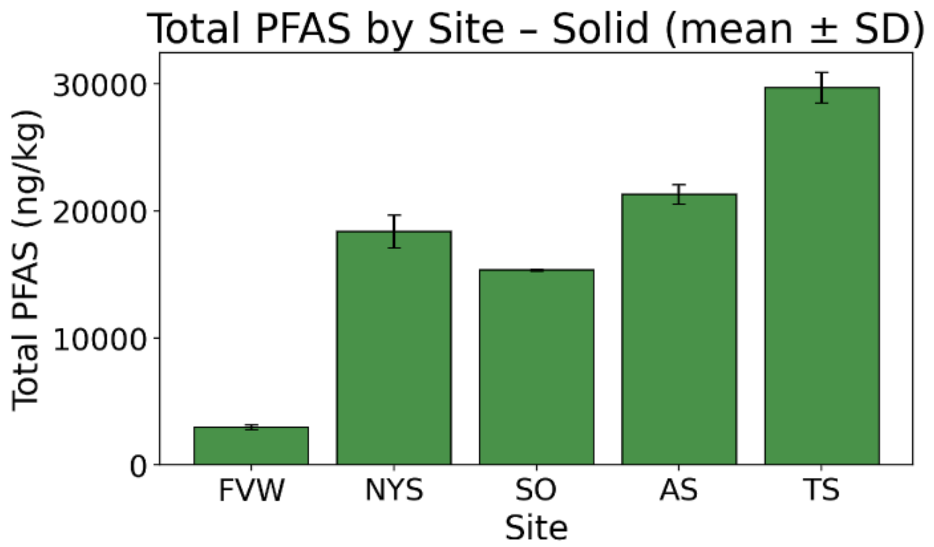
NYS

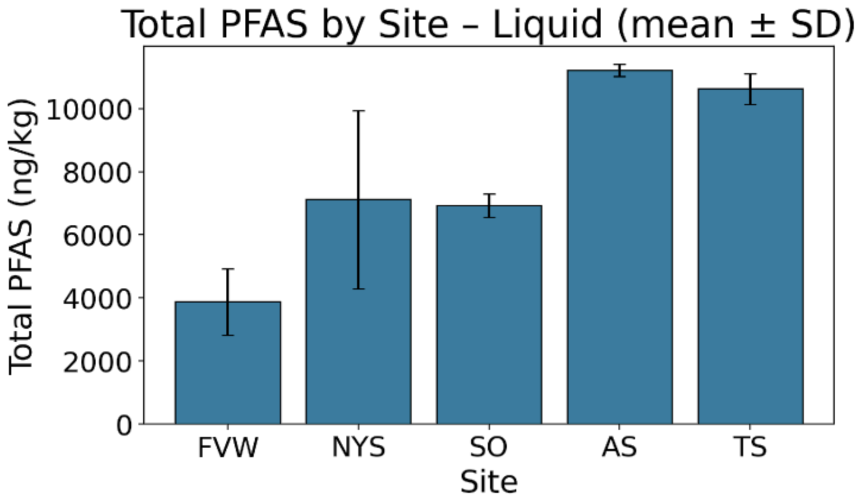
SO

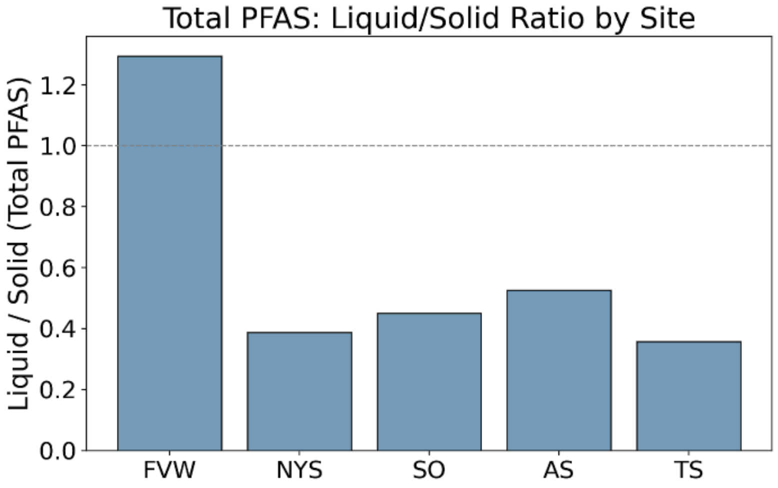
Ag Spec Turf Spec

Two types of finished compost product

Results – Year 2







