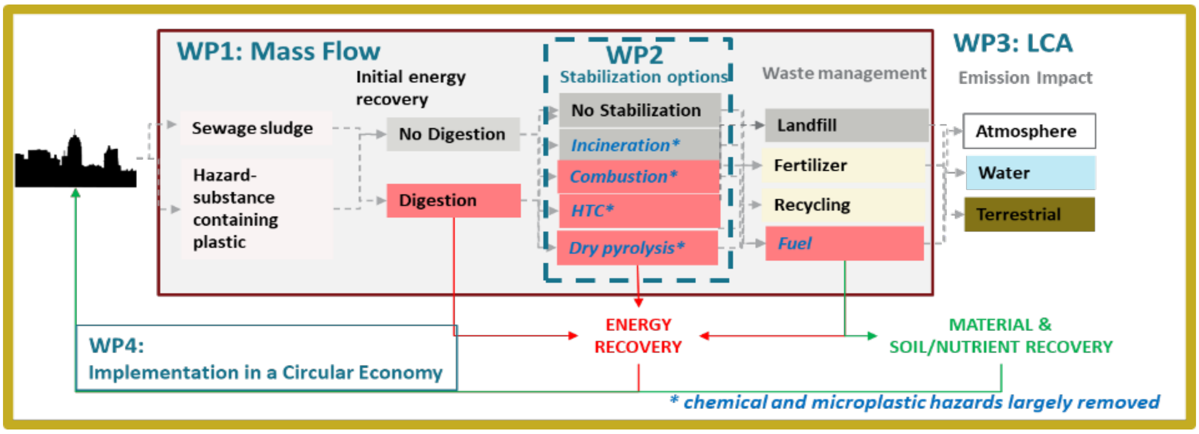
SLUDGEFFECT SYMPOSIUM

Towards mitigating hazardous substances in sludge and e-waste plastic

April 9, 2024 9:30-15:30



NTNU Trondheim: Room – Dragvoll Bygg 1 - 6: D1
Map: http://use.mazemap.com/?v=1&campuses=ntnu&sharepoitype=identifier&sharepoi=810-2305
Register: using this link

9:00-9:30 Teams link opens, Arrival at NTNU For Coffee
9:30-9:45 Welcome 😊

1. **Setting the Scene -** Hans Peter Arp NGI/NTNU

9:45-10:45 Part 1. Mass flow of contaminants in sludge in Norway

2. **Sludge Mass Flow in Norway –** Hans Peter Arp – 10 minutes
3. **Sludge Concentrations and Removal efficiencies in Norwegian WWTP -**Gabriela Castro, NTNU/USC – 30 minutes
4. **Sludge Contaminant Mass Flow in Norway -** Hans Peter Arp – 10 minutes
5. **Discussion –** 10 minutes

10:45-11:00 Coffee Break

11:00-11:45 Part 2. Effect of Pyrolysis on concentrations

6. **What happens to PFAS and other contaminants in organic waste when pyrolyzed into biochar? – 35 min** Erlend Sørmo, NGI and Gabriela Castro
7. **Discussion –** 15 min

11.45-12.30 Lunch Break

12:30-13:30 Part 3. Life Cycle Assessment of Sludge

8. **Comparison of environmental impacts of alternative sludge management/thermal treatment scenarios in Norway** Marjorie Morales & Francesco Cherubini NTNU – 40 min
9. **Discussion –** 20 min

13:30-14:15 Part 4. Mass Flow of Contaminants in E-waste in Norway

10. **E-waste concentrations –** Gabriela Castro– 15 min
11. **Mass flow of contaminants in Norwegian E-waste –** Mari Løseth, NGI - 20 min
12. **Discussion -** 10 min

14:15- 14:30 Coffee Break

14:30-15:30 Part 5. Implementation in a Circular Economy and General Discussion - Hans Peter Arp

The Research Council of Norway

SLUDGEFFECT was funded by the Research Council of Norway (Project 302371)
https://www.ngi.no/en/projects/sludgeffect/

Contact: Hans Peter Arp, hans.peter.arp@ngi.no

SLUDGEFFECT Symposium – Setting the Scene

Hans Peter Arp[1,2]

[1] Norwegian Geotechnical Institute (NGI), Oslo;
[2] Norwegian University of Science and Technology NTNU), Trondheim

SLUDGEFFECT Symposium
April 9, 2024

SLUDGEFFECT

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,
  - + so far 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

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

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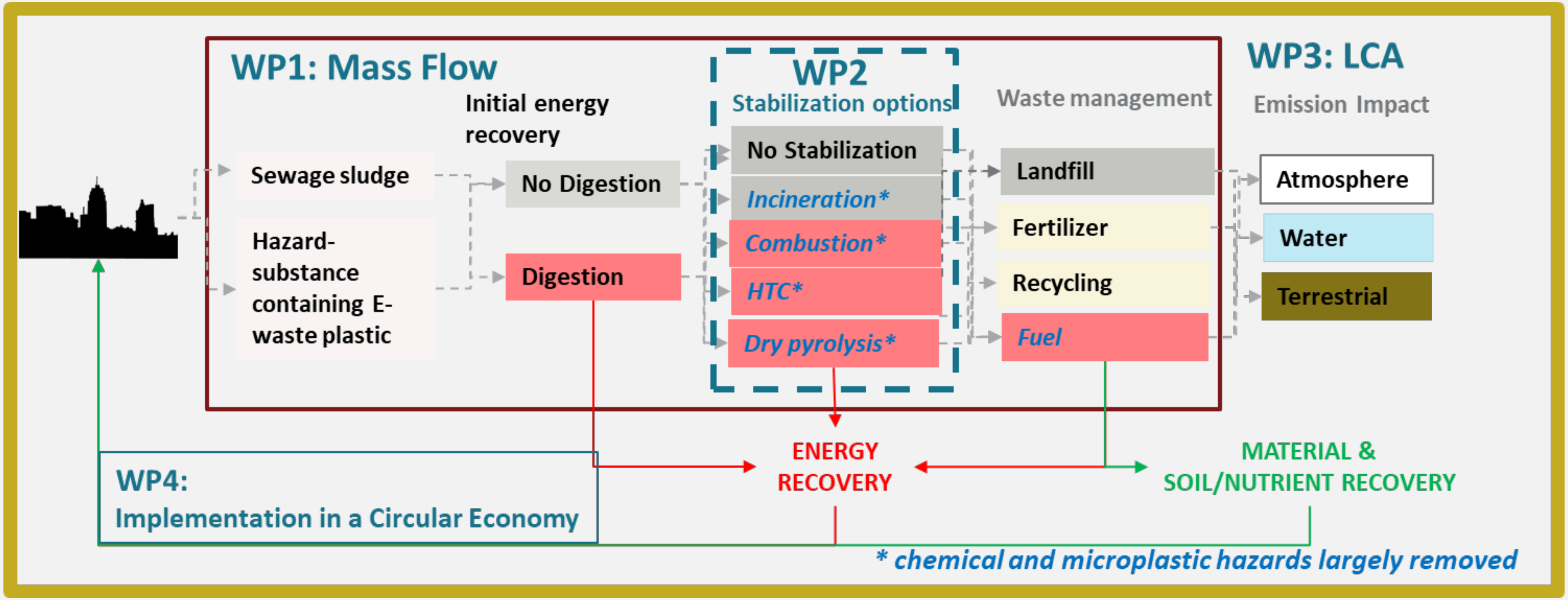
SLUDGEFFECT



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

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Years: 2020-2024

The Research Council of Norway

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

Why sludge and e-waste plastic?

- Hazard substances in sludge and e-waste cause problems for the circular economy: there is a dilemma between recycling valuable resources vs increasing exposure to toxic substances

- *If we can solve this dilemma for sewage sludge and e-waste plastic – we can solve this dilemma for anything!!!*

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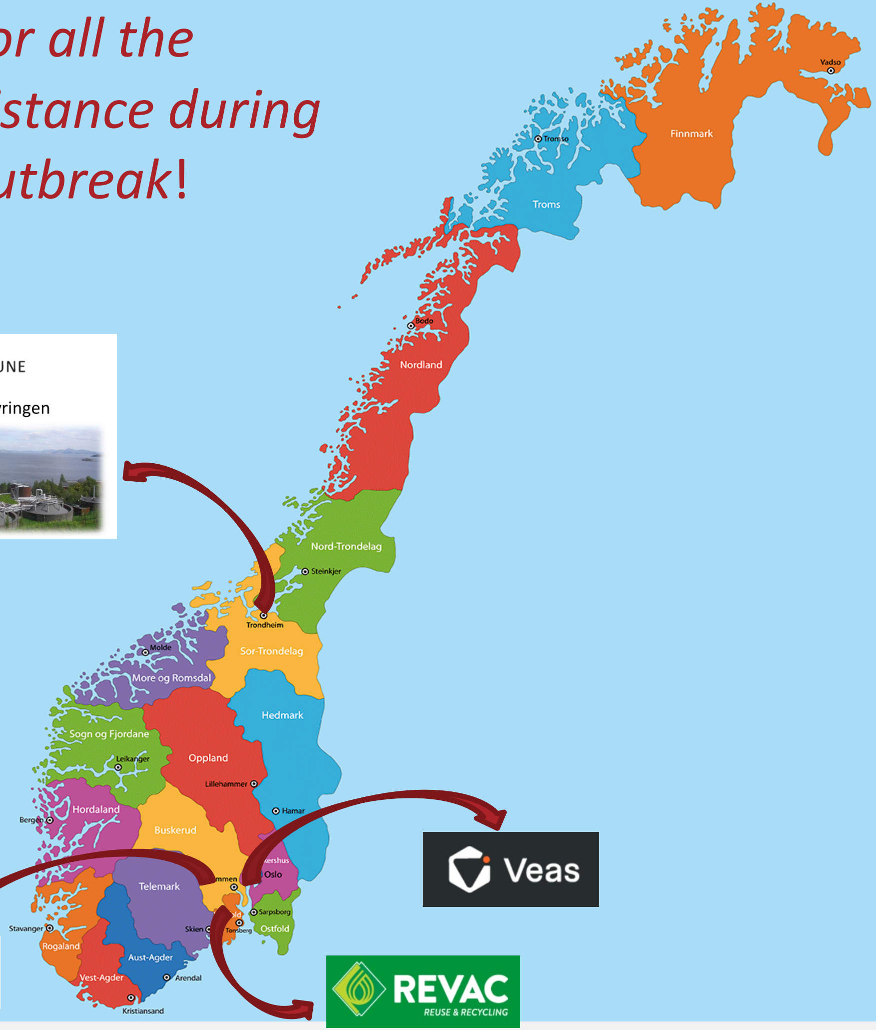
Overview

Thanks for all the sampling assistance during the Corona outbreak!

Sampling campaign

- Wastewater and sludge: 114 samples from 4 different STPs in Norway.
- Four seasons at Ladehammeren and Høvringen
- E-waste: 15 samples from 2 different plastic treatment facilities

