Highlights from VOW

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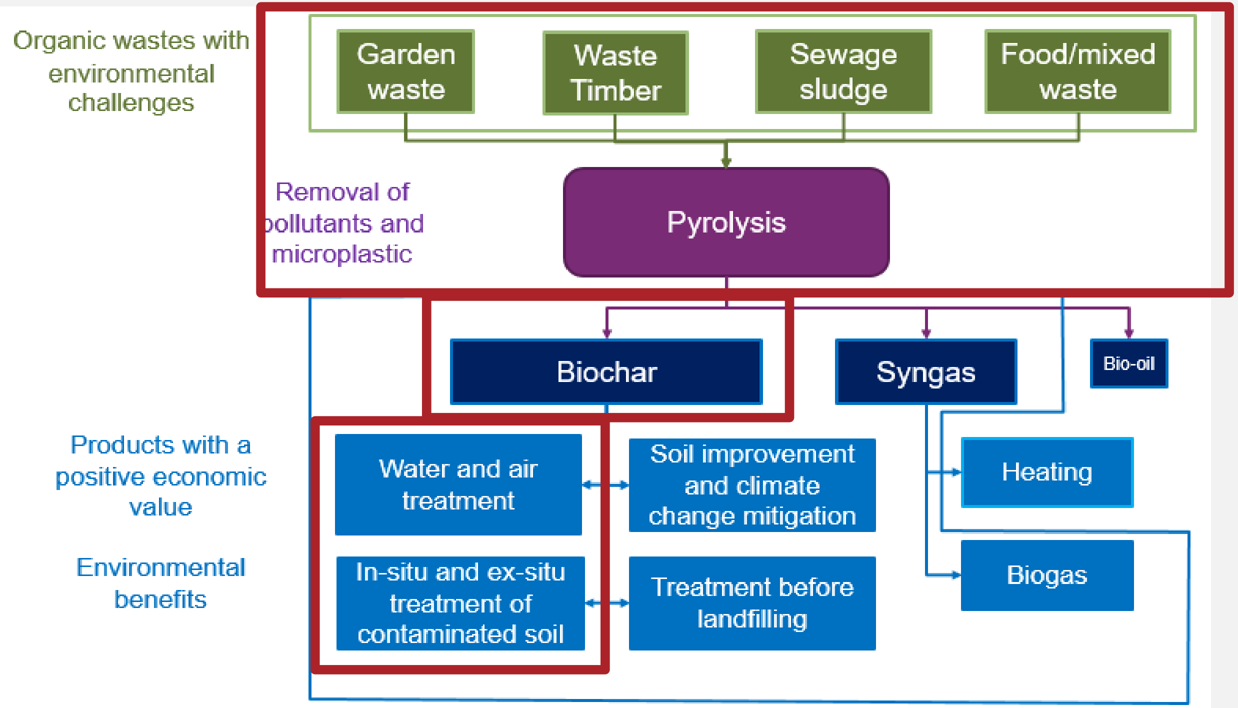
22.11.24

VOW: Valorization of Organic Waste into Sustainable Products for Clean-up of Contaminated Water, Soil, and Air

NFR BIA-X, 2019-2023, ≈20 mNOK



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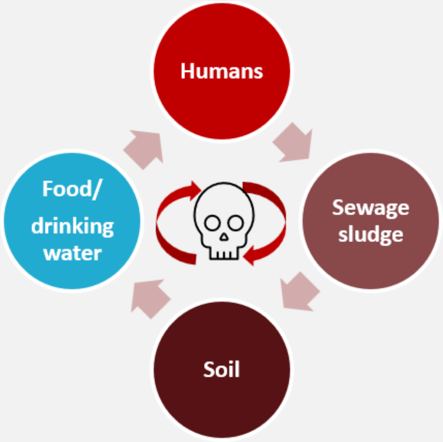
How can we reduce contaminant emissions (PFAS) from waste handling?

- PFAS present in many waste streams[1,2]
- Current waste handling leads to emissions: <u>a cyclical problem[1,2]</u>
- Thermal treatment could be an alternative option[1,3]



Source: PhD thesis, Erlend Sørmo

Photo: Ove Dahl, Lindum.no

Photo: NGI

1) Berg et al (2021) Jrn. Air & Waste Man. Ass. https://doi.org/10.1080/10962247.2021.2000903
2) Stoiber et al (2020) Chemosphere https://doi.org/10.1016/j.chemosphere.2020.127659
3) Buss (2021) ASC Sust Chem Eng https://doi.org/10.1021/acssuschemeng.1c03651

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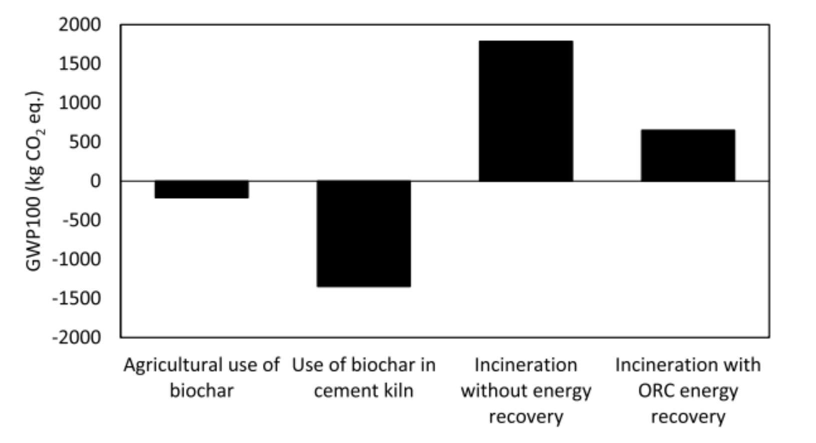
Pyrolysis – a promising treatment alternative for contaminated organic waste

