ZeroPM pieces #39

Construction and operation of ZeroPM sewage sludge treatment pilot plant

Athanasios Stasinakis

Professor

Department of Environment, University of the Aegean, Greece

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

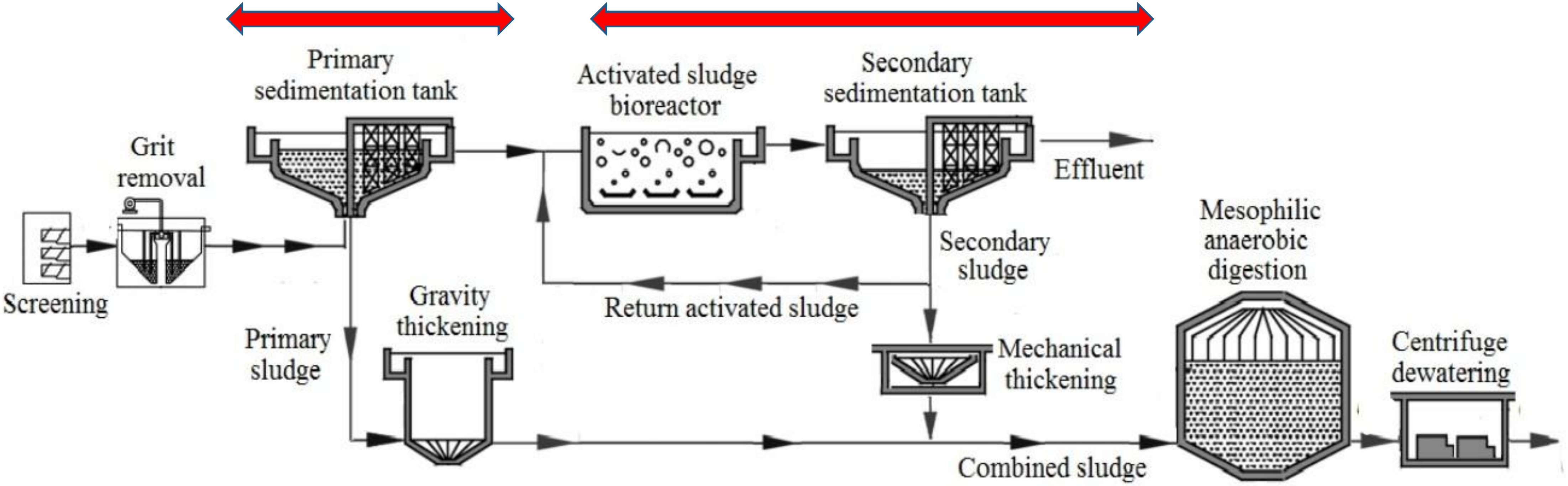
Structure of the presentation

- Information about PFAS occurrence in sewage sludge
- Construction, operation and performance of the pilot-plant
- Treatment of the hydrochar liquid
- Future challenges

Fate of PFAS along wastewater treatment line

- Sorption to TSS
- **Accumulation to primary sludge**

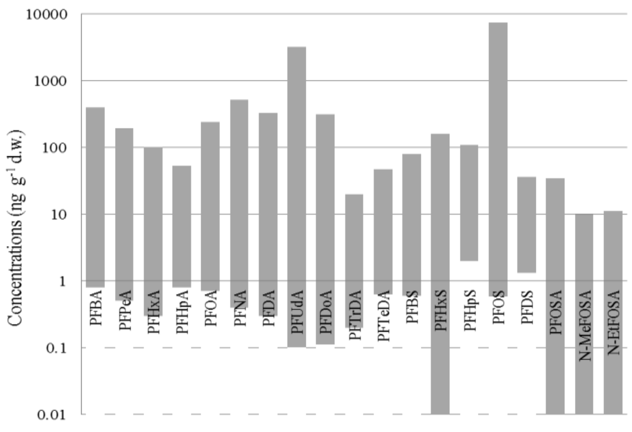
- Biotransformation of some precursors
- Sorption to activated sludge
- **Accumulation to secondary sludge**



Occurrence of PFAS in sewage sludge worldwide

2015[1]

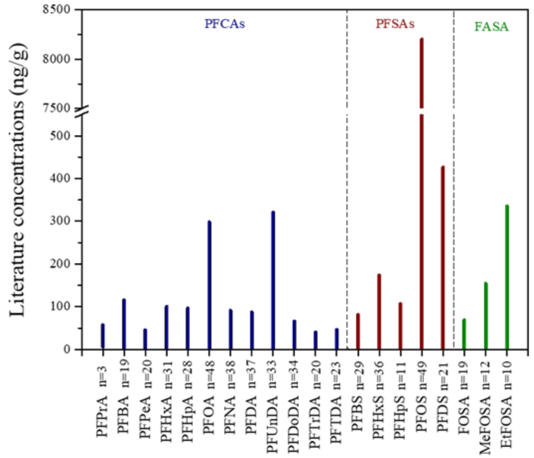
- Number of PFAS detected in sludge: 19
- PFCAs (C4 to C18); PFSAs (C4 to C10); perfluoroalkyl sulfonamides, FASA
- [C]: few ng/g to some hundred ng/g
- Most analytical methods focused to 6 to 10 PFAS



[1]Arvaniti & Stasinakis (2015)
https://doi.org/10.1016/j.scitotenv.2015.04.023

2024[2]