TRONDHEIM KOMMUNE



Veas

Lindum

REVAC REUSE & RECYCLING

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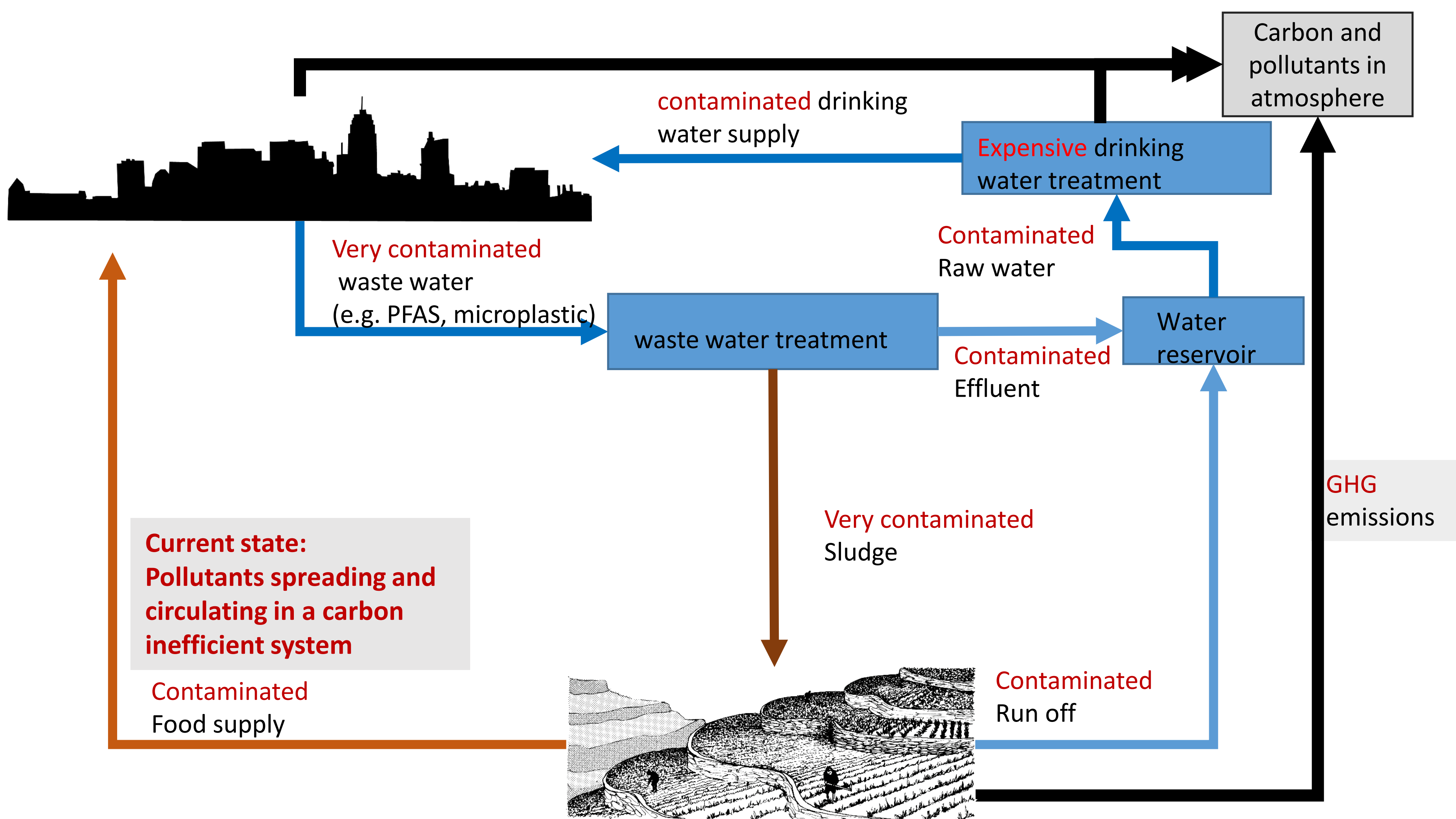
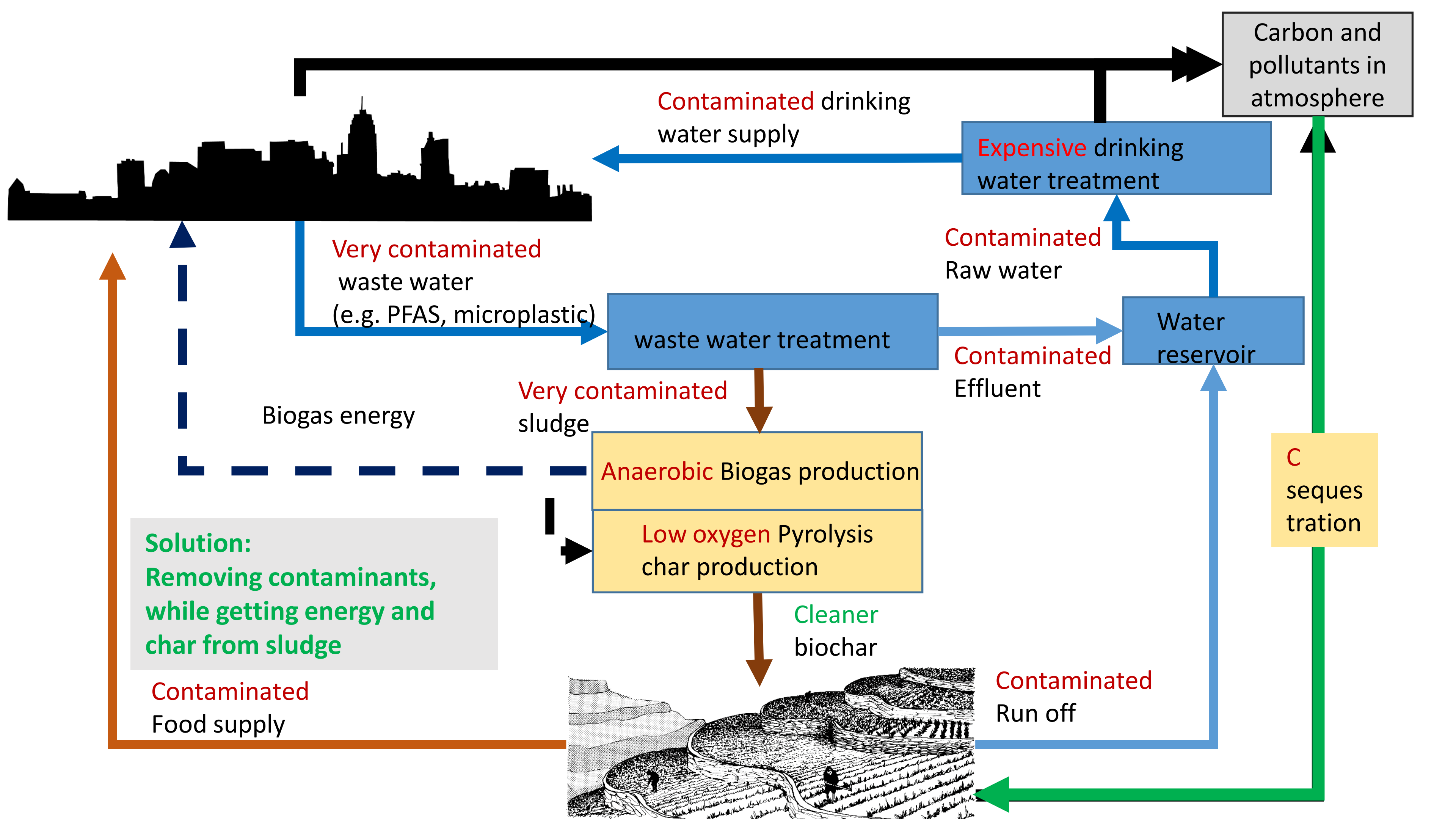
Sludge: Our starting hypothesis to the project



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



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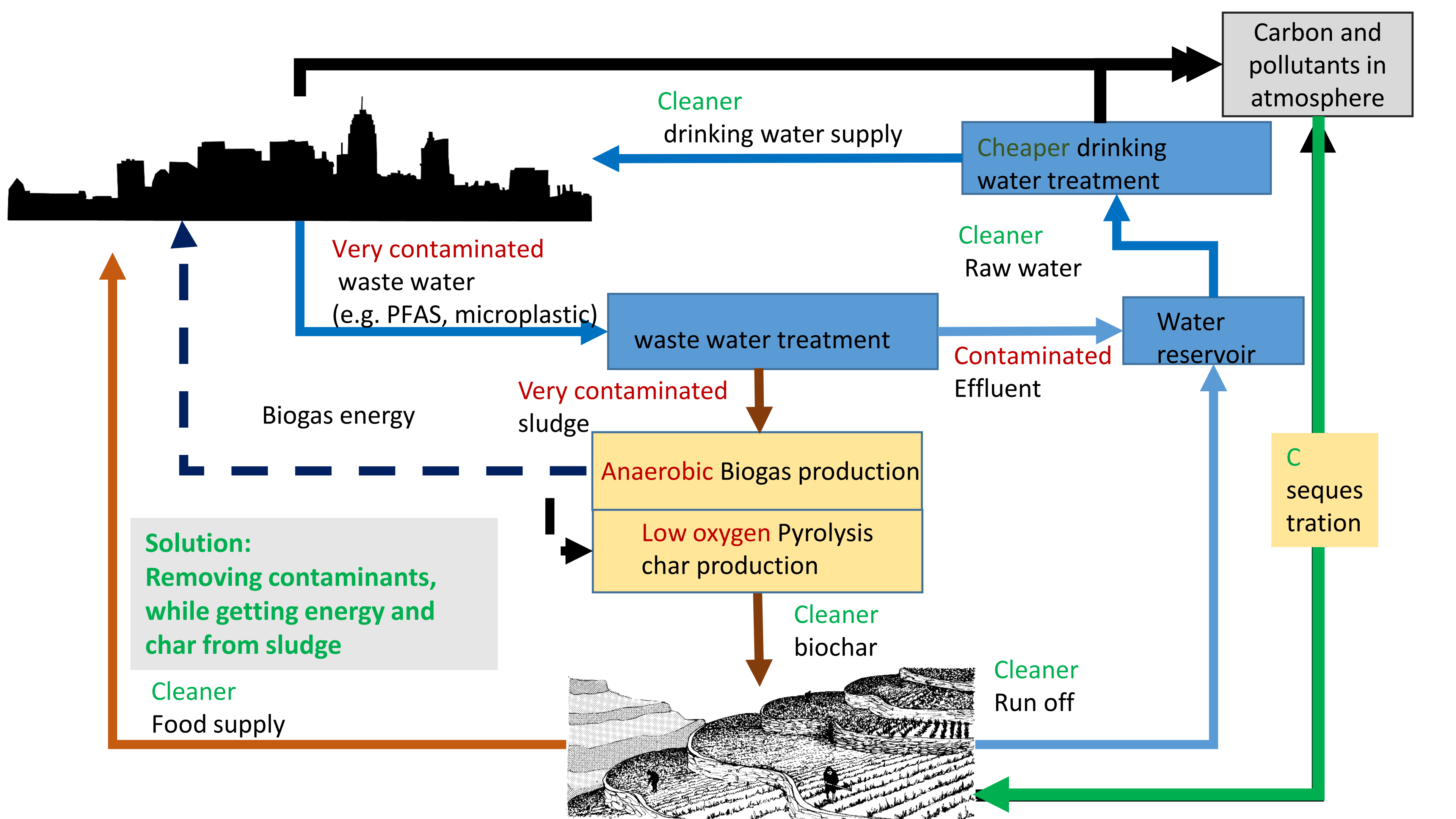
waste water treatment
Water reservoir
Contaminated Effluent
Very contaminated sludge
Biogas energy
Anaerobic Biogas production
Low oxygen Pyrolysis char production
C sequestration
Solution: Removing contaminants, while getting energy and char from sludge
Cleaner biochar
Contaminated Food supply
Contaminated Run off



Carbon and pollutants in atmosphere
Cleaner drinking water supply
Cheaper drinking water treatment
Very contaminated waste water (e.g. PFAS, microplastic)
Cleaner Raw water
waste water treatment
Water reservoir
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Very contaminated sludge
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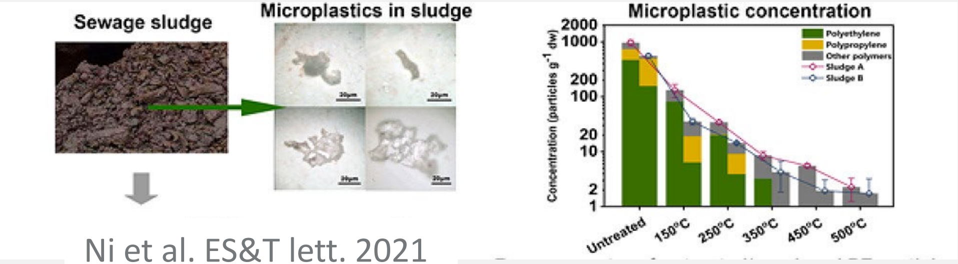
Solution:
Removing contaminants, while getting energy and char from sludge
Cleaner biochar
Cleaner Run off
Cleaner Food supply

Contaminants and thermal treatment

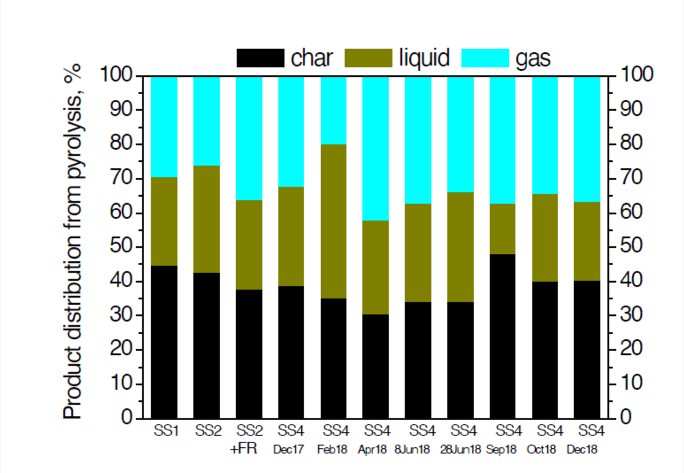
Contaminant	Reaction to sludge incineration/pyrolsis	Ref
PAHs / dioxins	Formed to a varying degrees. High temperature and long times tends to give less PAHs/dioxins, low temperature processes (e.g. gasification) tend to produce more. Often strongly sorbed to chars/soots (limited bioavailability).	Hale 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



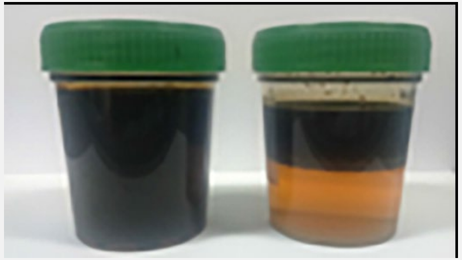
Ni et al. ES&T lett. 2021

Variation in fertilizer from dry pyrolysis

Sludge biochar fertilizer (30-50%)



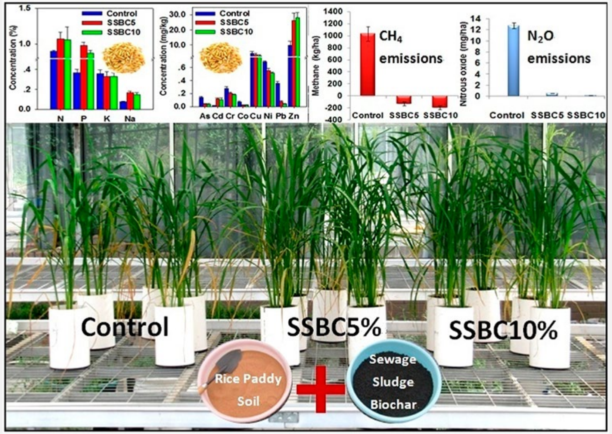
Kwapinska, M., Agar, D. A., Bonsall, B., & Leahy, J. J. (2020) Valorisation of Composted Organic Fines and Sewage Sludge Using Pyrolysis (OF-PYR). (2016-RE-MS-7). Irish EPA Research Report



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

Total phosphorous - Total phosphorous is retained (enriched) in sludge chars more than gas and condensates (on average doubles in concentration).

