SLUDGEFFECT: Enabling a circular economy for sludge through source control and thermal treatment methods

Hans Peter H. Arp[1,2], **Erlend Sørmo**[1] , Mari Løseth[1], Sarah Hale[1], **Heidi Knutsen**[1], Gerard Cornelissen[1], Håkon Langberg[1], Gregory Peters[2], Damia Barcelo[3], Antoni Ginebreda Marti[3], **Gabriela Castro**[2], Junjie Zhang[2], Otavio Cavalett[2], **Marjorie Morales**,[2] Francesco Cherubini[2], Alexandros Asimakopoulos[2]

1) Norwegian Geotechnical Institute (NGI), Oslo, Norway; 2) Chalmers University of Technology, Gothenburg, Sweden; 3) IDAEA-CSIC (Spanish National Research Council), Barcelona, Spain; 4) Norwegian University of Science and Technology (NTNU), Trondheim, Norway

Miljøringent temamøte - Helhetlig miljøforvaltning
April 17, 2024, Miljødirektoratet Oslo

Contact: hans.peter.arp@ngi.no

SLUDGEFFECT:
primary objective

Identify how thermal treatments can be optimized for removing hazardous substances in sludge and e-waste plastic for increasing recycling and sustainability

“Pyrolysis solves the issue with organic contaminants in sewage sludge”[1]

Boiling points deciding factor → volatilized or decomposed[2]

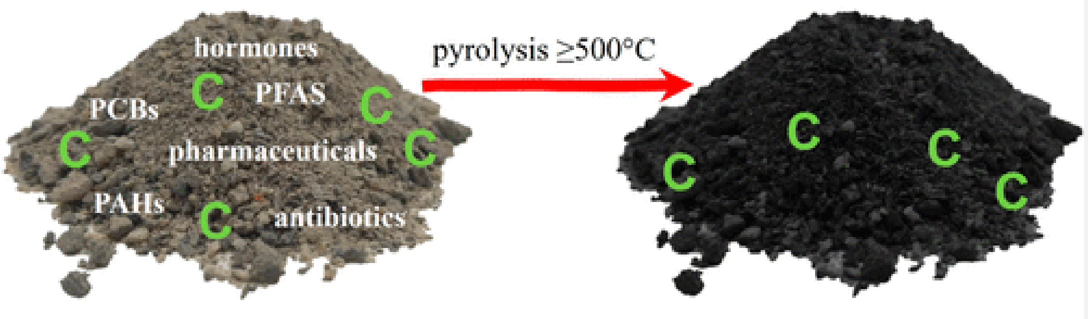


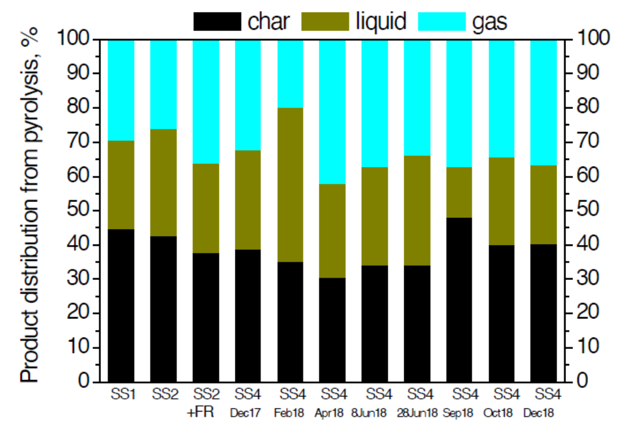
Figure: Buss (2021) ACS Sust Chem. Eng. https://doi.org/10.1021/acssuschemeng.1c03651

Is this really true for PFAS and other persistent contaminants?

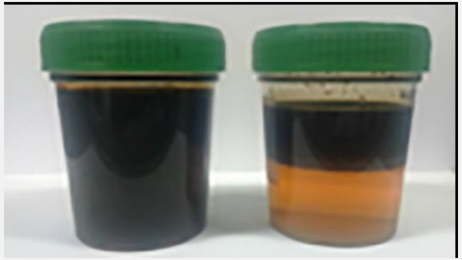
1) Buss (2021) ACS Sust Chem. Eng. https://doi.org/10.1021/acssuschemeng.1c03651
2) Moško et al (2021) Chemos https://doi.org/10.1016/j.chemosphere.2020.129082

Variation in fertilizer from dry pyrolysis

Sludge biochar fertilizer (30-50%)

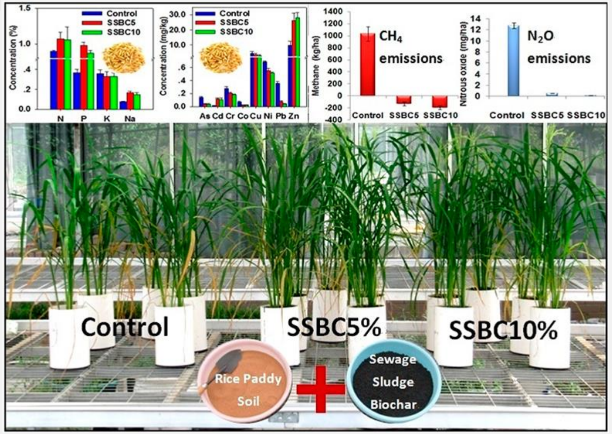


Kwapinska, M., Agar, D. A., Bonsall, B., & Leahy, J. J. (2020) Valorisation of Composted Organic Fines and Sewage Sludge Using Pyrolysis (OF-PYR). (2016-RE-MS-7). Irish EPA Research Report

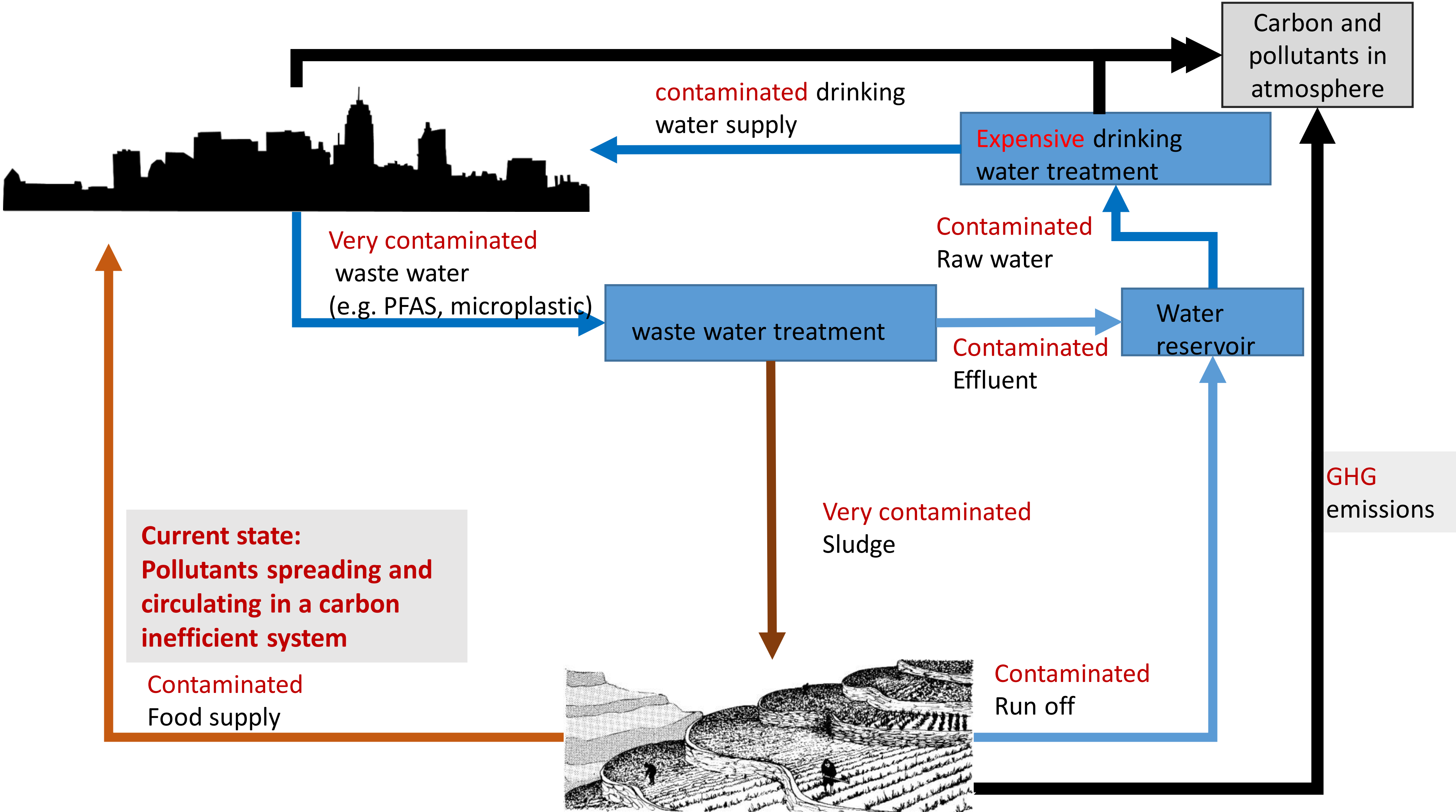


Pyrolysis condensates (complex) (20-40%), best for producing energy on-site, e.g. providing heat to pyrolyzer/co-incineration

Bioavailable phosphorous – Phosphorous is retained. The best studies indicated a doubling in soil fertility from sludge to sludge chare, due to diverse properties (e.g. alkalinity, water retention) (e.g. Khan et al. ES&T 2012)



NGI



Carbon and pollutants in atmosphere

contaminated drinking water supply

Expensive drinking water treatment

Very contaminated waste water (e.g. PFAS, microplastic)

Contaminated Raw water

waste water treatment

Water reservoir

Contaminated Effluent

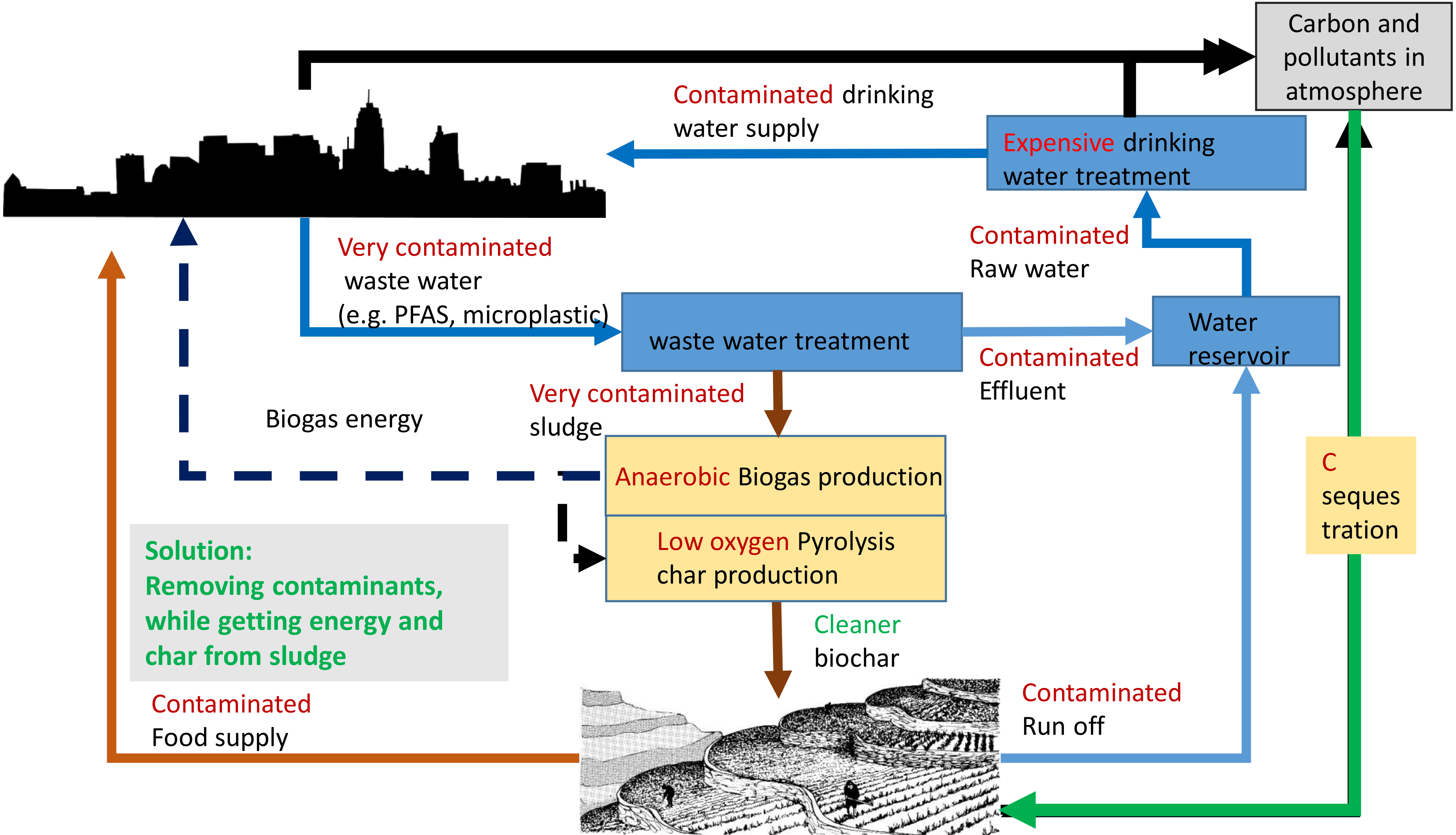
Very contaminated Sludge

GHG emissions

Current state: Pollutants spreading and circulating in a carbon inefficient system

Contaminated Food supply

Contaminated Run off



Carbon and pollutants in atmosphere

Contaminated drinking water supply

Expensive drinking water treatment

Very contaminated waste water (e.g. PFAS, microplastic)