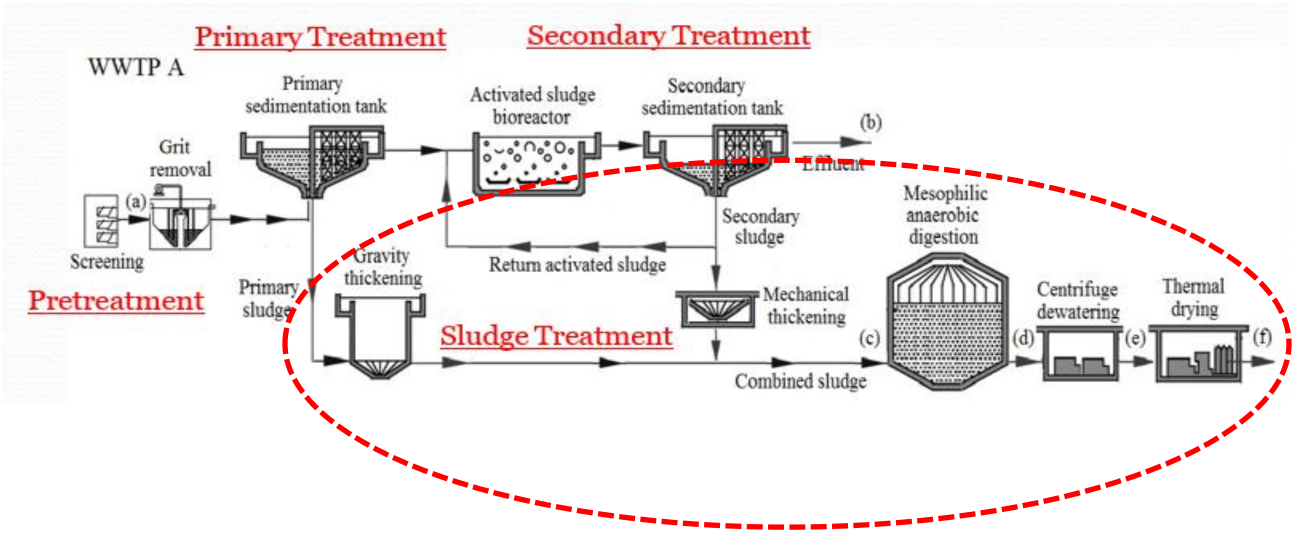
- Number of PFAS detected in sludge: 178
- Ultrashort- (C<4); new generations PFAS (e.g. GenX); PFAS precursors
- PFOS, PFDS, EtFOSA, PFOA at the highest C
- Analytical methods available for >40 PFAS



[2]Arvaniti et al (2024)
https://doi.org/10.1186/s12302-024-01031-3

PFAS removal during sewage sludge treatment

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



Fate of PFAS during conventional sludge treatment:

- Moderate decrease of ΣPFAS-F (10-38%) in some AD[3]
- Increase of specific PFAS up to 95%[3]
- Increase of PFAS mass after AD[4]
- Decrease of some precursors[4]

Fate of PFAS during thermal technologies:

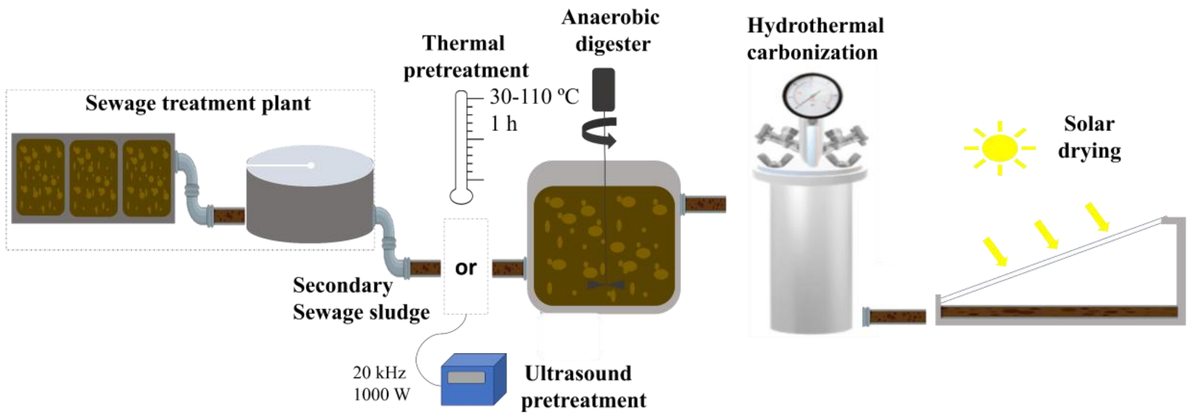
- High removal during incineration and pyrolysis[2]

[2]Arvaniti et al (2024) https://doi.org/10.1186/s12302-024-01031-3

[3]Lakshminarasimman et al. (2021) https://doi.org/10.1016/j.scitotenv.2020.142431

[4]Ozelcaglayan et al. (2024) https://doi.org/10.1021/acsestwater.3c00703

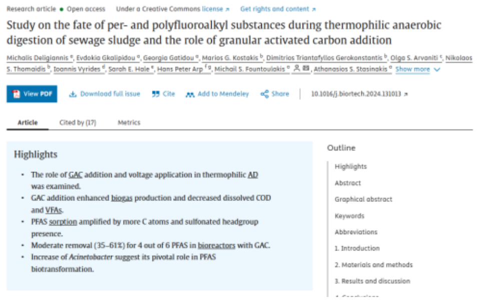
The idea of ZeroPM: test, modify, combine



test: HTC
modify: AD
combine: different technologies

Lab experiments

Duration: 2 years



Research article • Open access Under a Creative Commons license Get rights and content

