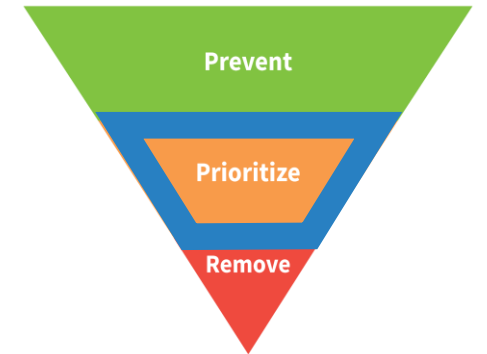


# 3<sup>rd</sup> ZeroPM Workshop



October 7<sup>th</sup> and 8<sup>th</sup>, 2025  
University of the Aegean  
Mytilene, Greece

ZeroPM



***Achieving Zero Pollution of Persistent and Mobile Substances  
Removal through Technical Solutions***



# PFAS in sewage sludge: occurrence, removal technologies and threats for the environment

**Nasos Stasinakis, Professor**

**Department of Environment, University of the Aegean**



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101036756.

# Structure of the presentation

- What we know about PFAS occurrence and fate in Sewage Treatment Plants?
- Is there any threat for the environment due to application of sewage sludge to the soil?
- Are PFAS removed during conventional sludge treatment?
- Which is the contribution of ZeroPM on PFAS and sewage sludge treatment?



# PFAS in Sewage Treatment Plants: first findings

2005

## Detection in Sewage Sludge (USA, SF)



- ✓ Digested and primary sludge from 11 STPs
- ✓ [PFOS] in sludge: 14-2610 ng/g
- ✓ [PFOS] in sediments: up to 3.8 ng/g
- ✓ Existence of PFOS precursors in sludge samples: N-MeFOSAA, N-EtFOSAA

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### Quantitative Determination of Perfluorochemicals in Sediments and Domestic Sludge

Christopher P. Higgins, Jennifer A. Field, Craig S. Criddle, and Richard G. Luthy

View Author Information

Cite this: *Environ. Sci. Technol.* 2005, 39, 11, 3946-3956  
Publication Date: April 30, 2005  
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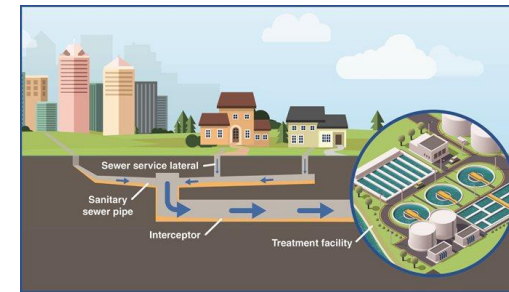
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Environmental Science & Technology

2006

## Detection in domestic wastewater (USA, NY)



- ✓ Raw and treated WW from 6 STPs
- ✓ [PFOA] > [PFOS]
- ✓ [PFOA] in WW: 58-1050 ng/L

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### Mass Loading and Fate of Perfluoroalkyl Surfactants in Wastewater Treatment Plants

Ewan Sinclair and Kurunthachalam Kannan

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Cite this: *Environ. Sci. Technol.* 2006, 40, 5, 1408-1414  
Publication Date: January 21, 2006  
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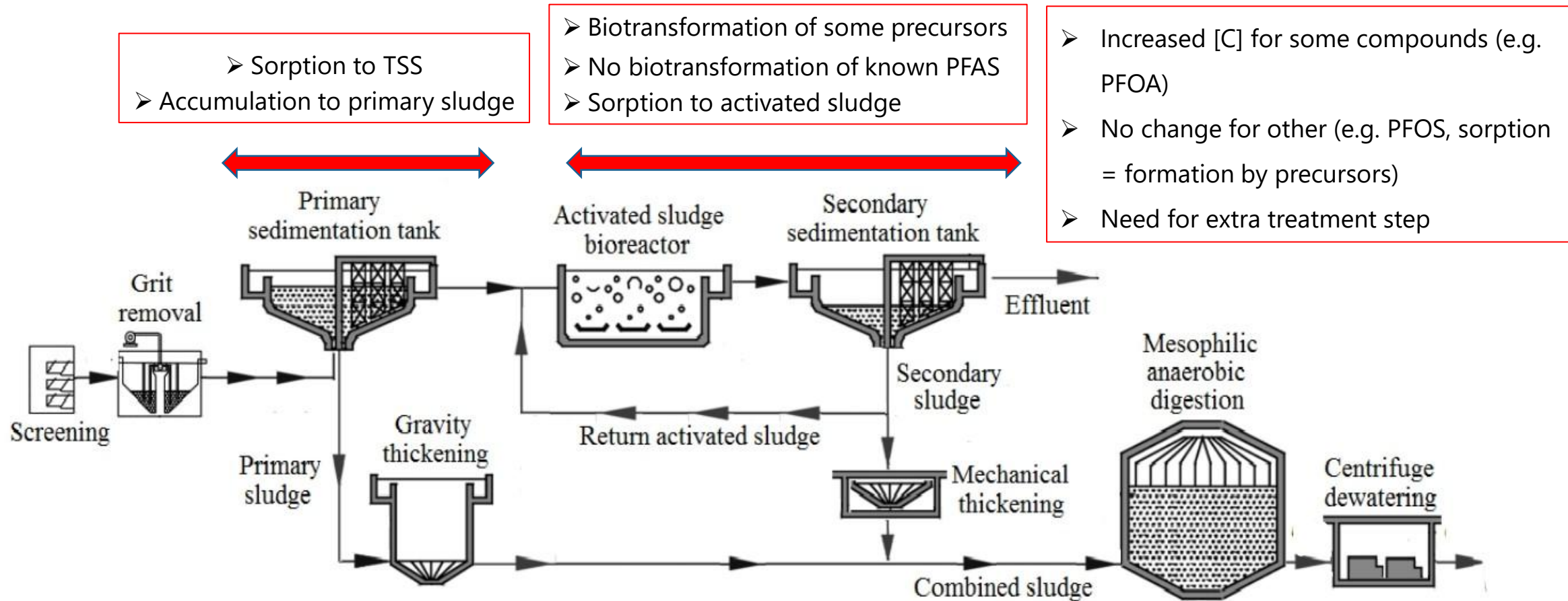