Contaminated Raw water

waste water treatment

Water reservoir

Contaminated Effluent

Very contaminated sludge

Biogas energy

Anaerobic Biogas production

Low oxygen Pyrolysis char production

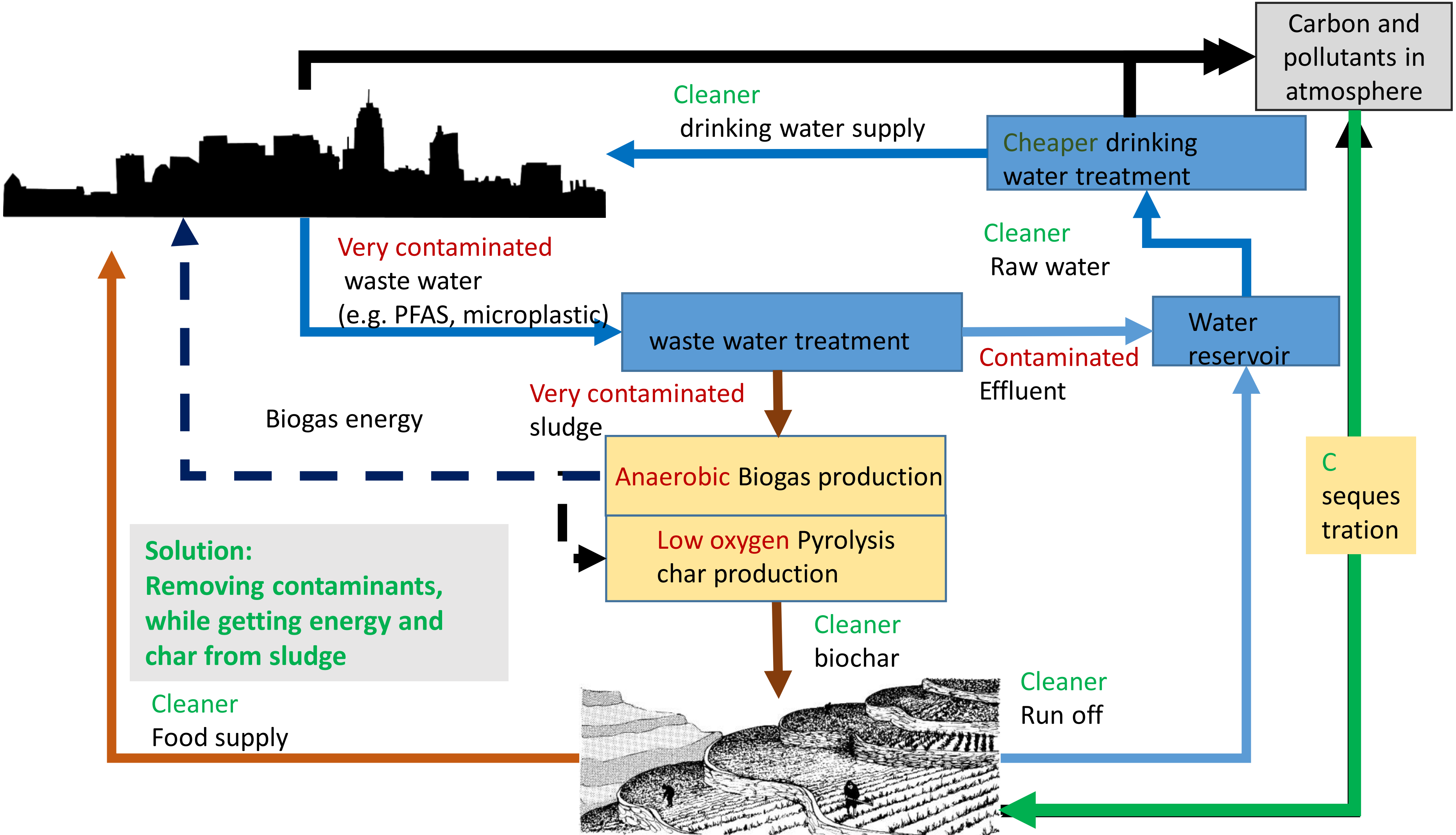
C sequestration

Solution:
Removing contaminants, while getting energy and char from sludge

Cleaner biochar

Contaminated Run off

Contaminated Food supply



Carbon and pollutants in atmosphere

Cleaner drinking water supply

Cheaper drinking water treatment

Very contaminated waste water (e.g. PFAS, microplastic)

waste water treatment

Cleaner Raw water

Contaminated Effluent

Water reservoir

Biogas energy

Very contaminated sludge

Anaerobic Biogas production

Low oxygen Pyrolysis char production

C sequestration

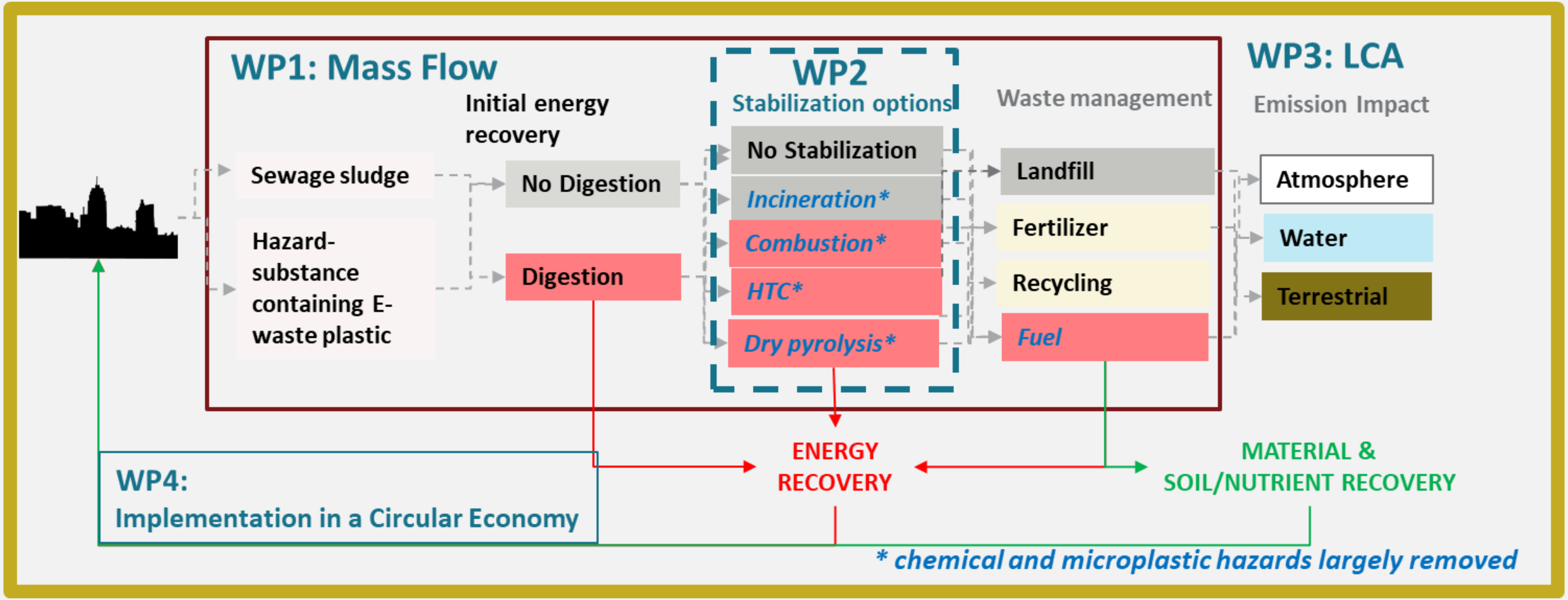
Solution:
Removing contaminants, while getting energy and char from sludge

Cleaner biochar

Cleaner Run off

Cleaner Food supply

SLUDGEFFECT



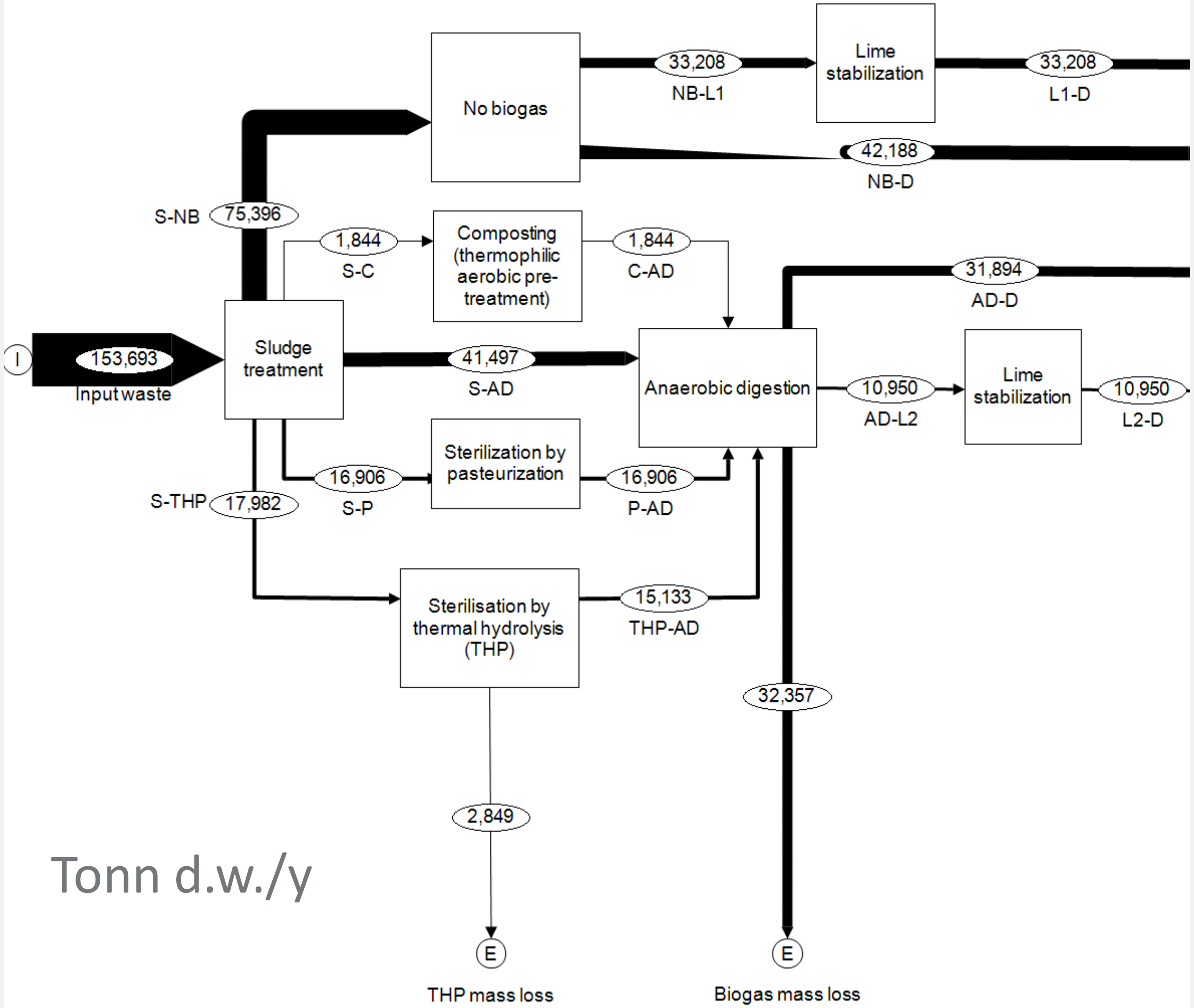
Life cycle effects from removing hazardous substances in sludge and plastic through thermal treatment.

Sludge management in Norway compared to the EU

Figure	Norway (2018)	EU-27 (2019)
Population	5.3 million	447.7 million
Total sludge produced	118 kton/y (22 kg/capita)	8300 kton/y (19 kg/capita/y)
% used for biogas production	**49%**	?? (no data, but expected to grow)
% agriculture/soil	**82%**	**40%**
% incinerated	**1%**	**27%**
% landfilled (+ composted/other)	5% (+ 12%)	11% (+10%)

Sources: SSB Norway,
Collivignarelli et al., 2019
Preliminary SLUDGEFFECT results (biogas)

Norwegian Sludge Processing in 2020



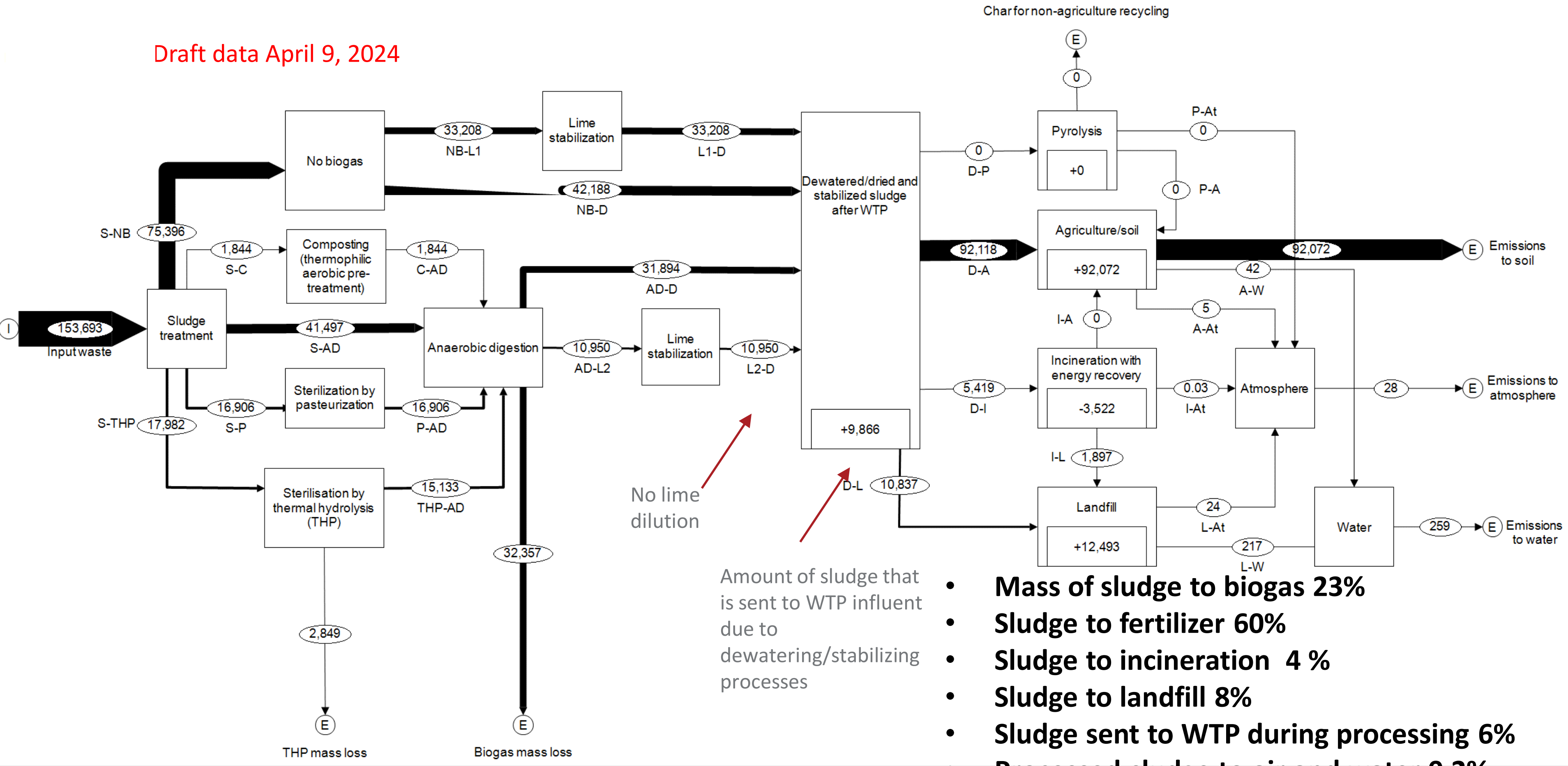
Tonn d.w./y

- No treatment **22%**
- Lime stabilization **27%**
- Aerobic digestion (AD) **21%**
- AD + lime stabilization **7%**
- Composting + AD **1%**
- Pasteurization + AD **11%**
- Thermal hydrolysis + AD **12%**

Basert på data samlet fra SSB, Norskvann og renseanlegger

Mass flow of sludge in all Norway (tonn dw/y) (2020)

Draft data April 9, 2024



No lime dilution

Amount of sludge that is sent to WTP influent due to dewatering/stabilizing processes

- **Mass of sludge to biogas 23%**
- **Sludge to fertilizer 60%**
- **Sludge to incineration 4 %**
- **Sludge to landfill 8%**
- **Sludge sent to WTP during processing 6%**
- **Processed sludge to air and water 0.2%**

What about the flow of contaminants in Norwegian sludge?