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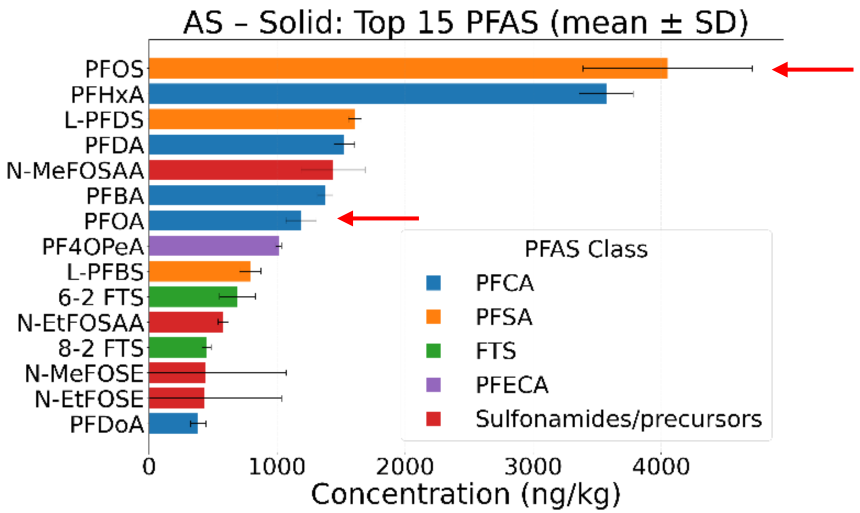
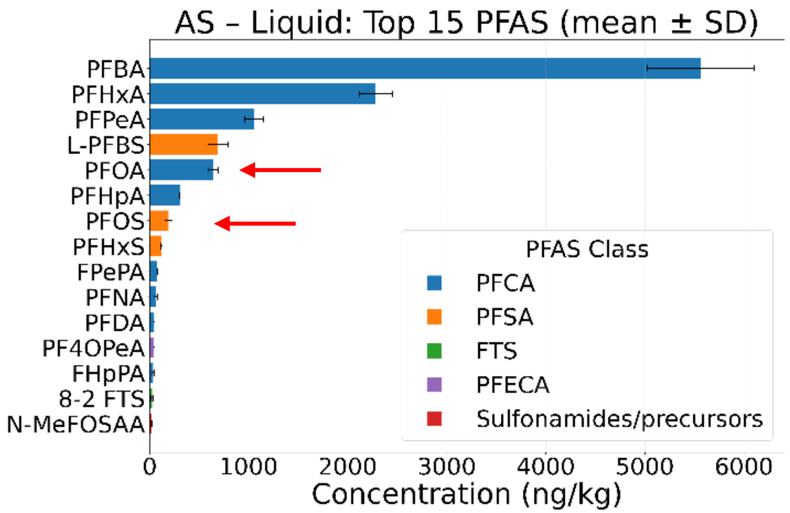
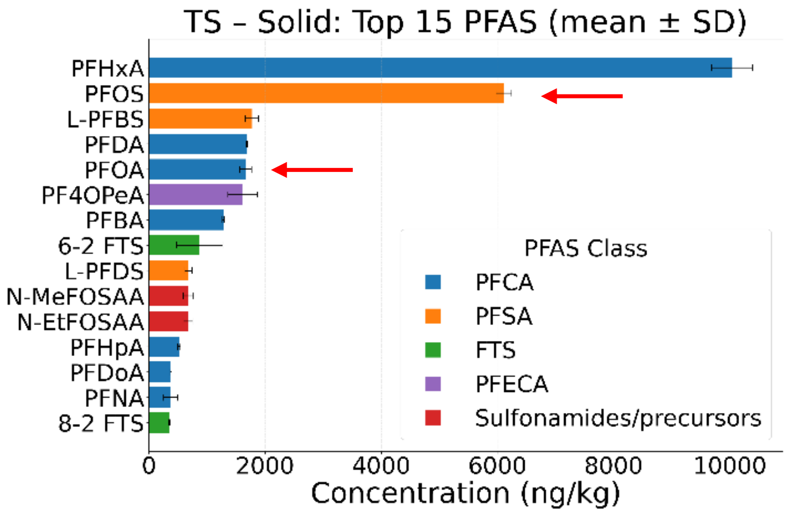
Results – Year 2