Environmental Science & Technology

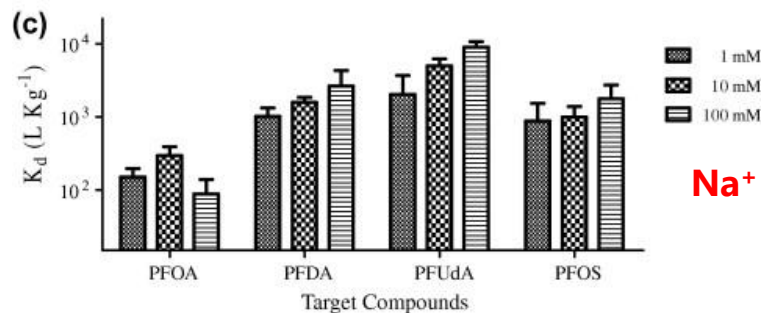
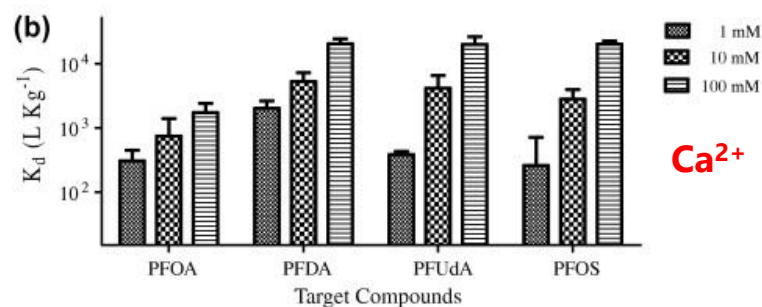
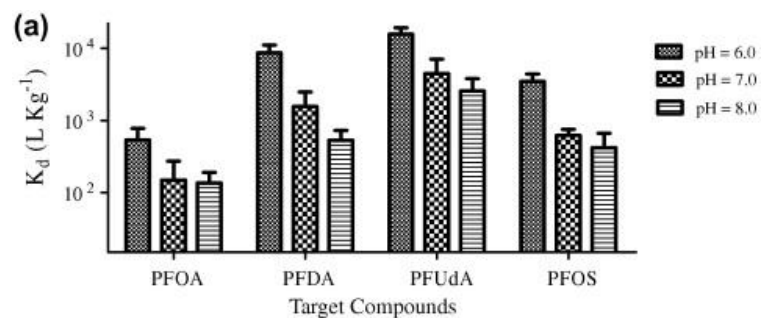
Higgins et al (2005)  
<https://doi.org/10.1021/es048245p>

Sinclair and Kannan (2006)  
<https://doi.org/10.1021/es051798v>

# Fate of PFAS along wastewater treatment line

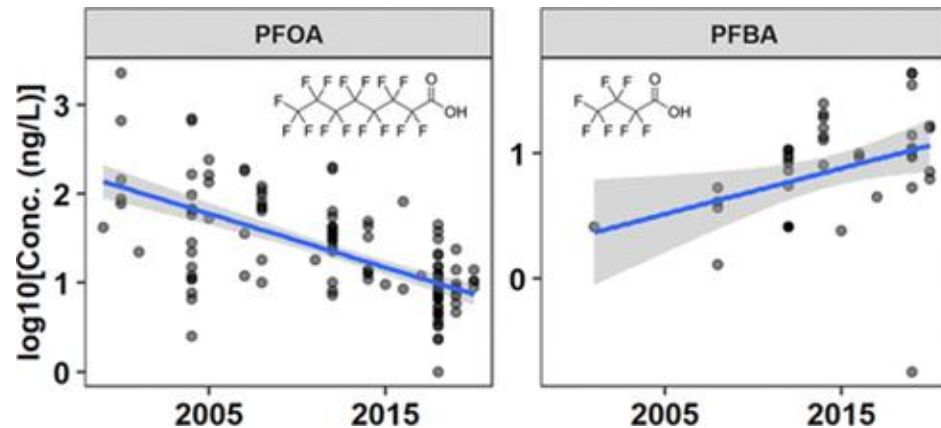


# PFAS sorption to sludge



- Partitioning coefficients increase with increased fluoroalkyl chain length
- PFSA compounds had higher sorption capacities compared to PFCA compounds
- Lower pH and higher  $[Ca^{2+}]$  increased PFAS sorption

# Trends in PFAS concentrations found in STPs (USA)



Correlations between log-transformed wastewater effluent PFOA and PFBA concentrations and sample year in the US without stated industrial sources.