Target Analytes

9 Bisphenols

41 PFAS

21 OPFRs

7 Benzotriazoles

5 Benzophenones

17 monoester phthalate

11 Parabens

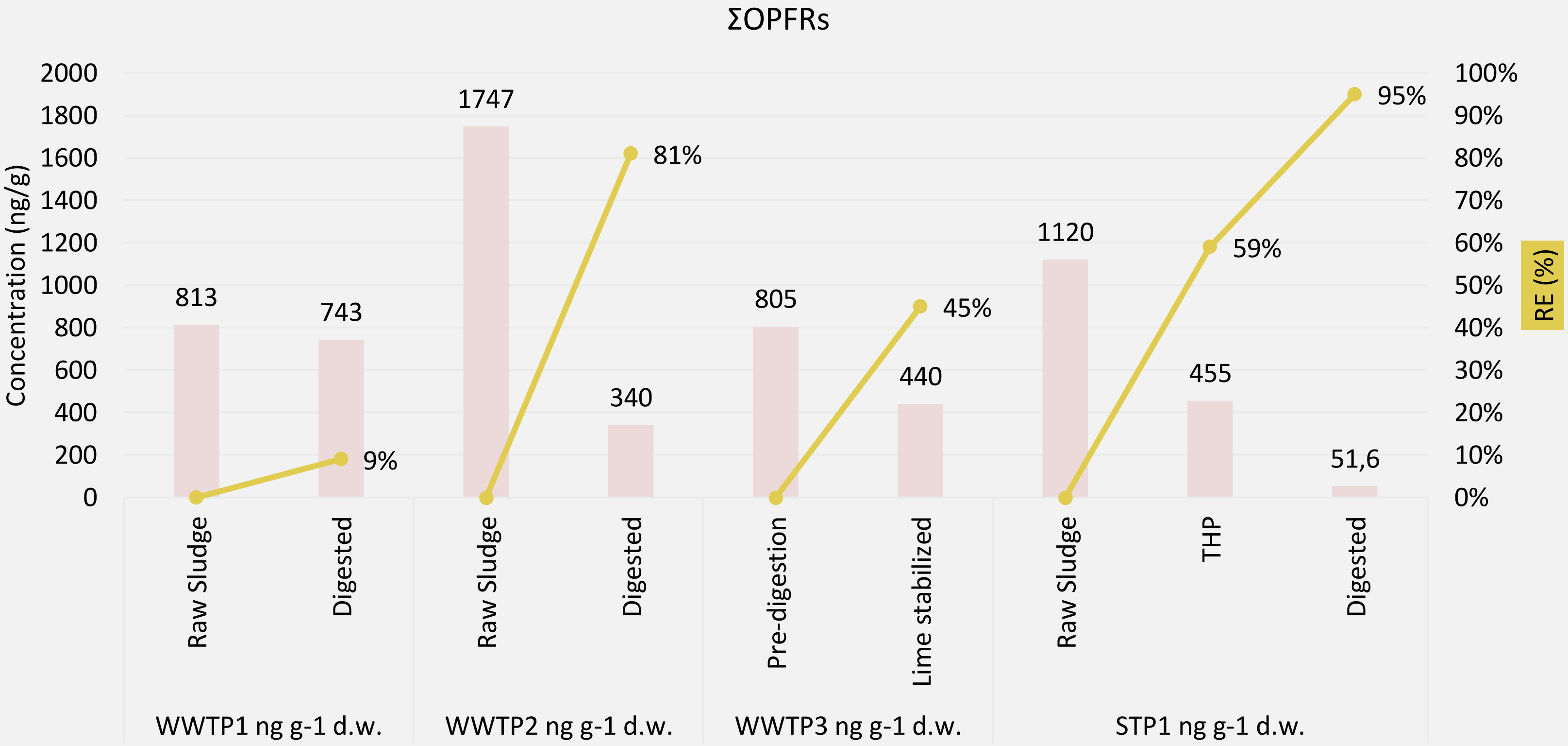
9 Benzothiazoles

13 BFRs

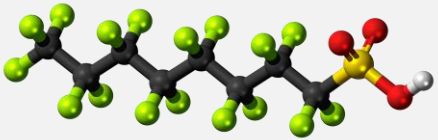
A total of 133 organic pollutants were analyzed + hazardous metals

- Development of new analytical methodologies
- Analysis of 87 sludge samples
- Quantification of several families of emerging pollutants and metals

Removal Efficiency of OPFRs in the WWTPs



Removal Efficiency of PFAS in the WWTPs



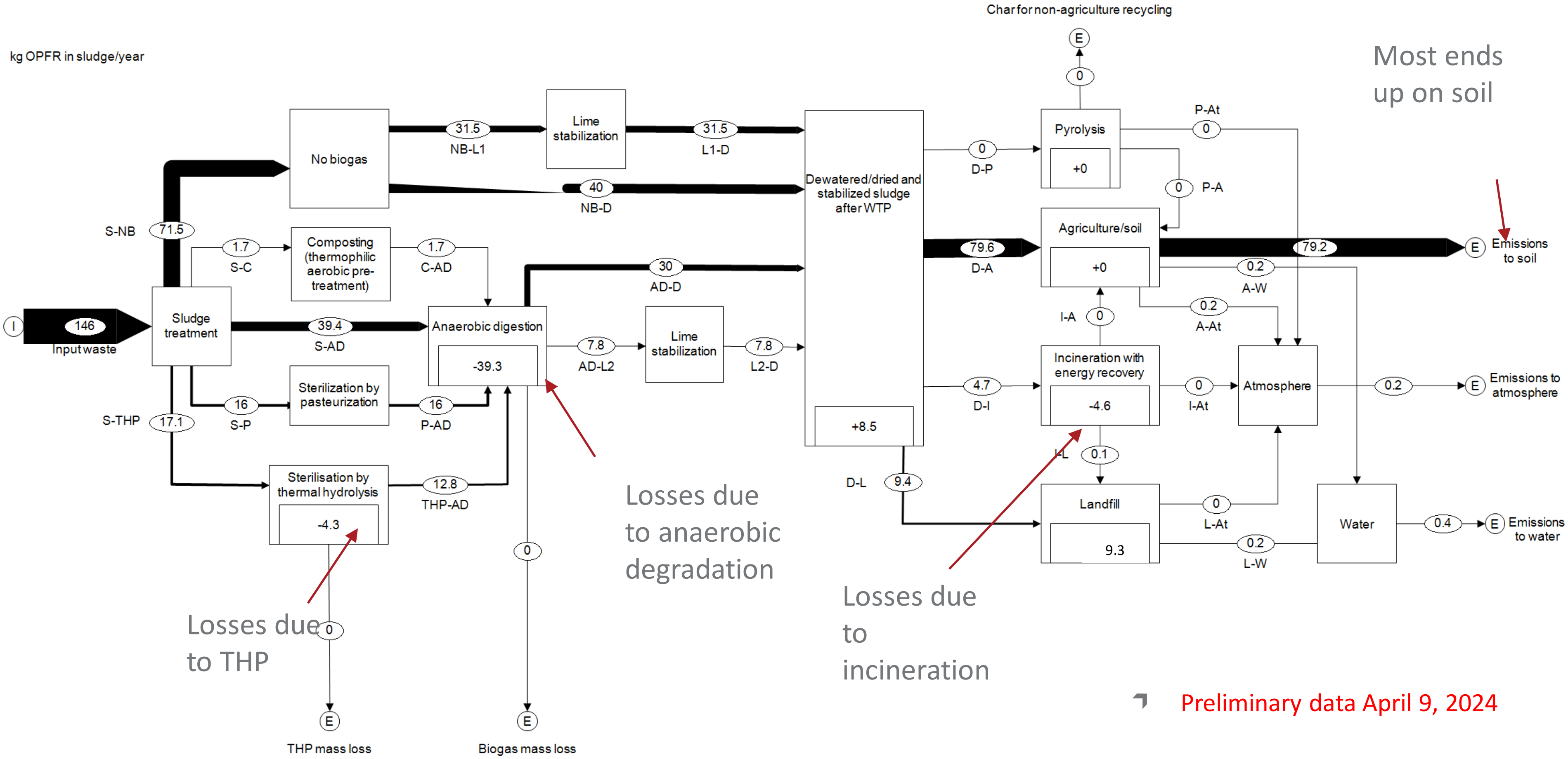
Anerobic digestion of PFAS

- Anaerobic digestion in WWTP1 leads to the transformation of precursors into short-chain PFCAs.
- The combination of primary treatment and subsequent hygienization with lime removed the 26% of the total PFAS concentration, favouring the **transformation** from the precursors and PFSA into long-chain PFCAs (94% transformation).

		Concentration ng/g				
		Raw sludge	**Post-pasteurization**	**Digested**	**Lime stabilized**	**Anaerobic transformation (%)**
WWTP1 **WWTP2**	**∑Uncategorized**	0.16	0.33	9.53	-	-98%
	∑FTS	5.51	5.02	0.66	-	88%
	∑PFCA	4.58	18.53	93.07	-	-95%
	Long-chain PFCA	3.73	4.82	2.59	-	31%
	Short-chain PFCA	0.86	13.71	90.48	-	-99%
	∑PFSA	25.65	17.49	2.09	-	92%
	Long-chain PFSA	2.90	1.81	0.86	-	70%
	Short-chain PFSA	22.75	15.68	1.23	-	95%
	∑PreFOS	n.d.	1.09	n.d.	-	n.d.
	∑PFAS	35.90	42.47	105.35	-	-66%
WWTP3	**∑Uncategorized**	3.56	-	13.02	n.d.	100%
	∑FTS	7.93	-	1.29	102.58	-92%
	∑PFCA	437.28	-	824.39	308.11	30%
	Long-chain PFCA	17.92	-	14.85	308.11	-94%
	Short-chain PFCA	419.36	-	809.54	0.00	100%
	∑PFSA	90.21	-	32.25	36.60	59%
	Long-chain PFSA	0.00	-	n.d.	0.00	n.d.
	Short-chain PFSA	90.21	-	32.25	36.60	59%
	∑PreFOS	79.13	-	2.11	11.45	86%
	∑PFAS	618.11	-	873.06	458.74	26%

E. Sørmo et al. (2023). The decomposition and emission factors of a wide range of PFAS in diverse, contaminated organic waste fractions undergoing dry pyrolysis. Journal of Hazardous Materials 454, 131447.

Mass flow of OPFRs in Norway (kg d.w./y)



Most ends up on soil

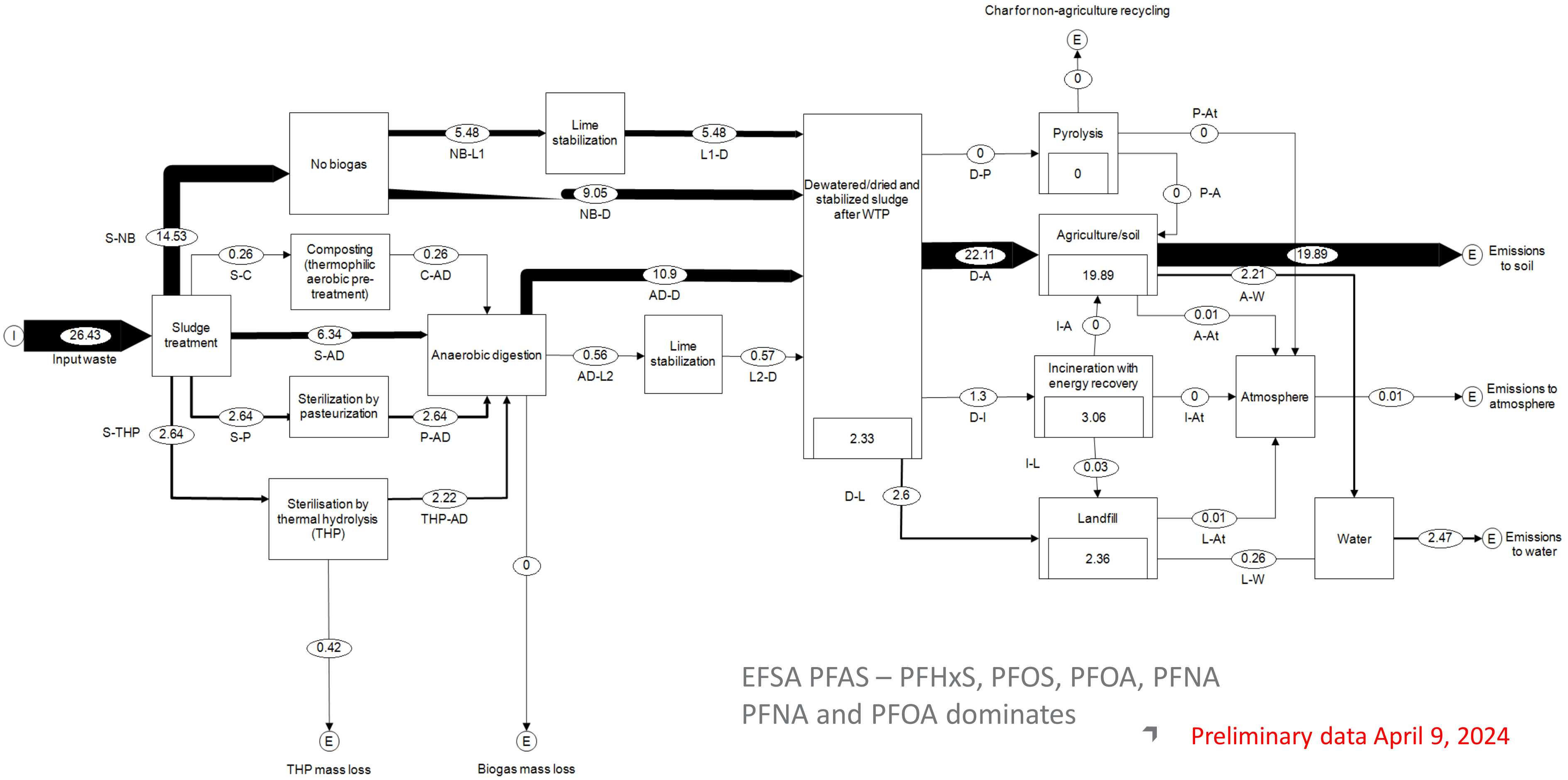
Losses due to anaerobic degradation

Losses due to THP

Losses due to incineration

Preliminary data April 9, 2024

Mass Flow of EFSA PFAS in Norway (kg d.w./y)

