Landfill Disposal of Perfluoroalkyl and Polyfluoroalkyl Substances State of the Science

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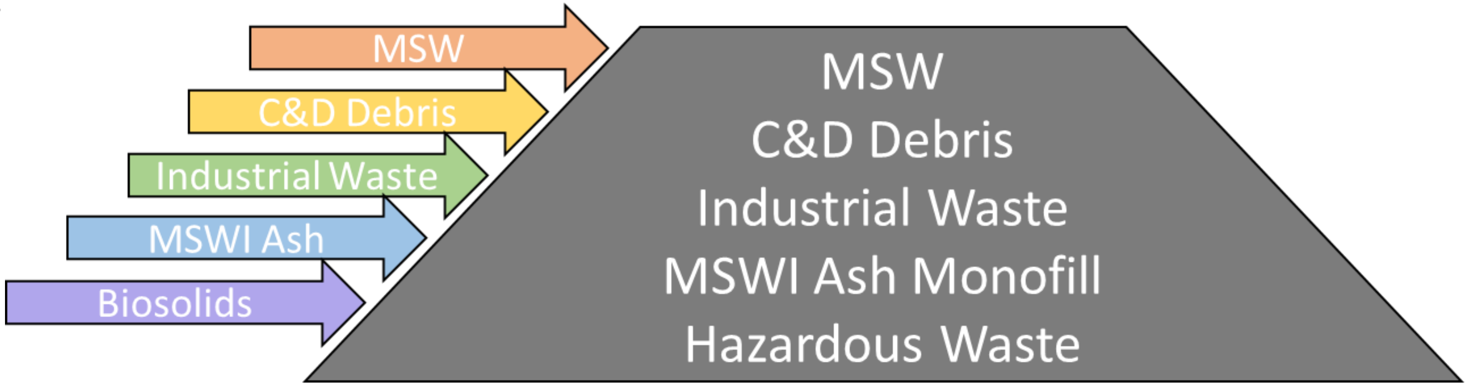
Introduction

- Thousands of PFAS used in consumer products
- A significant quantity of PFAS in solid waste
- Characterizing PFAS in waste is challenging
- This review discusses the state of waste-derived PFAS in landfills and the associated environmental impacts

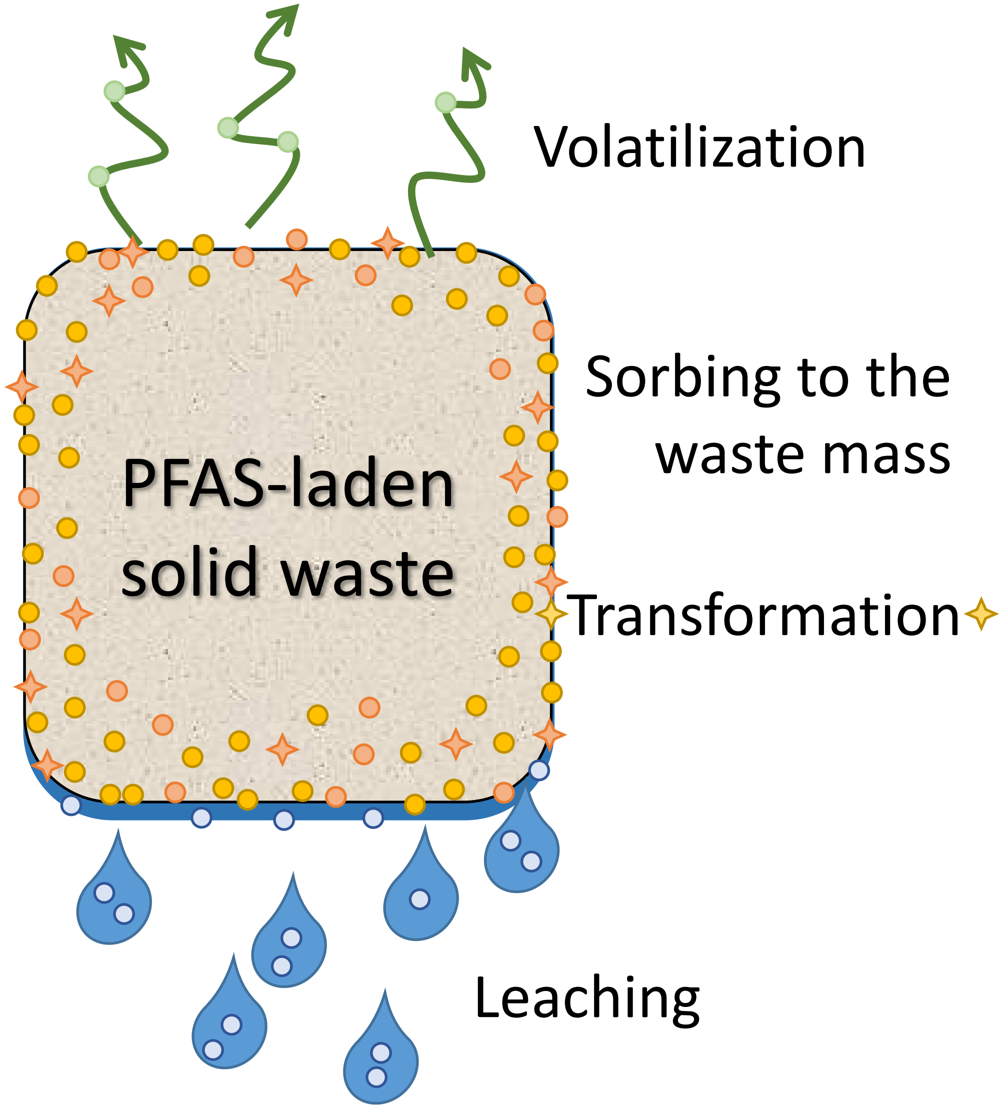
PFAS Loading at Different Landfill Types

- Household waste
  - Biodegradable and non-biodegradable fractions
- Industrial Waste
  - Biosolids
  - MSWI ash
  - Manufacturing wastes
  - PFAS remediation residuals