- Heating in absence of O_2
- Advantages to incineration[1]
  - Biochar
- Decomposes various organic contaminants[2,3]
- Can reduce mobility of heavy metals[4]
- Might be suitable to decompose PFAS[5]



Source: Barry et al (2019) Biomass & Bioenergy https://doi.org/10.1016/j.biombioe.2019.01.041

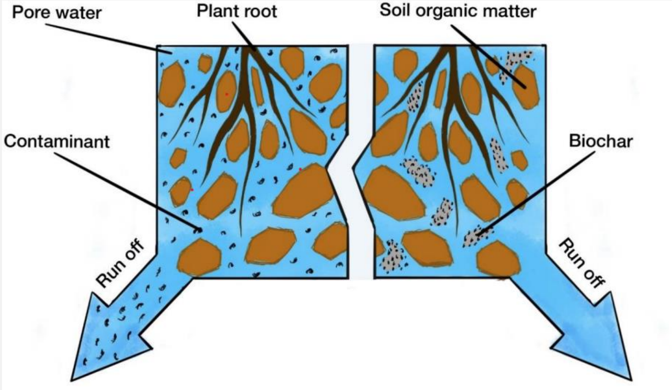
1) Barry et al (2019) Biomass & Bioenergy https://doi.org/10.1016/j.biombioe.2019.01.041
2) Moško et al. (2021) Chemosphere https://doi.org/10.1016/j.chemosphere.2020.129082
3) Castro et al (2023) STOTEN https://doi.org/10.1016/j.scitotenv.2023.161856
4) C. Udanyaga (2019) STOTEN https://doi.org/10.1016/j.scitotenv.2019.07.095
5) Alinezhad et al (2022) ES&T Eng. https://doi.org/10.1021/acsestengg.1c00335

What is biochar?

- Stable, carbon rich, and highly porous material[1]
- Multiple applications for biochars:
  - Biochar carbon storage (BCS)[1,2]
  - Soil amendment[1,2,3]
  - Sorbents for contaminants[3]

Source: Bjerkli (2019) MSc Thesis, NMBU
http://hdl.handle.net/11250/2612018

Photo: Lindum AS



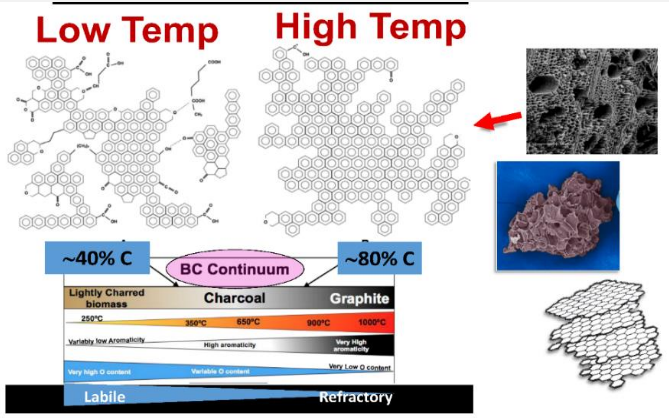
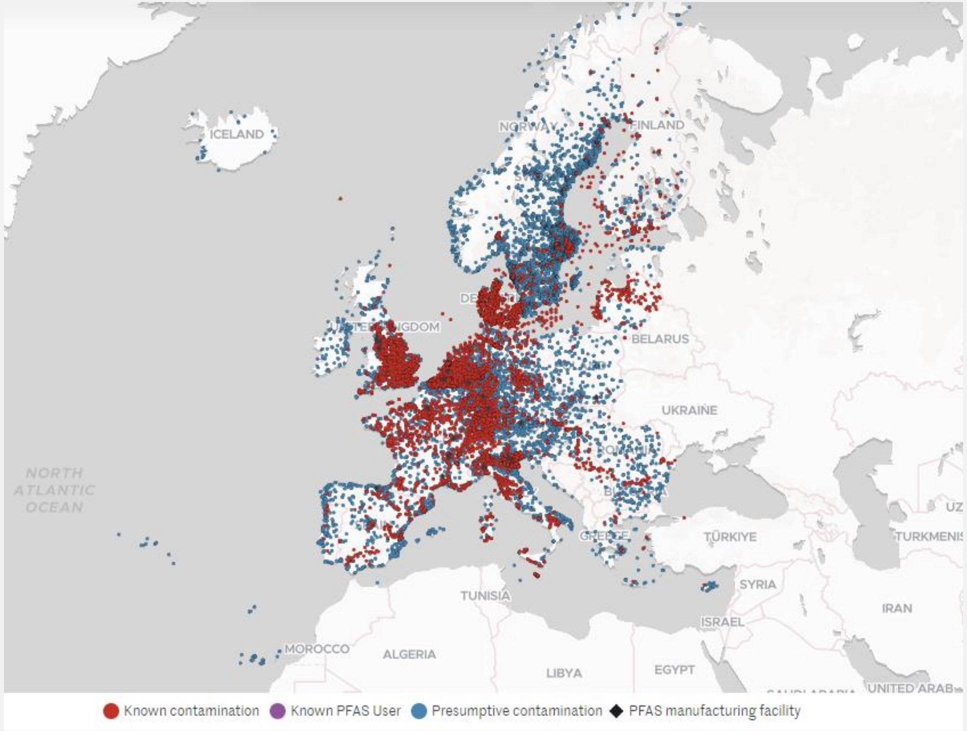


Figure: Adapted from Zimmerman & Ouyang (2019) Soil Biol. and Biochem. https://doi.org/10.1016/j.soilbio.2018.12.011

1) Lehmann et al (2006) Mitig. Adapt. Strateg. Glob. Chang https://doi.org/10.1007/s11027-005-9006-5
2) Barry et al (2019) Biomass & Bioenergy https://doi.org/10.1016/j.biombioe.2019.01.041
3) Ahmad et al (2014) Chemos https://doi.org/10.1016/j.chemosphere.2013.10.071

Remediation of PFAS-contaminated sites needed!