Study on the fate of per- and polyfluoroalkyl substances during thermophilic anaerobic digestion of sewage sludge and the role of granular activated carbon addition

Michalis Deligiannis a, Evdokia Gkalipidou a, Georgia Gatidou a, Marios G. Kostakis b, Dimitrios Triantafyllos Gerokonstantis b, Olga S. Arvaniti c, Nikolaos S. Thomaidis b, Ioannis Vyrides d, Sarah E. Hale e, Hans Peter Arp f g, Michail S. Fountoulakis a, Athanasios S. Stasinakis a Show more

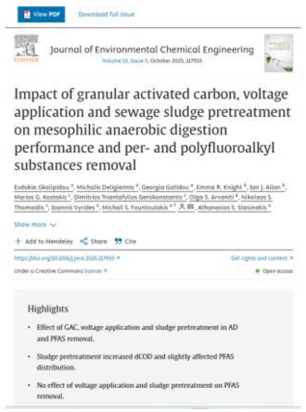
View PDF Download full issue Cite Add to Mendeley Share 10.1016/j.biortech.2024.131013

Article Cited by (17) Metrics

Highlights

- The role of GAC addition and voltage application in thermophilic AD was examined.
- GAC addition enhanced biogas production and decreased dissolved COD and VFAs.
- PFAS sorption amplified by more C atoms and sulfonated headgroup presence.
- Moderate removal (35–61%) for 4 out of 6 PFAS in bioreactors with GAC.
- Increase of *Acinetobacter* suggest its pivotal role in PFAS biotransformation.

Outline: Highlights, Abstract, Graphical abstract, Keywords, Abbreviations, 1. Introduction, 2. Materials and methods, 3. Results and discussion



View PDF Download full issue

Journal of Environmental Chemical Engineering
Volume 13, Issue 5, October 2025, 117933

Impact of granular activated carbon, voltage application and sewage sludge pretreatment on mesophilic anaerobic digestion performance and per- and polyfluoroalkyl substances removal

Evdokia Gkalipidou a, Michalis Deligiannis a, Georgia Gatidou a, Emma R. Knight b, Ian J. Allan b, Marios G. Kostakis c, Dimitrios Triantafyllos Gerokonstantis c, Olga S. Arvaniti d, Nikolaos S. Thomaidis c, Ioannis Vyrides e, Michail S. Fountoulakis a f, Athanasios S. Stasinakis a

Show more

Add to Mendeley Share Cite

https://doi.org/10.1016/j.jece.2025.117933 Get rights and content

Under a Creative Commons license Open access

Highlights

- Effect of GAC, voltage application and sludge pretreatment in AD and PFAS removal.
- Sludge pretreatment increased dCOD and slightly affected PFAS distribution.
- No effect of voltage application and sludge pretreatment on PFAS removal.

Environmental Technology & Innovation
Volume 41, March 2026, 104727

Study on the removal of PFAS during hydrothermal carbonization of sewage sludge

G. Altiparmaki a, G. Gatidou b, Emma Knight c, Ian Allan c, D. Liakos d, A.S. Stasinakis b, S. Vakalis a d

Show more

Add to Mendeley Share Cite

https://doi.org/10.1016/j.eti.2025.104727 Get rights and content

Under a Creative Commons license Open access

Highlights

- HTC of sewage sludge reduced PFAS levels in all product phases.
- C5–C10 PFAS achieved >94% removal via HTC of sewage sludge.
- PFOS showed moderate removal, ranging from 55% to 75%.
- TFA was detected in gases but eliminated after pH adjustment to 9.
- Hydrochar is unsuitable for use as soil amendment.

Pilot-scale experiments

Duration: 2 years

Start–up: 1st March 2024

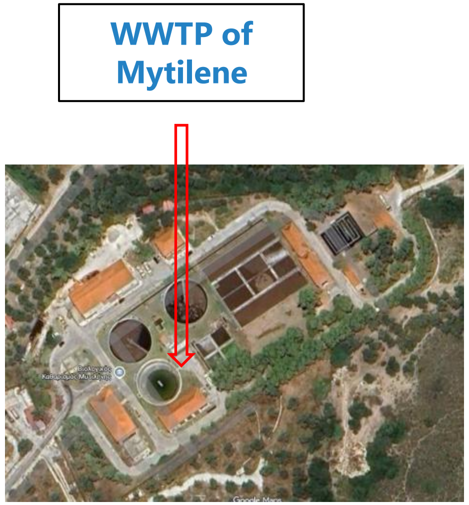
[5] Deligiannis et al. (2024) 10.1016/j.biortech.2024.131013

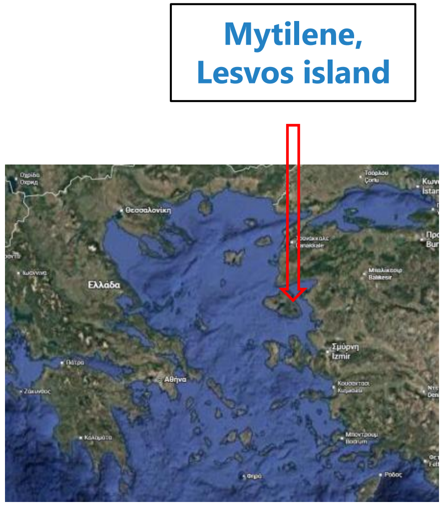
[6] Gkalipidou et al. (2025) https://doi.org/10.1016/j.jece.2025.117933