Fate of PFAS in Landfills

- Two mechanisms – transformation and partitioning
- Behavior influenced by PFAS structure (class and carbon chain length)
  - Short chain, terminal PFAS are more mobile and more difficult to treat
- Ongoing transformation and changes in the landfill environment will affect PFAS profile of the effluent
  - Conversion to terminal PFAS over time



Literature Review: PFAS Partitioning to Landfill Leachate

	Studies	Samples
US MSW landfill leachate	10	330
US C&D landfill leachate (Florida)	2	15
MSWI ash monofill leachate (Florida)	2	33
Hazardous waste landfill leachate (California)	2	29
Number of PFAS included in leachate analysis	2 - 70	
PFAS quantified	2 - 38	All
Number of PFAS with RSLs reported in landfill leachate	5 (of 6)	

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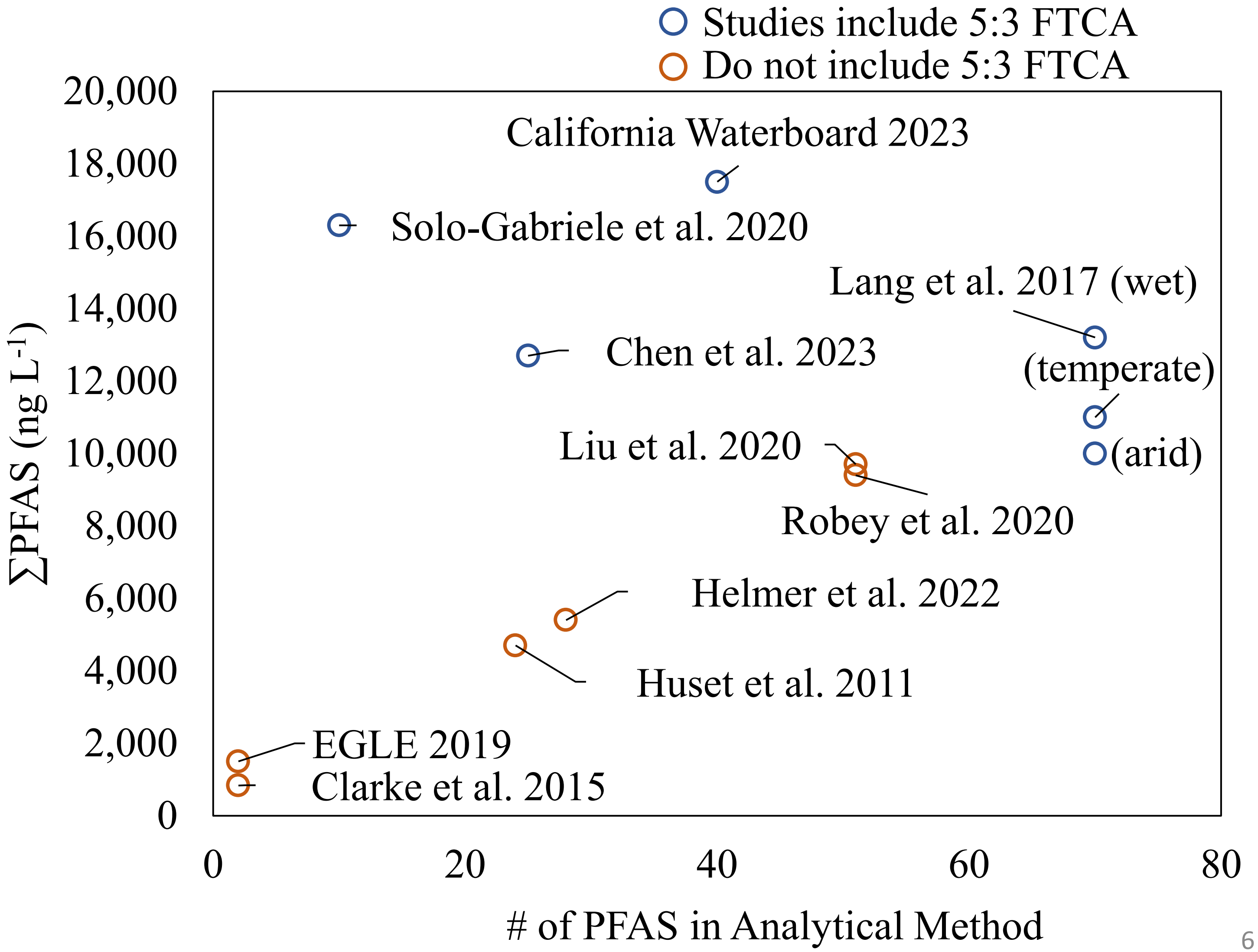
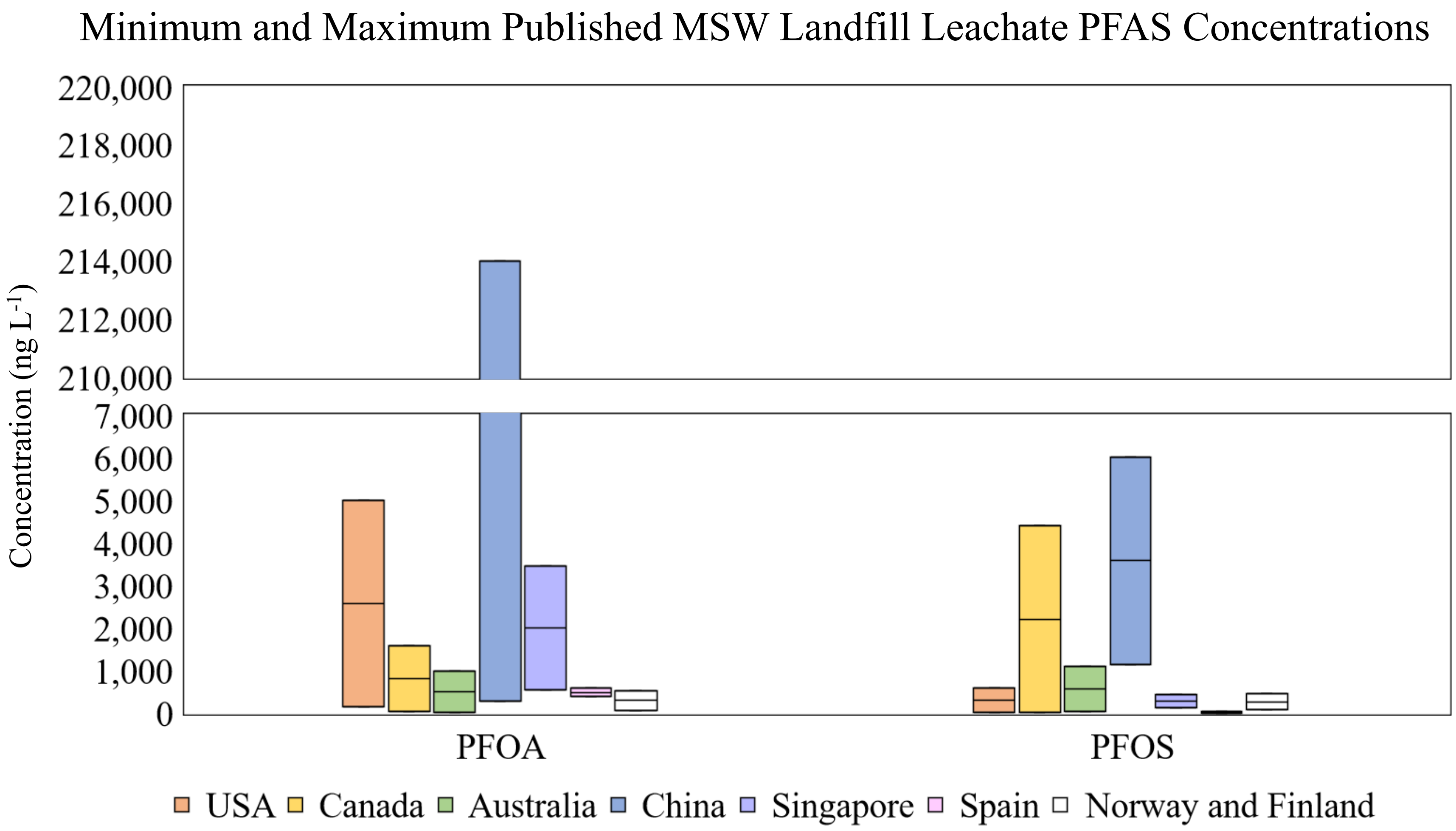
PFAS in MSW Landfill Leachate (US Studies)