Bioavailable phosphorous – are variable from different studies. The best studies indicated a doubling in soil fertility from sludge to sludg chare, also due to other properties of char (e.g. alkalinity, water retention) (e.g. Khan et al- ES&T 2012)



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

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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

Different views and Different Tradeoffs for Thermal Treatments

Negative


European Commission

JRC SCIENCE FOR POLICY REPORT

Technical proposals for selected new fertilising materials under the Fertilising Products Regulation (Regulation (EU) 2019/1009)

Process and quality criteria, and assessment of environmental and market impacts for precipitated phosphate salts & derivates, thermal oxidation materials & derivates and pyrolysis & gasification materials

Huygens D, Saveyn HGM, Tonini D, Eder P, Delgado Sancho L

2019

- JRC recommends mono-incineration and nutrient extraction (fertilizer regulation)
- *Precautionary principle*: unknown chemical hazards- do not use sludge for fertilizer, pyrolyzed or otherwise

Positive

3.2.6.4 **Life Cycle Impact Assessment**

Barry, Devon J., "Pyrolysis as an Economical and Ecological Treatment Option for Solid Anaerobic Digestate and Municipal Sewage Sludge" (2018).

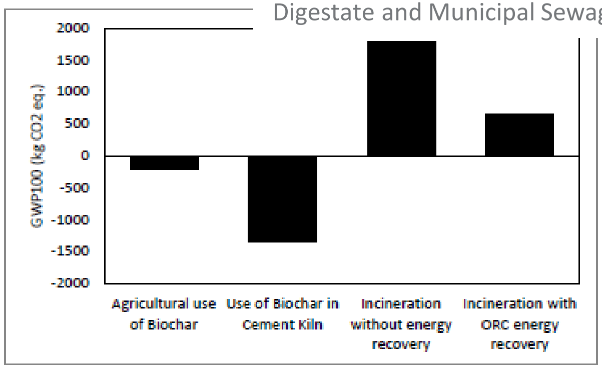

Figure 3.25: LCA Global Warming Potential Results

- Incineration worse than pyrolysis from an LCA perspective
- Dry pyrolysis is carbon negative in agriculture
- Sewage sludge biochar for co-combustion in cement kilns is even more carbon negative

WEEE

Chemical pyrolysis of ewaste plastic??

Biogreen® process for plastic conversion (Scanship)

- **Char (3-5%)**
- **Liquid fuel ca 30%**
- **Gas fuel ca 60%**

Chemical recycling (naptha)?

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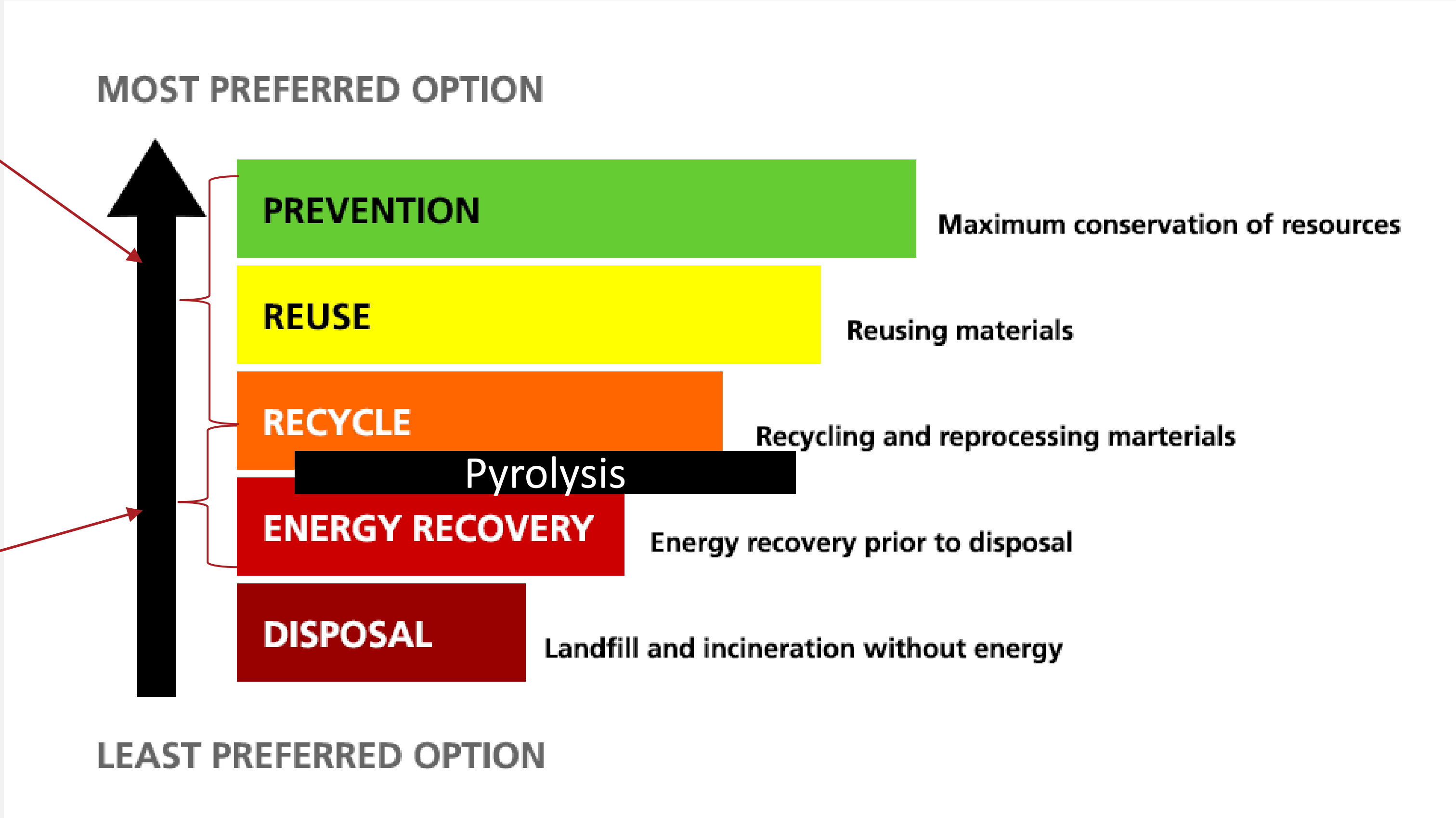
- **Contaminants??**

Pyrolysis of E-waste plastic with hazardous chemicals?

- < RoHS levels
- > RoHS levels

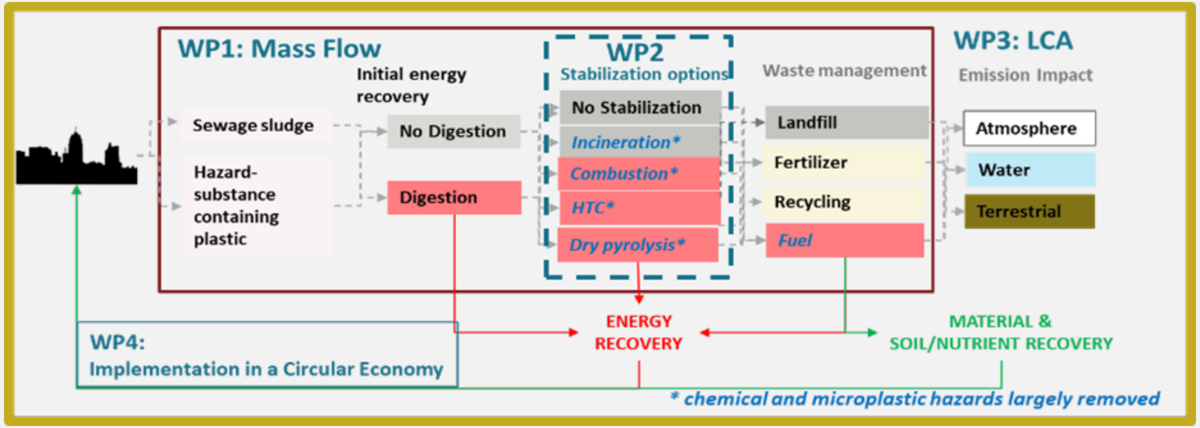


Nele Rosenstock, DG ENV, SWD-UWWD Meeting April 21-22, 2021

Setting the Scene – Goals of the workshop

- Disseminate the results of the SLUDGEFFECT research project
- Multi-stakeholder discussion on the role thermal treatments in the circular economy for sludge and e-waste plastic
- There are tradeoffs that effect different sectors differently

Schedule



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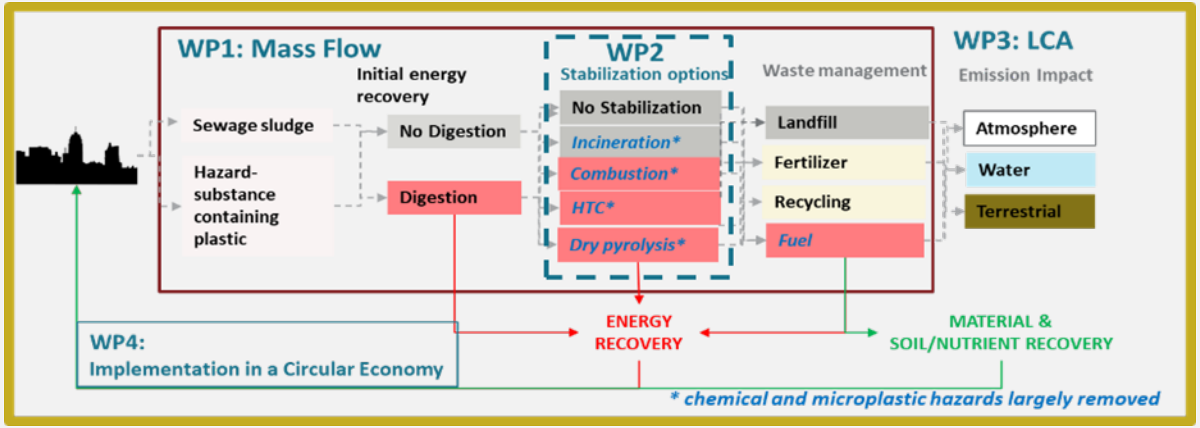

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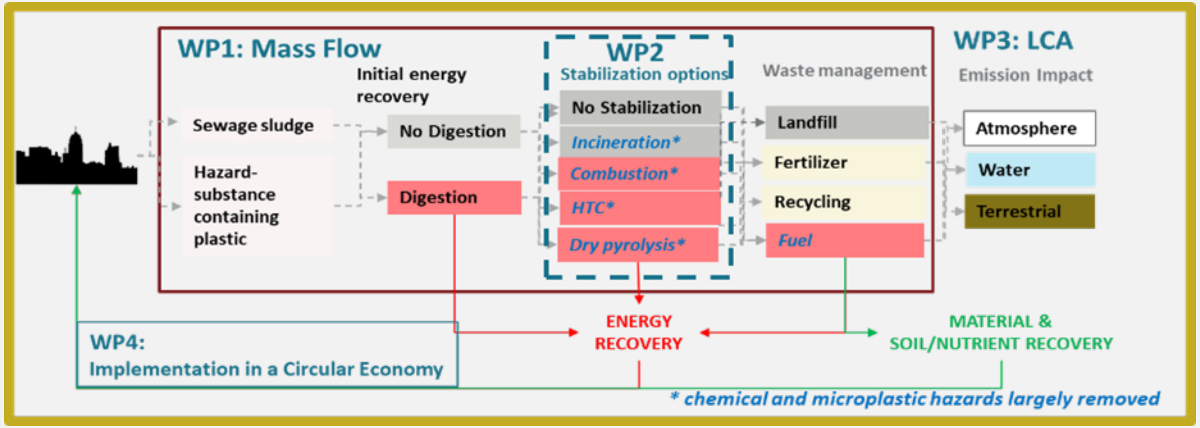

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Thank-you!