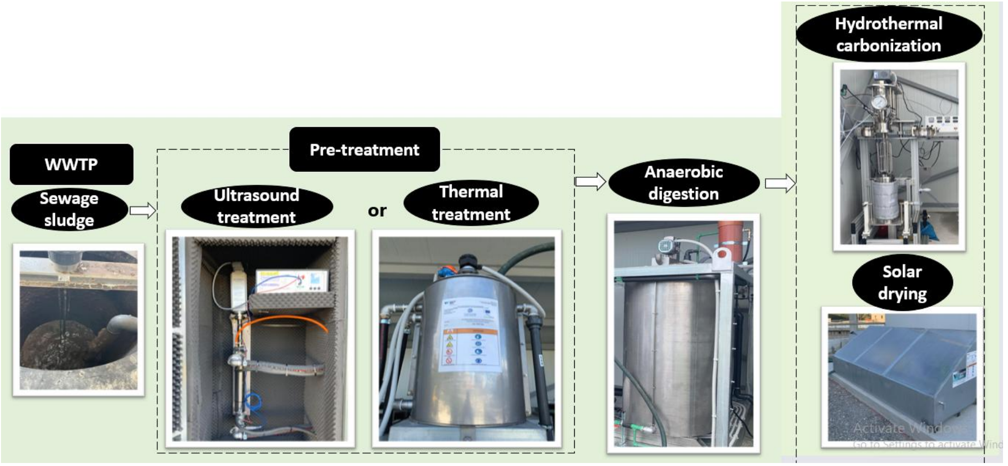
[7] Altiparmaki et al. (2026) https://doi.org/10.1016/j.eti.2025.104727

The pilot-system

- **Installation**: WWTP of Mytilene (Lesvos Island, Greece)
- **Thermal pretreatment reactor**: 30 L (stainless steel)
- **Ultrasound sonicator**: maximum output power 1,000 W, operating frequency 20 kHz (Hielscher UIP1000hdT ultrasound sonicator)
- **Anaerobic digester**: 500 L (stainless-steel, externally insulated, continuously stirred tank reactor, heated by a boiler, equipped with an agitator)
- **Hydrothermal carbonization reactor**: 8 L (Parr 4550, equipped with a controller to control P and motor speed)
- **SCADA system**: remote control of key process parameters, alarm management, historical data logging
- **Three-phase energy meter**: monitor energy consumption







Experimental methodology

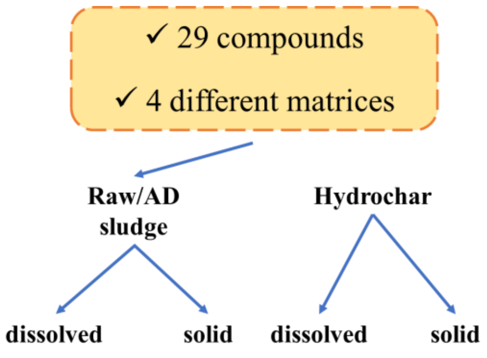
- **Start-up of the AD:** anaerobic sludge from a UASB reactor
- **Feeding**: secondary sewage sludge (Q_{in}: 28 L/d)
- **Operational conditions of the AD**: mesophilic range (37 °C) and hydraulic retention time of 18 d

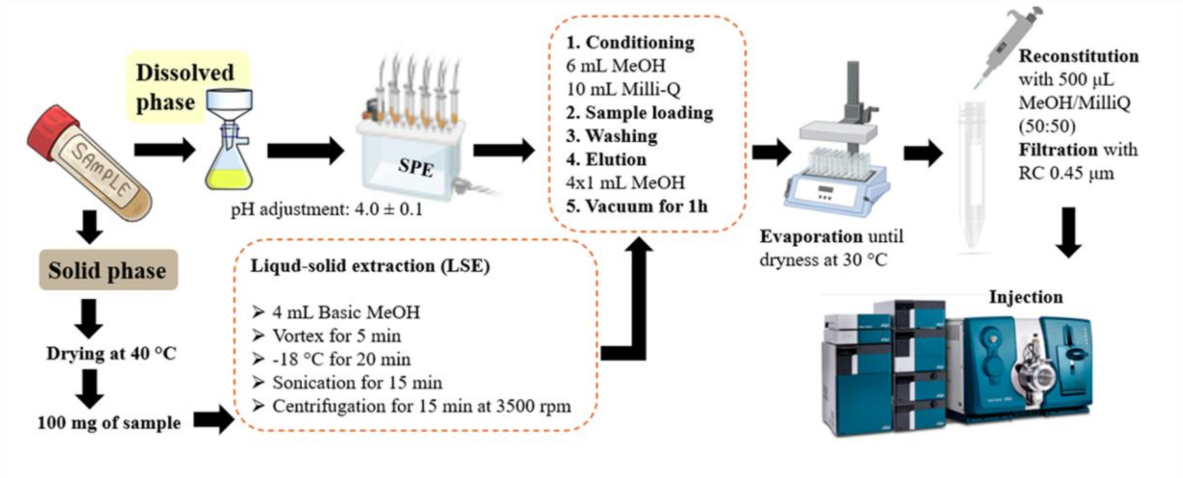
- **Acclimatization Phase**: 50 d
- **Experimental Phase A**: AD+ HCT (200 °C, 17 bar, 2 h)
- **Experimental Phase B**: Thermal Pretreatment (80 °C, 1 h) + AD+ HCT (200 °C,17 bar, 2 h)
- **Experimental Phase C**: US Pretreatment (20 kHz, 900 Watt, 15 min) + AD+ HCT (250 °C,36 bar, 2 h)
- **Experimental Phase D**: AD (GAC addition: 10 g/L)
- **Experimental Phase E**: AD (GAC addition: 10 g/L +electric potential: 2 V)