- ∑PFAS content of MSW landfill leachate in nine published US studies ranges from BDL - 104,000 ng L^{-1}
  - Weighted average: 12,300 ng L^{-1}



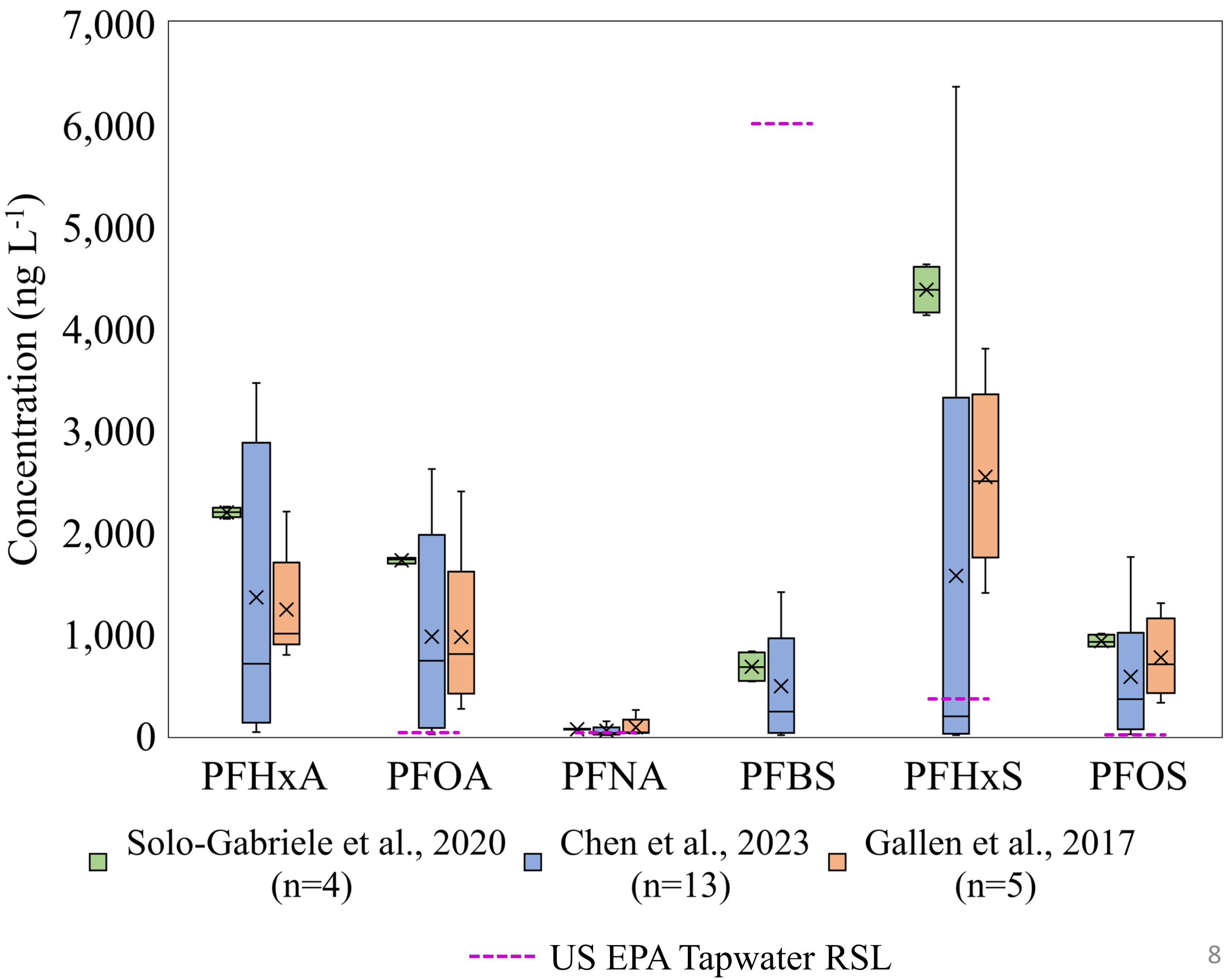
PFAS in MSW Landfill Leachate (International)