- Ground and surface water impacted for centuries without remediation[1]
- Stabilization with biochar a promising alternative[2,3]



Source: Compiled by The Forever Pollution Project, using OpenStreetMap (CC BY-SA 2.0)

1) Ruyle et al (2023) ES&T https://doi.org/10.1021/acs.est.3c00675
2) Sörengård et al (2019) Jrn Env Man https://doi.org/10.1016/j.jece.2020.103744
3) Navarro et al (2023) Env Pol https://doi.org/10.1016/j.envpol.2023.121249

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Industrially relevant testing

8 large waste fractions were studied (>50k tonnes yr^{-1})

Source: Sørmo (2023) PhD Thesis, 2023:77 NMBU

Biogreen by ETIA Ecosolutions (VOW ASA)

- Full-scale, medium size (2-5 kg biochar/hr)
- Electrically heated Spirajoule® (up to ≈850 °C)
- Condensation of pyrolysis oils
- Pyrolysis gas combustion in simple "torch" (700-900 °C)

Figure: http://www.biogreen-energy.com/spirajoule/


Photo: NGI

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Contamination can be decomposed, volatilized, or fixed in the biochar by using a high enough pyrolysis temperature

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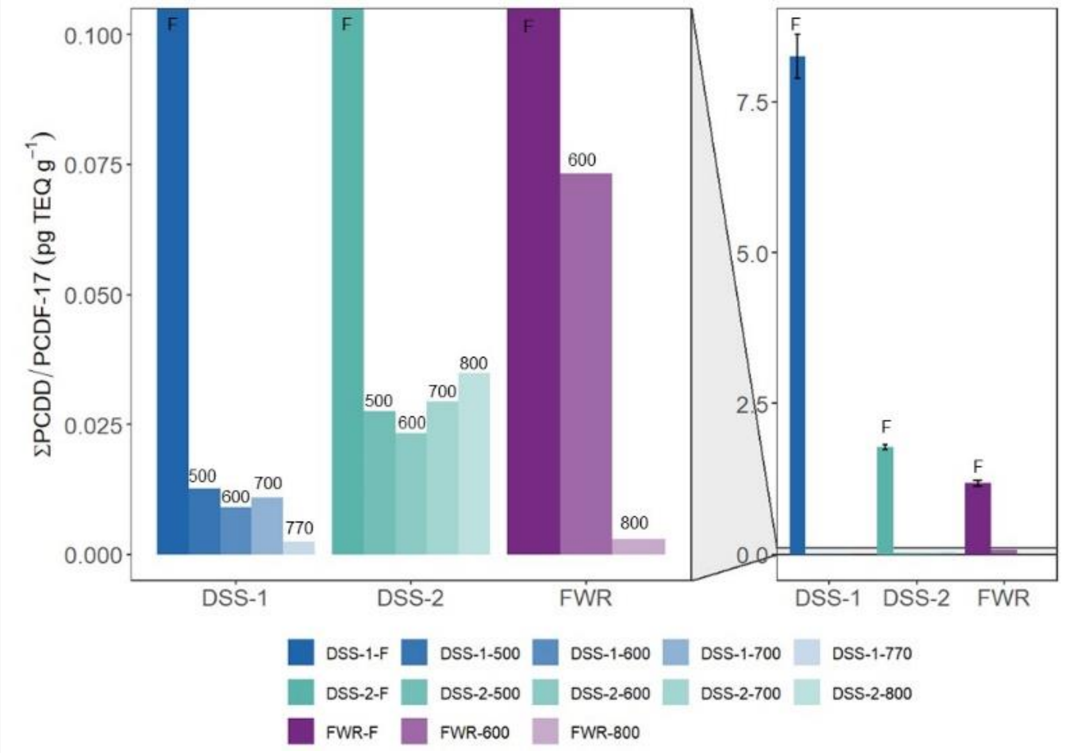
Organic contaminants are volatilized/decomposed

- **Pyrolysis temperature key**
  - ≥600 °C
- PFAS most important (C-F)
  - REs >96%
- PCBs and PCDD/Fs
  - REs >99%
- PAHs unpredictable
- Similar for other contaminants[1,2,3]

