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Release of per- and polyfluoroalkyl substances (PFAS) from soil to groundwater

Importance of PFAS family and substance

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PFAS – Management of Envrionmental & Health Risks – June, 20, 2025 – Paris

Content

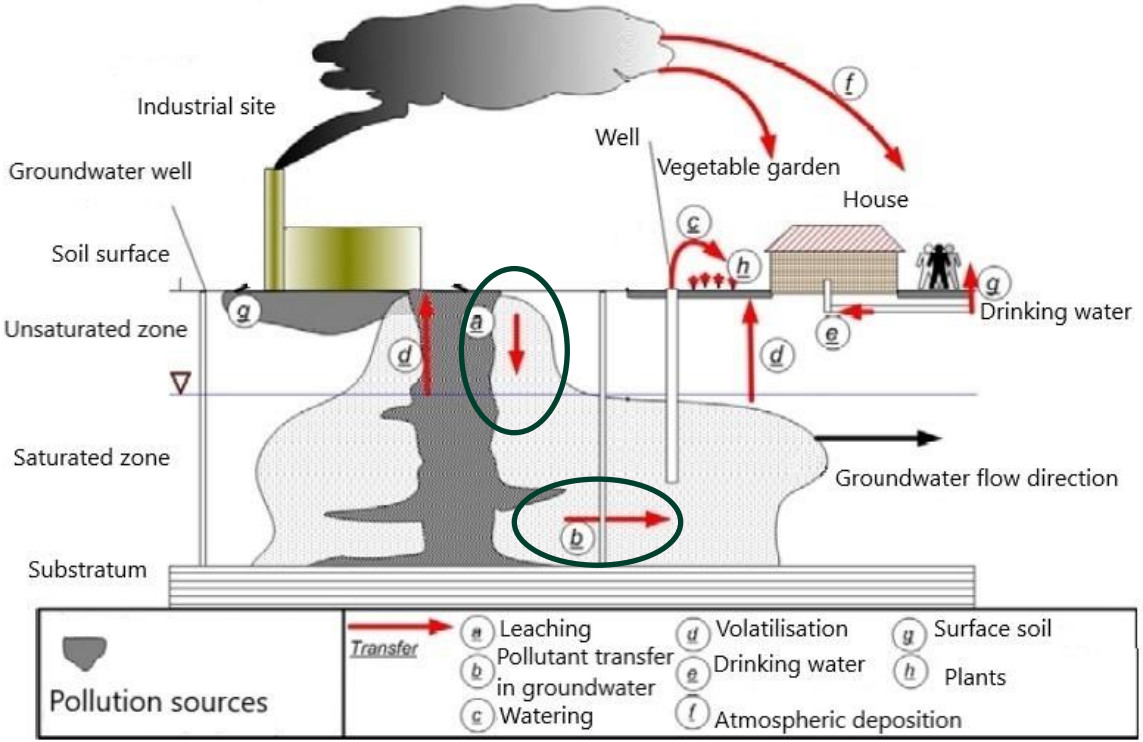
PFAS in soils and groundwater - Context

- PFAS main sources
- Typical concentrations
- Behaviour in soils and groundwater
  - What is known
  - Research needs

PFAS release from 3 polluted soils

- Soil pollution
- Experiments at the laboratory scale
- Results and discussion

Perspectives



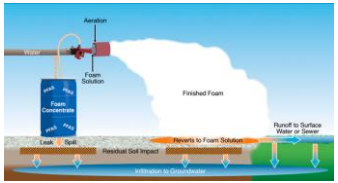
1. PFAS in soils and groundwater - Context

PFAS in soils and groundwater

Main PFAS pollution sources for soils and groundwater

- ✓ PFAS manufacturing sites

- ✓ Use of AFFF



- ✓ Landfill

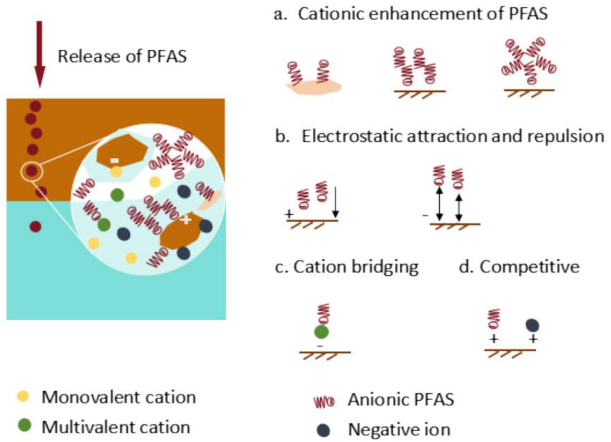
- ✓ Contaminated sludge

Typical concentrations

- ✓ **Soils**: hundreds of mg/kg (polluted sites), up to hundreds of µg/kg (distant sites),
- ✓ **Groundwater**: mg/L (polluted sites), up to tens of µg/L (downstream)