- PFAS in international studies are comparable
- Overall, leachate described in studies from China have more PFOS and PFOA than US landfills



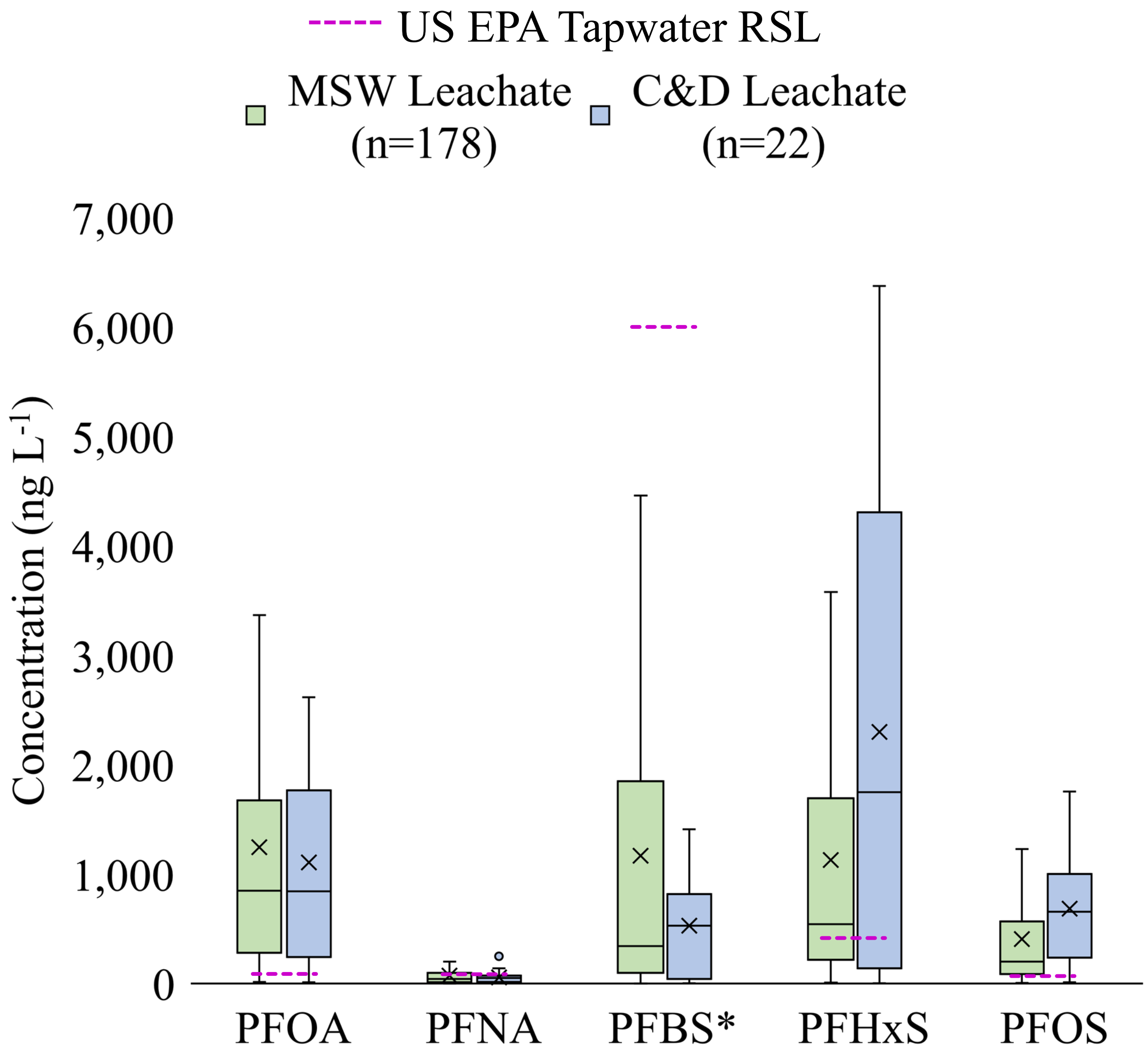
PFAS in C&D Landfill Leachate

- ∑PFAS content of C&D landfill leachate in two published US studies (both from Florida landfills) ranges from 270 - 30,500 ng L^{-1}
  - Weighted average of 10,300 ng L^{-1}
- Significantly, most C&D landfills are not required to use liners or collect leachate
- One study from Australia included five C&D landfill leachate samples



MSW vs. C&D Landfill Leachate

- Three studies (two US, one Australian) measure PFAS in MSW and C&D landfill leachates
- ∑PFAS in MSW and C&D landfill leachates are similar, individual PFAS may be higher or lower, on average
- C&D landfill leachates contain proportionally more terminal PFAS
- Variability in density, decomposition, and surface area