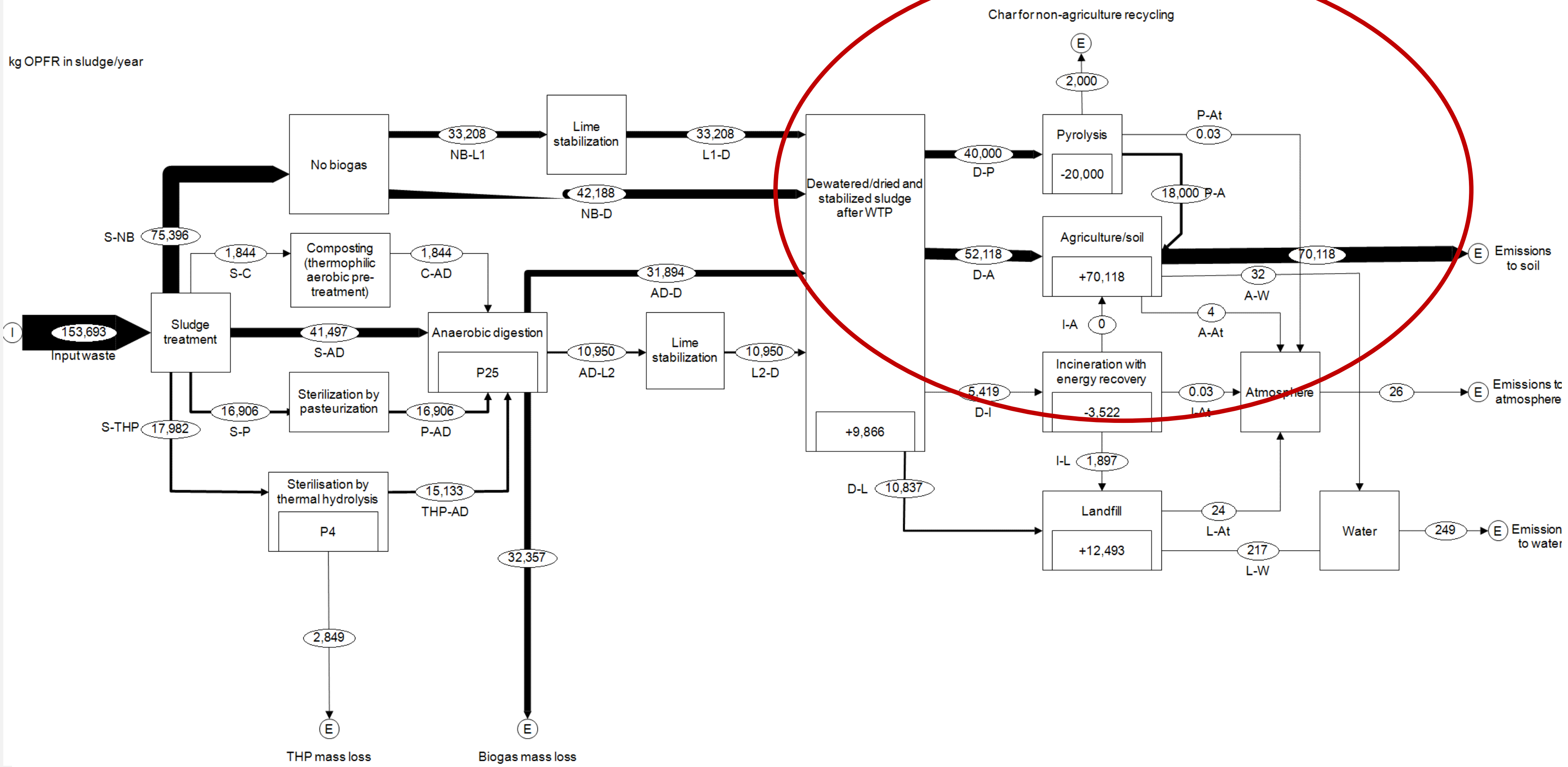


EFSA PFAS – PFHxS, PFOS, PFOA, PFNA

PFNA and PFOA dominates

Preliminary data April 9, 2024

Imagine a future with pyrolysis …



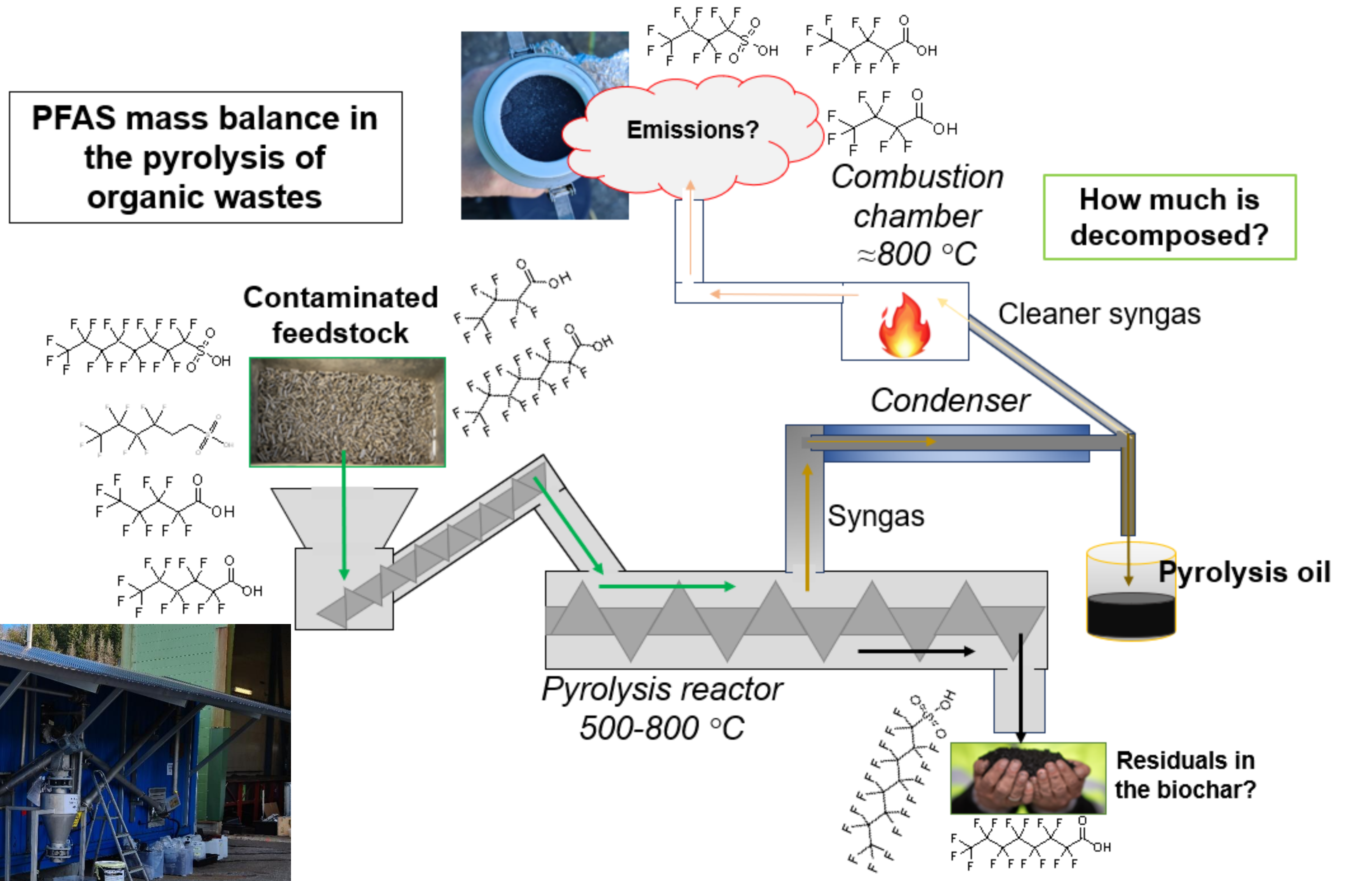
Biogreen by ETIA Ecosolutions (VOW ASA)

- Full-scale relevant, 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

What happens to PFAS and other organic contaminants in full-scale pyrolysis?



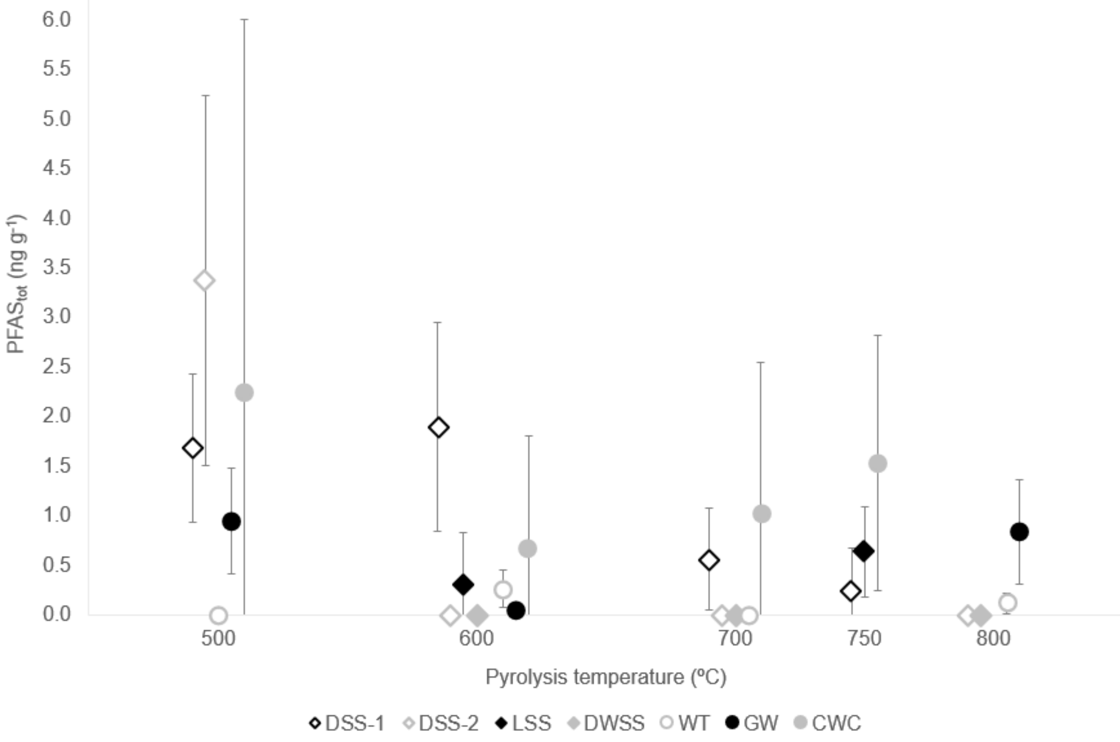
Source: Sørmo et al (2023) JHazMat

Photo: NGI

PFAS-residuals were found in the biochar

Source: Sørmo et al (2023) JHazMat

- PFAS decreased by factors of 10 – 1000, more loss with increasing temp dependence
- 60-100% fewer congeners
- Shift towards long chain PFAS (>6xCF_2)



Digested sewage sludge (DSS-1 and DSS-2), limed sewage sludge (LSS), de-watered sewage sludge (DWSS), food waste reject (FWR), waste timber (WT), garden waste (GW), & wood chips from forestry (CWC)

PFAS Emissions from pyrolysis to air (without a scrubber)

		DSS-1			DSS-2				LSS	
		500	**600**	**700**	**500**	**600**	**700**	**800**	**600**	**750**
Emission conc. (ng m^{-3})		59 ± 23	217 ± 110	96 ± 62	0.6 ± 0.8	27 ± 23	7.4 ± 0.5	20 ± 1	9.6 ± 0.5	12 ± 2
EF (mg tonne^{-1})		**0.2 ± 0.1**	**3.1 ± 1.6**	**1.2 ± 0.8**	**0.01 ± 0.02**	**0.9 ± 0.8**	**0.32 ± 0.02**	**0.7 ± 0.1**	**0.0010 ± 0.0005**	**0.9 ± 0.2**
Fractions	Gaseous (%)	97	94	88	0	87	0	55	0	0
	Particles (%)	3	6	12	100	13	100	45	100	100

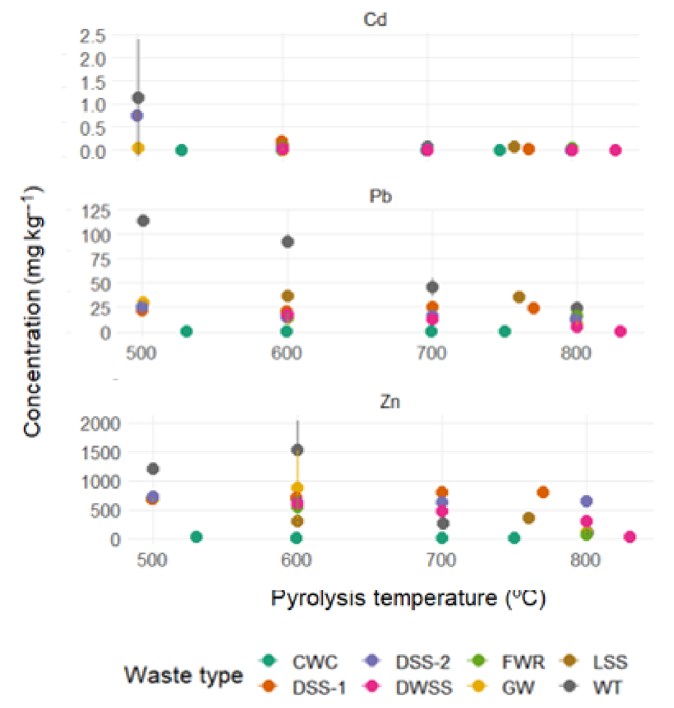
Adapted from: Sørmo et al (2023) JHazMat

Digested sewage sludge (DSS-1 and DSS-2) & limed sewage sludge (LSS)

- Some PFAS are emitted
  - 0.01 to 3.1 mg tonne-1 of biochar produced
  - Account for up to 2.8 % of analysed PFAS total mass
  - Dominated by short chain PFAS

Heavy metal concentrations in biochars reduced by increasing pyrolysis temperature