## *Treated wastewater*

- Declined concentrations of long chain PFAS over time
  - Average [PFOA] : 68.9 ng/L (data 1998-2020)
  - Average [PFOA] : 12.8 ng/L (data 2013-2020)
- Increased concentrations of short chain PFAAS
- Higher concentrations in case that industrial WW are discharged to the STP

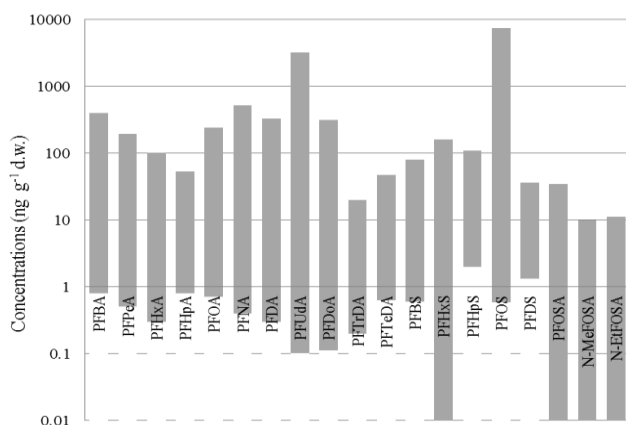
## *Sludge*

- Average [PFOA] : 23.8 ng/g (data 1998-2020)
- Average [PFOS] : 233 ng/g (data 1998-2020)

# Occurrence of PFAS in sewage sludge worldwide

## 2015<sup>1</sup>

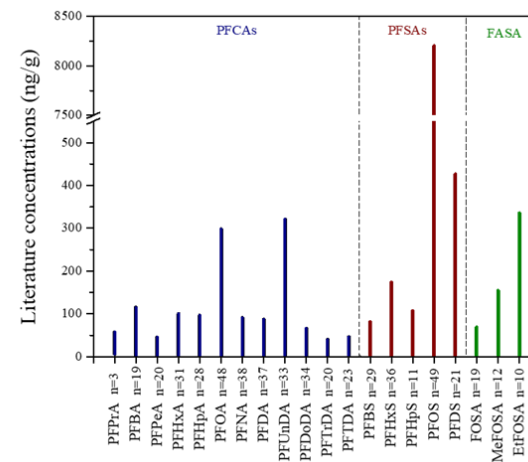
- Number of PFAS detected in sludge: 19
- PFCAs (C4 to C18); PFSA (C4 to C10); perfluoroalkyl sulfonamides, FASA
- [C]: few ng/g to some hundred ng/g
- Most analytical methods focused to 6 to 10 PFAS



<sup>1</sup>Arvaniti & Stasinakis (2015)  
<https://doi.org/10.1016/j.scitotenv.2015.04.023>

## 2024<sup>2</sup>

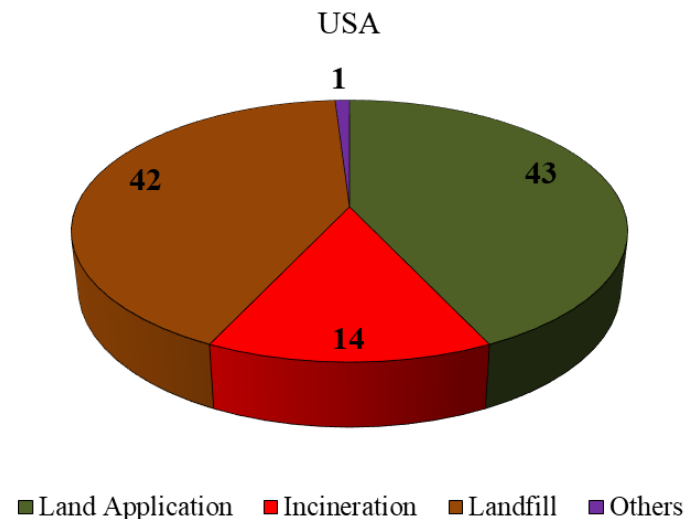
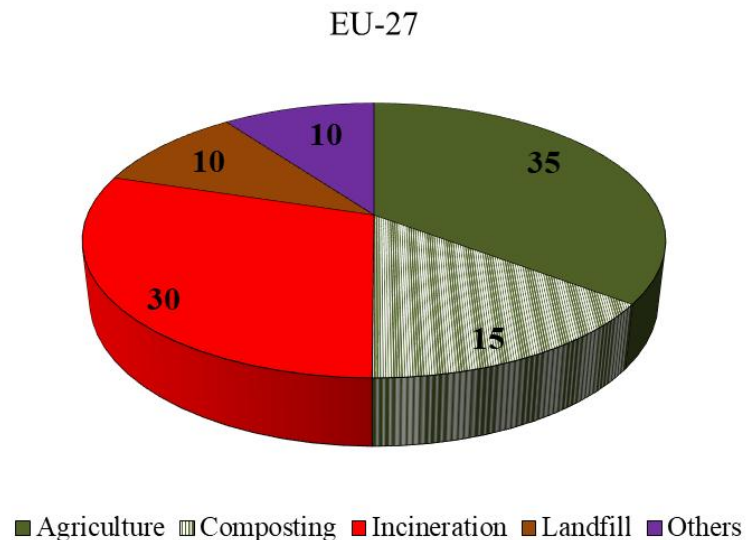
- Number of PFAS detected in sludge: 178
- Ultrashort- (C<4); new generations PFAS (e.g. GenX); PFAS precursors
- PFOS, PFDS, EtFOSA, PFOA at the highest C
- Analytical methods available for >40 PFAS