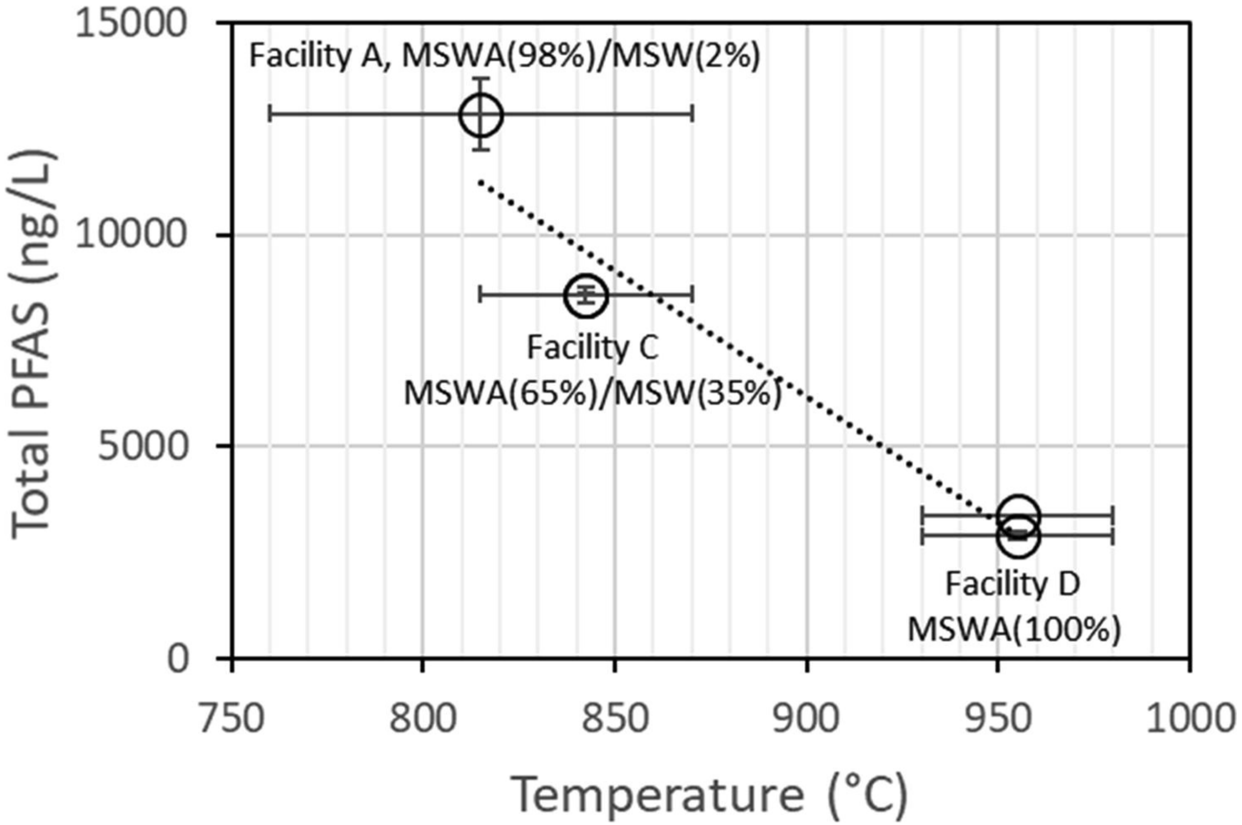
PFAS in Hazardous Waste Landfill Leachate

- Two sites in CA report PFAS concentrations in HW leachate
  - Primary leachate 570 – 377,000 ng L^{-1}
    - Average 68,000 ng L^{-1}
  - Secondary leachate 25 – 3,700 ng L^{-1}
    - Average 1,800 ng L^{-1}
- PFAS are not currently classified as hazardous wastes
- PFAS-containing wastes are sometimes managed as hazardous wastes
  - Chrome sludge (F006)
  - AFFF waste
- Subtitle C requirements result in minimal biological activity, minimal leachate generation
- Traditional solidification techniques do not immobilize PFAS
- Leachate managed as hazardous waste (F039)

Chromium-rich electroplating sludge

PFAS in MSWI Ash Monofill Leachate

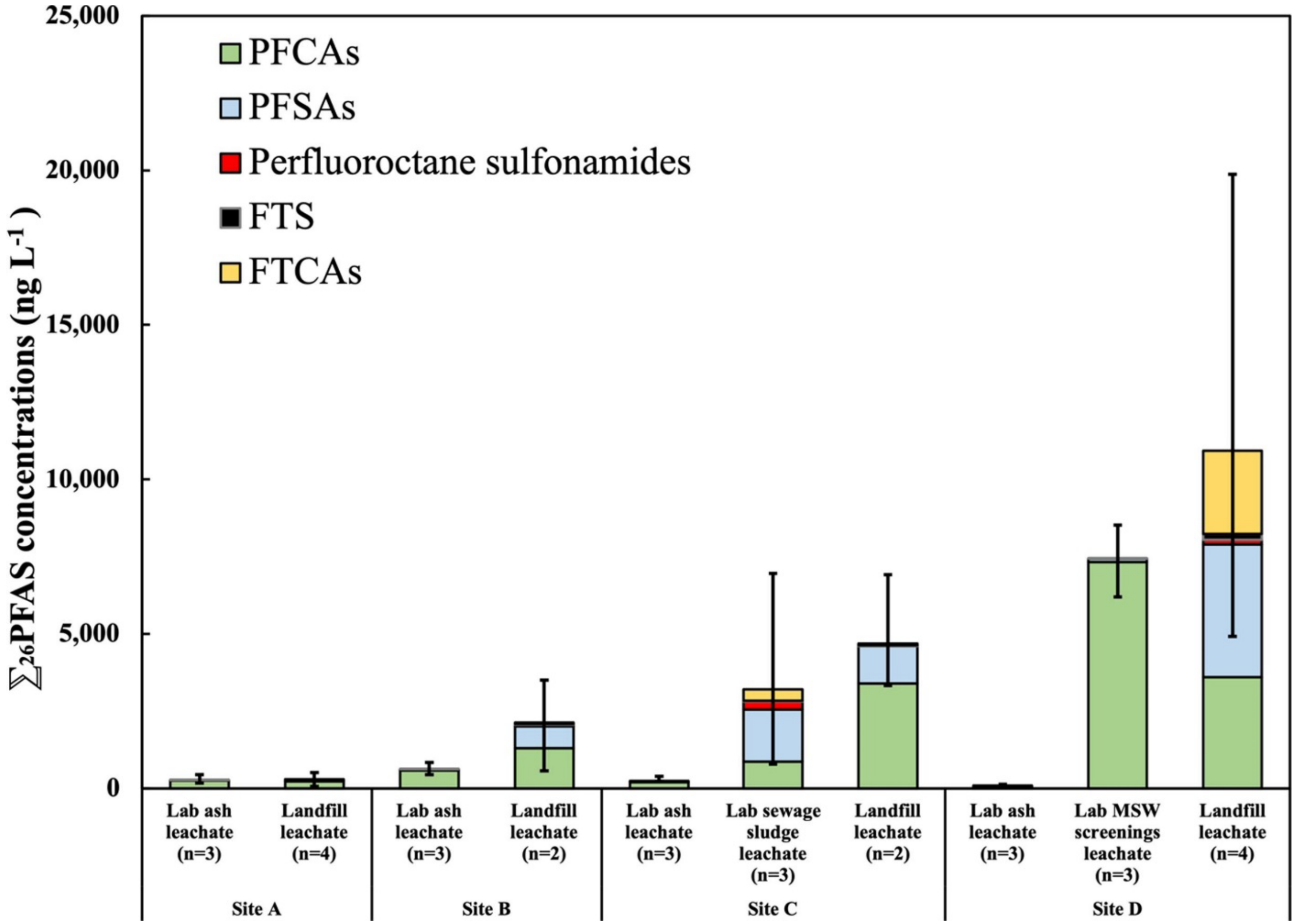
- Ash monofill leachates contain lower PFAS concentrations than MSW and C&D landfill leachates.
  - 39 – 54,500 ng L^{-1}
- Negative correlation between ∑PFAS and incineration temperature