Behaviour in soils: what is known

- ✓ Sorption positively correlated to the carbon chain length
- ✓ Sorption negatively correlated to pH
- ✓ **Not only a partitioning between** SOM/DOM
- ✓ **Several mechanisms** : electrostatic interactions, ion and ligand exchanges, hydrophobic interactions, surface complexation, hydrogen bonds
- ✓ Influence of **soil organic matter** and **mineral components**
  - ➢ Al, Fe oxydes/hydroxydes
- ✓ Influence of protein content, CEC, pH, ionic strength, etc…



Lan *et al.*, 2025 (Journal of Hydrology)

PFAS in soils and groundwater

Behaviour in soils: what are the scientific challenges/research needs?

PFAS release from soil pollution sources

- ✓ Need for kinetics
- ✓ Assessment of PFAS type released / type of pollution sources

PFAS family

- ✓ Little / no data on PFOS/PFOA substituent behaviour: need for data on shorter chain PFAS and fluorotelomers (FTS, FTOH)

PFAS retention in soils

- ✓ No consensus on the influence of key soil properties
- ✓ Relative contribution of soil components not well understood
- ✓ Aging?

PFAS sorption at air/water interfaces

- ✓ Soil water content influence?

Tackling these scientific challenges

First step in

- ✓ Human exposure & health risk assessment
- ✓ Remediation

2. PFAS release from soil pollution sources

- **Aim of the study**
  - ✓ Evaluate PFAS distribution in soils vs in leachates
  - ✓ Obtain kinetics for different PFAS (incl. FTS) / different pollution sources
  - ✓ Assess mechanisms and soil properties governing their behaviour