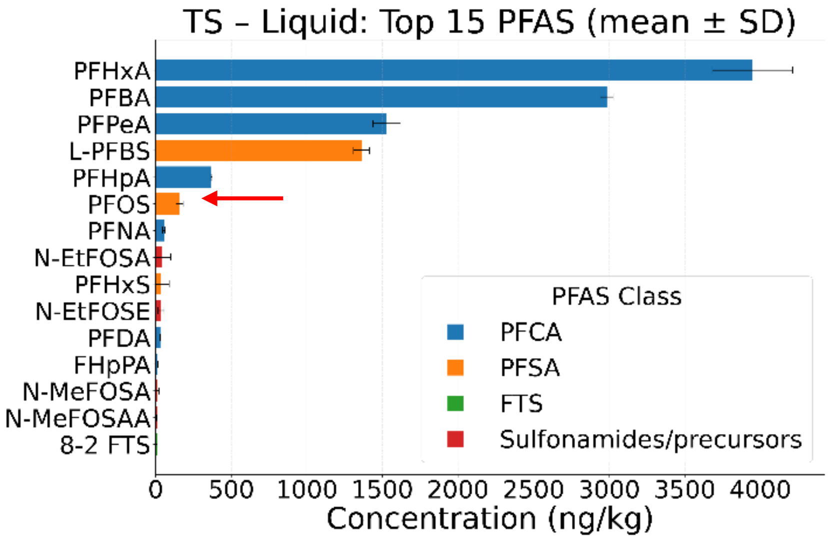
Ag Spec





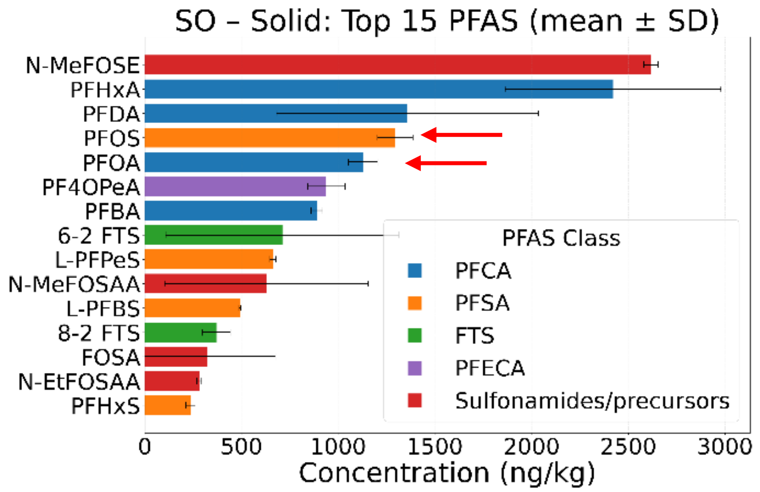
Turf Spec

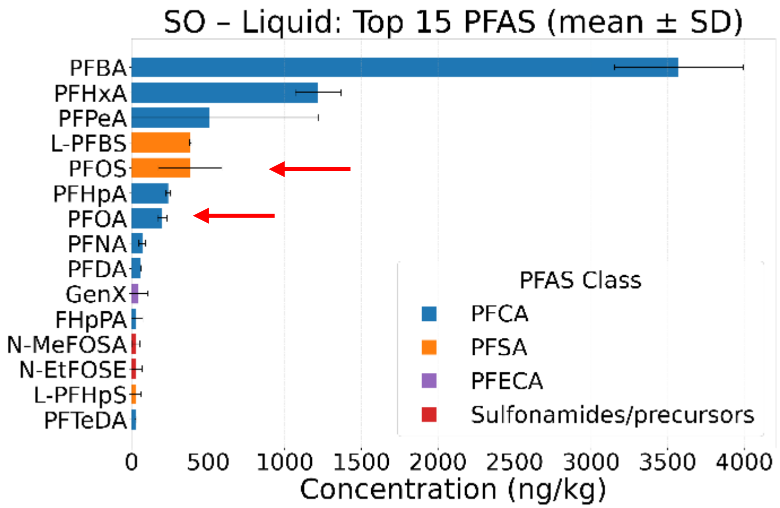




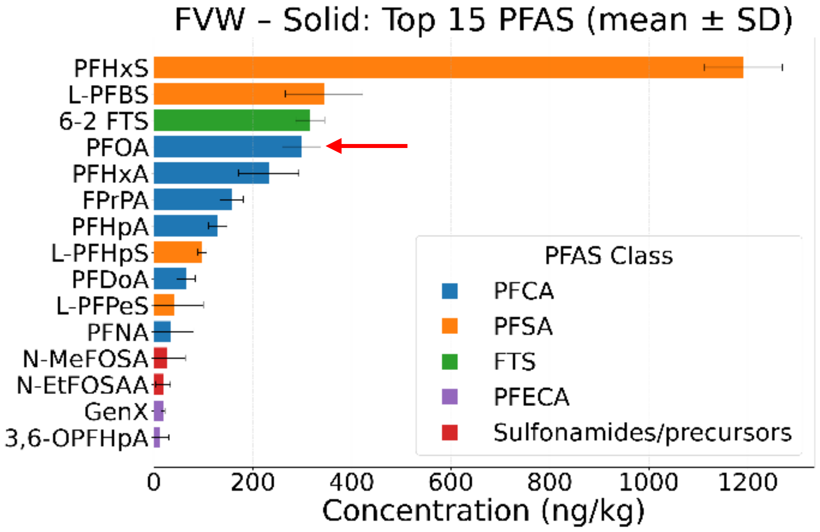
Results – Year 2

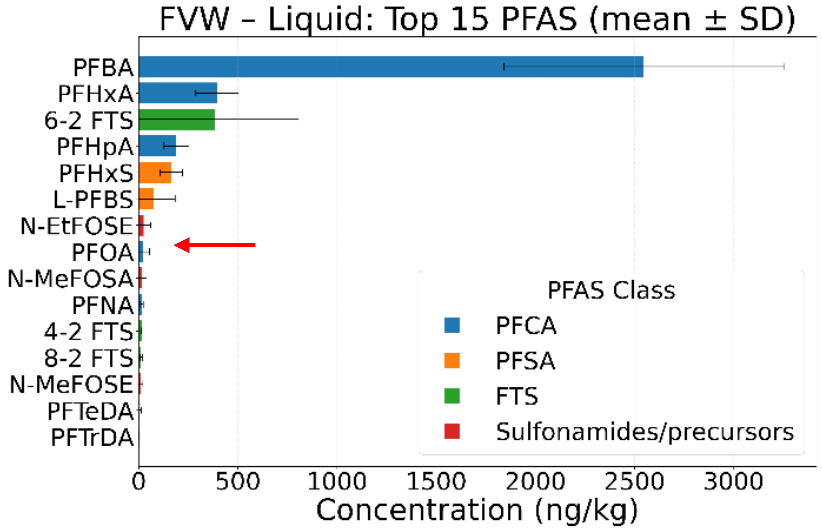
Screen Overs





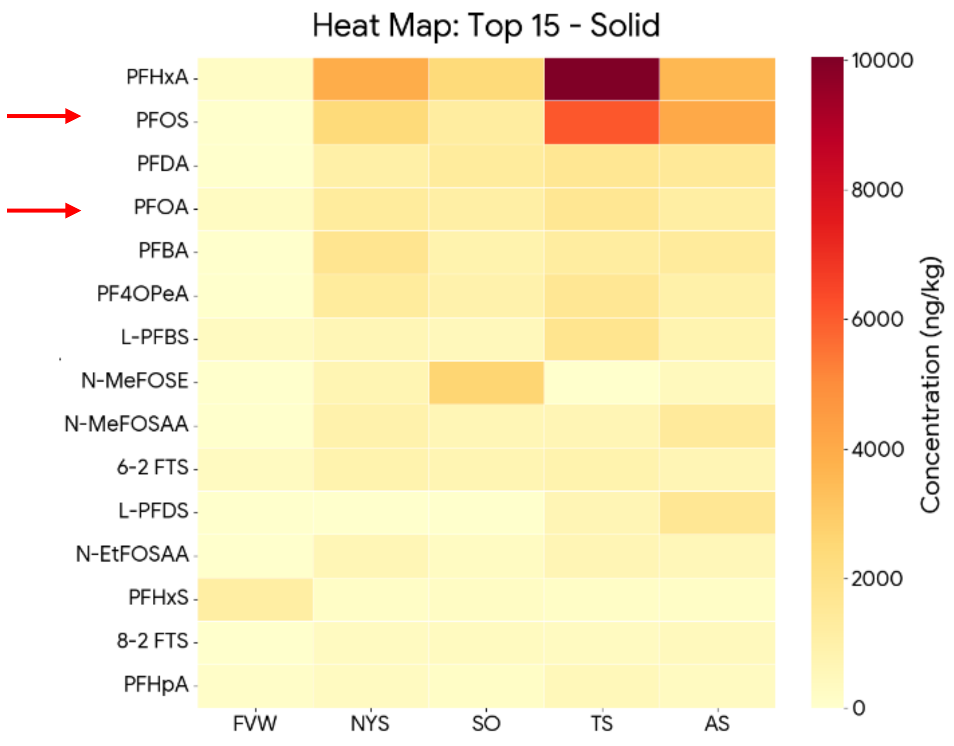
Fresh Vegetative Waste



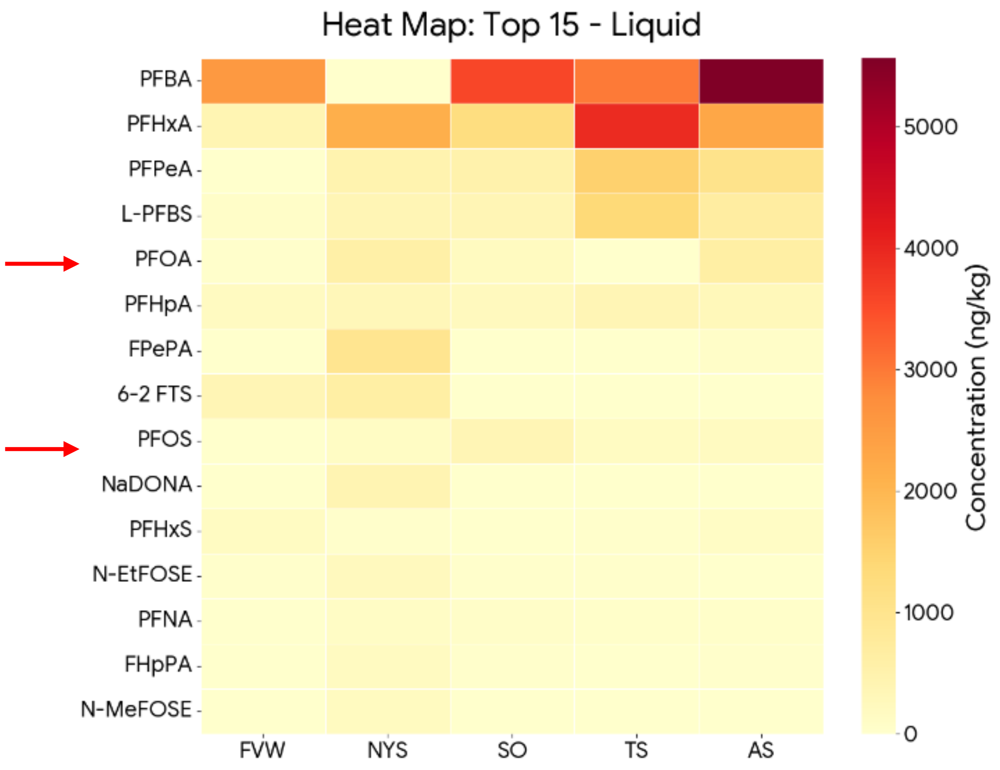


Results – Year 2

Solids

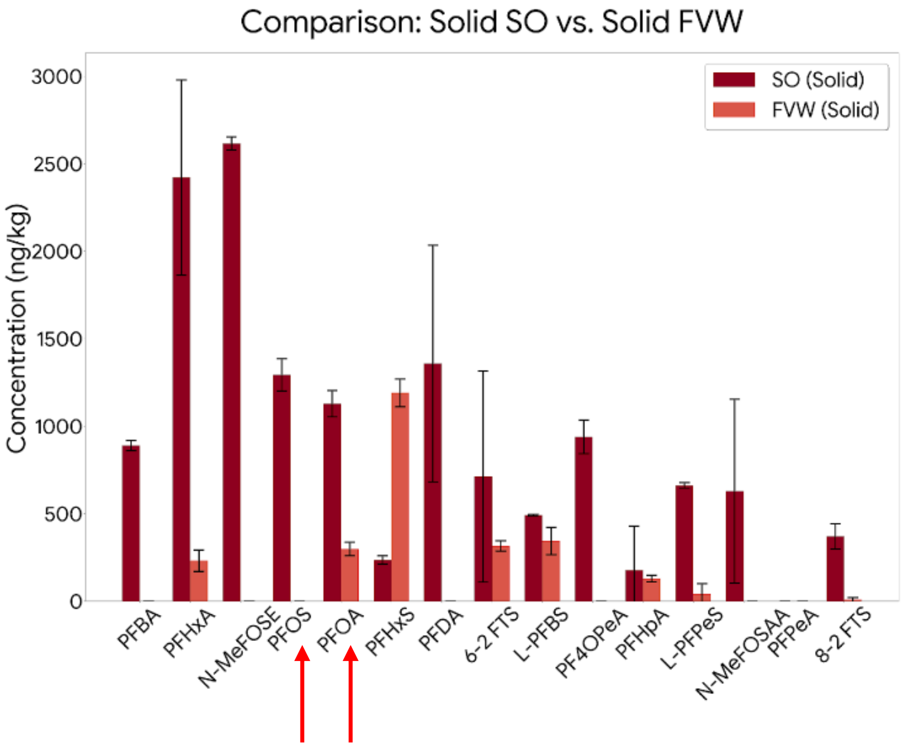


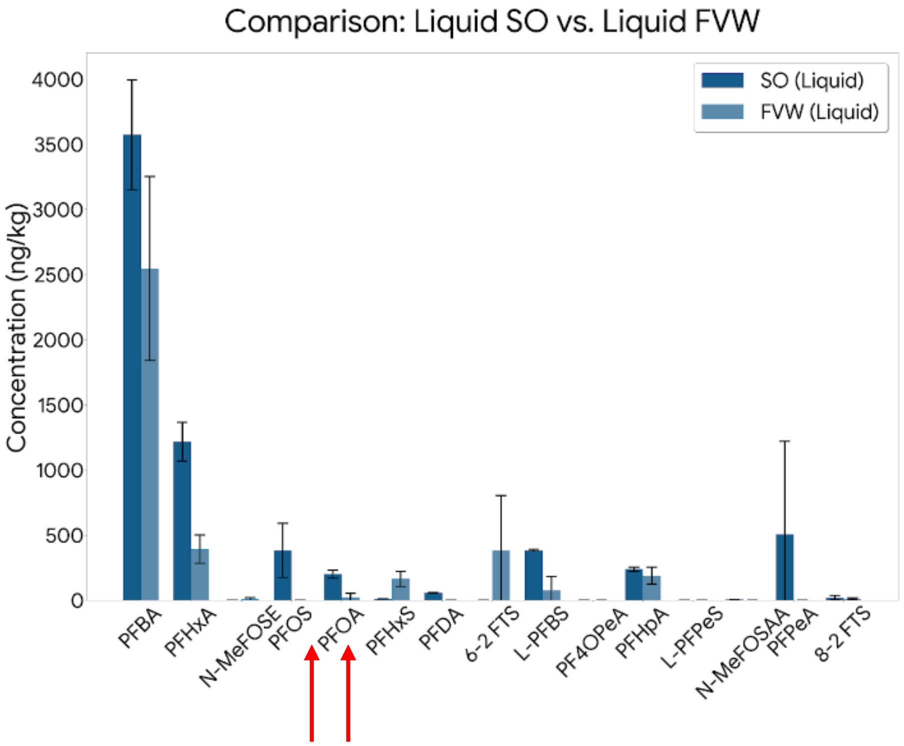
Liquids



Results – Year 2

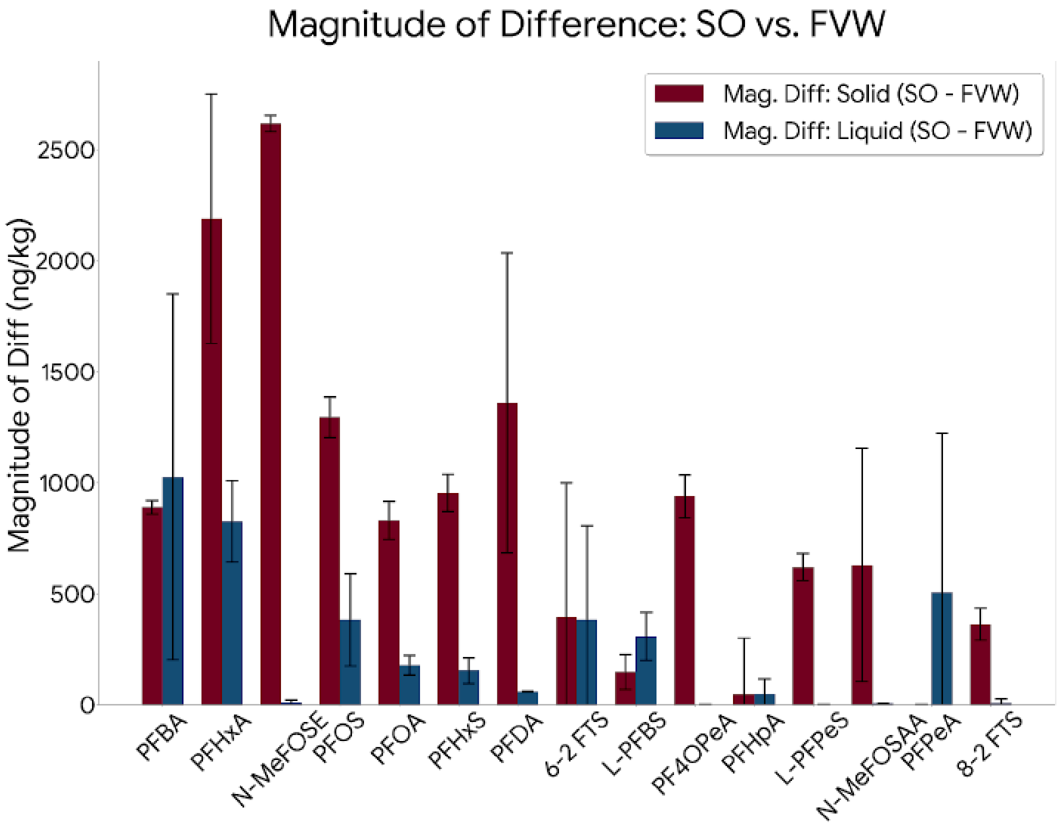
Screen overs vs Fresh vegetative waste





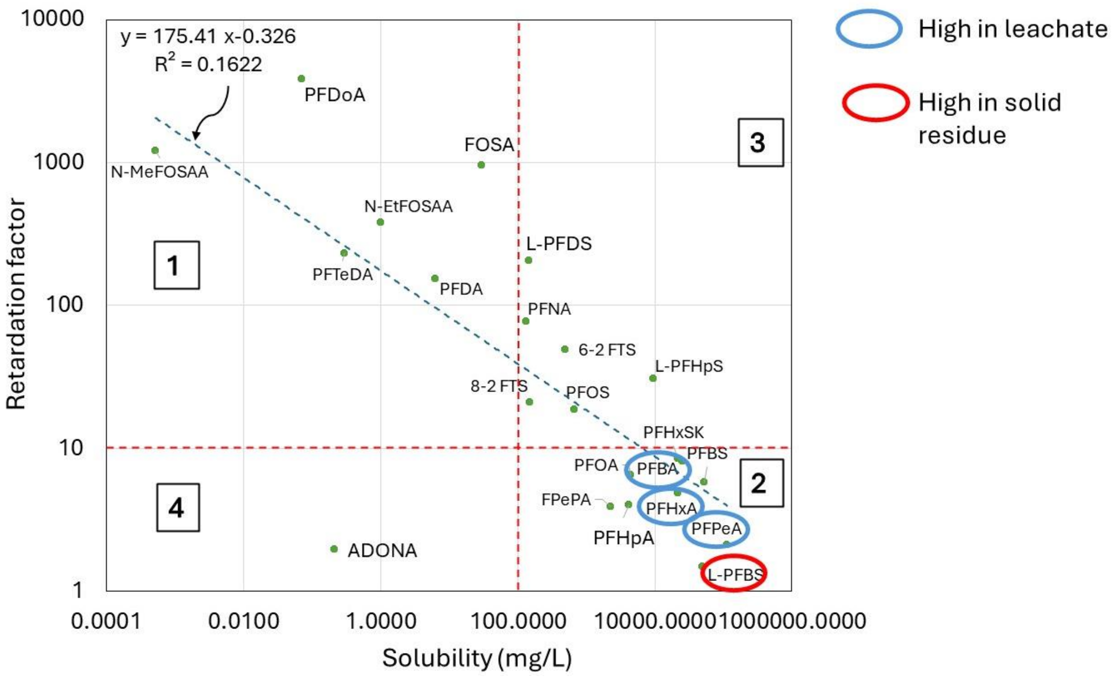
Results – Year 2

Accumulation of PFAS on vegetative fraction