<sup>2</sup>Arvaniti et al (2024)  
<https://doi.org/10.1186/s12302-024-01031-3>

# Sludge management and threats from PFAS detection

- 8.3 million tonnes per year of sewage sludge (as DS) are produced in EU
- In EU 50% of the produced sludge is disposed to soil (agriculture + composting)
- In US 43% of the produced sludge is disposed to soil
- Important amounts are also disposed to landfills



# Legislation for PFAS in sewage sludge/biosolids

- EU Directive 86/278 for sludge disposal to the soil: PFAS are not included
- National legislations of Nordic countries:
  - Sweden: 0.05 µg/g d.w. for PFOS
  - Norway: 0.1 µg/g d.w for PFOS
  - Denmark: 0.01 µg/g d.w. for sum of 4 PFAS
- EPA (2025) draft risk assessment: 1 ng/g PFOS or PFOA in biosolids could lead to risks to human health
  - 25,385 (!) comments were received up to 14 August 2025 that the platform closed

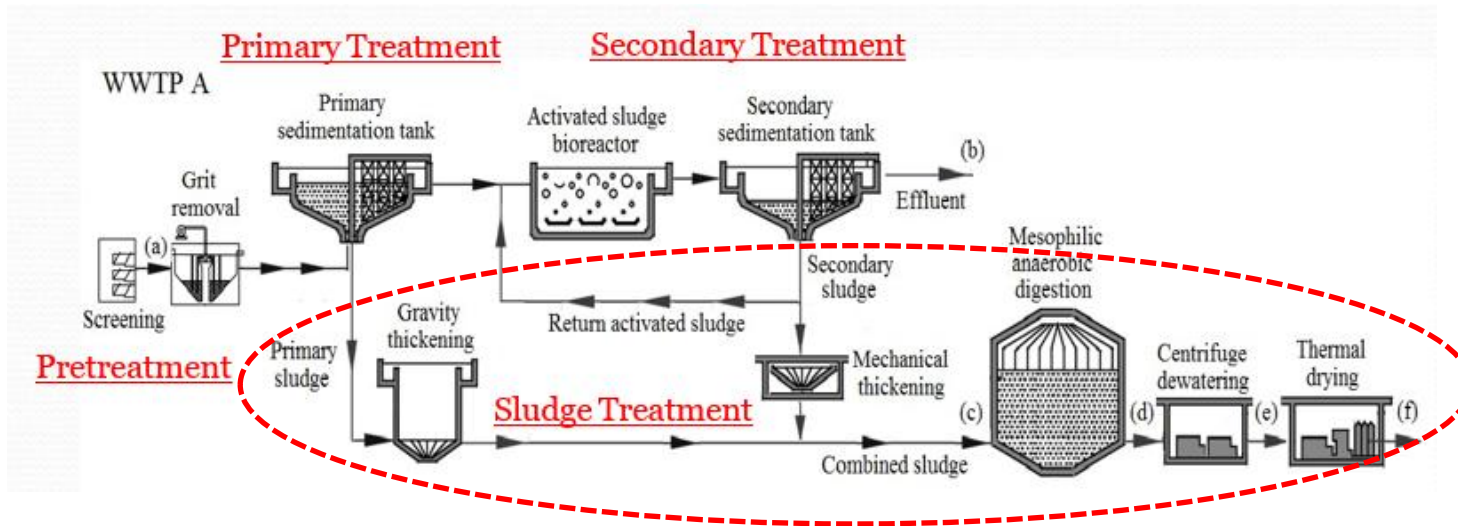
# Occurrence of PFAS in sludge amended soil