Solo-Gabriele, H.M., Jones, A.S., Lindstrom, A.B., Lang, J.R., 2020. Waste type, incineration, and aeration are associated with per-and polyfluoroalkyl levels in landfill leachates. Waste Management 107, 191–200.

Co-disposal of PFAS-laden Wastes

- Co-disposal of unburned waste (e.g., biosolids, MSW screenings) results in disproportionately high ∑PFAS in leachate
  - Suggests short-circuiting of leachate
  - Care should be taken to dispose of MSW and MSWI ash separately



Liu, Y., Mendoza-Perilla, P., Clavier, K.A., Tolaymat, T.M., Bowden, J.A., Solo-Gabriele, H.M., Townsend, T.G., 2022. Municipal solid waste incineration (MSWI) ash co-disposal: Influence on per- and polyfluoroalkyl substances (PFAS) concentration in landfill leachate. Waste Management 144, 49–56. https://doi.org/10.1016/j.wasman.2022.03.009

PFAS in Industrial Waste Landfill Leachate

- No PFAS characterizations of US industrial waste landfill leachates found
- Leachate quality (including PFAS content) will depend on types of industrial waste
- Examples in the literature of PFAS contamination from unlined industrial waste landfills
- One study of PFAS in industrial waste landfill leachate from Japan
  - Average $\sum_{17}$PFAA: 45,000 ng L^{-1}

US MSW, C&D, MSWI Ash, Hazardous Waste Landfill Leachate Dilution Factors (RSL)

PFAS	MSW Landfill		C&D Landfill		MSWI Ash Landfill		HW Landfill (Primary)		HW Landfill (Secondary)	
	Mean	DF	Mean	DF	Mean	DF	Mean	DF	Mean	DF
PFOA	1,400	23	1,100	19	800	13	4,900	81	100	1.7
PFOS	260	6.6	660	17	400	10	4,100	102	14	0.4
PFNA	67	1.1	50	0.9	59	1.0	530	8.7	40	0.7
PFBS	800	0.1	530	0.1	1,400	0.2	6,500	1.1	57	0.01
PFHxS	550	1.4	2,200	5.7	510	1.3	12,000	32	86	0.2
PFHxA	2,800	n/a	1,600	n/a	1,300	n/a	12,000	n/a	440	n/a
5:3 FTCA	3,500	n/a	1,400	n/a	700	n/a	n/a	n/a	n/a	n/a

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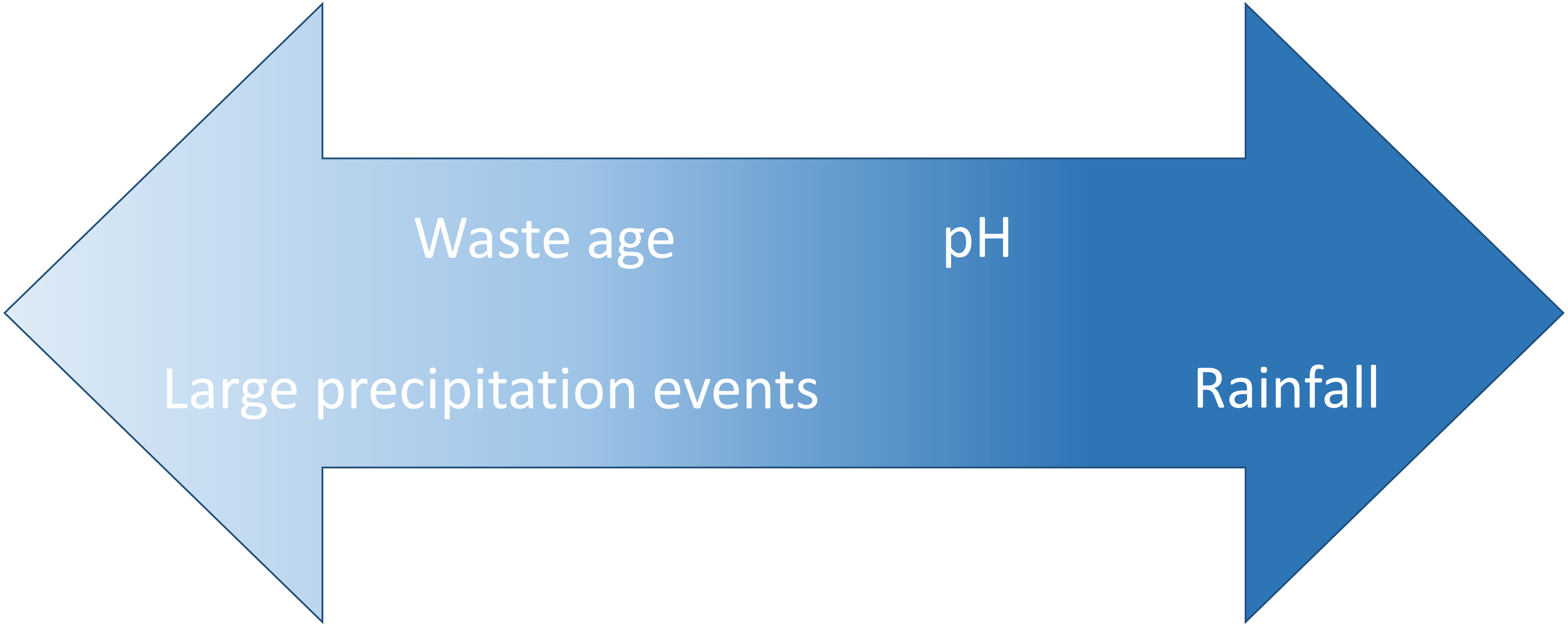
Other Factors Affecting PFAS in Leachate