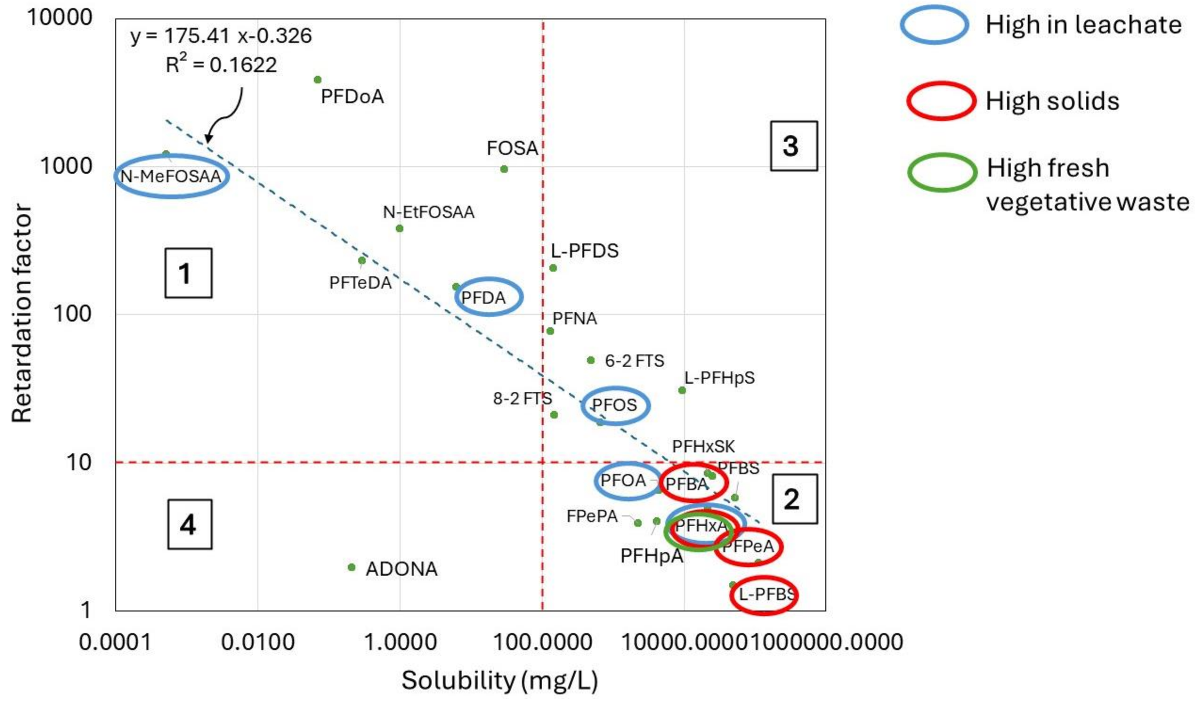


Results – Year 2

Biosolids



Compost



What we learned

1. pH did not have a significance effect on PFAS partitioning.
2. Most long-chain and sulfonamide-related PFAS (e.g., PFDoA, N-EtFOSAA, and PFOA) were concentrated in the solid phase, due to their higher hydrophobicities and affinity for organic matter.
3. PFDoA (12 carbons) was nearly absent in liquids (5.7 ng/kg) but high in solids (253.0 ng/kg).
4. Precursor (N-EtFOSAA) was almost exclusively found in the solid phase (438 ng/kg vs 9 ng/kg), suggesting it binds tightly to particles before it can degrade.
5. While the mean PFCA (carboxylates) concentration was higher in the solids, the difference was not statistically