SLUDGEFFECT Researchers: Hans Peter H. Arp[1,2], Sarah Hale[1], Heidi Knutsen[1], Mari Løseth[1], Erlend Sørmo[1],Gerard Cornelissen[1], Alexandros Asimakopoulos[2], Gabriela Castro[2], Junjie Zhang[2], Otavio Cavalett[2], Francesco Cherubini[2], Gregory Peters[3], Damia Barcelo[4]

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

Industry, municipal and regulatory partners: Norwegian Environment Agency; Norwegian Food Safety Authority; Lindum AS; Norsirk; Scanship AS; VEAS IKS; Trondheim Kommune; Bio4Fuel

https://www.ngi.no/eng/Projects/SLUDGEFFECT

NGI The Research Council of Norway

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

Thank you!

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Sludge Mass Flow in Norway

Heidi Knutsen[1,2] and Hans Peter Arp[1,3]

SLUDGEFFECT Symposium
April 9, 2024

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)

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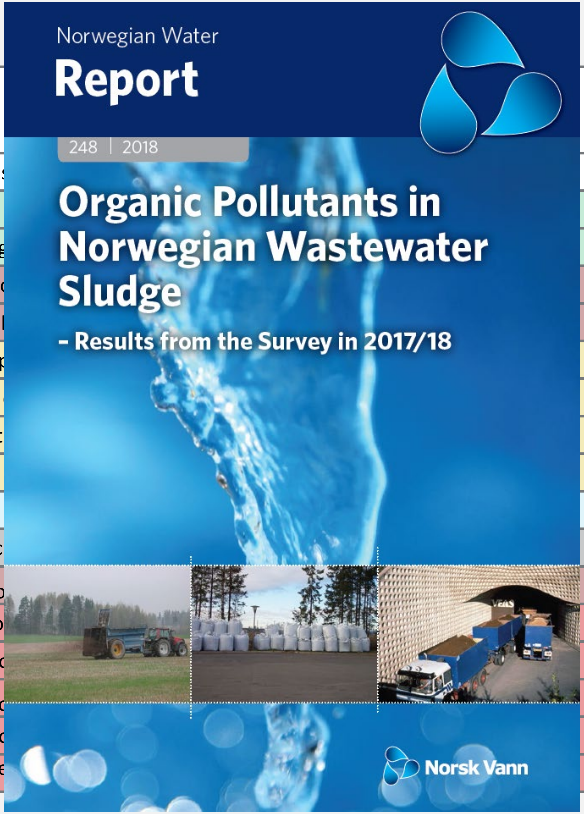
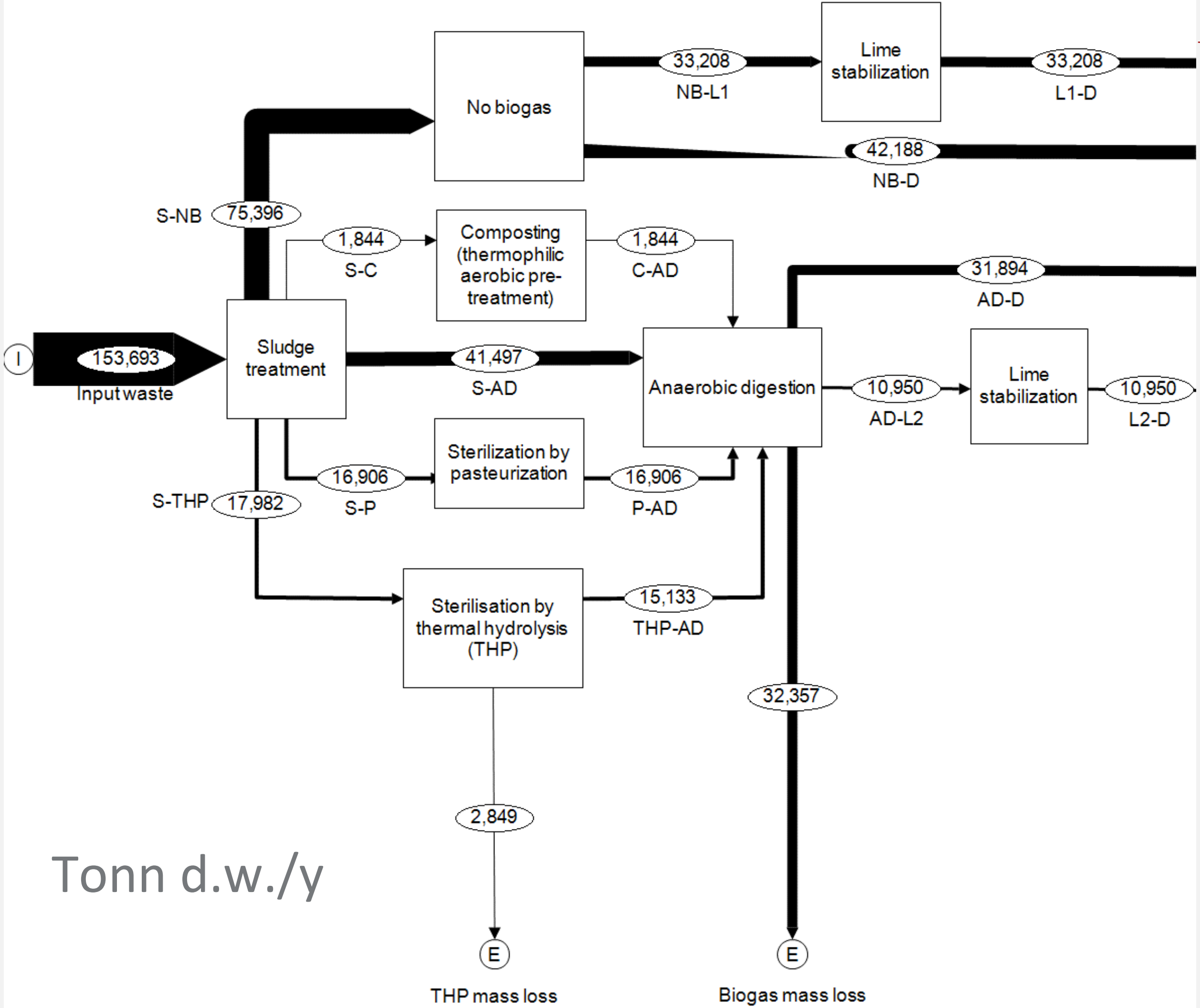
Lots of data in Norway for the 17 largest WTP plants

Plant/waste stream	Sludge treatment	Sludge deposition
VEAS	Mesophilic anaerobic digestion, lime	Agricultural
Tønsberg IKS	Lime stabilization - the Orsa method	Agricultural
NRA	Lime stabilization (of dewatered sludg	Agricultural
Lindum Biogas (Drammen)	Thermal hydrolysis, mesophilic anaer	Agricultural
GBA (Grødaland biogassanlegg)	Thermal hydrolysis and anaerobic stal	Agriculture, reject to incineration/landfill
Bekkelaget (Oslo)	Thermophilic digestion at 55 °C. Pump	Agricultural
SNJ (Ivar)	Anaerobic digestion, dewatering and	Agricultural
Rambekk (Gjøvik)	Meshophilic anaerobic stabilization, t	Agricultural, some to landfill
Gardermoen (Ullensaker)	Thermophilic anaerobic stabilization	Agricultural
ÅRIM (Ålesund)	Raw sludge	Delivered to Åse which incinerates the sludge
Fuglevik (MOVAR)	Aerobic pretreatment and mesophilic	Agricultural
Hias IKS (Hamar)	Thermal hydrolysis mesophilic anaero	Agricultural
Høvringen (Trondheim)	Pasteurization and anaerobic digestio	Agricultural
Sandefjord	Pasteurization with anaerobic digestic	Agricultural
Bergen biogas	Pasteurization at 70 °C for 1 h, thermc	Agricultural
Ladehammeren (Trondheim)	Pasteurization with mesophilic anaer	Agricultural
Øra (Fredrikstad)	Pasteurization with thermophilic anae	Agricultural



Norwegian Sludge Processing in 2020

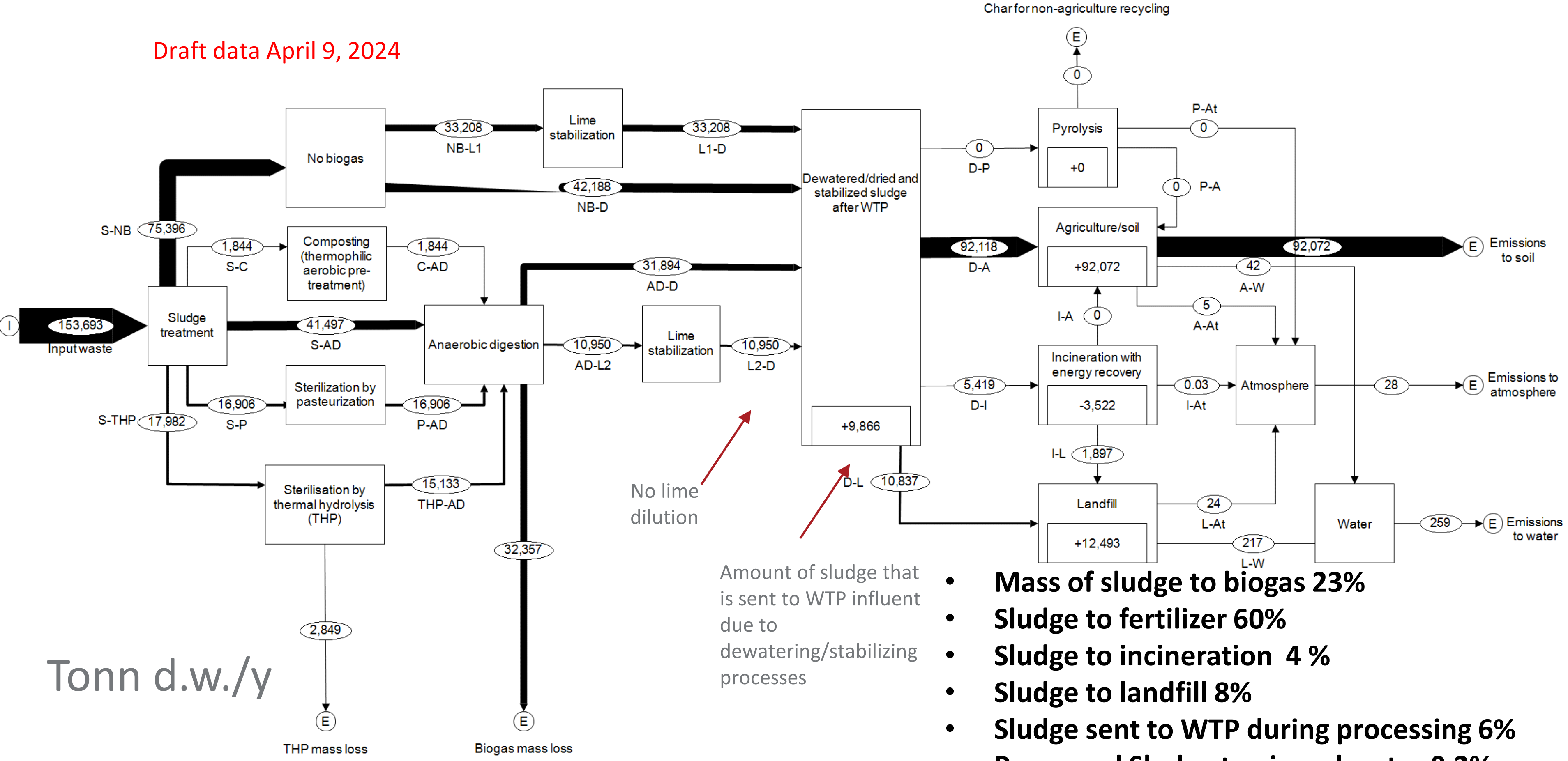


Tonn d.w./y

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

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

Draft data April 9, 2024



Tonn d.w./y

- **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%**

Uneven distribution of treatment methods and statistical data between cities and rural areas

Sources	Agriculture[1]	Landfill[2]	Incineration	Other[3]	Pyrolysis[4]
Results from 2019 from Statistics Norway (2020).	77 %	9 %	5 %	9 %	0%
17 biggest WWTPs/STPs (near urban areas)	98 %	1.4 %	0.50 %	0 %	0 %
Relative mass percentages used as conversion factors in SLUDGEFFECT MFA for Norway.	85 %	10 %	5 %	N/A	0 %

Overview of relative mass percentages of produced sludge to different disposal methods. [1]Including use on green areas and as soil conditioner; [2]including use as topsoil; [3]not included in MFA as this category is very uncertain according to Statistics Norway (pers. comm.); [4]not utilized today but included in MFA as it could be a potential disposal method in near future.

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So… what contaminants can we measure in this SLUDGE?

Thank you!