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Literature Review: PFAS in MSW Landfill Gas

- Neutral PFAS well-documented to volatilize
  - AFFF headspace study (PFAAs, FTS, neutral PFAS)
  - 15,000 µg m^{-3} PFOA
- One peer-reviewed study of *in situ* MSW LFG PFAS
  - FTOHs highest
  - ∑Neutral PFAS average 10,200 ng m^{-3}
- Minnesota LFG study
  - PFAAs and FASA 4.1 to 18.7 ng m^{-3}

Fate of PFAS in Traditional Landfill Leachate Management Systems

- Limited studies suggest minimal diffusion of PFAS through HDPE liners
  - Liner integrity imperative for preventing PFAS transmission to the environment
- Liner leachate collection efficiency: 98.1%
- Compacted clay liners ineffective (based on bentonite clay studies)
- Traditional leachate treatment is not effective PFAS treatment
  - Many rely on chemical or biological oxidation
    - Likely to facilitate transformation to terminal (potentially regulated) PFAS
    - Actual total PFAS may not change but terminal PFAS and *apparent* total PFAS may increase
  - PFAS should be removed prior to treatment targeting other constituents (e.g., ammonia, COD)

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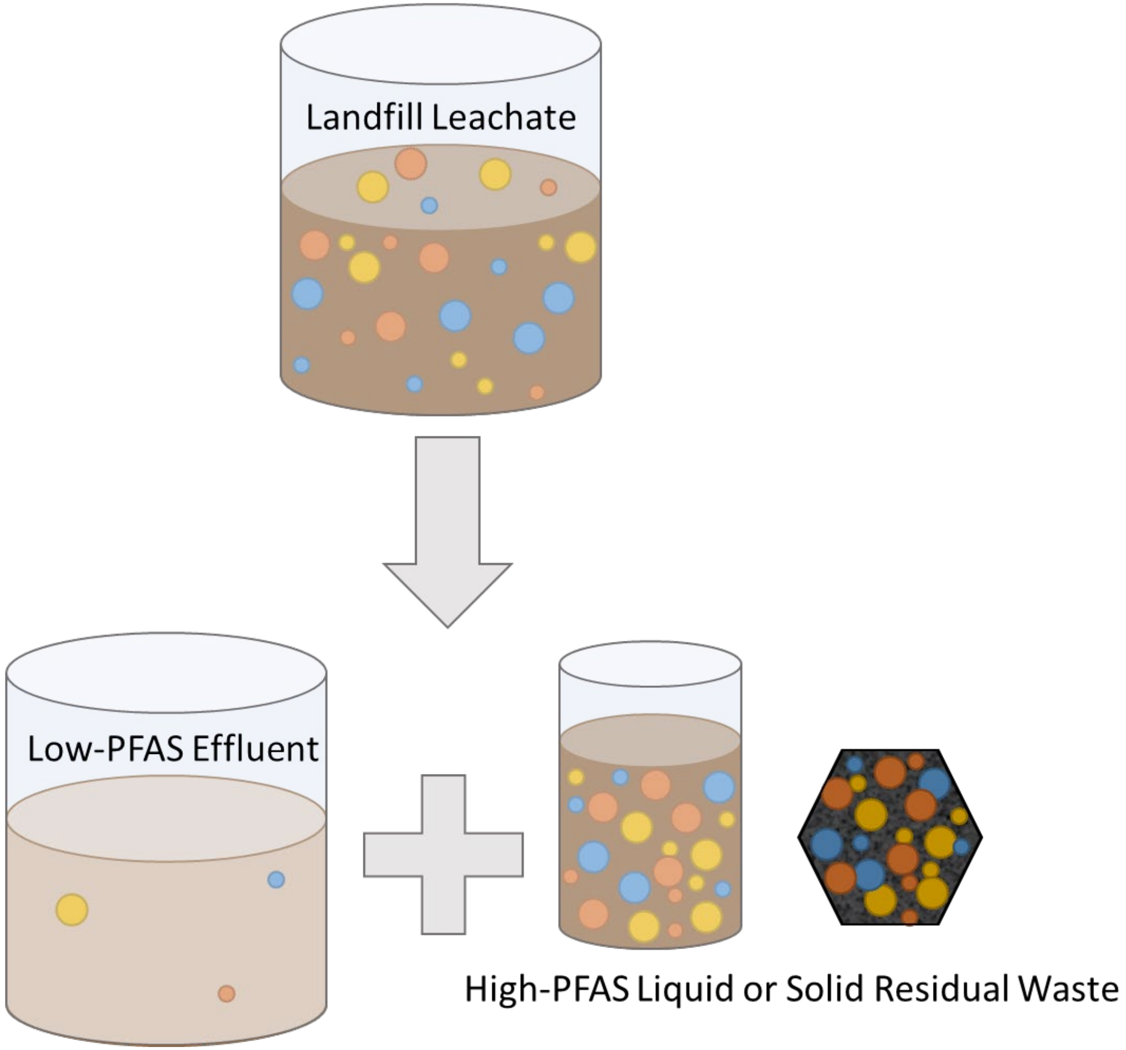
Targeted Removal of PFAS from Landfill Leachate

- PFAS-targeted treatment falls into two categories: separation and destruction
- Separation treatment results in solid or liquid residuals which require management
- Destructive treatment requires high energy chemical reactions, localized high temperatures
  - Limited studies focused on PFAS in landfill leachate
- PFAS-specific effluent limits for landfill leachate will necessitate treatment prior to leachate disposal