Source: Paper III



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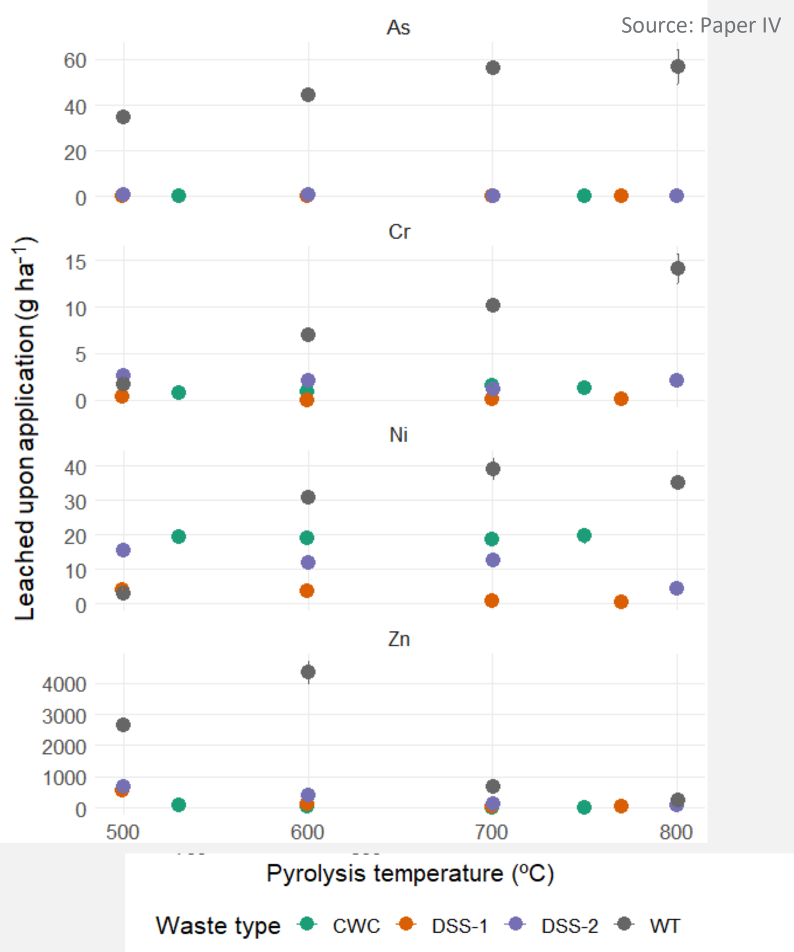
1) Castro et al (2023) STOTEN, https://doi.org/10.1016/j.scitotenv.2023.161856
2) Moško et al (2020) Chemosphere, https://doi.org/10.1016/j.chemosphere.2020.129082
3) Buss (2021) Sus Chem Eng https://doi.org/10.1021/acssuschemeng.1c03651

Source: Paper II

Heavy metals are immobilized at the same high temperatures

- Mobility high in wood based compared to sludge based biochars
- Clean biochar (CWC) can leach more or same as sludge biochar (pH 4)
- Long term effect in soil?

Source: Paper IV



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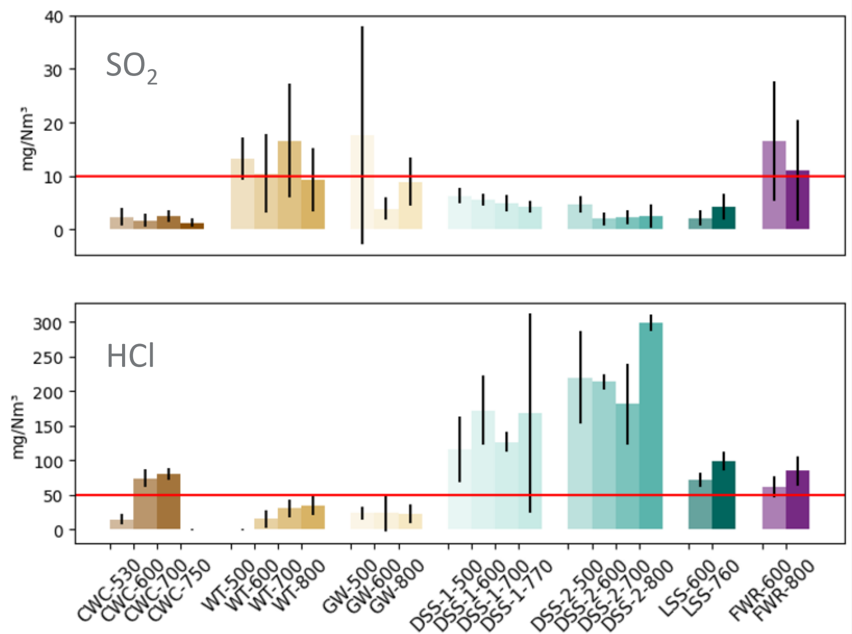
The trade-off = flue gas emissions

- Increasing pyrolysis temperature can result in increased emissions
  - PFAS, PAHs, & heavy metals
  - HCl & SO_2
- Carbon yield goes down
- Flue gas cleaning needed?

Photo: NGI



Source: Paper V

To condense or not to condense?

- Organic contaminants accumulate in pyrolysis condensate
  - PAHs (2563 – 8285 mg kg^{-1}), PCBs (22 – 113 µg kg^{-1}) and PCDD/Fs (1.8 – 50 ng TEQ kg^{-1}) (paper III)
  - PFAS[1]
- Hazardous waste (PAH) and HSE-concern
- Incineration for energy generation the best alternative?
  - Integrated (Pyreg-500) or two step (Biogreen)?