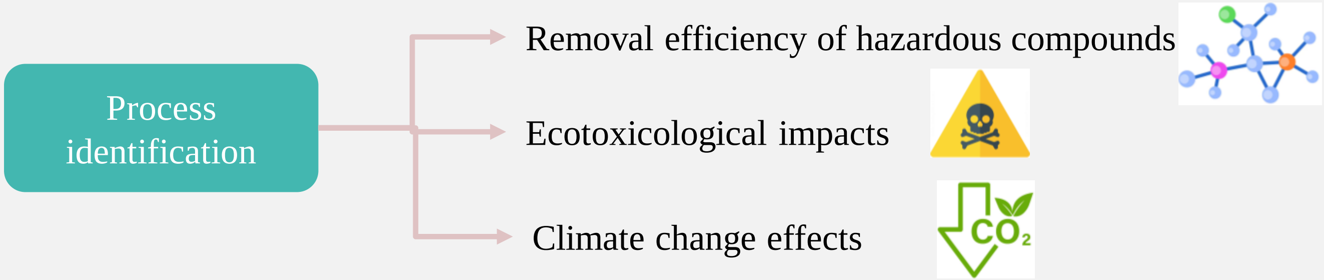
- Cd most easily volatilized
  - <0.2 mg kg^{-1} left in biochar made at ≥600 °C
- Volatilization of Pb and Zn at ≥700°C
  - Matrix dependent



Source: Sørmo et al (submitted)

NGI

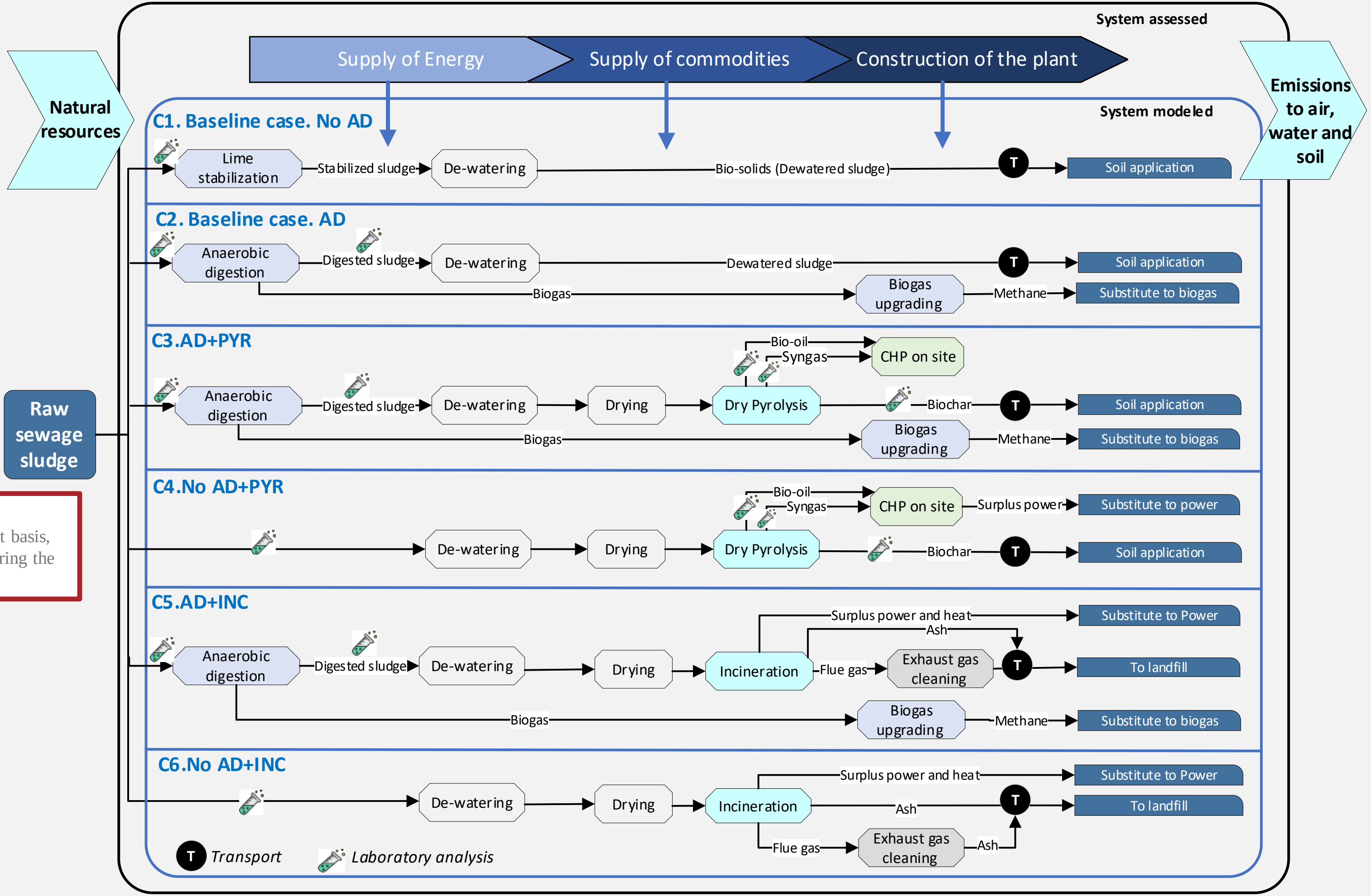
Toxicological, Ecotoxicological and Climate change impacts of thermal treatments



Process identification

- Removal efficiency of hazardous compounds
- Ecotoxicological impacts
- Climate change effects

Life Cycle Assesssment System Boundary and Functional unit



System assessed

Natural resources

Supply of Energy

Supply of commodities

Construction of the plant

Emissions to air, water and soil

System modeled

Raw sewage sludge

C1. Baseline case. No AD

Lime stabilization → Stabilized sludge → De-watering → Bio-solids (Dewatered sludge) → T → Soil application

C2. Baseline case. AD

Anaerobic digestion → Digested sludge → De-watering → Dewatered sludge → T → Soil application

Biogas → Biogas upgrading → Methane → Substitute to biogas

C3.AD+PYR

Anaerobic digestion → Digested sludge → De-watering → Drying → Dry Pyrolysis

Bio-oil, Syngas → CHP on site

Biochar → T → Soil application

Biogas → Biogas upgrading → Methane → Substitute to biogas

C4.No AD+PYR

De-watering → Drying → Dry Pyrolysis

Bio-oil, Syngas → CHP on site → Surplus power → Substitute to power

Biochar → T → Soil application

C5.AD+INC

Anaerobic digestion → Digested sludge → De-watering → Drying → Incineration

Surplus power and heat → Substitute to Power

Ash → T

Flue gas → Exhaust gas cleaning → T → To landfill

Biogas → Biogas upgrading → Methane → Substitute to biogas

C6.No AD+INC

De-watering → Drying → Incineration

Surplus power and heat → Substitute to Power

Ash → T → To landfill

Flue gas → Exhaust gas cleaning → Ash → T

T *Transport*

Laboratory analysis

FU:
1 ton of raw SS (wet basis, 75% moisture) entering the process alternatives

Hazardous Organic compounds (HOCs) and Heavy metals evaluated in the LCA

OPFRs (Organosphosphate flame retardants)

21 OPFRs included

Bisphenols

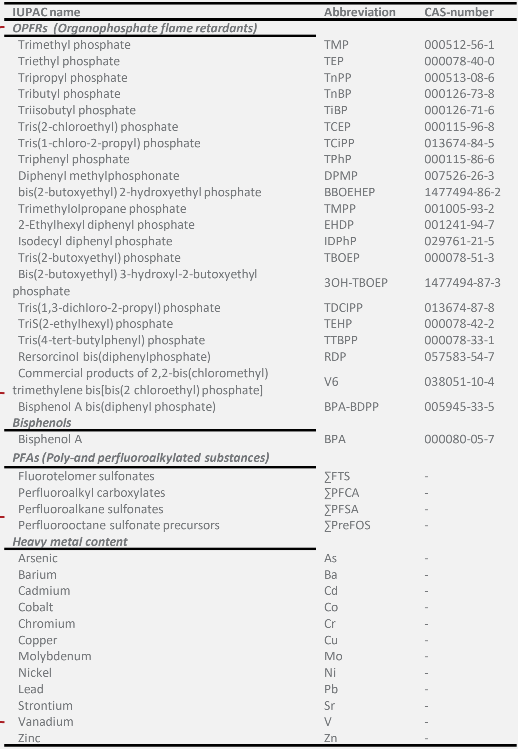
1 Bisphenol included

PFAS (Poly-and perfluoroalkylated substances)

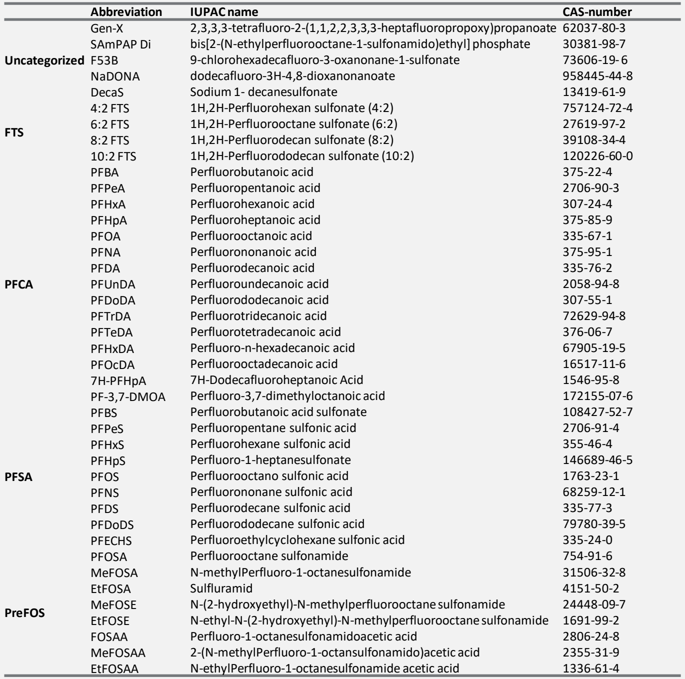
41 PFAs included

HMs (Heavy metals)

12 HMs included

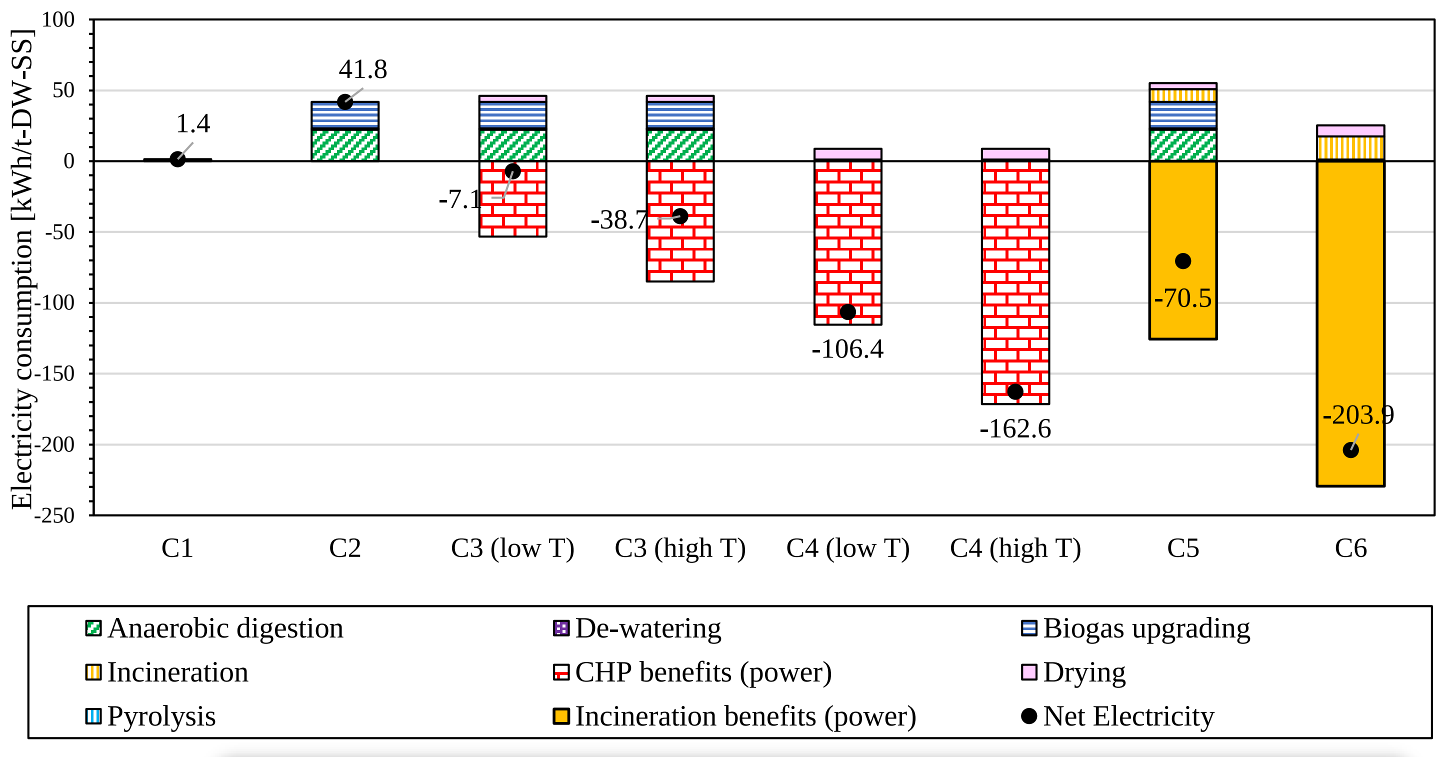


IUPAC name	Abbreviation	CAS-number
OPFRs (Organophosphate flame retardants)		
Trimethyl phosphate	TMP	000512-56-1
Triethyl phosphate	TEP	000078-40-0
Tripropyl phosphate	TnPP	000513-08-6
Tributyl phosphate	TnBP	000126-73-8
Triisobutyl phosphate	TiBP	000126-71-6
Tris(2-chloroethyl) phosphate	TCEP	000115-96-8
Tris(1-chloro-2-propyl) phosphate	TCiPP	013674-84-5
Triphenyl phosphate	TPhP	000115-86-6
Diphenyl methylphosphonate	DPMP	007526-26-3
bis(2-butoxyethyl) 2-hydroxyethyl phosphate	BBOEHEP	1477494-86-2
Trimethylolpropane phosphate	TMPP	001005-93-2
2-Ethylhexyl diphenyl phosphate	EHDP	001241-94-7
Isodecyl diphenyl phosphate	IDPhP	029761-21-5
Tris(2-butoxyethyl) phosphate	TBOEP	000078-51-3
Bis(2-butoxyethyl) 3-hydroxyl-2-butoxyethyl phosphate	3OH-TBOEP	1477494-87-3
Tris(1,3-dichloro-2-propyl) phosphate	TDCIPP	013674-87-8
TriS(2-ethylhexyl) phosphate	TEHP	000078-42-2
Tris(4-tert-butylphenyl) phosphate	TTBPP	000078-33-1
Rersorcinol bis(diphenylphosphate)	RDP	057583-54-7
Commercial products of 2,2-bis(chloromethyl) trimethylene bis[bis(2 chloroethyl) phosphate]	V6	038051-10-4
Bisphenol A bis(diphenyl phosphate)	BPA-BDPP	005945-33-5
Bisphenols		
Bisphenol A	BPA	000080-05-7
PFAs (Poly-and perfluoroalkylated substances)		
Fluorotelomer sulfonates	∑FTS	-
Perfluoroalkyl carboxylates	∑PFCA	-
Perfluoroalkane sulfonates	∑PFSA	-
Perfluorooctane sulfonate precursors	∑PreFOS	-
Heavy metal content		
Arsenic	As	-
Barium	Ba	-
Cadmium	Cd	-
Cobalt	Co	-
Chromium	Cr	-
Copper	Cu	-
Molybdenum	Mo	-
Nickel	Ni	-
Lead	Pb	-
Strontium	Sr	-
Vanadium	V	-
Zinc	Zn	-