- **Few studies** concerning the agricultural land contamination with PFAS due to long-term application of biosolids
- PFOS and PFOA were the predominant compounds
- PFAS levels were correlated to sludge loadings
- Higher concentrations at the upper part of the soil (0-30 cm)
- **Few studies regarding** the uptake of PFAS from sludge-amended soils to plants and on their leaching to groundwater
- Short chain PFAS are more prone to plant uptake (mainly in leaf, fruit) than long chain PFAS (mainly in roots)



# PFAS removal during sewage sludge treatment

**Typical Sewage Sludge Treatment Processes:** Thickening, **Anaerobic Digestion**, Dewatering, Drying



# Fate of PFAS during sludge anaerobic digestion

## Limited information

Monitoring of full-scale anaerobic digesters shows:

- Moderate decrease of  $\Sigma$ PFAS-F (10-38%) in some AD<sup>1</sup>
- No clear trend for the removal of specific PFAS (increase up to 95% for some)<sup>1</sup>
- Increase of PFAS mass after anaerobic digestion, decrease of some precursors<sup>2</sup>



## Problems

- Monitoring of a small number of PFAS
- Presence of precursors
- Collection of grab samples

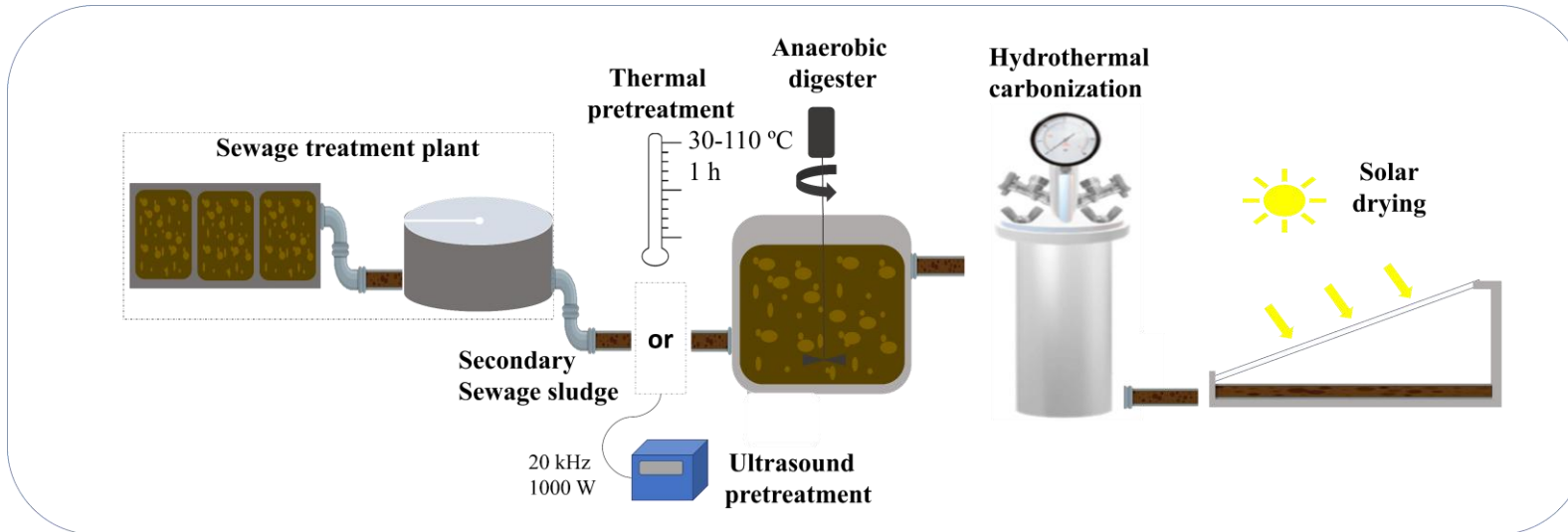


No clear results on the ability of AD to remove (specific) PFAS

<sup>1</sup>Lakshminarasimman et al. (2021)  
<https://doi.org/10.1016/j.scitotenv.2020.142431>

<sup>2</sup>Ozelcaglayan et al. (2024)  
<https://doi.org/10.1021/acsestwater.3c00703>

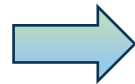
# The idea of ZeroPM: test, modify, combine