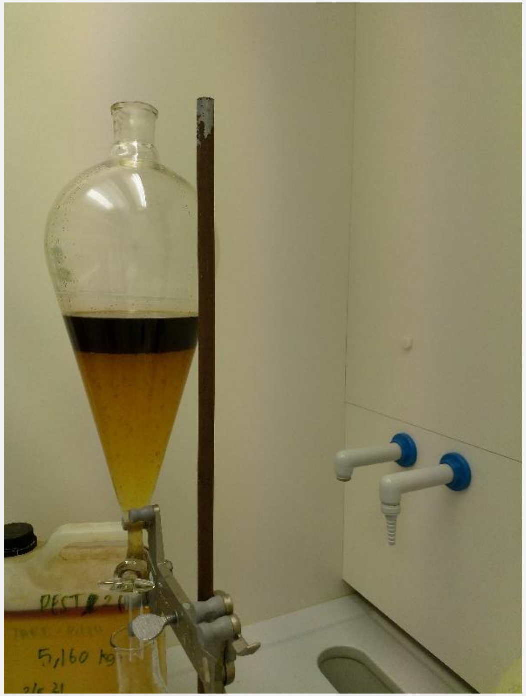


Photo: Gudny Ø. Flatabø

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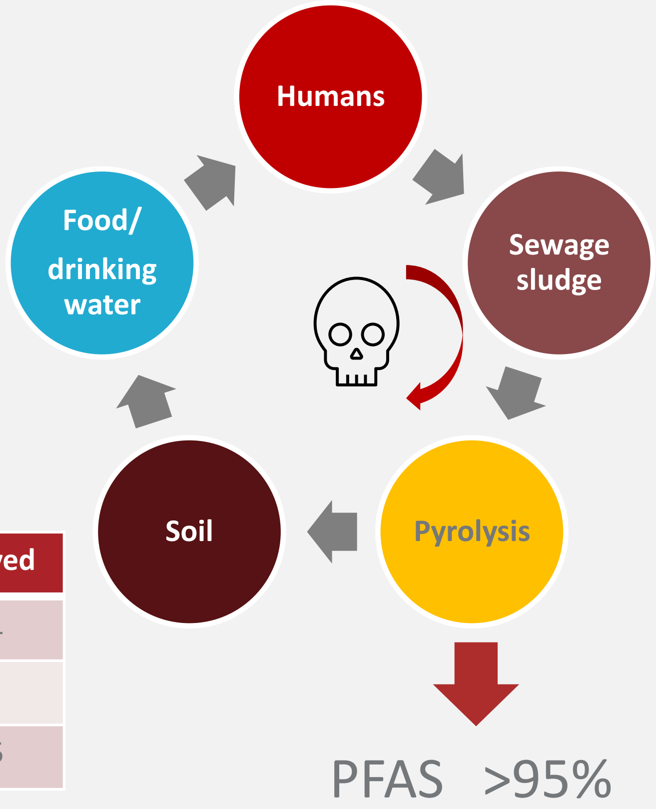
1) McNamara (2023), Env Sci Water Rsch & Techm, DOI: 10.1039/d2ew00677d

Flue gas emissions vs. taking contaminants out of circulation

- 134 000 tonnes of sewage sludge in Norway per year[1]
- Pyrolyze everything at ≥600 °C
- Projected global emissions of PFCAs (2016-2030): 20 – 6420 tonnes[1]

	Feedstock	Biochar	Condensate	Emitted	Destroyed
PFAS (56) (kg)	59.09	0.03	?	0.05	59.01
PCBs (7) (kg)	1.02	0.02	0.73	0.01*	0.26
PCDD/Fs (17) (g TEQ)	0.239	0.001	0.060	0.002	0.175



Source: PhD thesis, Erlend Sørmo

1) Wang et al (2014) Env. International https://doi.org/10.1016/j.envint.2014.04.013

Effective waste biochar sorbents might be produced using the same high pyrolysis temperature needed to tackle contamination

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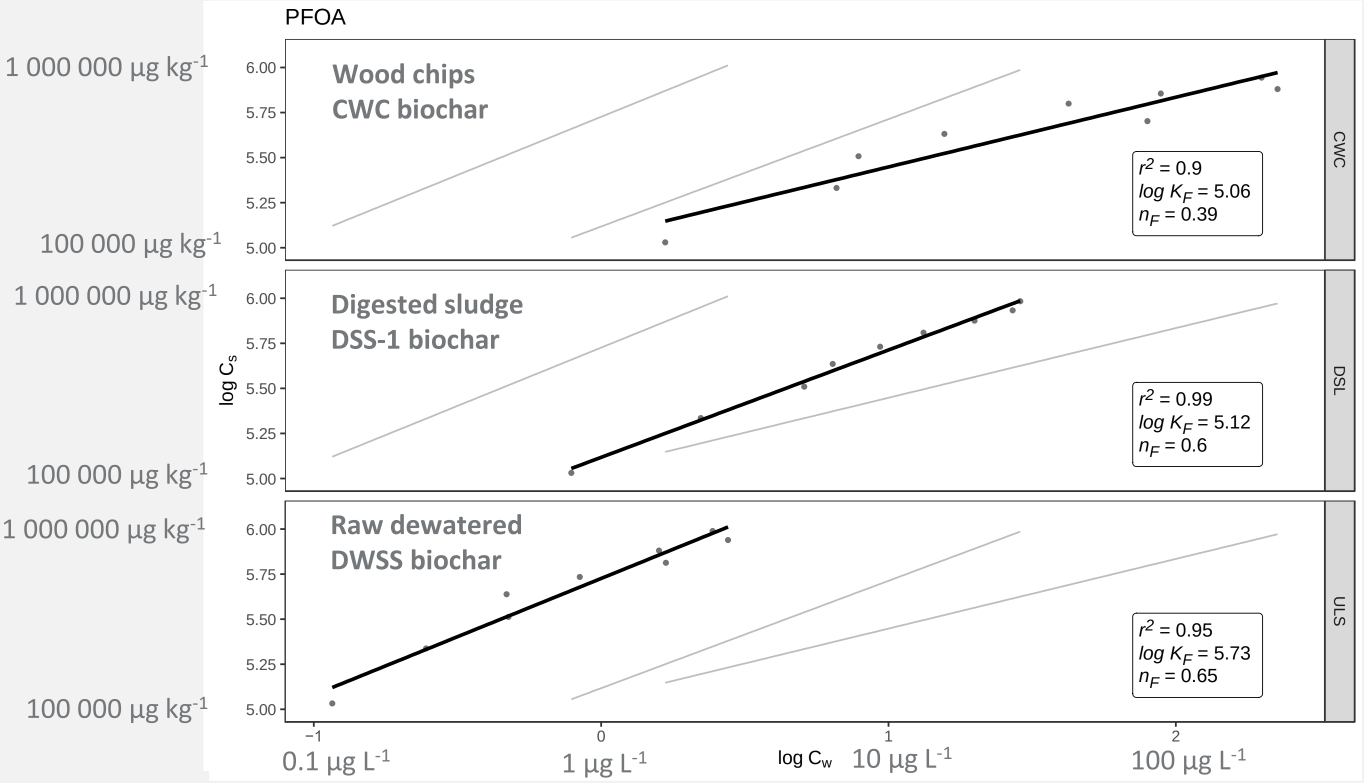
Sewage sludge biochars better than wood chips biochar and equal to commercial AC