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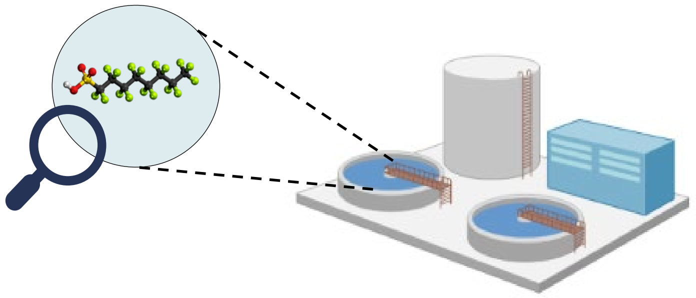
SLUDGEFFECT

Sludge Concentrations and Removal efficiencies in Norwegian WWTPs



Gabriela Castro
9th April 2024

NTNU
Department of Chemistry

NGI

The Research Council of Norway

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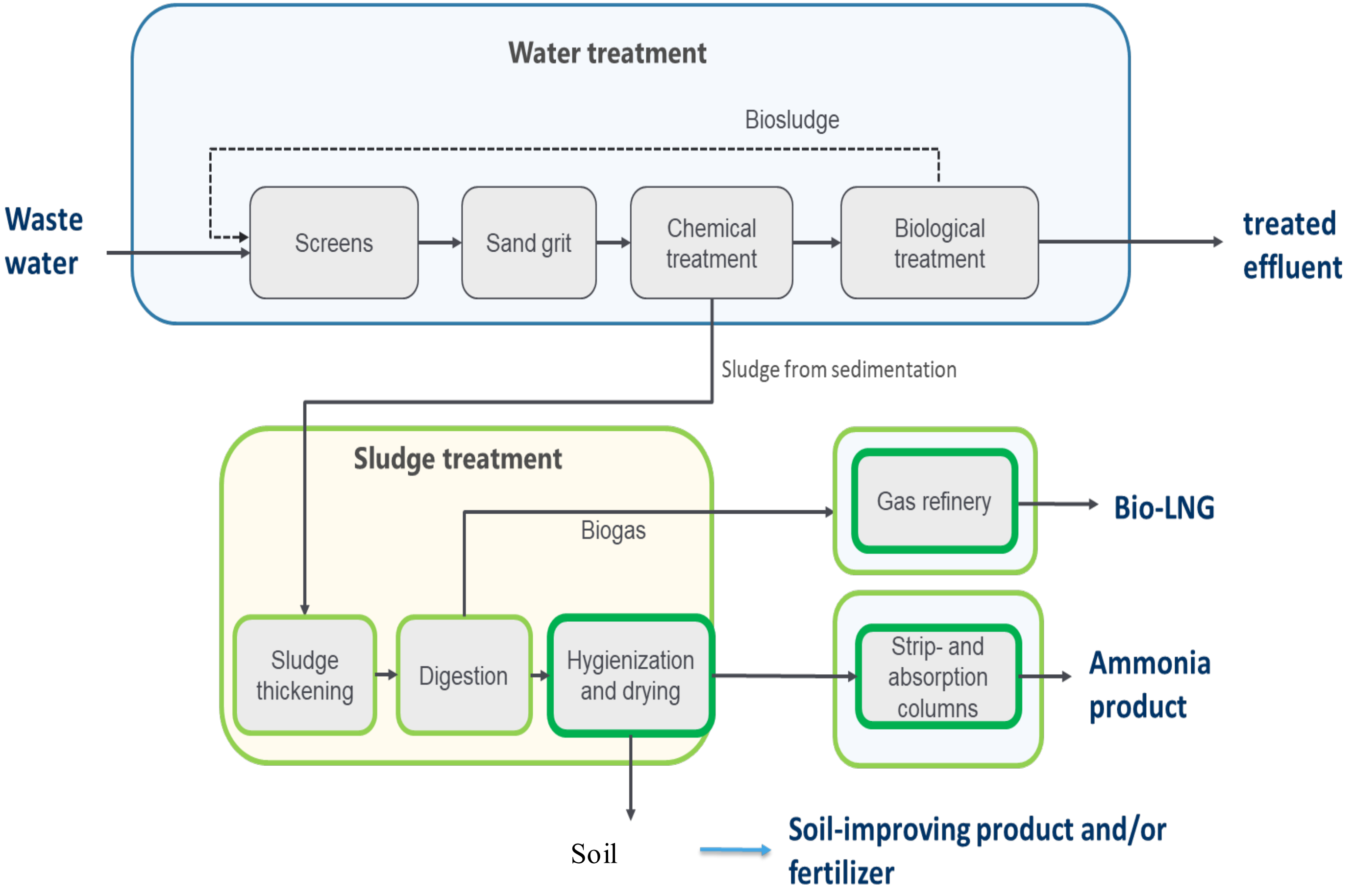


What can cause concentration changes in a WWTP?

- Biogas production
- Anaerobic digestion
- Dilution with the lime addition (39% in WWTP3)
- Complete degradation
- Transformation into another chemicals (TPs)

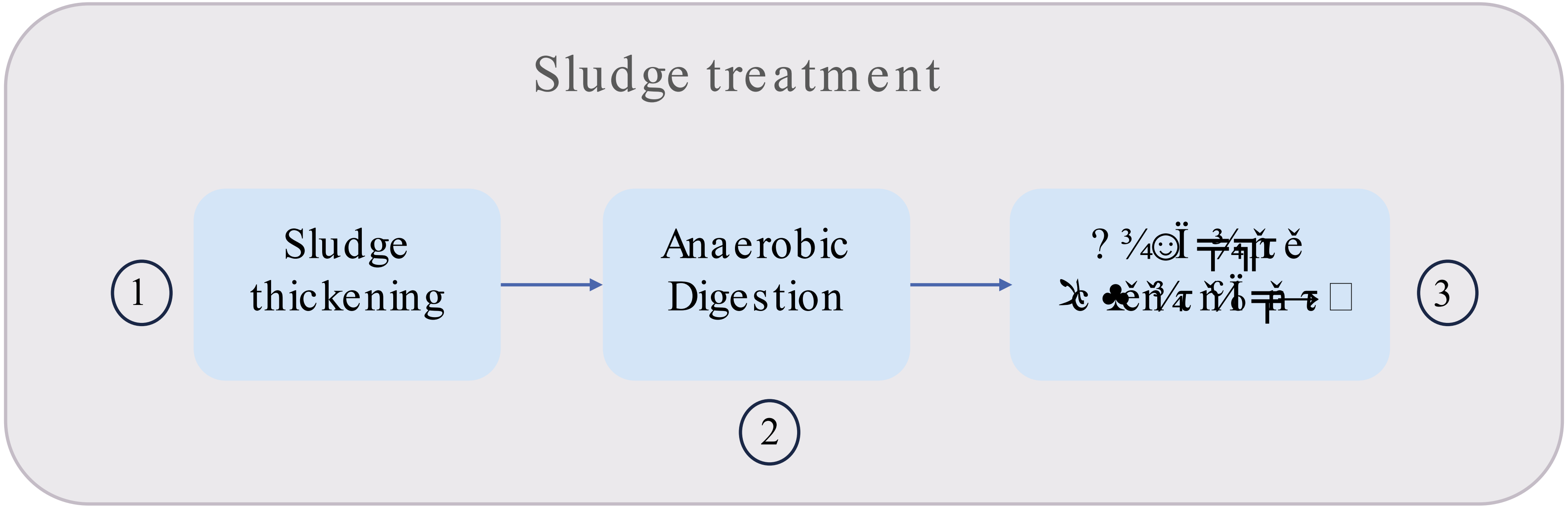
Veas

Sampling WWTPs in Norway

- 2 WWTPs located in Trondheim
- 3 WWTPs and 1 STP located in Oslo

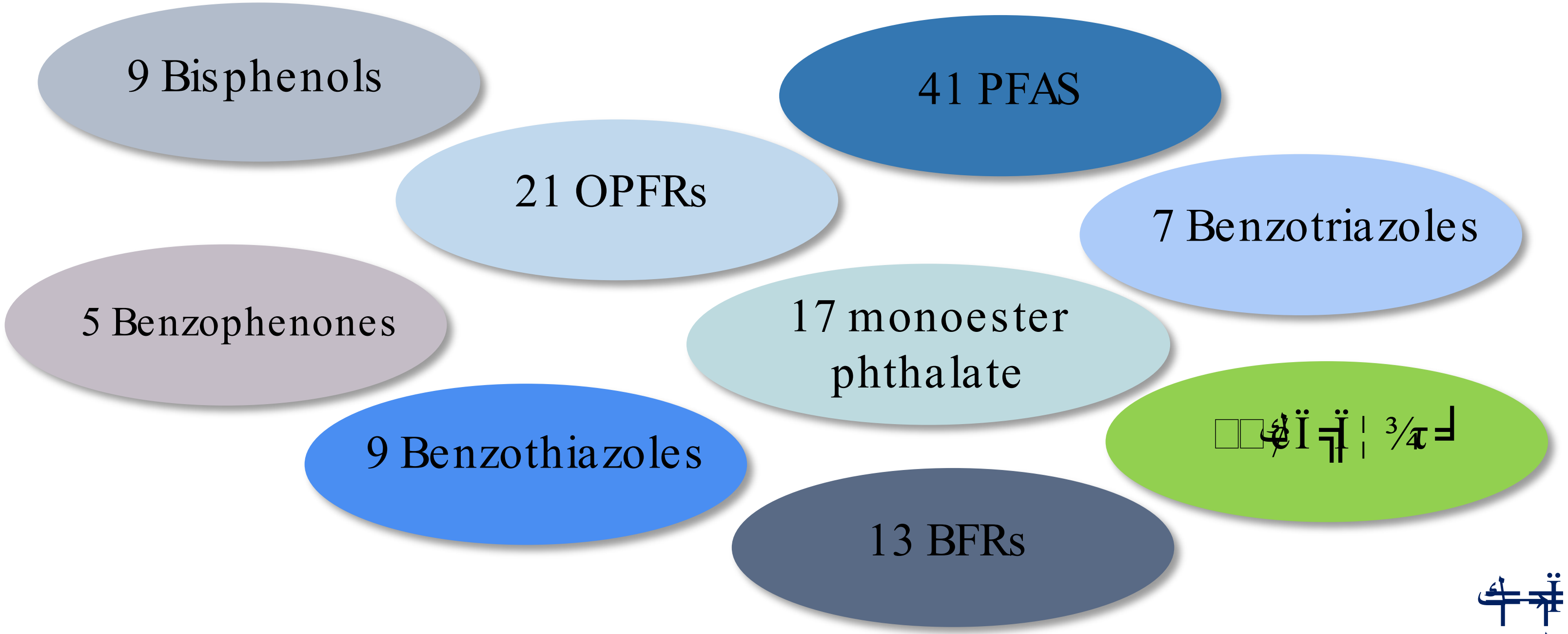
WWTP code	Treatment description
WWTP-1	Primary treatment (anaerobic digestion)
WWTP-2	Primary treatment (anaerobic digestion)
WWTP-3	Primary and secondary (anaerobic digestion stabilization + hygienization with lime)
WWTP-4	Primary treatment
WWTP-5	Primary treatment
STP-1	Thermal treatment (CAMBI thermal hydrolysis (THP) and anaerobic digestion)

Sampling WWTPs in Norway



1. Raw sludge
2. Digested sludge
3. Dewatered sludge (Hygienizated)

Target analytes

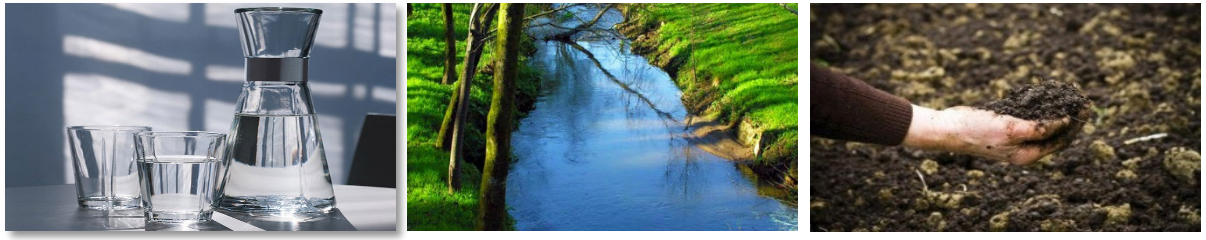


- ❑ Development of new analytical methodologies
- ❑ Analysis of 87 sludge samples
- ❑ Quantification of several families of emerging pollutants and metals