Monitoring and chemical analyses

Parameters monitored

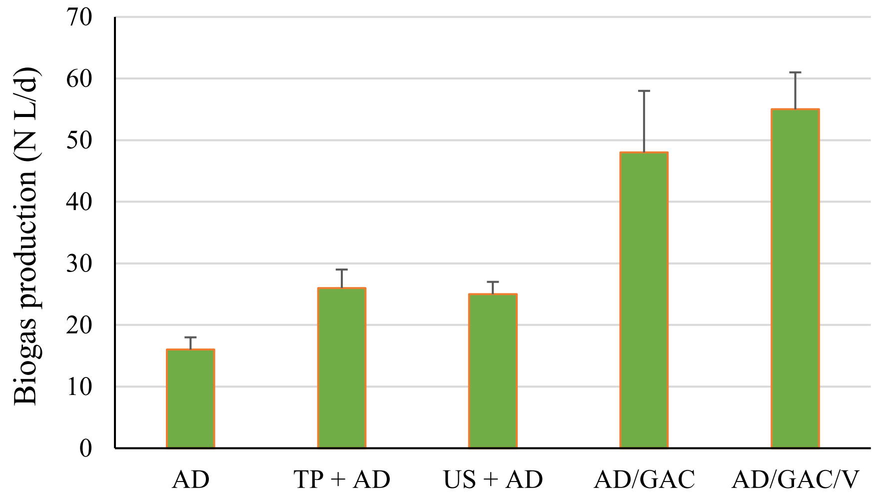
- TS, VS, $_{total}$COD, $_{soluble}$COD, BOD_5, NH_4-N, PO_4-P, VFAs, alkalinity, pH, conductivity, temperature: twice a week, influent/effluent of each reactor
- Biogas production (L/d), biogas composition: twice a week, AD
- Biomass characterization: end of each Phase, AD
- PFAS: consecutive days at the end of each Phase, influent/effluent of each reactor, dissolved & particulate phase

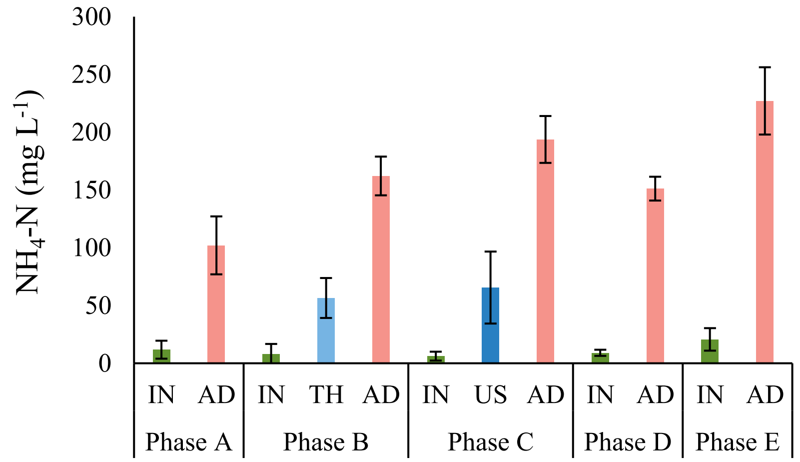




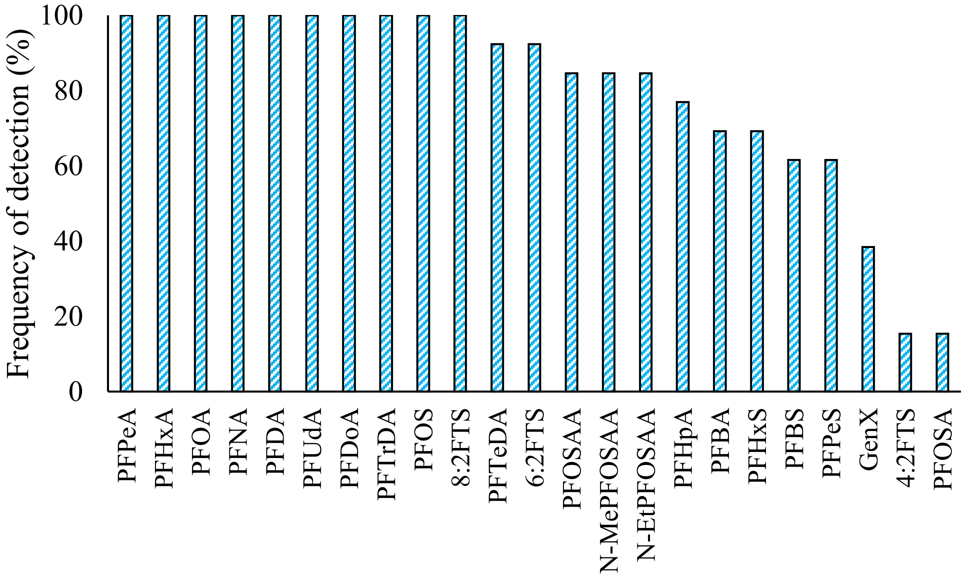
Results – performance of the pilot system

- Increased biogas production in the anaerobic digester after sludge pretreatment (enhanced hydrolysis), GAC addition (promoted direct interspecies electron transfer, DIET) and voltage application (DIET, accelerated hydrolysis and acidogenesis)
- Increased NH_4-N concentrations after AD (conversion of organic N through ammonification) and HTC (enhanced release of organic N into the aqueous phase)
- Characteristics of HTC liquid: pH 6.5-6.8, high $_{sol}$COD (6000 to 10500 mg/L) and NH_4-N concentrations (200 to 350 mg/L), detection of some PFAS (up to10.5 ng/L)