**test:** HTC  
**modify:** AD  
**combine:** different technologies

## Lab experiments

Duration: 2 years



## Pilot-scale experiments

Duration: 2 years

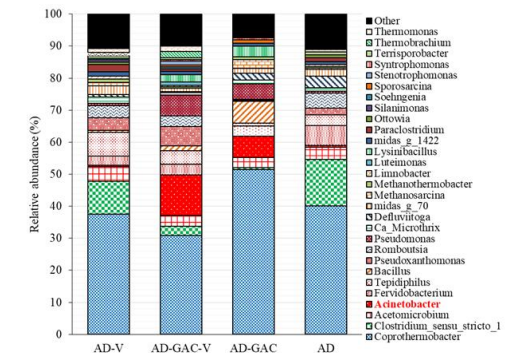
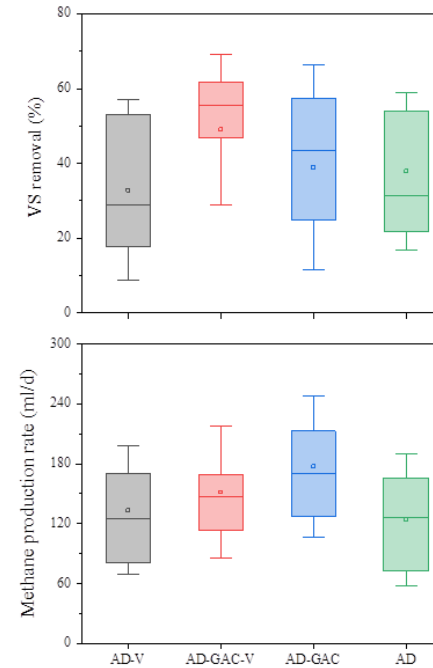
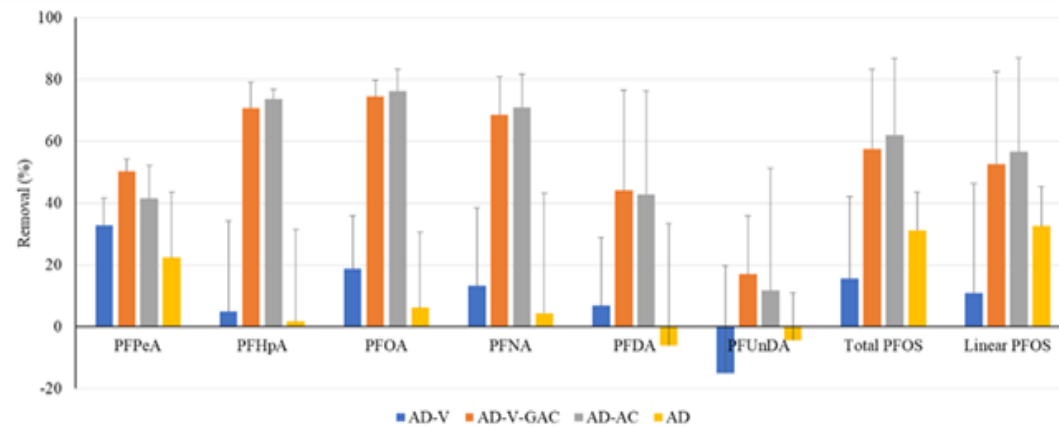
Start-up: 1<sup>st</sup> March 2024



# Lab experiments: modified anaerobic digestion<sup>1,2</sup>

## Addition of GAC

- ✓ Higher methane production
- ✓ Partial removal of PFAS



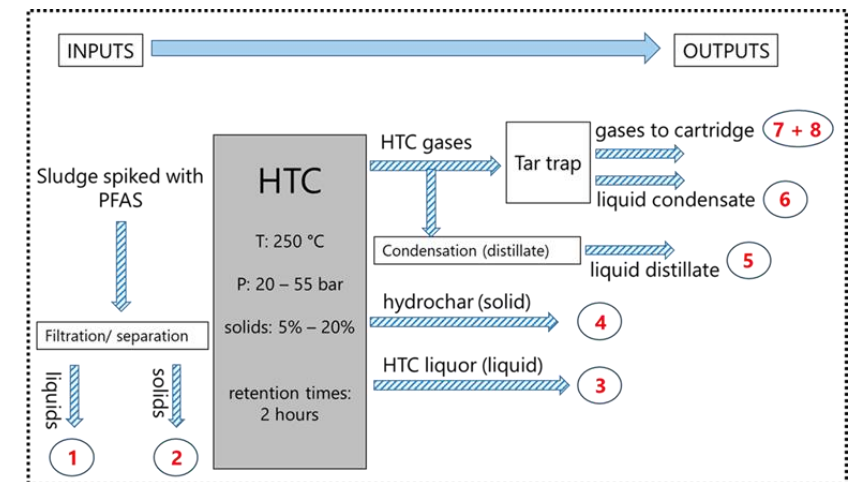
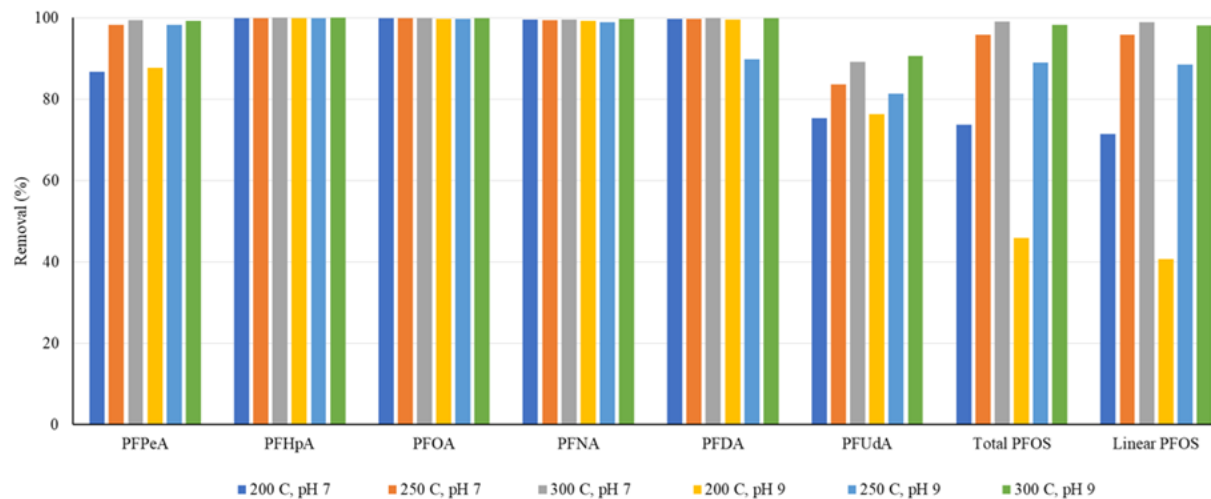
Removal efficiencies based on analysis of dissolved & particulate phase and application of mass balance