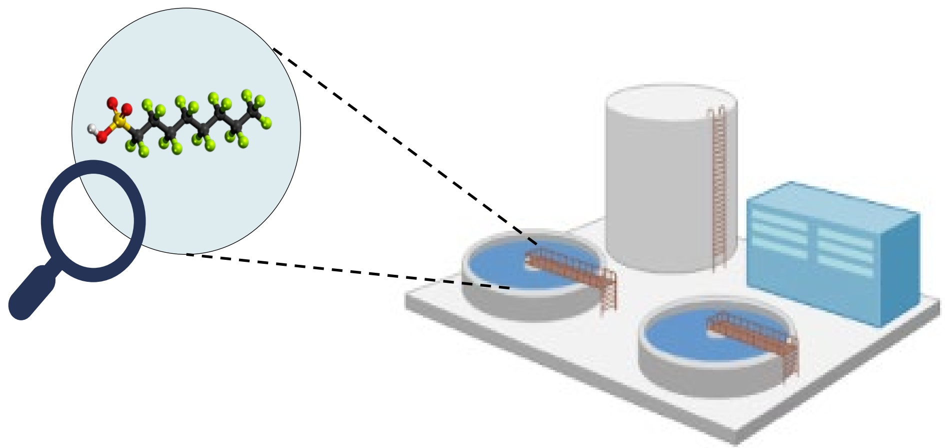
Environmental distribution

- Human use
- Direct spills

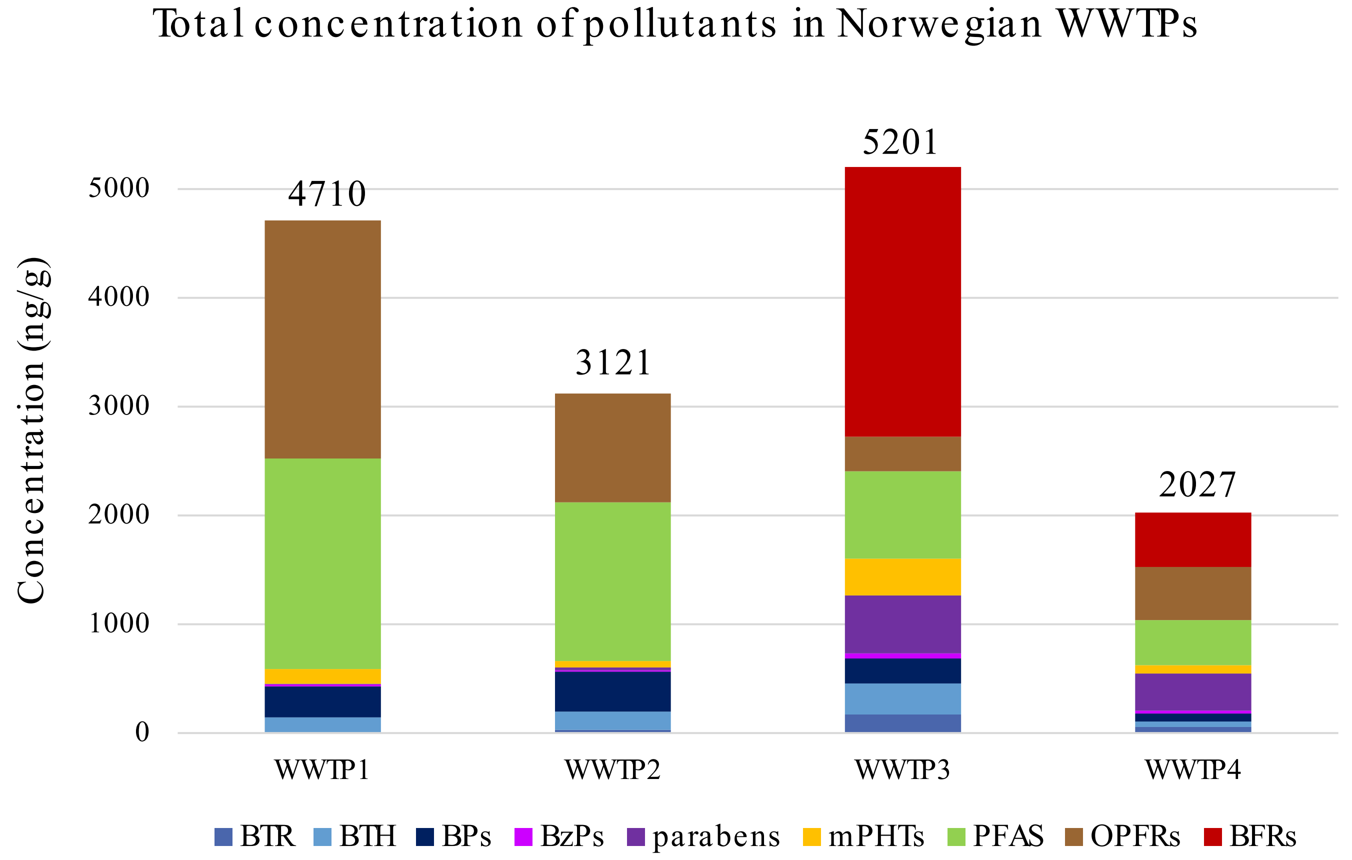
Wastewater treatment plants

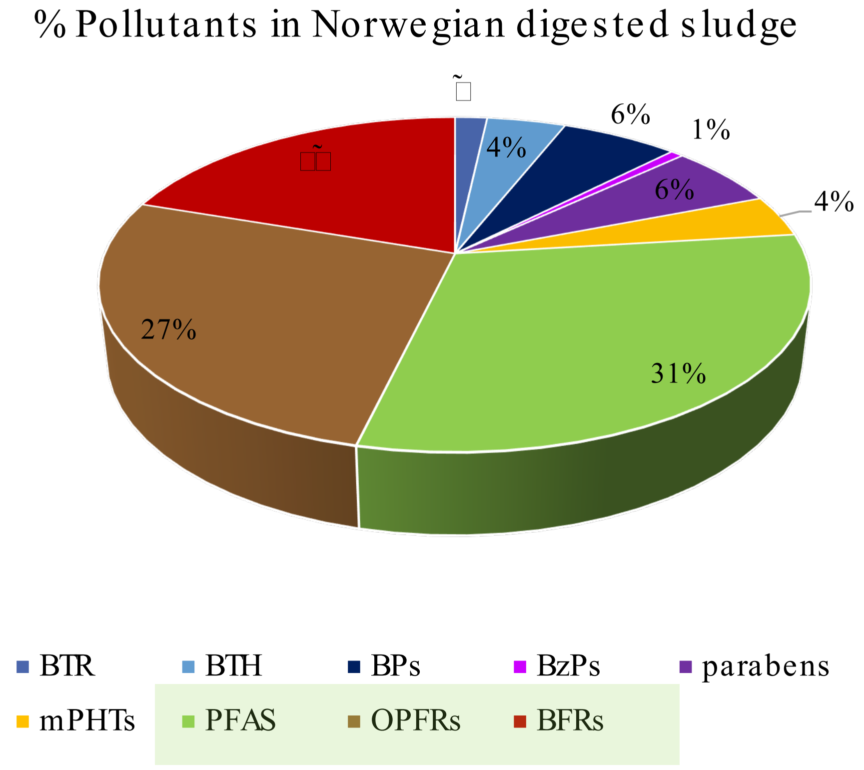


What is in our sludge?



Occurence in Norwegian digested sludge





- Persistence
- Ubiquity
- Toxicity

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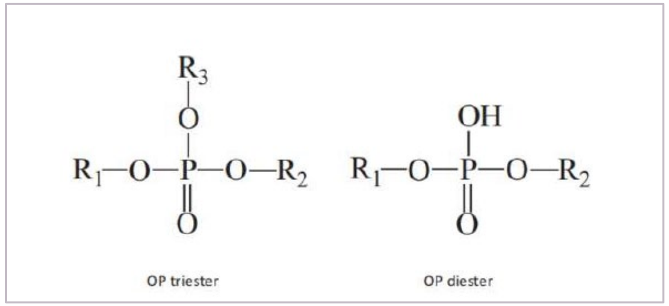
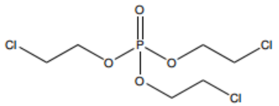
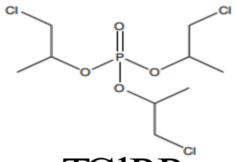
- Chemical additives widely used in combustible materials to prevent fire or delay combustion processes.
- High volume production chemicals.

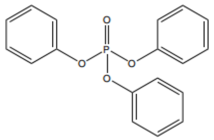




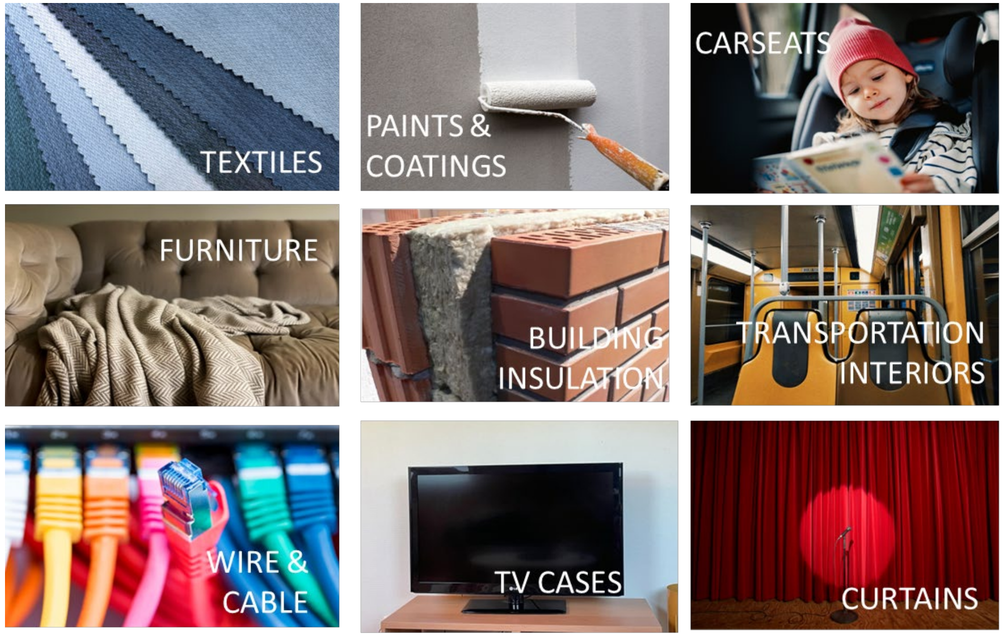
TCEP



TClPP



TPhP



Organophosphate flame retardants (OPFRs)

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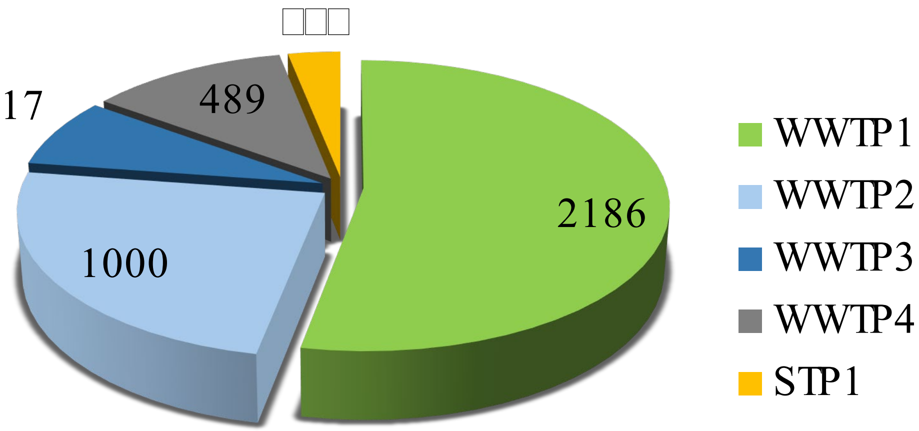
ΣOPFRs concentration (ng/g)



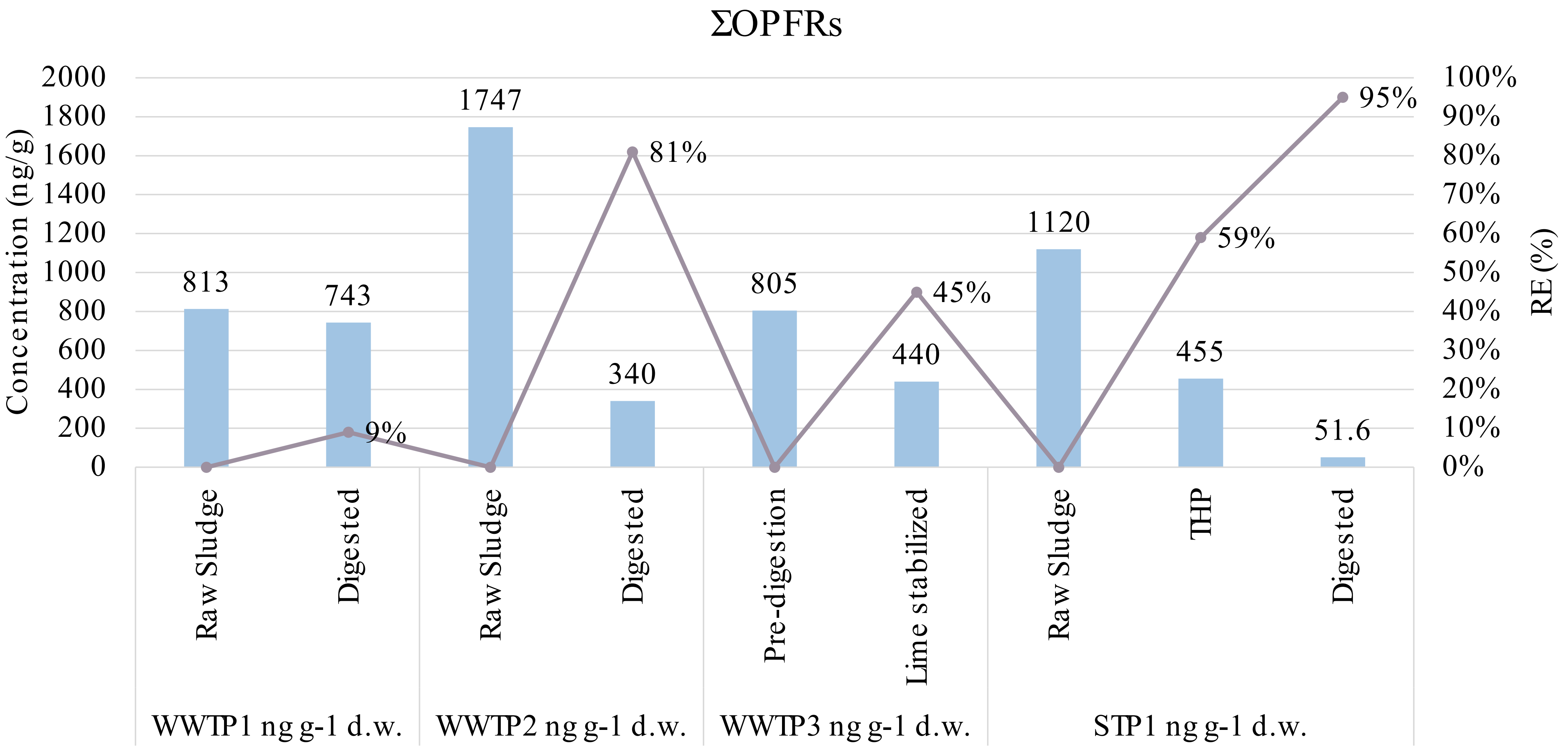
- ✓ 16 out of 21 studied OPFRs were detected
- ✓ 100 % DF for TnBP, TiBP, TBOEP and BPA-BDPP
- ✓ Higher concentrations in WWTPs with primary treatment (WWTP1, WWTP2 and WWTP4)
- ✓ Among chlorinated OPFRs (TCEP, TClPP and TDClPP), only TClPP was detected in one facility (WWTP2, 396 ng/g)