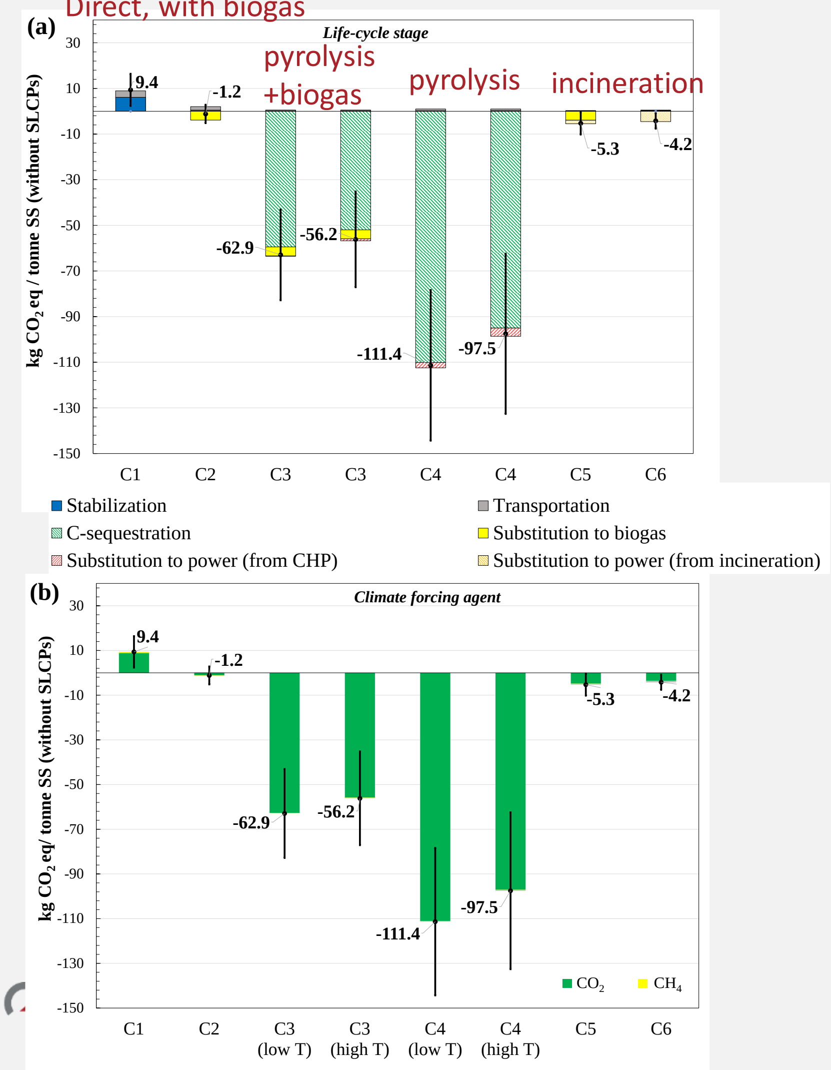


	Abbreviation	IUPAC name	CAS-number
Uncategorized	Gen-X	2,3,3,3-tetrafluoro-2-(1,1,2,2,3,3,3-heptafluoropropoxy)propanoate	62037-80-3
	SAmPAP Di	bis[2-(N-ethylperfluorooctane-1-sulfonamido)ethyl] phosphate	30381-98-7
	F53B	9-chlorohexadecafluoro-3-oxanonane-1-sulfonate	73606-19- 6
	NaDONA	dodecafluoro-3H-4,8-dioxanonanoate	958445-44-8
	DecaS	Sodium 1- decanesulfonate	13419-61-9
FTS	4:2 FTS	1H,2H-Perfluorohexan sulfonate (4:2)	757124-72-4
	6:2 FTS	1H,2H-Perfluorooctane sulfonate (6:2)	27619-97-2
	8:2 FTS	1H,2H-Perfluorodecan sulfonate (8:2)	39108-34-4
	10:2 FTS	1H,2H-Perfluorododecan sulfonate (10:2)	120226-60-0
PFCA	PFBA	Perfluorobutanoic acid	375-22-4
	PFPeA	Perfluoropentanoic acid	2706-90-3
	PFHxA	Perfluorohexanoic acid	307-24-4
	PFHpA	Perfluoroheptanoic acid	375-85-9
	PFOA	Perfluorooctanoic acid	335-67-1
	PFNA	Perfluorononanoic acid	375-95-1
	PFDA	Perfluorodecanoic acid	335-76-2
	PFUnDA	Perfluoroundecanoic acid	2058-94-8
	PFDoDA	Perfluorododecanoic acid	307-55-1
	PFTrDA	Perfluorotridecanoic acid	72629-94-8
	PFTeDA	Perfluorotetradecanoic acid	376-06-7
	PFHxDA	Perfluoro-n-hexadecanoic acid	67905-19-5
	PFOcDA	Perfluorooctadecanoic acid	16517-11-6
	7H-PFHpA	7H-Dodecafluoroheptanoic Acid	1546-95-8
	PF-3,7-DMOA	Perfluoro-3,7-dimethyloctanoic acid	172155-07-6
PFSA	PFBS	Perfluorobutanoic acid sulfonate	108427-52-7
	PFPeS	Perfluoropentane sulfonic acid	2706-91-4
	PFHxS	Perfluorohexane sulfonic acid	355-46-4
	PFHpS	Perfluoro-1-heptanesulfonate	146689-46-5
	PFOS	Perfluorooctano sulfonic acid	1763-23-1
	PFNS	Perfluorononane sulfonic acid	68259-12-1
	PFDS	Perfluorodecane sulfonic acid	335-77-3
	PFDoDS	Perfluorododecane sulfonic acid	79780-39-5
	PFECHS	Perfluoroethylcyclohexane sulfonic acid	335-24-0
PreFOS	PFOSA	Perfluorooctane sulfonamide	754-91-6
	MeFOSA	N-methylPerfluoro-1-octanesulfonamide	31506-32-8
	EtFOSA	Sulfluramid	4151-50-2
	MeFOSE	N-(2-hydroxyethyl)-N-methylperfluorooctane sulfonamide	24448-09-7
	EtFOSE	N-ethyl-N-(2-hydroxyethyl)-N-methylperfluorooctane sulfonamide	1691-99-2
	FOSAA	Perfluoro-1-octanesulfonamidoacetic acid	2806-24-8
	MeFOSAA	2-(N-methylPerfluoro-1-octansulfonamido)acetic acid	2355-31-9
	EtFOSAA	N-ethylPerfluoro-1-octanesulfonamide acetic acid	1336-61-4

Energy



Thermal treatments (Pyrolysis and Incineration) result on power benefits.



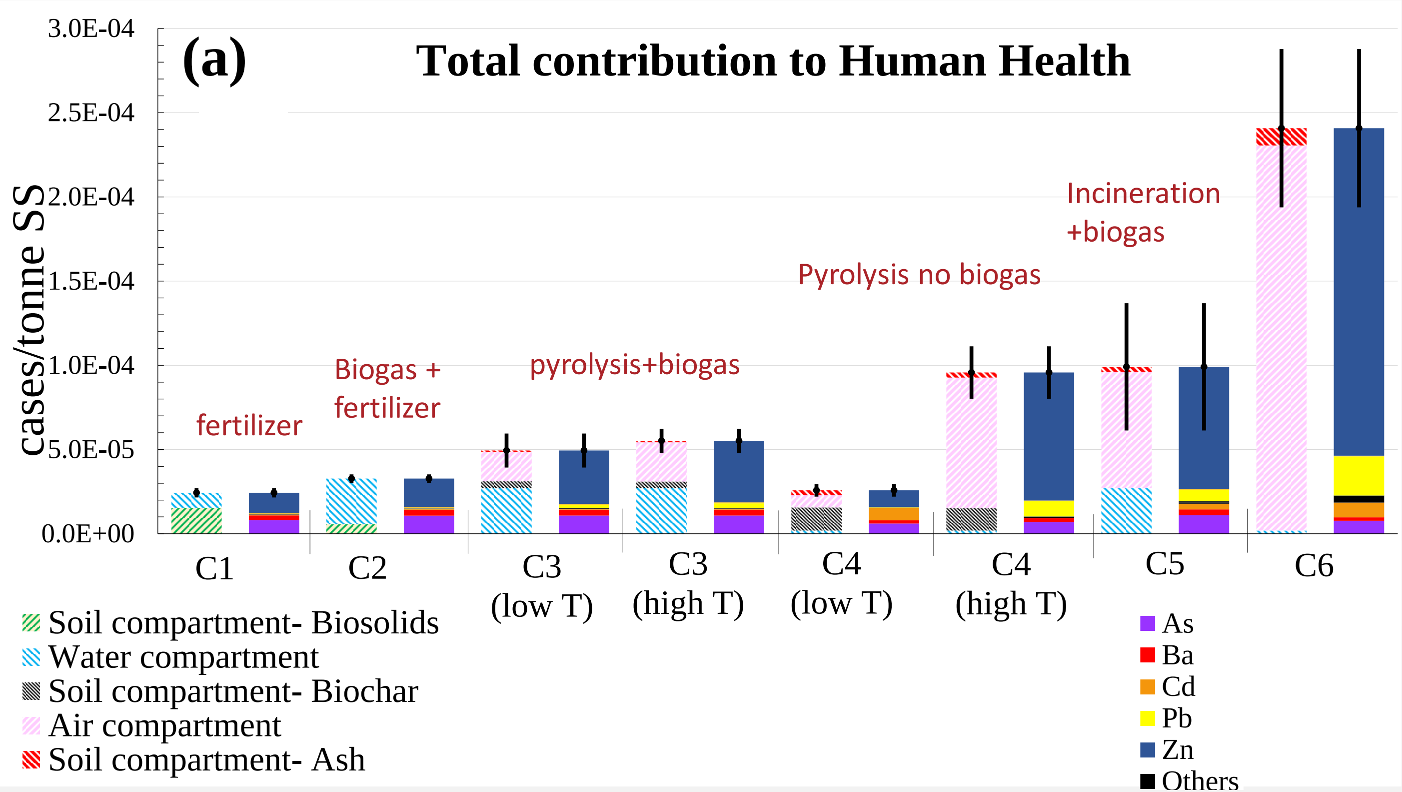
Climate change (GWP100)

Pyrolisis benefits

- ✓ Negative climate change effects.
- ✓ Climate change benefits from:
  - ✓ Biochar: carbon capture and storage
  - ✓ Energetic products: power and biogas substitution.

Black dots represent the net GWP100 impacts, and the whiskers show uncertainty range from Monte-Carlo analysis (± Standard deviation).

Toxicity to Human Health (non-cancer effects)



fertilizer

Biogas + fertilizer

pyrolysis+biogas

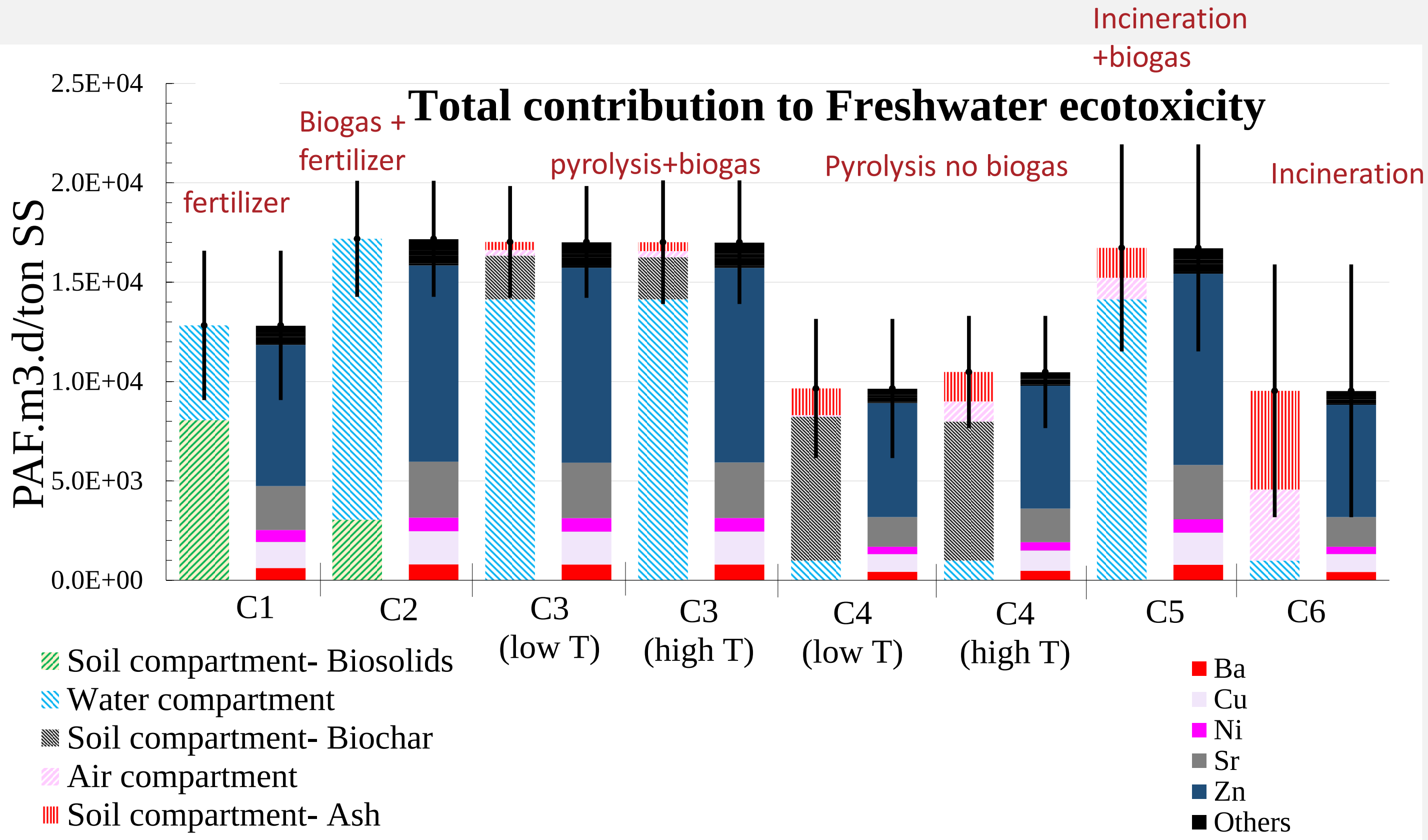
Pyrolysis no biogas

Incineration +biogas

Incineration

Human toxicity due to air emissions of heavy metals (can be reduced by scrubbing)