Fate of PFAS in Traditional Landfill Gas Management Systems

- Flare, LFG combustion systems have not been demonstrated to be effective for PFAS treatment
- Flare temperatures (650 °C – 850 °C) may be too low to destroy PFAS (~1,000 °C)
  - Residence times also may be too short
- Likely contribute to transformation of volatile PFAS to PICs and other PFAS
- LFG pretreatment or PFAS-optimized flare operation may mitigate emissions

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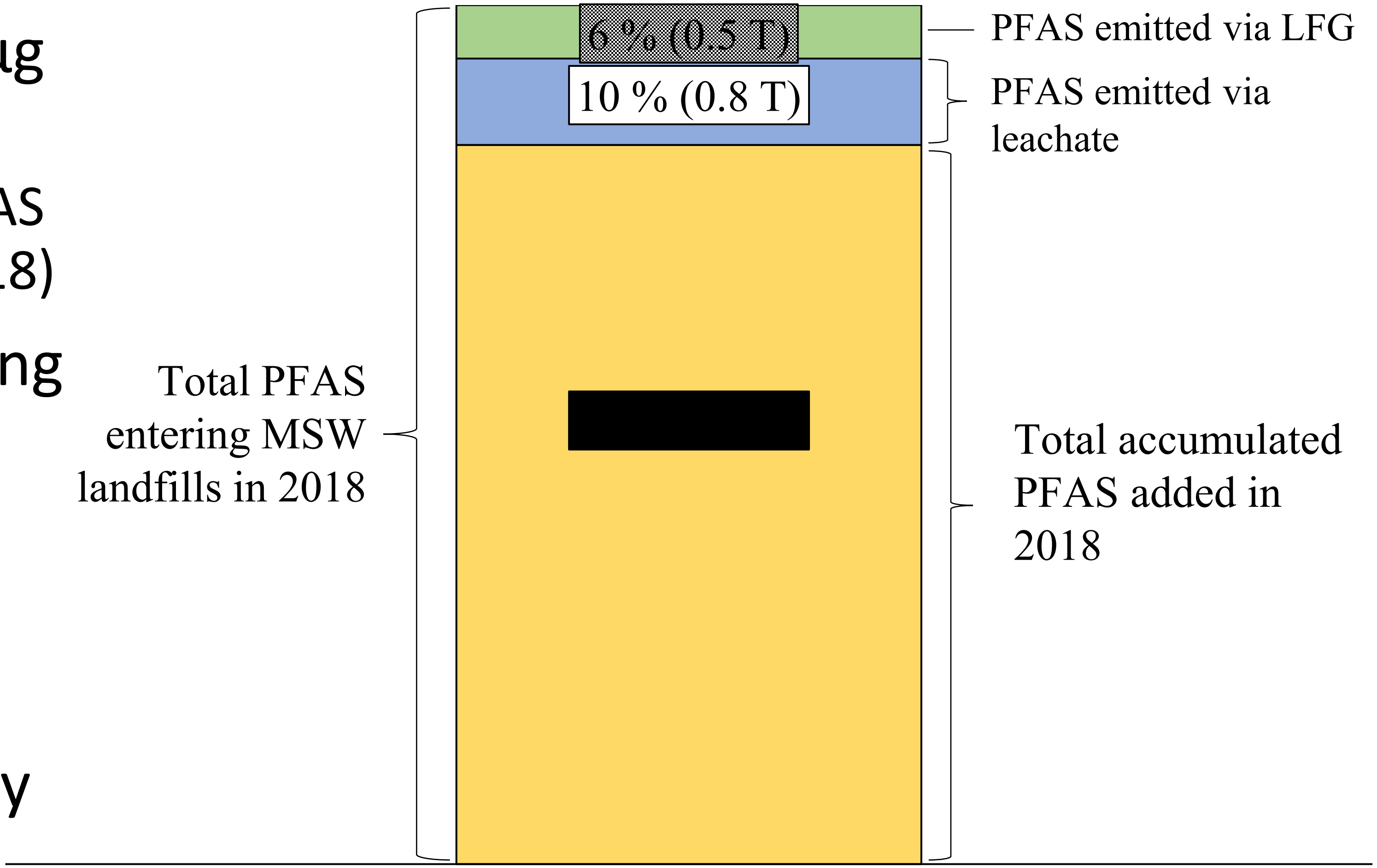
Estimate of US MSW Landfill PFAS Mass Balance

- Conservative estimate of 50 µg PFAS per kg of MSW
  - Corresponds to 6,600 kg of PFAS entering landfills annually (2018)
- Additional 850 of PFAS entering landfills via biosolids (2018)
- 750 kg emitted from MSW landfills via leachate annually
- 460 kg PFAS emitted from MSW landfills via LFG annually



Major Findings

- Solid waste management strategies impact PFAS emissions
- Biological activity and the presence of biodegradable waste increases PFAS transformation, leaching
- In both C&D and MSW landfill leachates, PFOA has the highest ratio to its respective RSL
- MSWI ash contains less PFAS, but co-disposal with unburned waste results in disproportionately high leachate PFAS
- C&D landfills present a significant source of PFAS to the environment since PFAS concentrations are similar to MSW and many C&D landfills are not lined
- The majority of PFAS in landfills remains within the waste mass, indicating landfills will remain a source of PFAS for the long term

Data Gaps

- Outside of MSW landfills, leachate data are regional and/or limited
  - US C&D landfill leachate data are limited to Florida landfills
    - C&D waste streams may vary due to regional construction requirements
  - Hazardous waste landfill leachate data is limited to California
  - Leachate data is not available for relevant US industrial waste landfills
- More research is needed on both controlled and uncontrolled LFG emissions
- Closer evaluation of the fate of PFAS during leachate treatment and LFG management
- Long-term interactions between PFAS and liner systems, especially in complex matrices such as landfill leachate
- Long-term implications of PFAS in the landfill environment, since the bulk of PFAS remain within the solid waste mass
- Evaluation of PFAS fate during other solid waste management processes are needed
  - e.g., anaerobic digestion, thermal treatment, composting, and recycling

Disclaimer

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Questions?