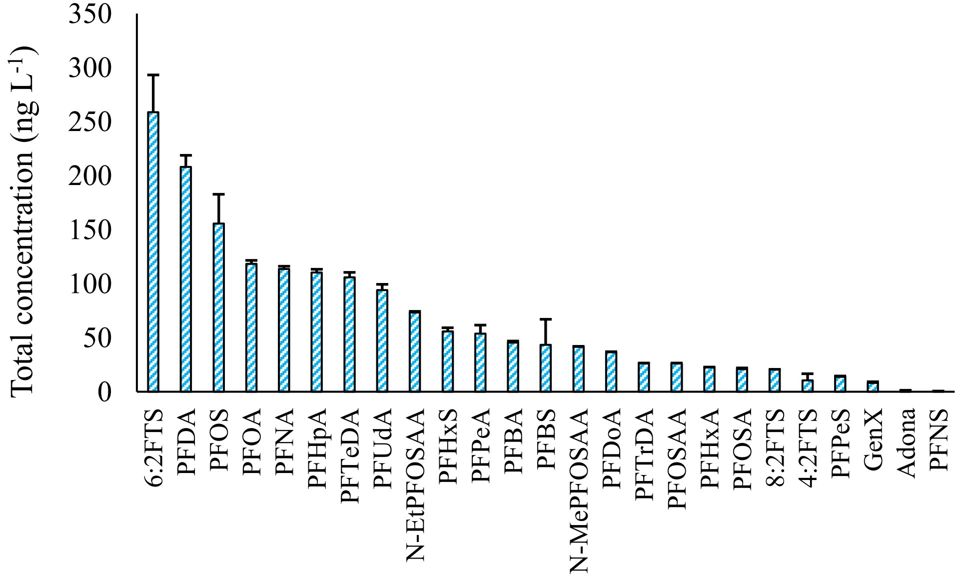


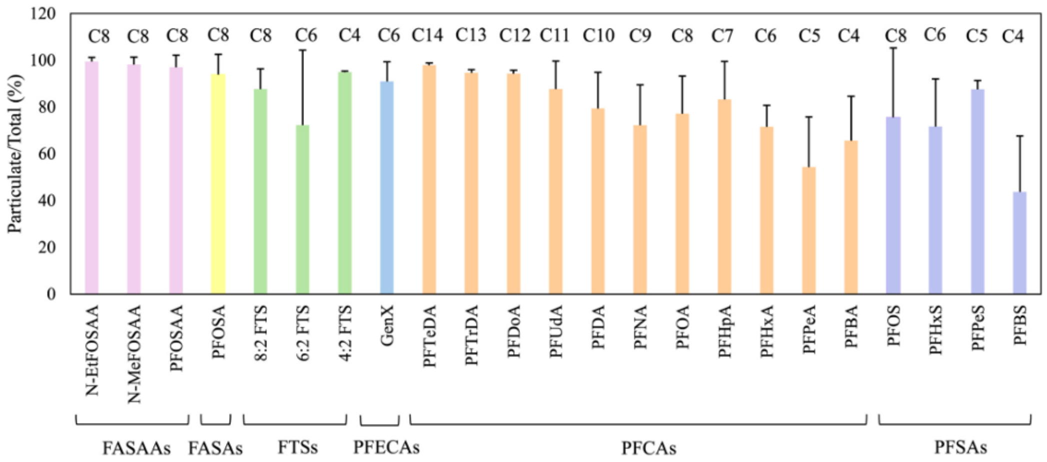


Results – PFAS detection (raw sludge, Phases A to C)[7]



- 25 out of 27 monitored PFAS were detected
- 6 compounds with total [C] > 100 ng/L
- The highest total concentrations were found for 6:2FTS (258.8 ng L^{-1}), PFDA (208.1 ng L^{-1}), and PFOS (155.8 ng L^{-1})
- Most of the target compounds were found in the particulate phase





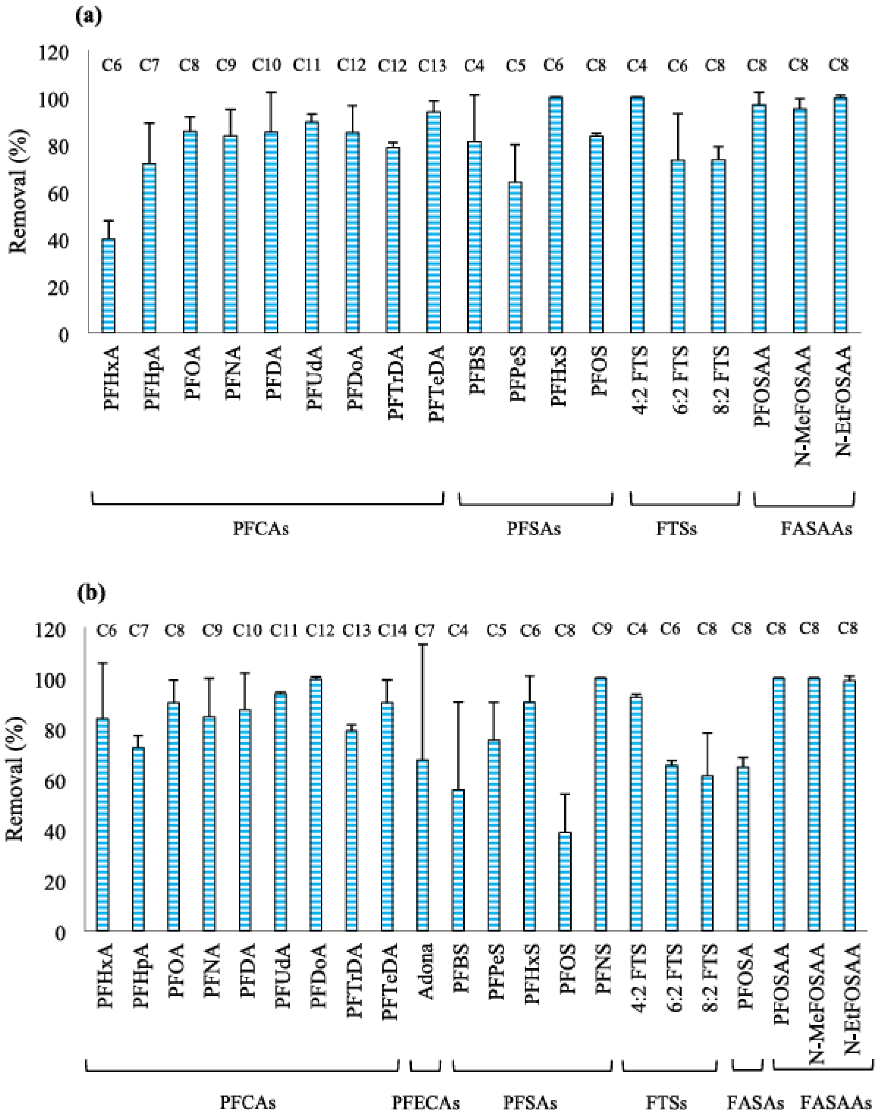
[7]Gkalipidou et al (2026)
10.1016/j.cej.2026.174358