Comparison of median concentrations in digested sludge from WWTP3

Samping year	TCEP	TClPP	TPhP	TDClPP	TnBP/TiBP	TCrP	TBOEP	EHDP	REF
2011 (n=4)	140	2320	94	54	140	110	5600	3040	Thomas K.V. et al 2011
2013 (n=5)	<39.5	570	24	n.d.	n.d.	9.5	n.d.	n.d.	Thomas K.V. et al 2014
2017/2018 (n=5)	<1.5	710	n.d.	4.4	55	19	910	250	Blytt et al. 2018
2021 (n=9)	n.d.	n.d.	n.d.	<LOQ	19.4	n.d.	140	n.d.	This study

G. Castro et al. (2023). Analysis, Occurrence and Removal Efficiencies of Organophosphate Flame Retardants (OPFRs) in Sludge undergoing Anaerobic Digestion followed by diverse Thermal Treatments, Science of the Total Environment 870, 161856

Organophosphate flame retardants (OPFRs)

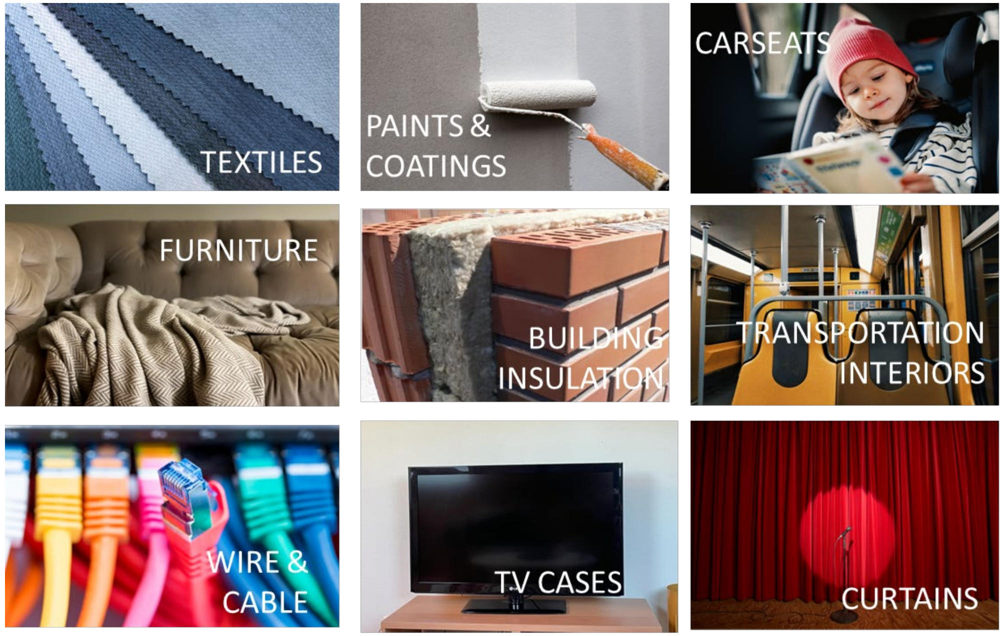


Brominated flame retardants (BFRs)

❖ Mixtures of man-made chemicals that are added to a wide variety of products, including for industrial use, to make them less flammable.

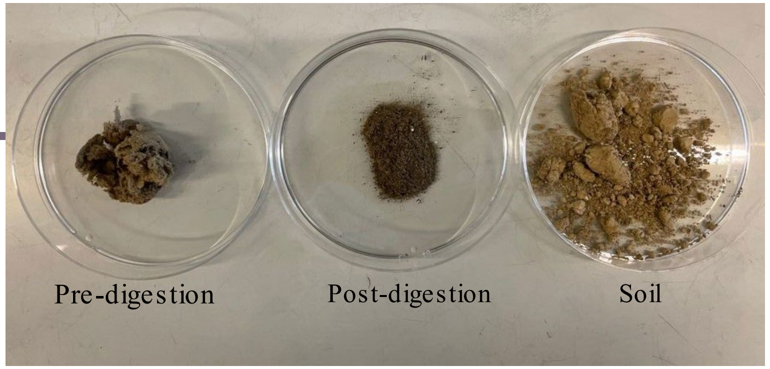
There are five main classes of BFRs, listed here with their common uses:

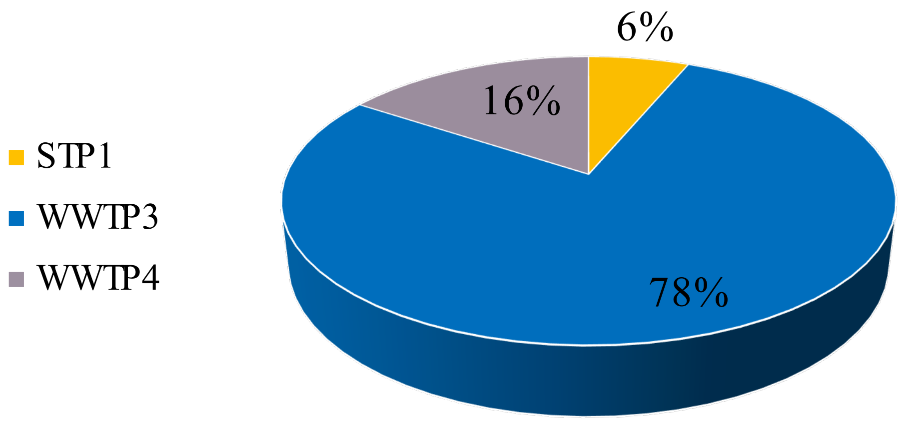
- Polybrominated diphenyl ethers (PBDEs) – plastics, textiles, electronic castings, circuitry.
- Hexabromocyclododecanes (HBCDDs) – thermal insulation in the building industry.
- Tetrabromobisphenol A (TBBPA) and other phenols – printed circuit boards, thermoplastics (mainly in TVs).
- Polybrominated biphenyls (PBBs) – consumer appliances, textiles, plastic foams.
- Other brominated flame retardants

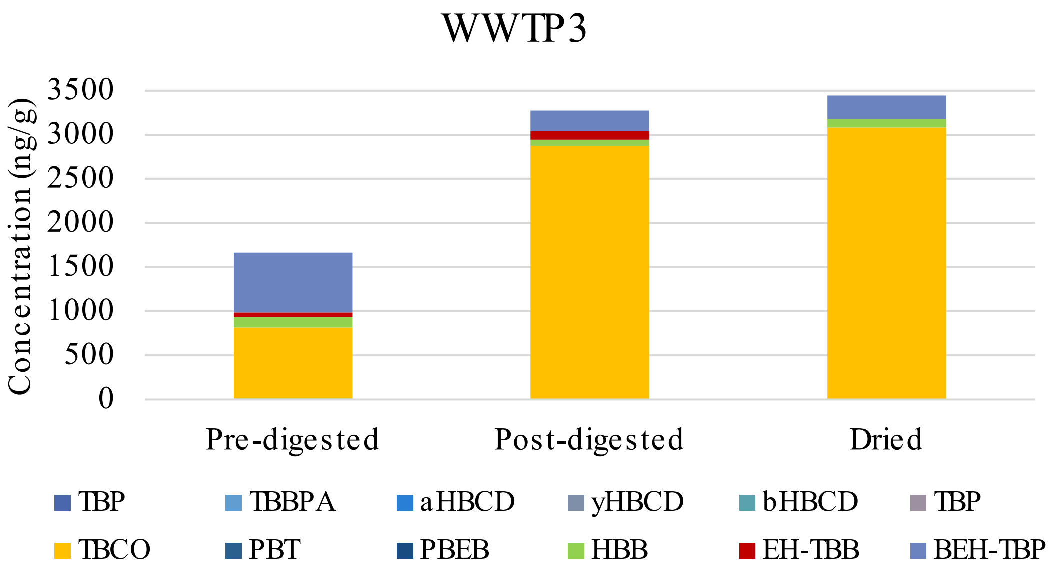


Brominated flame retardants (BFRs)

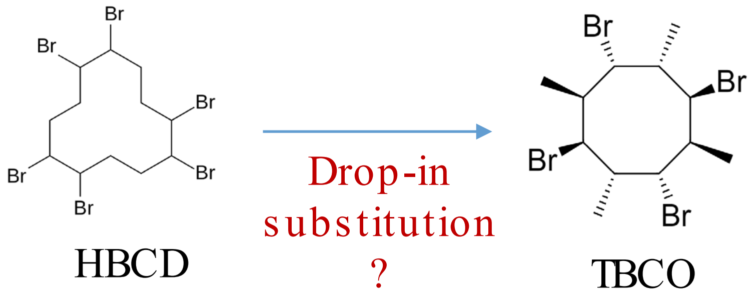
- Occurrence of BFRs in Norwegian digested sludge







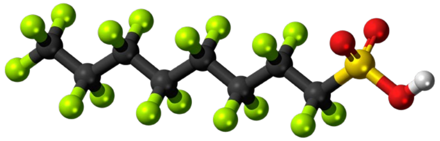
100% DF for HBB in digested sludge.
TBCO was found in the highest concentrations.



Per- and polyfluoroalkyl substances (PFAS)

❖ Group of synthetic chemicals that have been widely used in a variety of consumer products and industrial applications for over 70 years.

- perfluorooctanoic acid (PFOA)
- perfluorooctane sulfonate (PFOS)
- perfluorononanoic acid (PFNA)
- perfluorohexane sulfonic acid (PFHxS)



❖ Persistent, Mobile and Toxic substances (PMTs)

❖ Don't break down in the environment or in the human body, and can accumulate over time.

"forever chemicals"

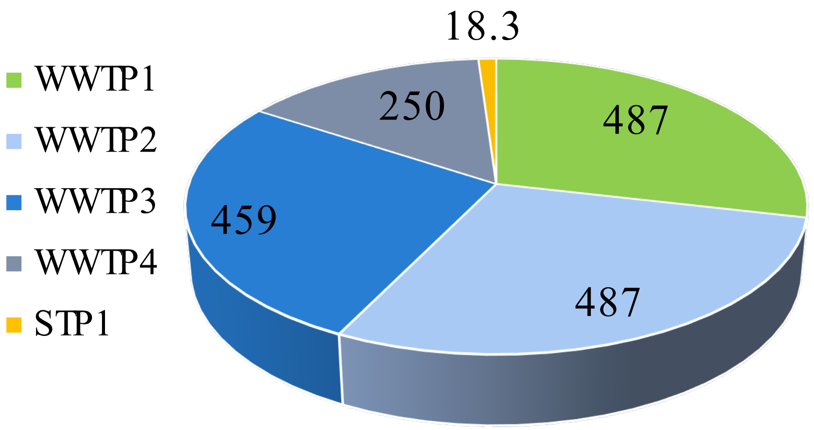
❖ Exposure to PFAS may lead to adverse health effects.

https://www.seacc.org/water-quailty/pfas/

Per- and polyfluoroalkyl substances (PFAS)

- Occurrence of PFAS in Norwegian digested sludge

ΣPFAS concentration (ng/g)



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).

- Anerobic digestion of PFAS

- Anaerobic digestion in WWTP1 leads to the transformation of precursors into short-chain PFCAs.