PFAS release from soil pollution sources

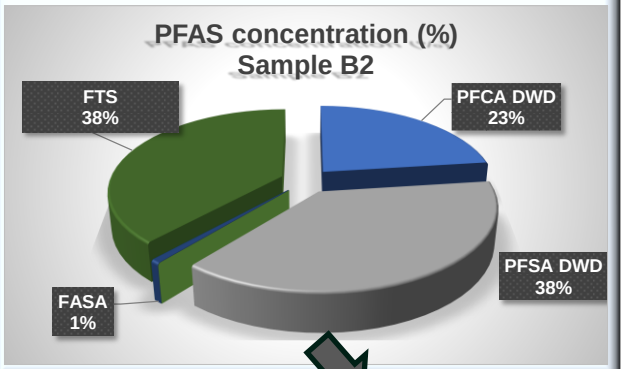
- Material: 3 soils

Fire fighting area – Chemical industry

OM = 0.2% / Clay: 12% / Silt: 35% / Sand: 53%

58 PFAS analyzed

15 PFAS quantified = 80 µg/kg

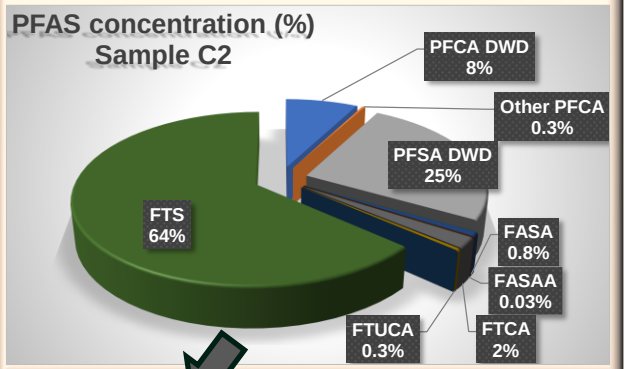


Fire training area – Fire-fighter

OM = 1.7% / Clay: 8% / Silt: 15% / Sand: 77%

58 PFAS analyzed

30 PFAS quantified = 390 µg/kg

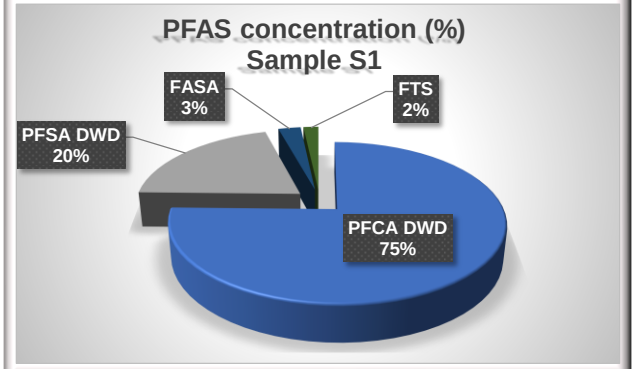


Textile factory

OM = 4% / Clay: 5% / Silt: 11% / Sand: 84%

22 PFAS analyzed

15 PFAS quantified = 140 µg/kg



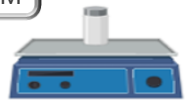
Analysis of 20 PFAS from DWD: inaccurate description of the pollution
Health risk assessment?

PFAS release from soil pollution sources

Method: batch experiments

PFAS polluted soil (4g)
20 mL solution: $CaCl_2$ 0.5 mM

2 conditions for soil C2
Condition 1: with NaN_3 0.2 g/L
Condition 2: without NaN_3 0.2 g/L



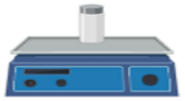
Shaking
275 rpm

1h, 6h, 16h,
24h, 72h (3d),
120h (5d),
168h (7d)

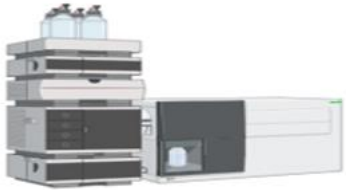
Centrifugation
3 000 G, 30 min

Mixture 50/50 (v/v):
10 mL supernatant
10 mL MeOH
200 µL internal standards

Shaking
15 min



Centrifugation
20 000 G
20 min



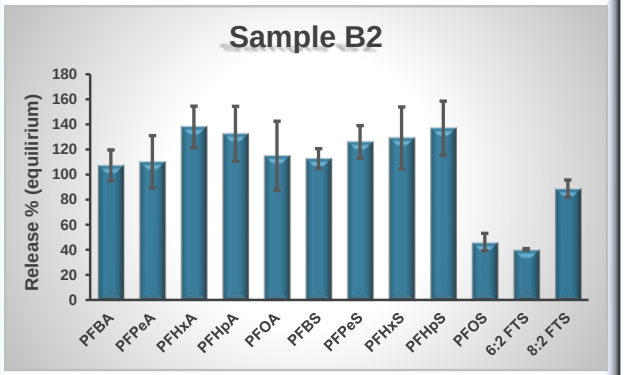
Analysis (LC-MS/MS)

PFAS analysis: 30 PFAS

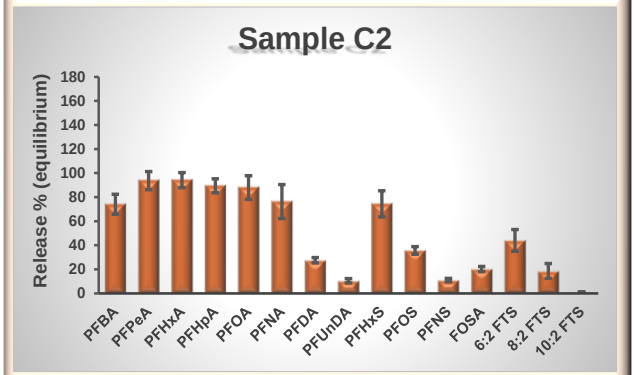
- ✓ **20 PFAS** from the DWD (10 PFCA + 10 PFSA)
- ✓ **Other PFCA**: PFTeDA, PFODA
- ✓ **4 FTS** (4:2 FTS, 6:2 FTS, 8:2 FTS and 10:2 FTS)
- ✓ **PFOA substituent**: ADONA, GenX
- ✓ **1 FASA**: FOSA
- ✓ **1 Cl-PFESA**: 9Cl-PF3ONS