Freshwater Ecotoxicity



Freshwater Ecotoxicity

fertilizer

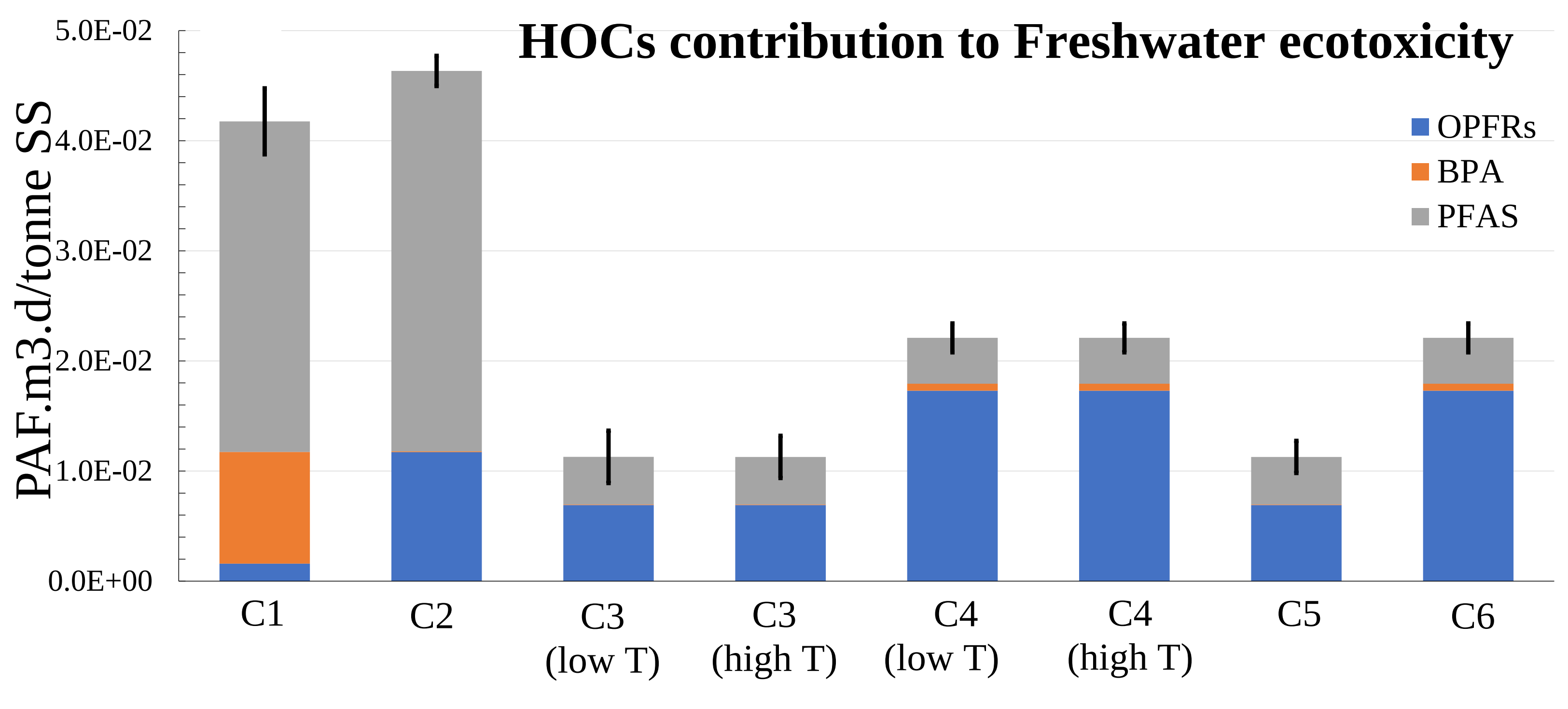
Biogas + fertilizer

pyrolysis+biogas

Pyrolysis no biogas

Incineration +biogas

Incineration



NGI

Key findings on climate change and toxicity impacts

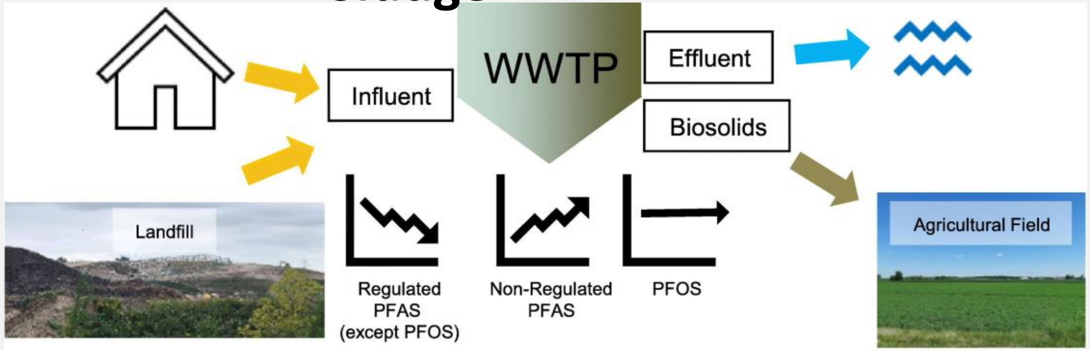
- Pyrolysis without AD represents the most eco-friendly treatment for sewage sludge
  - Negative climate change impacts.
  - C-storage (Biochar)
  - Energy benefits
  - Reduce contaminants and ecotoxicological impacts.

- However – burden shifting from hazardous metals releases to air (recommend to use a air scrubber, pyrolyse outside urban centers)

Sludge in a circular economy

Source control matters

Sludge

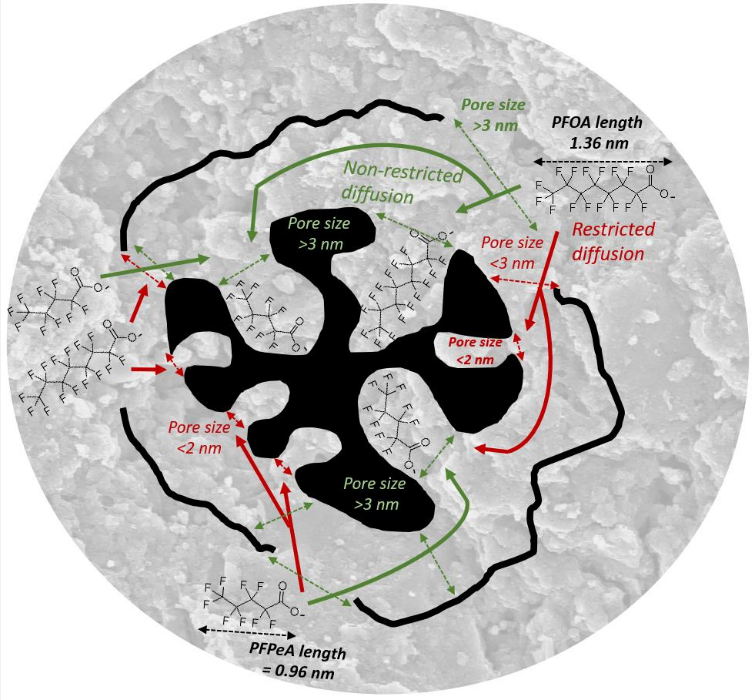


- Gewurtz et al STOTEN 2024
- Decreasing trends for other persistent pollutants in Zennegg, Environ. Int. 60, 202–208. https://doi.org/10.1016/j.envint.2013.08.020

- Chemicals that become regulated tend to decrease in sludge over time
- New contaminants introduced to the market increase over time
- Hazardous metals and persistent organic substances are a chronic issue

Several markets for pyrolysed sludge in a circular economy

- Fertilizer (phosphorous retention)
- As a PFAS sorbent at PFAS polluted sites/WWTP
- Replacement for coal in cement or metallurgy



Recommendations

The best solution is local, and depends on contaminants in the sludge, need for phosphorous, climate mitigation targets, goals towards zero pollution and ability for innovation. New thermal technologies can have a role.

Recommendations *inspired* by EurEau (2021) are:

1. **Control at source** (prevent pollution from entering sludge, e.g. PFAS restriction) *is the most important part* of sludge management (see: REVAQ system in Sweden)
2. **Biosolids have a role, as do pyrolyzed biosolids**, for agriculture and land reclamation in a climate mitigating way (particularly if chemical risks are low)
3. **Risk assessment for chemicals is important**
4. **Incineration / co-combustion only in extreme situations**: if chemical risks are unacceptable, phosphorous not needed locally, land application not feasible, etc.
5. **Innovation** towards zero pollution should not be hindered by over-complex/contradicting regulation

May 2021

Briefing note

EurEau

Waste water treatment – sludge management

A regulatory framework is needed to support sustainable and resilient sludge management, incorporating a broader scope for risk assessment and strict sludge quality control.

SLUDGEFFECT in a nut shell

- Reduce pollutants upstream
- Pyrolyse more (with gas scrubing) for climate benefits and diverse uses of sludge-char in a circular economy
- Areas affected by contaminants will receive most benefit from generating sludge char (e.g. removal of PFAS, use of char for PFAS remediation or other markets)
- Lots of potential for green investment but needs regulatory clarity

Thank-you!

Funding : SLUDGEFFECT: The Research Council of Norway, Project No. 302371

Researchers

- *NGI:* Hans Peter H. Arp (PI), Sarah Hale, Gerard Cornelissen, Erlend Sørmo, Heidi Knutsen, Mari Løseth
- ***NTNU***: Hans Peter H. Arp, Alexandros Asimakopoulos, Gabriela Castro, Otavio Cavalett, Francesco Cherubini, Junjie Zhang, Marjorie Morales + over 20 MSc students ☺
- ***Chalmers (Gothenberg, Sweden)***: Gregory Peters
- ***IDAEA-CSIC (Barcelona, Spain):*** Damia Barcelo, Antoni Ginebreda Martí

National regulators

- ***Norwegian Environment Agency (Miljødiretoratet)*** – Vanessa Korsbakken Ivanov
- ***Norwegian Food Safety Authority (Mattilsynet)*** – Anne Synnøve Bøen

Industry

- ***Lindum*** – Thomas Hartnik, Katinka Krahn
- ***Norsirk*** – Idar André Haselrud
- ***Scanship AS*** – Pål Jahrne Nilsen, Nataliia Kasian, Oda Svennevik
- ***REVAC*** – Kay Riksfjord

Waste water sector

- ***VEAS IKS*** – Kirsti Grundness Berg, Rune Holmstad
- ***Trondheim Kommune*** – Frank Batey

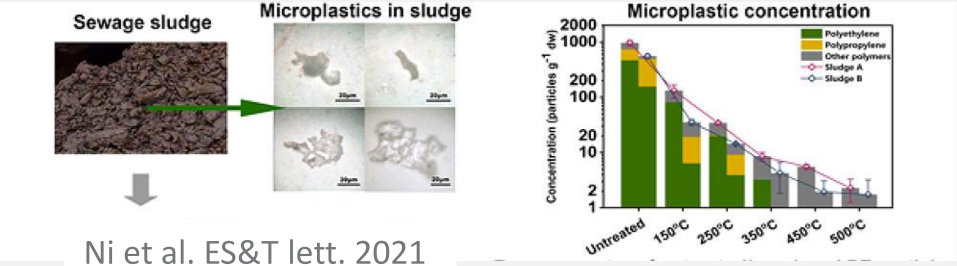
Funding

- ***The Research Council of Norway*** – Inger Austrem

Thank you!

Contaminants and thermal treatment

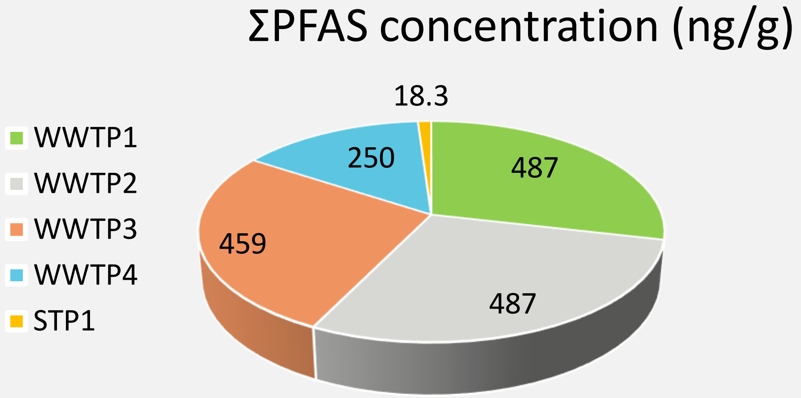
Contaminant	Reaction to sludge incineration/pyrolsis	Ref
PAHs / dioxins	Formed to a varying degrees. High temperature and long times tends to give less PAHs/dioxins, low temperature processes (e.g. gasification) tend to produce more. Often strongly sorbed to chars/soots (limited bioavailability).	Hale et al. ES&T 2012
Heavy metals	Some lost to flue gas, remainder is enriched in the ash/char. Bioavailability tends to decrease though treatment dependant (incineration -> insoluble oxides, pyrolysis increases pH to insoluble oxidation states)	Kahn et al. ES&T 2012
Microplastics	Converted to volatiles (e.g. monomers) or mineralized by 500 ˚C given enough time (more efficient at higher temp)	Ni et al. ES&T lett. 2021
PFAS	Converted to volatiles or mineralized to CO_2/chars starting at 600 ˚C given enough time (more efficient at higher temp)	Simon & Kaminsky (1998)
Other organic contaminants	Converted to volatiles (e.g. monomers) or mineralized by 500 ˚C given enough time (more efficient at higher temp)	SLUDGEFFECT



Ni et al. ES&T lett. 2021

Per- and polyfluoroalkyl substances (PFAS)

- **Occurrence of PFAS in Norwegian digested sludge**



Median WWTP1-WWTP2	Concentration (ng/g)	
Analyte	This study	PFAS in the nordic sludge 2017
PFOA	10.56	1.18-1.29
PFBA	0.75	<0.04
PFPeA	1.84	<0.04
PFNA	79.67	0.56-0.67
PFDoDA	5.23	n.d. - 1.10
PFOS	0.90	2.60-2.82
PFPeS	0.86	<0.04
Gen-X	9.47	NA
6:2 FTS	0.01	0.06-0.1

100% DF for **FTS (4:2, 6:2, 8:2, 10:2)**, **PFHpS** and **PFOS** in digested sludge.