- Coal AC: log K_F= 5.6[1]
- Activated biochar: log K_F = 5.4[2]



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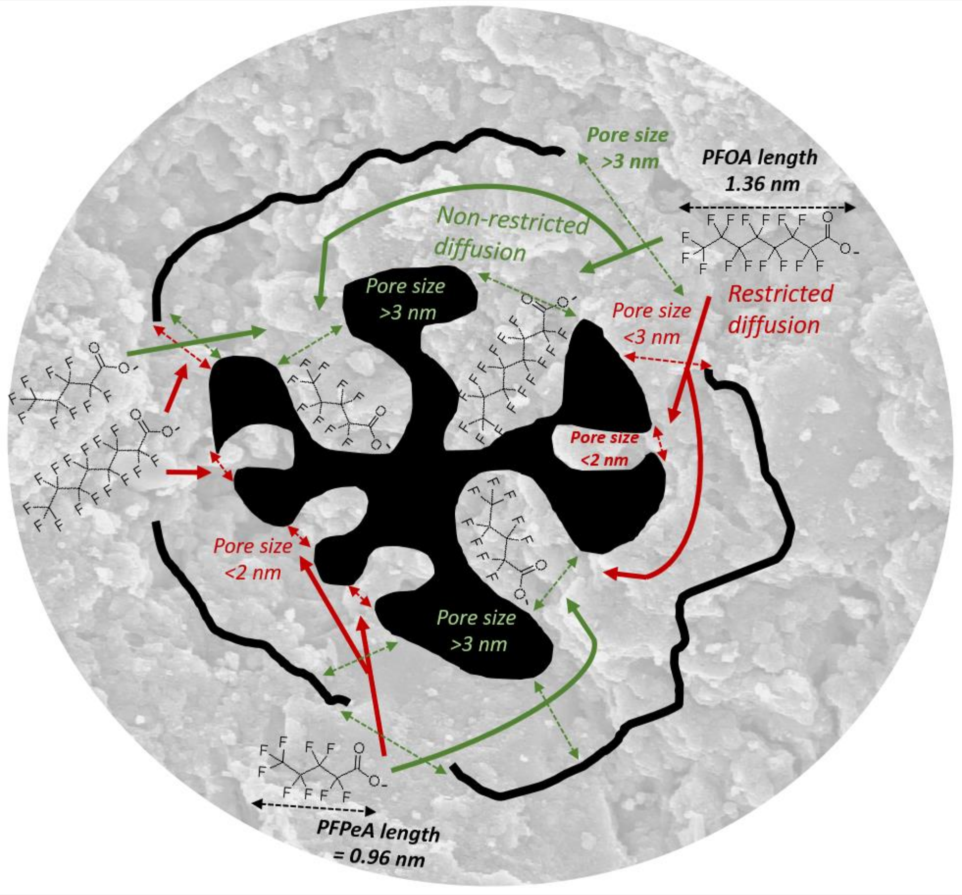
1) Kupryianchyk et al. (2016), Chemosphere https://doi.org/10.1016/j.chemosphere.2015.04.085
2) Silvani et al. (2019), STOTEN https://doi.org/10.1016/j.scitotenv.2019.133693

Source: Paper VIII

Why were the sludge chars more effective than the wood chars?

CWC: SA 683 m^2/g
DWSS: SA 165 m^2/g
DSS-1: SA 87 m^2/g

Wood char pores too narrow to accommodate large PFAS molecules!