PFAS release from soil pollution sources

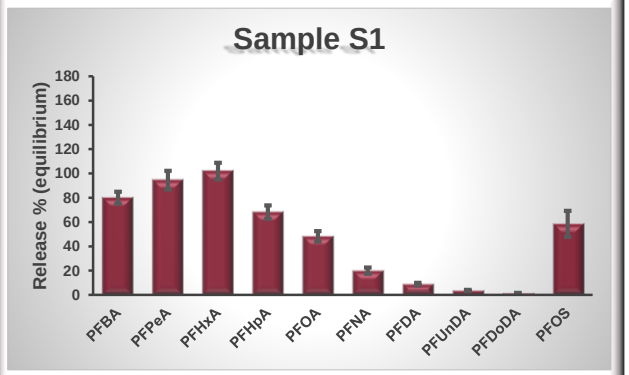
- **Results: PFAS release at equilibrium (24h - with NaN_3 0,2 g/L)**



- ✓ **12 PFAS released** / 15 PFAS in the soil
- ✓ **PFCA** + **PFSA** : high release (**similar**), except for PFOS
- ✓ Release % > 100: analytical uncertainty



- ✓ **15 PFAS released** / 30 PFAS in the soil
- ✓ **PFCA C4-C9: high release** (similar: 75-95%)
- ✓ **PFCA C10-C11: lower release** (10-30%), decrease when C increases
- ✓ **PFCA** release **> PFSA** release



- ✓ **10 PFAS released** / 15 PFAS in the soil
- ✓ **PFCA C4-C6: high release** (similar: 80-100%)
- ✓ **PFCA C7-C12: lower release** (2-70%), decrease when C increases
- ✓ **PFCA** release **= PFSA** release (PFOA/PFOS)

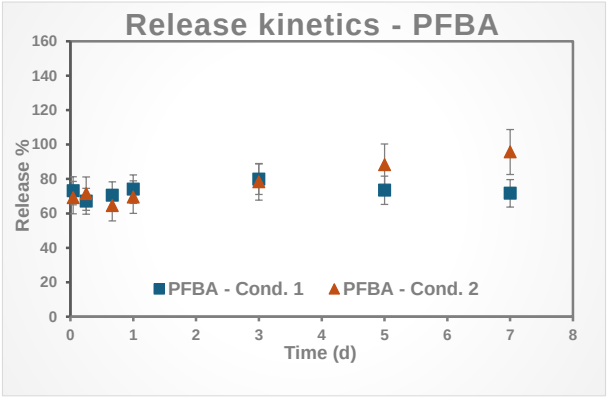
High PFAS release for the 3 soils
➡ **High mobility of PFAS in soils**
➡ **High potential to form large pollution plumes**

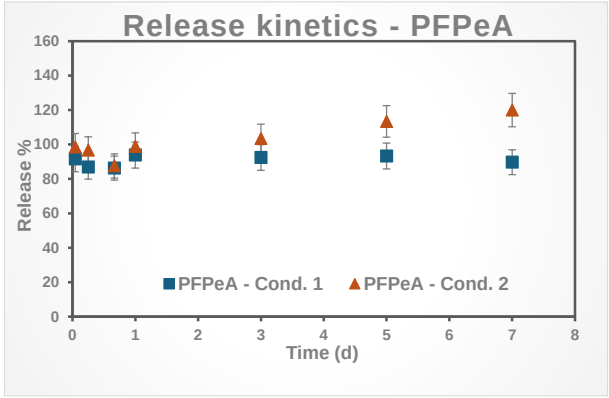
Different release pattern (PFAS, %) / different soil properties
➡ Next step: statistical tests (under processing)
➡ Soil properties influencing PFAS release

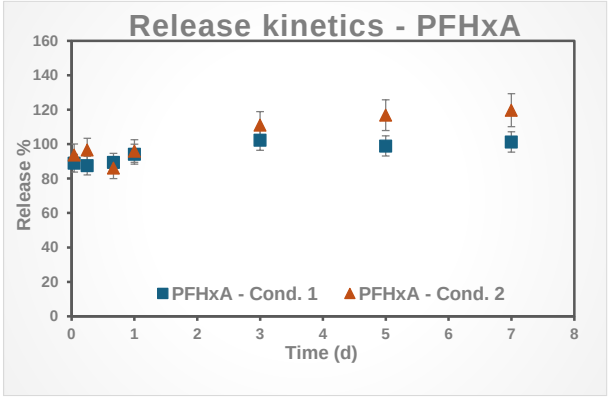
PFAS release from soil pollution sources