Higher concentrations were detected in the WWTPs with primary treatment (WWTP1 and WWTP2).

Overview of thermal treatment recycling technology categories

Thermal treatment category	Description	Recycling Negatives ☹	Recycling Positives ☺
Monovalent Incineration	Dedicated sewage sludge incinerators	Carbon is lost, ash and flue gas management, air emissions*	energy recycling, P can be extracted (struvite)
Co-combustion	Combusting sludge with e.g. coal, municipal waste, cement kilns	Carbon is lost, fertilizer is lost, air emissions,* ash management unless cement	energy recycling, cement raw material
Wet-pyrolysis/ gasification	Heating wet sludge with no oxygen	Fertilizer is lost?, ash and flue gas management, air emissions	efficient for energy recapture (e.g. syngas & liquid fuel)
Dry-pyrolysis	Heating dry sludge with no oxygen	Heavy metals concentrate in fertilizer, air emissions	C-sequestration, fuel, bioavailable P concentrates

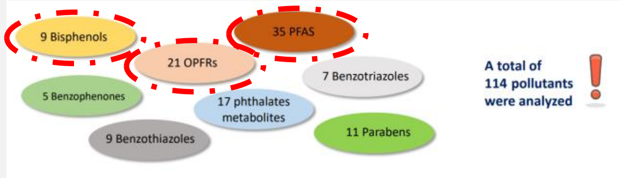
* Incinerators and co-combusters (also pyrolyzers?) need to fulfill air emission regulations, such as Directive 2010/75/EU and Directive 2001/80/EC

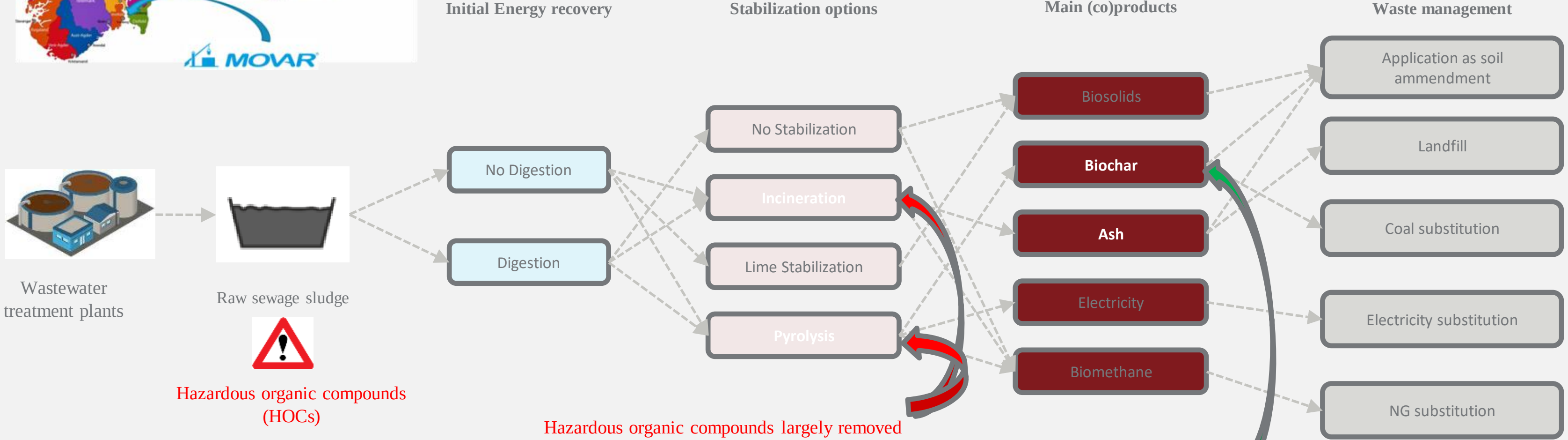
Further reading:
https://www.umweltbundesamt.de/en/publikationen/technical-guide-on-the-treatment-recycling-0
https://www.eureau.org/resources/news/545-key-to-a-circular-future

Summary – several benefits for pyrolysis to pursue

	Direct soil application	Incineration	HTC	Pyrolysis
Energy recovery	None	High	Medium	Medium
Carbon storage	Low	None	Medium?	High
Fertilizer/soil improvement	High/high	None	Medium/medium	Low/medium
Other benefits	-	None	Sorbents, fuel	Sorbents, coal substitute, fillers
Destruction of contaminants	None	High	Medium?	High
Emissions to soil	High	Low	Low	Low
Emissions to air	Low	High/medium	Low?	Medium
Emissions to water	High	Medium	Medium/low?	Low

Sludge management





Initial Energy recovery

Stabilization options

Main (co)products

Waste management

Wastewater treatment plants

Raw sewage sludge

Hazardous organic compounds (HOCs)

No Digestion

Digestion

No Stabilization

Incineration

Lime Stabilization

Pyrolysis

Biosolids

Biochar

Ash

Electricity

Biomethane

Application as soil ammendment

Landfill

Coal substitution

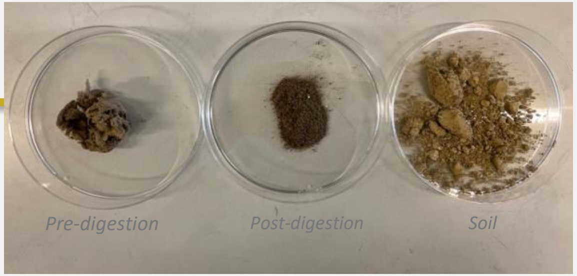
Electricity substitution

NG substitution

Hazardous organic compounds largely removed

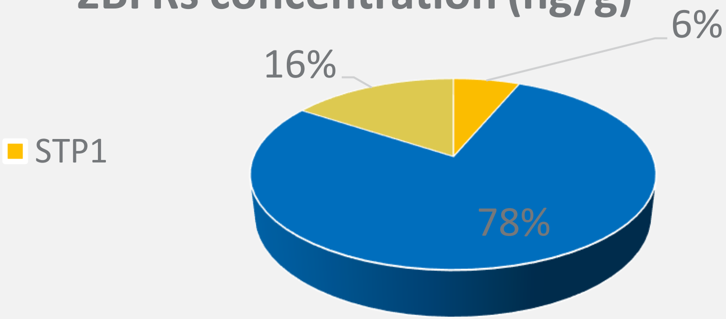
Eco-friendly product:
- Solution in terms of carbon sequestration → GHGs reductions

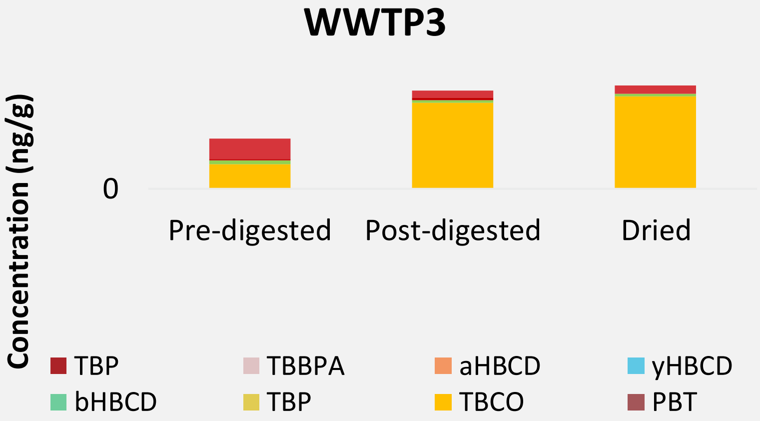
Brominated flame retardants (BFRs)



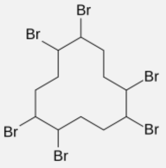
- Occurrence of BFRs in Norwegian digested sludge

ΣBFRs concentration (ng/g)



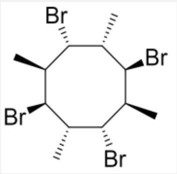


100% DF for HBB in digested sludge.
TBCO was found in the highest concentrations.

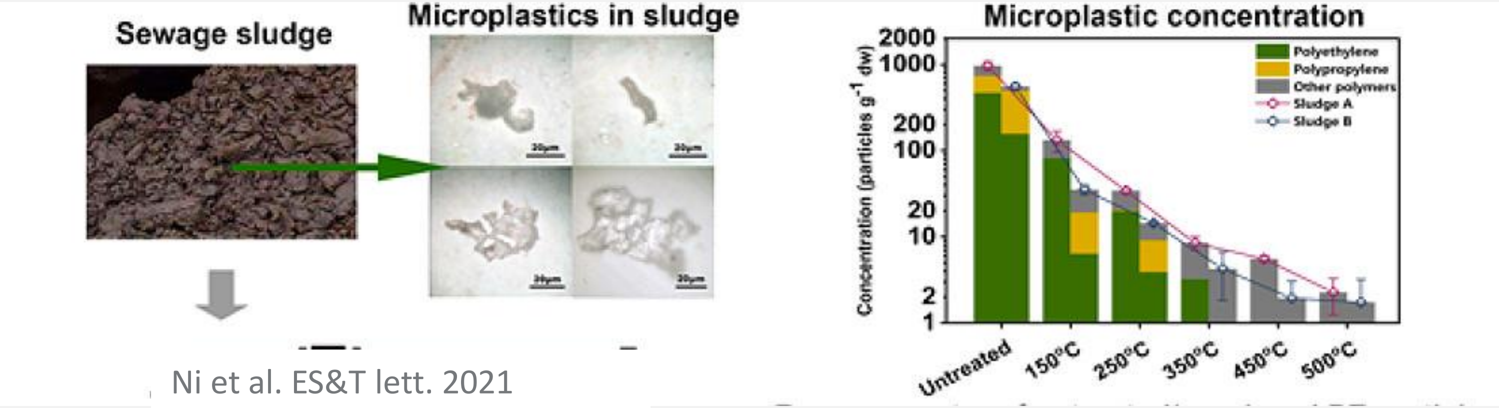


HBCD

Drop-in substitution?

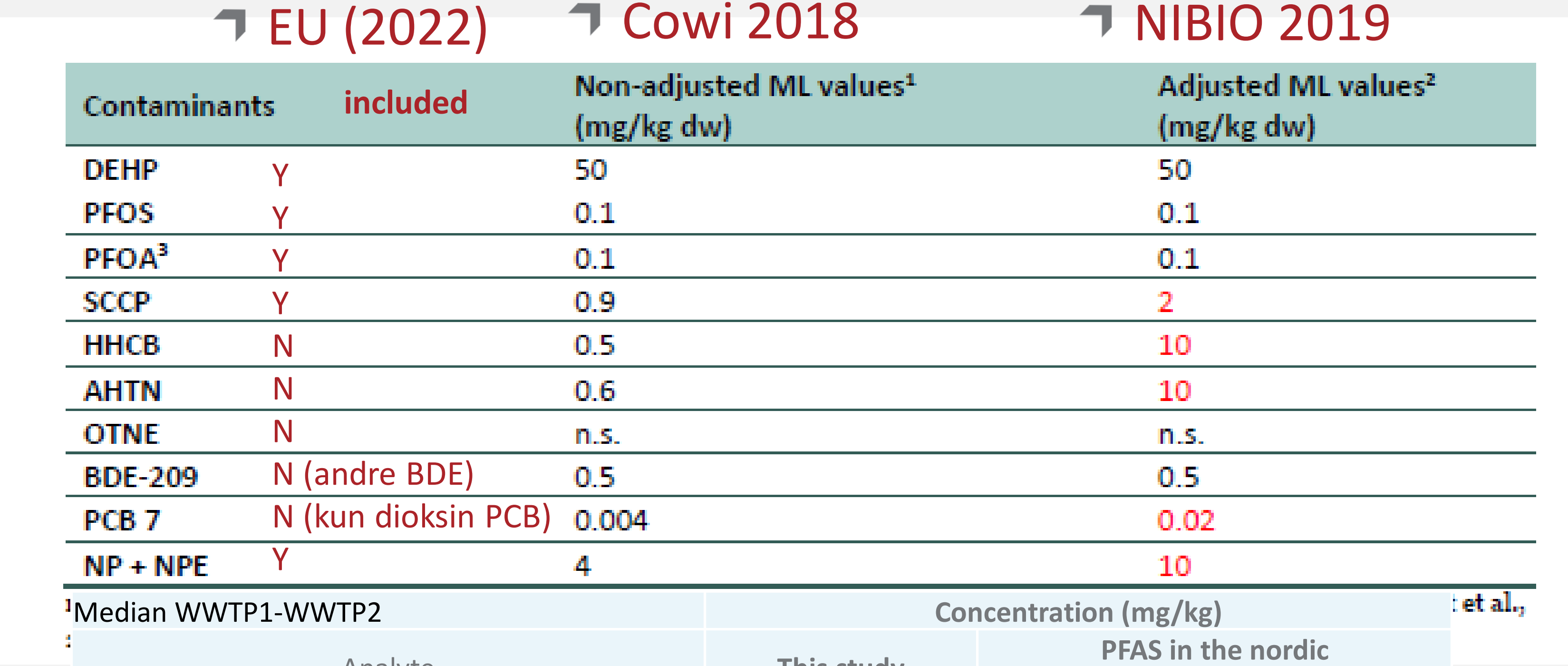


TBCO



Ni et al. ES&T lett. 2021

Proposed upper limits for contaminants in sluge in Norway



	EU (2022)	Cowi 2018	NIBIO 2019
Contaminants	included	**Non-adjusted ML values[1] (mg/kg dw)**	**Adjusted ML values[2] (mg/kg dw)**
DEHP	Y	50	50
PFOS	Y	0.1	0.1
PFOA[3]	Y	0.1	0.1
SCCP	Y	0.9	2
HHCB	N	0.5	10
AHTN	N	0.6	10
OTNE	N	n.s.	n.s.
BDE-209	N (andre BDE)	0.5	0.5
PCB 7	N (kun dioksin PCB)	0.004	0.02
NP + NPE	Y	4	10

Median WWTP1-WWTP2	Concentration (mg/kg)	
Analyte	This study	PFAS in the nordic sludge 2017
PFOA	0.011	0.001
PFOS	0.01	0.003

https://www.miljodirektoratet.no/publikasjoner/2019/november-2019/maximum-limit-values-for-selected-hazardous-organic-contaminants-hocs-in-secondary-raw-materials-used-in-fertilisers-and-soil-products/

NGI

#onsafeground

NORWEGIAN GEOTECHNICAL INSTITUTE
NGI.NO