significant. This suggests that carboxylates are more evenly distributed or more mobile across both phases compared to the other groups.

What we learned

1. PFSA, FTS, and precursor groups were significantly higher in the solid matrices for the finished products (AS, TS), indicating that sulfonates and sulfonamide-related compounds have a higher affinity for the solid phase compared to carboxylates.
2. Fresh vegetative waste showed dominance of PFCAs in the liquid phase, with sulfonamides at significantly higher concentrations in solids.
3. Screen overs showed similar trends, with PFCA and PFSA significantly partitioning into the solid matrix.
4. Turf spec compost had distinct solid-phase dominance across all major classes. Agriculture spec compost also had higher levels of most groups in the solid phase, particularly for PFCAs and PFSAs.

What do these findings mean?

Time after application	Soil	Water (porewater and groundwater)	Plants (roots, shoots, edible parts)	Compost decomposition & release
0–1 month	Sorption of long-chain PFAS to organic carbon and mineral fractions	Initial leaching of short-chain PFAAs (e.g., PFBA, PFBS)	Plant uptake via roots; BAF is highest for C4–C6 PFAS; root-to-shoot transfer decreases with chain length	Fresh piles undergo moisture/pH changes; precursors begin biotransformation to terminal PFAAs
1–6 months	Retention for long-chain PFAS in surface soil; soil organic matter	Short-chain PFAS dominate leachate	Translocation to leaves for short chain PFAS	Decomposition of organic matter releases sorbed PFAS to pore water, vertical transport of PFAS
6–24 months	Precursors converted to PFAAs within; long-chain PFAS build up in the upper soil profile	Seasonal water table fluctuations can enhance leaching, especially for longer chain PFAS	Long-chain PFAS remain mainly in roots; short chains translocate to shoots	Compost-derived PFAS profiles persist
> 2 years	Surface soil acts as a long-term reservoir (retarded transport)	Legacy PFAS persist; short-chain PFAS move to groundwater	Long-chain PFAS remain mainly in roots; short chains translocate to shoots	Potential human health risks (land application, surface disposal, incineration) (EPA, 2025)

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Research article

PFAS in biosolids: Accumulation characteristics and fate profiles after land application

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Leaching profile of per- and polyfluoroalkyl substances (PFAS) from biosolids after thickening, anaerobic digestion, and dewatering processes, and significance of protein, phosphorus, and selected ions

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Analytical protocol for detection and prioritization of per- and polyfluoroalkyl substances (PFAS) in biosolid leachates

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Thank you for your attention!