Results: effect of bacterial inhibitor – Soil C2

Short chain PFCA (PFBA, PFPeA, PFHxA, PFHpA)







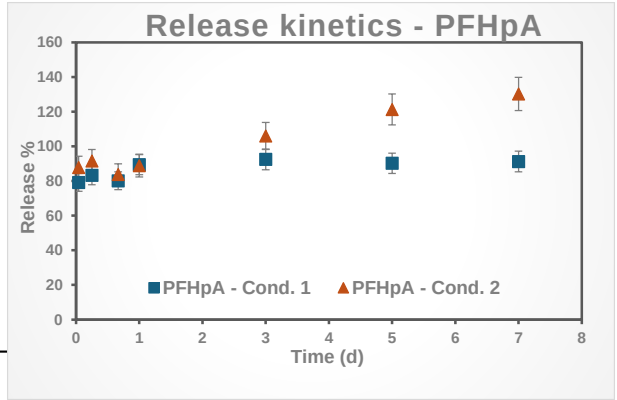
With NaN_3

- **Constant release** over time
- **Equilibrium** reached quickly: **1h**

Without NaN_3

- **Release** rates **increased** over time
- **Release** rates significantly **higher than with NaN_3** (5 – 7 d), more pronounced for PFHpA
- **Release** rates **> 100%**

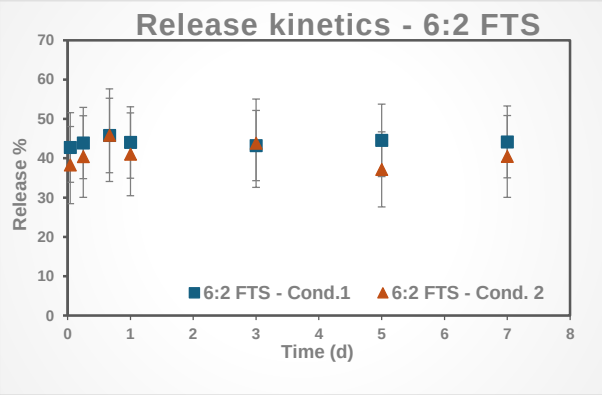
➡ **Bio transformation of precursors (FTS)?**

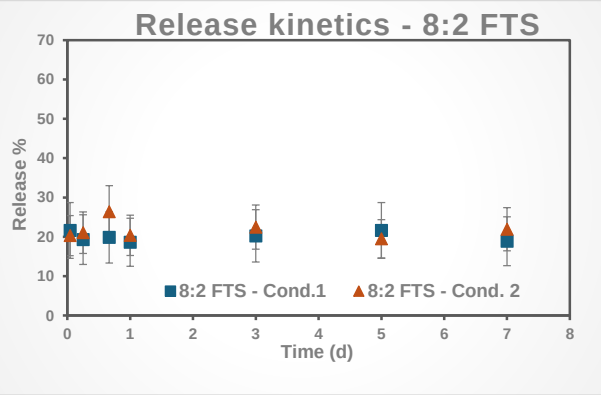


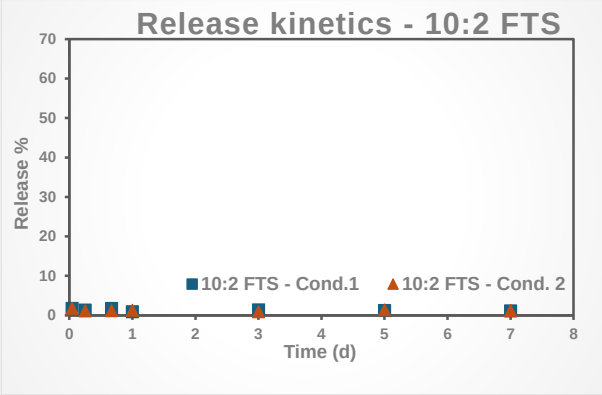
PFAS release from soil pollution sources

Results: effect of bacterial inhibitor – Soil C2

❖ FTS







With or without NaN_3

- **Constant release** over time
- **Equilibrium** reached quickly: **1h**
- **No differences**

Without NaN_3

- **No decrease in FTS** release over time as expected
- But high concentration in soil
  - ➡ Release from the soil when concentration in solution decreased (fast kinetics)
  - ➡ Equilibrium maintained