Results - PFAS fate during pretreatment and AD

- No removal of PFAS after the application of thermal or US pretreatment. Changes in the distribution of some compounds (↑ increase of the dissolved fraction)
- Calculation of PFAS mass at the influents and effluents of the anaerobic digester showed no PFAS removal during conventional AD.
- The addition of GAC and the application of voltage in the bioreactor resulted to partial removal of some PFAS.

ZeroPM

Results – PFAS removal during HTC

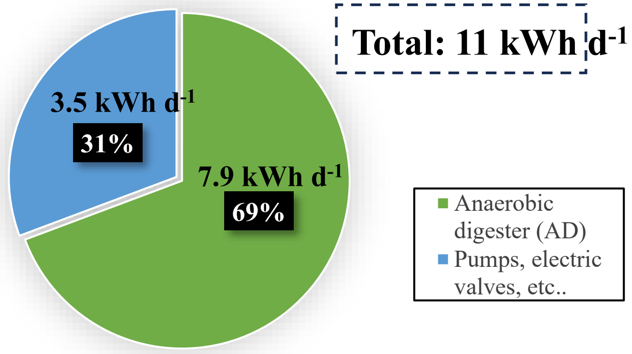


- The operation of the HTC reactor (250 °C, 36 bar 2 h) achieved substantial overall PFAS removal
- 13 compounds removed by >80%.
- The highest removal for perfluoroalkyl sulfonamides (>95%)
- The removal of perfluoroalkyl carboxylic acids and perfluoroalkyl sulfonic acids ranged from 40% to 100%

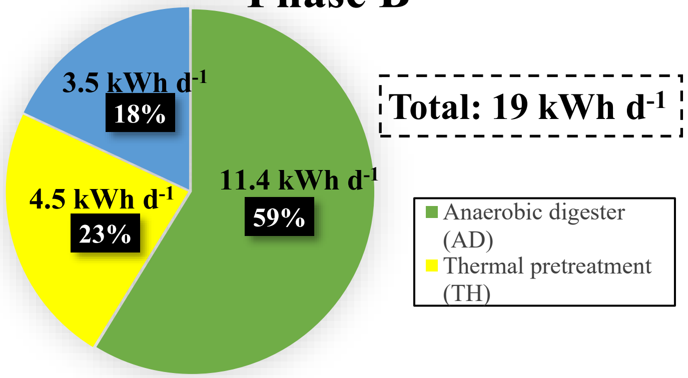
[3]Gkalipidou et al (2026)
10.1016/j.cej.2026.174358