<sup>1</sup>Deligiannis et al. (2024) <https://doi.org/10.1016/j.biortech.2024.131013>

<sup>2</sup>Galipidou et al. (2025) <https://doi.org/10.1016/j.jece.2025.117933>

# Lab experiments: hydrothermal carbonization

- With exception of PFOS and PFUdA, high removal (>85%) of PFAS under all tested conditions
- Detection of trace amounts of some PFAS in the gas phase



Removal efficiencies based on analysis of dissolved & particulate phase and application of mass balance

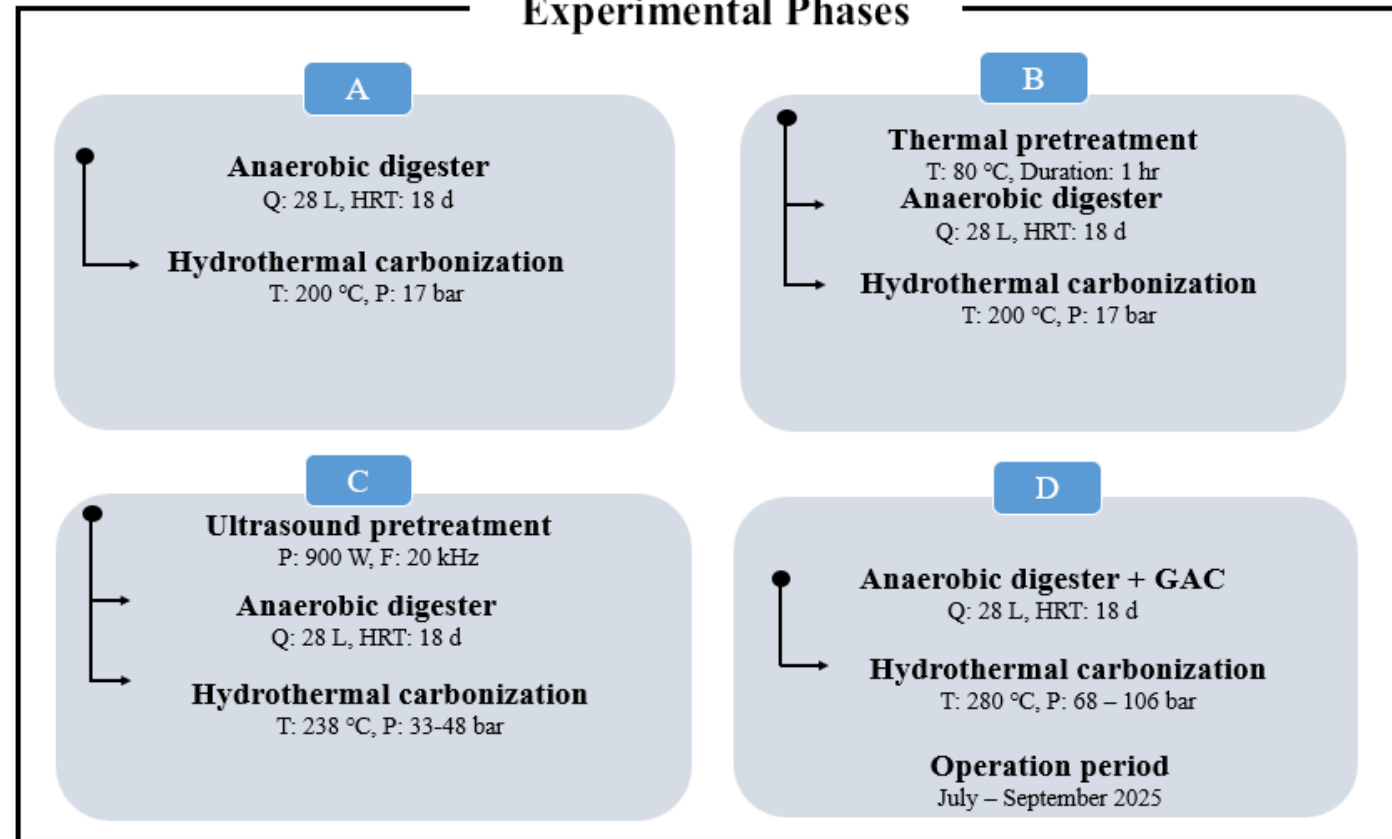
# Pilot-scale experiments: 1st year of monitoring – Phases A, B and C