Next step: release experiment on the soil already submitted to leaching

- ➡ Release of PFPeA, PFHxA, PFHpA (40%), lower release of FTS
- ➡ FTS degradation during the experiment without NaN_3
- ➡ "Fresh" results to be refined

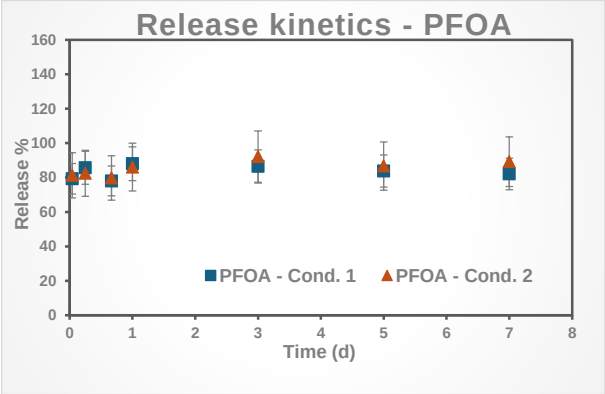
Next step

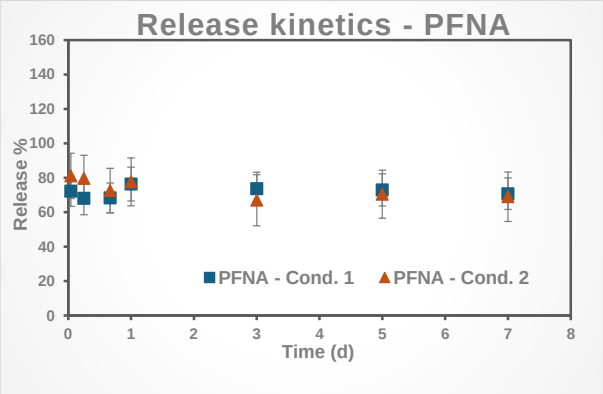
- ➡ FTS degradation evaluation in these conditions (under processing)

PFAS release from soil pollution sources

- Results: effect of bacterial inhibitor – Soil C2

❖ Long chain PFCA (PFOA, PFNA)





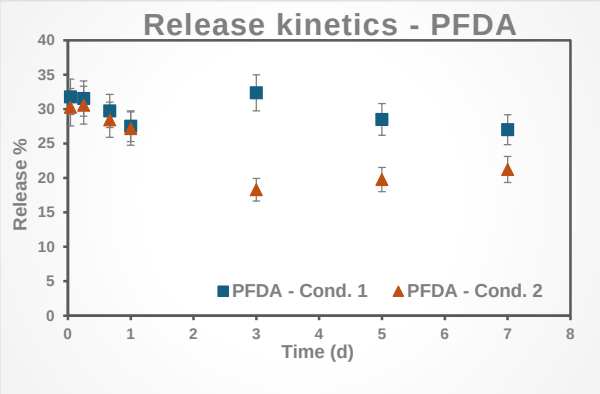
With or without NaN_3

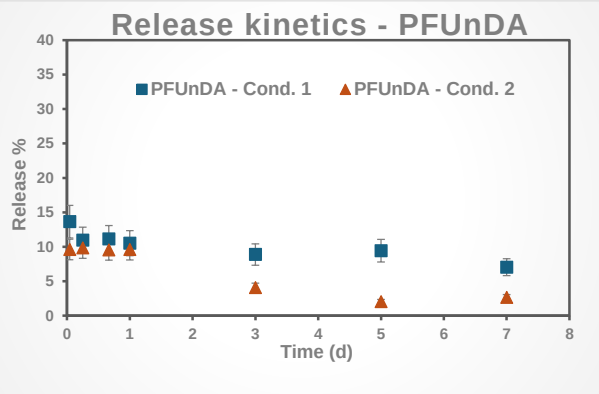
- **Constant release** over time
- **Equilibrium** reached quickly: **1h**
- **No differences**

PFAS release from soil pollution sources

Results: effect of bacterial inhibitor – Soil C2

Long chain PFCA (PFDA, PFUnDA)





With NaN_3

- **Constant release** over time (same order of magnitude for PFUnDA)
- **Equilibrium** reached quickly: **1h**

Without NaN_3

- **Release** rates **decreased** over time
- **Release** rates significantly **lower than with NaN_3** (after 3 d)