Paper VIII

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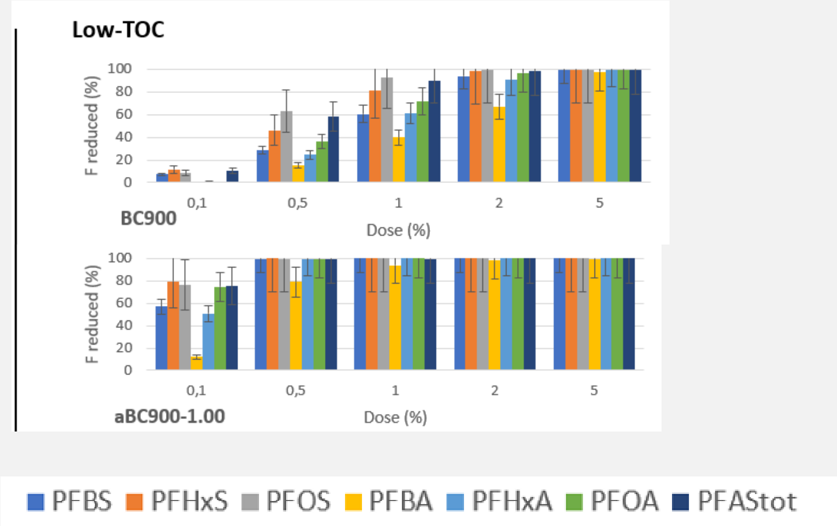
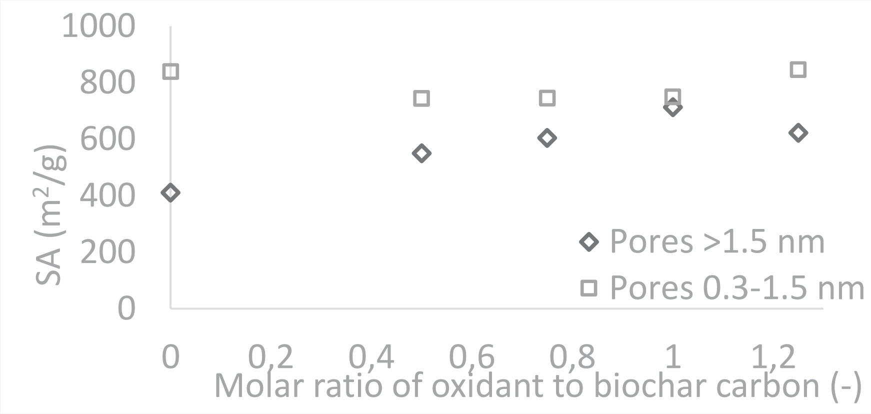
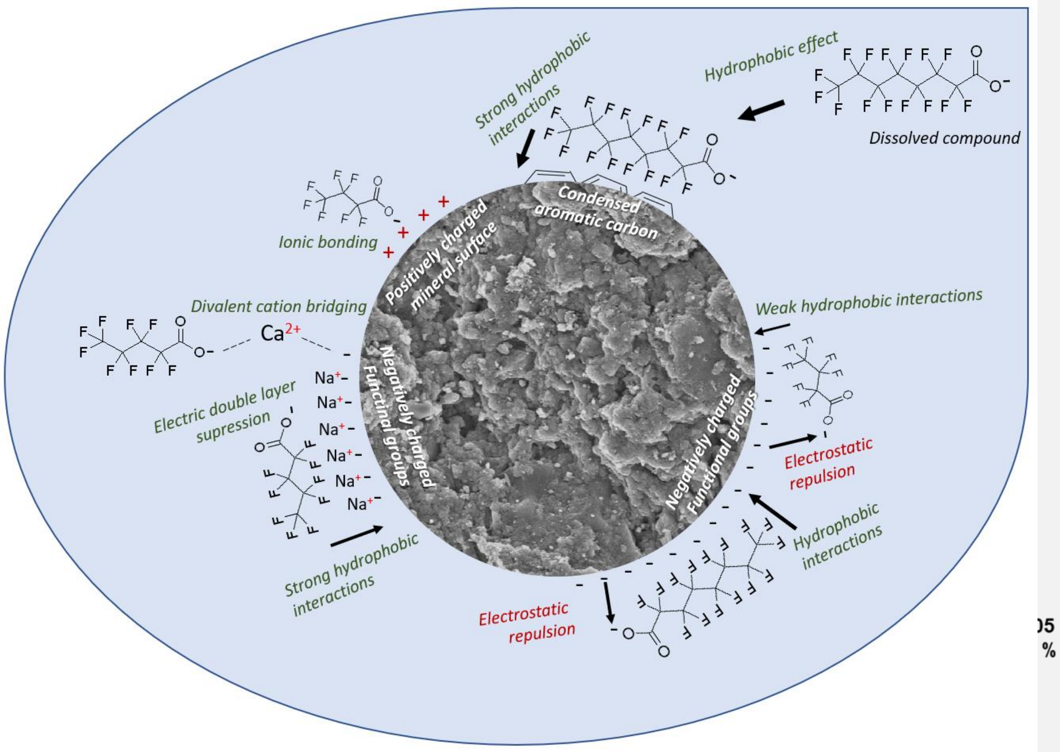
High temperature and activated wood biochars are excellent sorbents for PFAS





Biochar ability to sorb PFAS is correlated to amount of condensed aromatic carbon

- Relationship less clear for short chain PFAS ($<6xCF_2$)