## Pilot-scale sewage sludge treatment plant

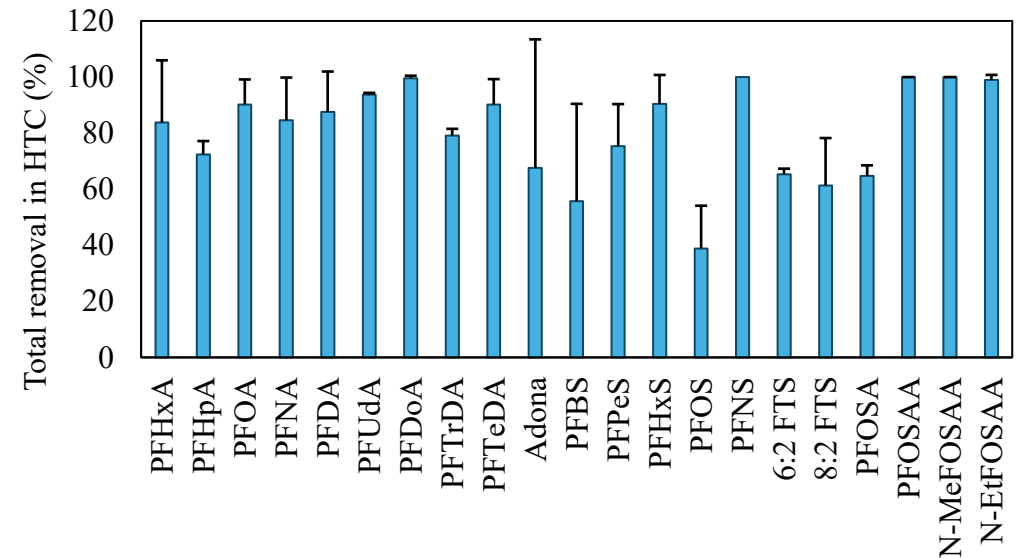
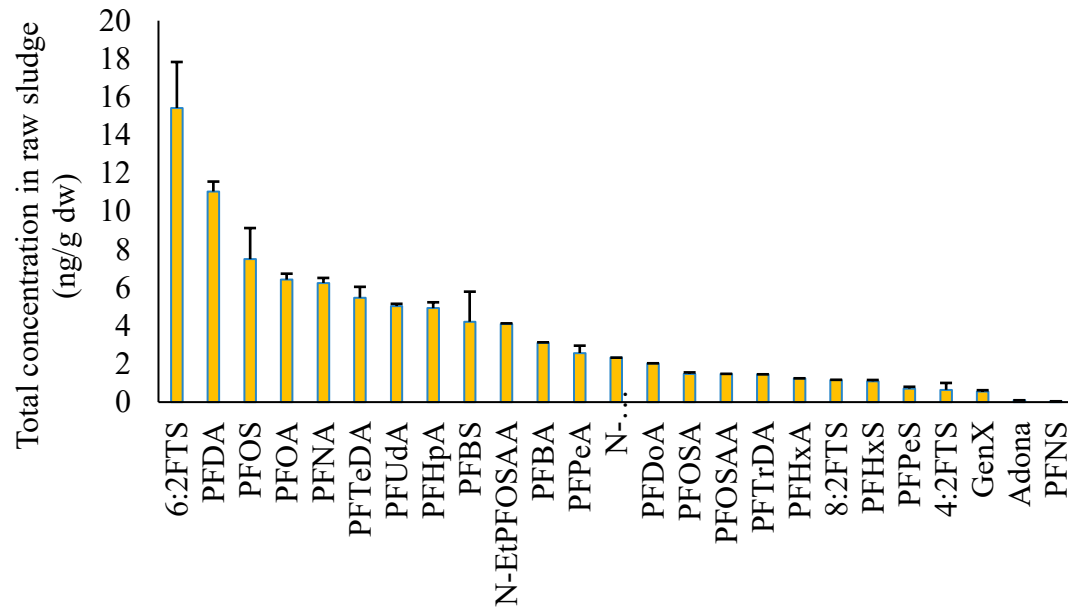


### Experimental Phases



# Pilot-scale experiments: 1st year of monitoring – Phases A, B and C

- 25 out of 27 target PFAS are detected in raw sludge, at concentrations up to 16 ng/g
- No important removal during conventional anaerobic digestion
- Significant removal ranging between 40 and 100% during hydrothermal carbonization



Removal efficiency: based on analysis of dissolved & particulate phase and application of mass balance

# Pilot-scale experiments: 2nd year of monitoring – further steps

- To investigate the role of GAC addition and voltage application in the AD
- To test different experimental conditions on the operation of HTC
- To study the characteristics of hydrochar and its sorption potential
- To examine the characteristics and the treatment of hydrochar liquid



# Thank you for your attention

## **Contact info**

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