Energy consumption

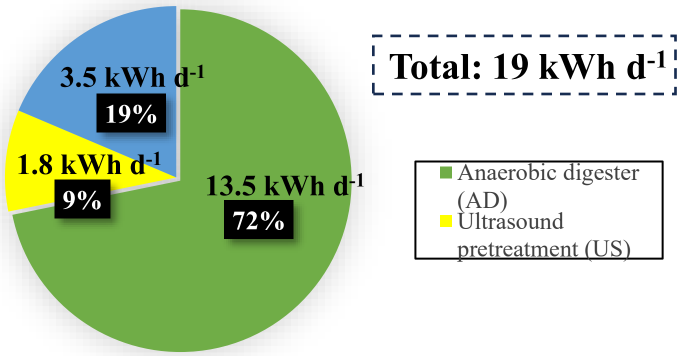
Phase A



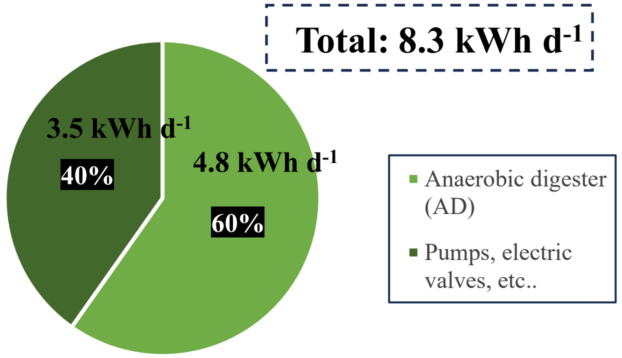
Phase B



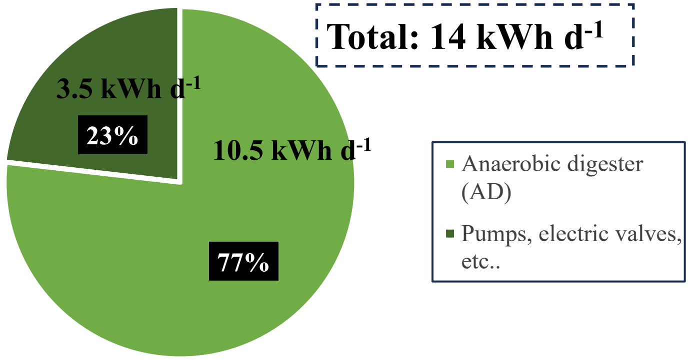
Phase C



Phase D



Phase E



- The energy consumption of the system (excluding HTC) ranged between 8.3 and 19 KWh/d, depending on the ambient T temperature and the pretreatment process
  - Thermal pretreatment: 161 kWh/m^3
  - Ultrasound pretreatment: 64 kWh/m^3
  - AD reactor: 186 – 482 kWh/m^3
  - HTC reactor: 125 kWh/m^3

Lab-scale experiments for HTC liquid treatment

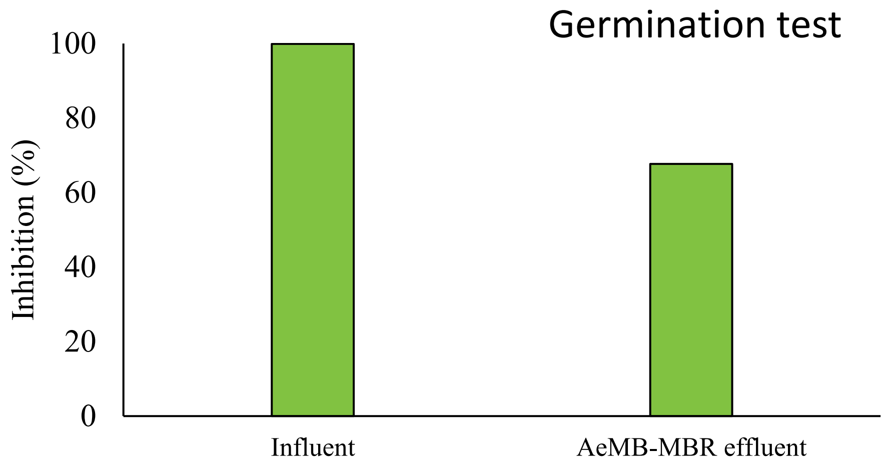
- **Lab-scale Aerobic Moving Bed-Membrane Bioreactor (AeMB-MBR):** 7 L, 40% v/v biocarriers, HRT: 24 h, SRT: 20 d

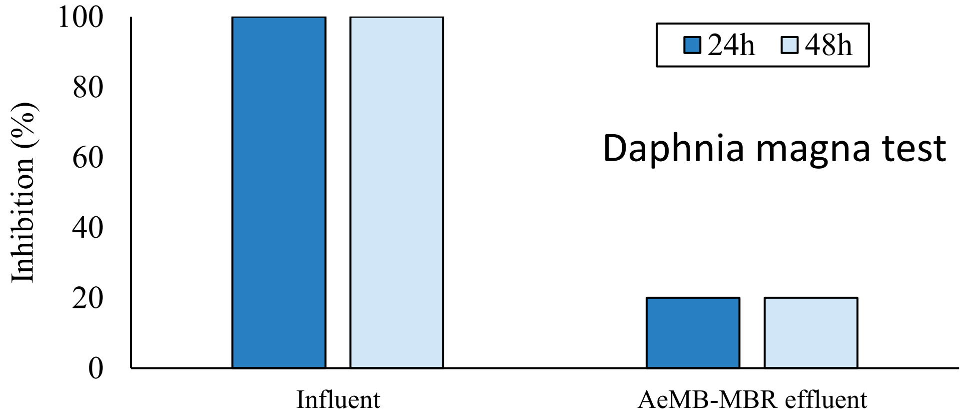
- **Experimental Phase A**: 10% HTC liquid in wastewater
- **Experimental Phase B**: 20% Supernatant struvite from HTC liquid in wastewater
- **Experimental Phase C**: 20% Supernatant struvite from HTC liquid in wastewater + 2 g/L PAC

- Nanofiltration as tertiary treatment
- Removal of major pollutants, PFAS, ecotoxicity and phytotoxicity experiments

Lab-scale experiments for HTCL treatment

- No significant removal of PFBS was observed during biological treatment.
- The increase in suspended solids concentration in the bioreactor and the addition of PAC resulted in significant removal of the other detected PFAS.
- The addition of PAC in the bioreactor resulted also to the decrease of the ecotoxicity of the final effluent.





Summary and work for the future

- The coupling of pretreatment processes with AD or GAC addition/voltage application in anaerobic digester enhances biogas production
- The operation of this pilot system indicates that substantial PFAS reduction is possible with a treatment train of AD and HTC
- The hydrochar liquid is heavily contaminated and required further treatment

Q1: Amount of PFAS released through HTC gases

Q2: Fate of PFAS during hydrochar disposal to the soil

Thank you for your attention

Contact info

Athanasios (Nasos) Stasinakis

Department of Environment, University of the Aegean

Email: astas@env.aegean.gr