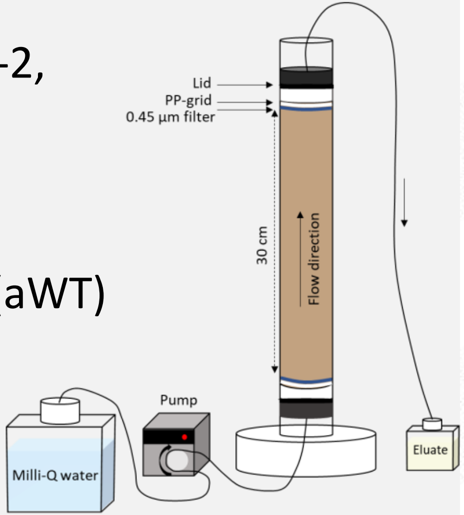


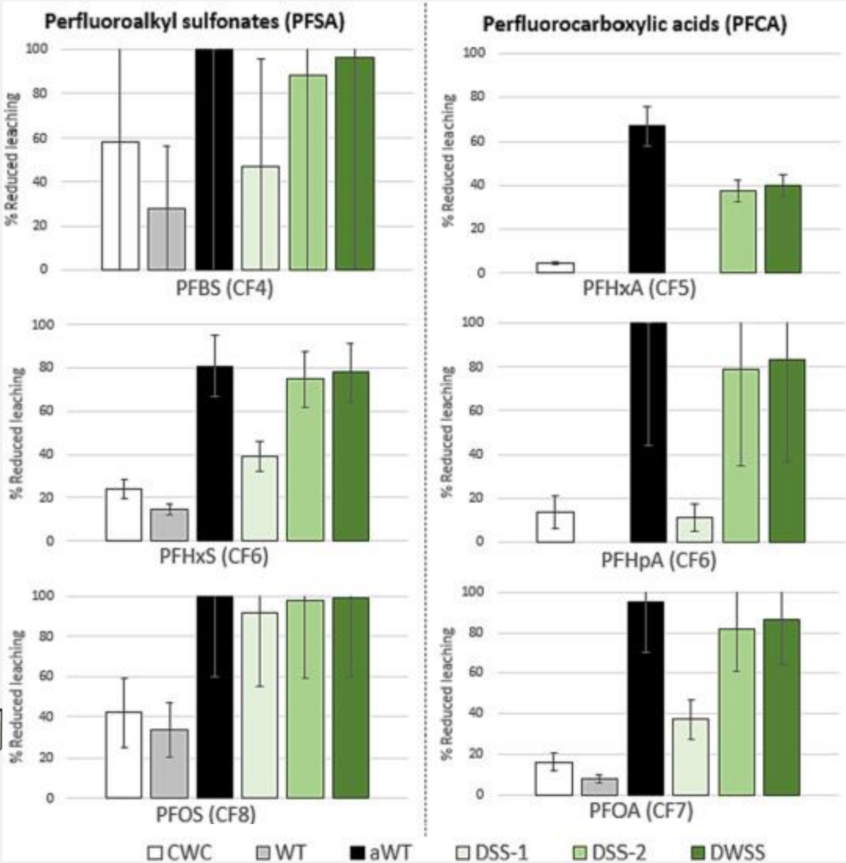
Source: Paper VII

Do sludge biochars work in soils?

Columns with AFF impacted soil and 1% biochar[1]

- Best effect for long chain PFAS (>6xCF_2)
- Sludge chars (DSS-1, DSS-2, DWSS) better than non-activated wood biochars (CWC, WT)
- Activated wood biochar (aWT) best

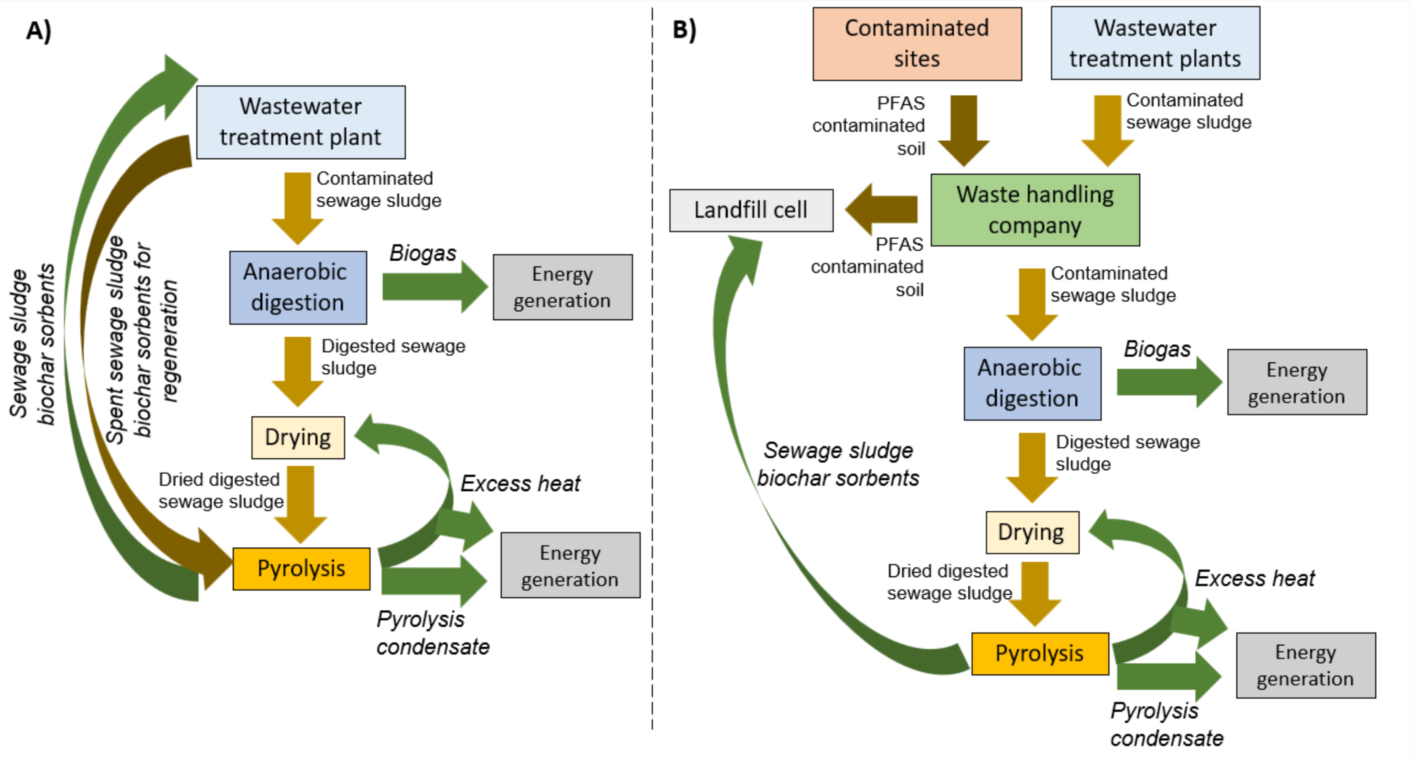




1) Sørmo et al. (2024) STOTEN https://doi.org/10.1016/j.scitotenv.2024.170971

Figures: Sørmo et al. (2024) STOTEN
https://doi.org/10.1016/j.scitotenv.2024.170971

The way forward: Integrated processes?



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