➡ **Bio degradation of long chain PFCA in these experimental conditions?**

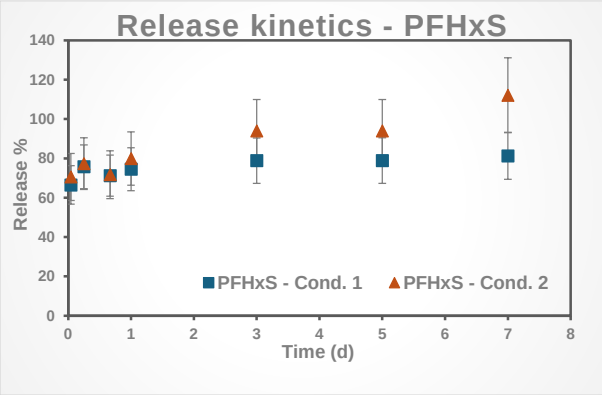
Next step

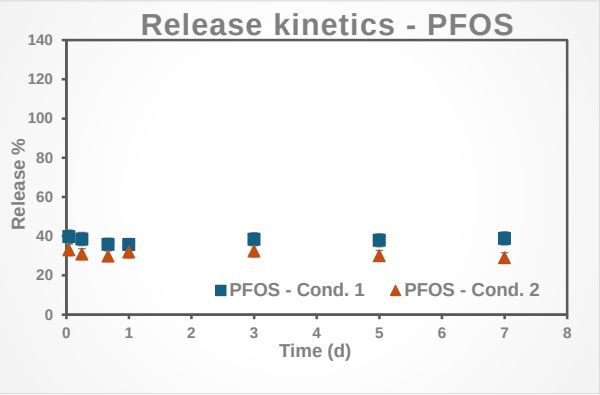
➡ PFDA + PFUnDA degradation evaluation in these conditions

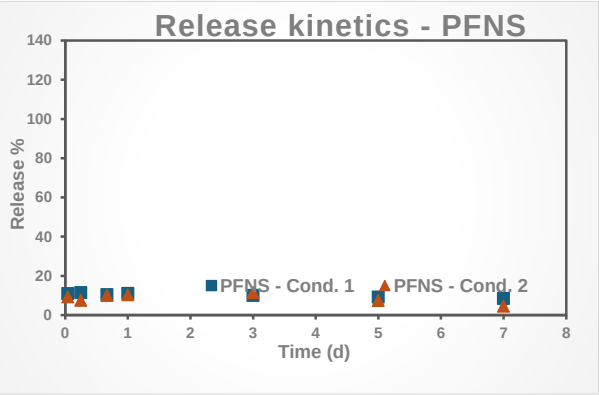
PFAS release from soil pollution sources

- Results: effect of bacterial inhibitor – Soil C2

❖ PFSA (PFHxS, PFOS, PFNS)







With NaN_3

- **Constant release** over time
- **Equilibrium** reached quickly: **1h**

Without NaN_3

- **PFHxS: release** rates **increased** over time / higher after 7 d than with NaN_3
- **PFOS: constant release** but **less release without NaN_3**
  - ➡ **Effect of salt?**
- **PFNS: concentration at LOQ** (similar)

Conclusion and perspectives

High PFAS release from soil pollution sources

- ➡ High mobility of PFAS in soils
- ➡ High potential to form large pollution plumes

Type of PFAS released from soil

- ✓ In general, retention in soil increased when C chain length increased
- ✓ FTS: lower release in general (but main PFAS in soils)
- ✓ Different release patterns for different soils
  - ➡ Different release rates (especially for long chain PFAS): relative influence of OM / clay
  - ➡ Similar release for PFCA / PFSA or PFCA release > PFSA release (depending on the soil)

Perspectives

- ✓ Statistical tests
- ✓ Release experiments under different conditions: different salt (cation/anion), different concentrations
  - ➡ Evaluation of soil components implied in PFAS retention and release

Rôle of PFAS bio degradation

- ✓ FTS and/or long chain PFCA bio degradation

Perspectives

- ✓ FTS + long chain PFCA (PFDA/PFUnDA)
  - ➡ ✓ Degradation evaluation (with and without soil)
  - ➡ ✓ Sorption of individual compounds

  ➡ Formation of shorter chain PFAS?

- ✓ Successive releases on the same soil: depletion of FTS? Formation of shorter chain PFAS?

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Thank you for your attention