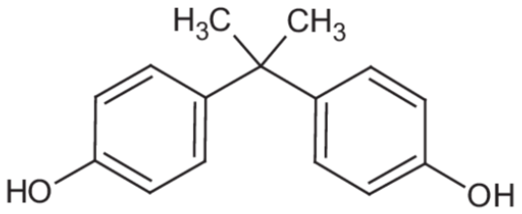
- The combination of primary treatment and subsequent hygienization with lime removed the 26% of the total PFAS concentration, favouring the transformation from the precursors and PFSA into long-chain PFCAs (94% transformation).

		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.

Bisphenols

- ❖ Group of chemicals widely used in polymer and plastic production.
  - Bisphenol A
  - Bisphenol S
  - Bisphenol F



BPA

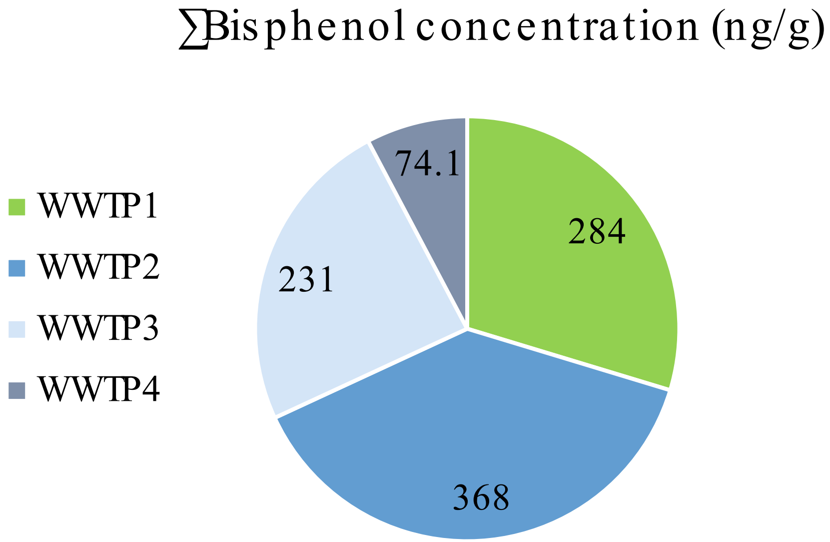
- ❖ High volume production chemicals.

- ❖ Endocrine disrupting chemicals (ECDs).

Regrettable substitution !

Bisphenols

- Occurrence of bisphenols in Norwegian digested sludge



100% DF for BPA and BPS
Higher concentrations were detected in the WWTPs with primary treatment (WWTP1 and WWTP2).

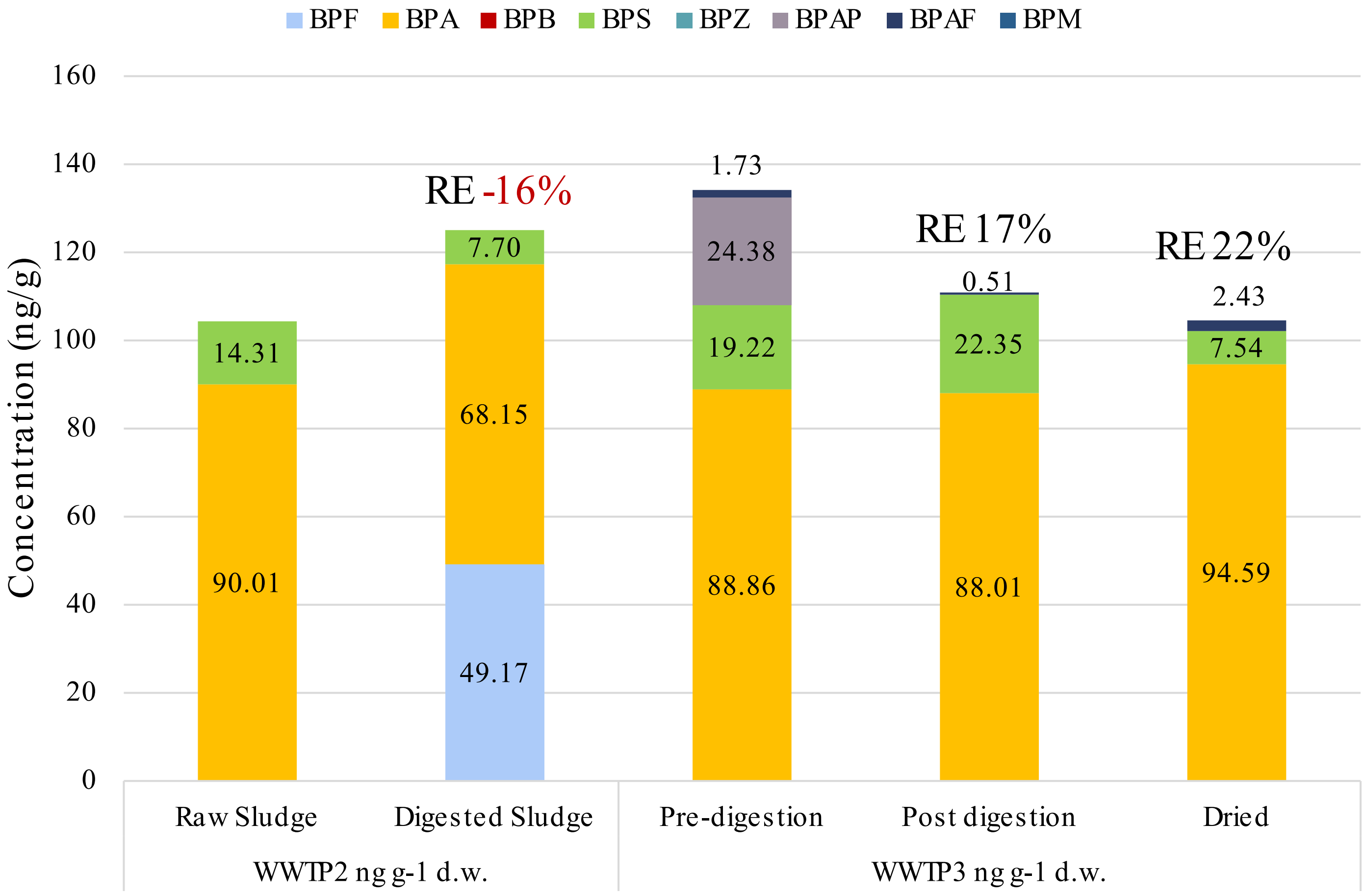
D. Gutierrez et al. Occurrence of emerging contaminants in Norwegian Sewage Sludge and E-waste (Under preparation)

Bisphenols

- Removal efficiency

Negative removal efficiencies might be attributed to:

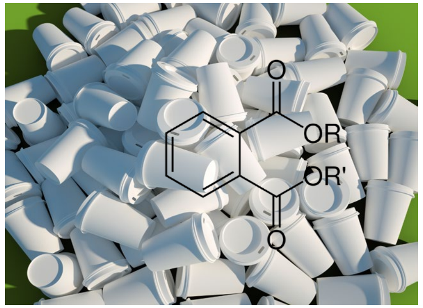
- Lack of homogeneity
- Lack of degrading bacteria
- Stable structures of the contaminants
- Analyte releasing from conjugated forms
- Extra BPs formed through the degradation of plastic during treatment at the WWTPs

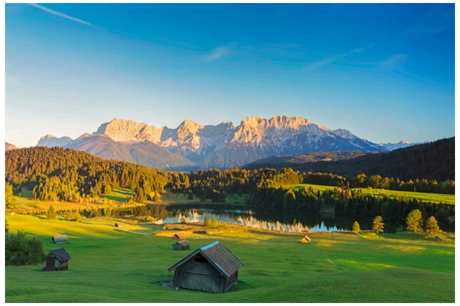


D. Gutierrez et al. Occurrence of emerging contaminants in Norwegian Sewage Sludge and E-waste (Under preparation)

Other emerging pollutants

- Benzophenone UV-filters
- Benzothiazoles and Benzotriazoles
- Parabens
- Monoester phthalate analogues

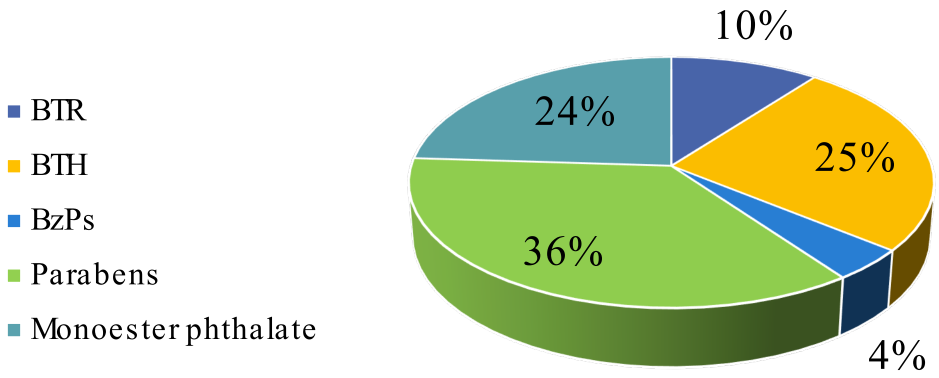




Additives → Not chemically bond to polymer.

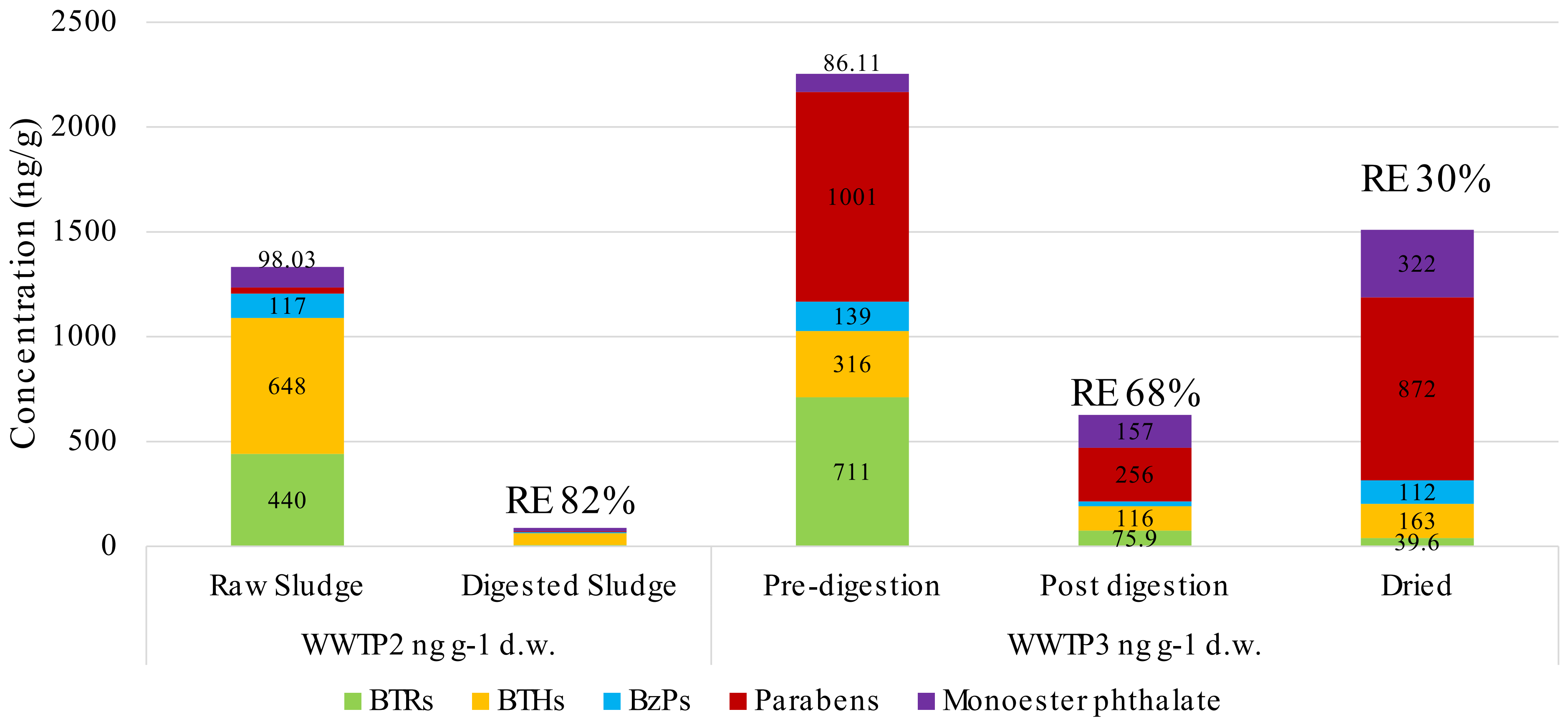
Other emerging pollutants

- Occurrence of other EP in Norwegian digested sludge
  - ❖ Emerging pollutants commonly reported in the environment.
  - ❖ Most of them are endocrine disrupting chemicals.



	Concentration (ng/g)			
	WWTP1	WWTP2	WWTP3	WWTP4
BTR	5.13	29.1	171	56.2
BTH	140	167	284	49.8
BzPs	17.9	13.0	46.8	27.1
Parabens	7.18	25.4	533	341
Monoester phthalate	133	59.3	336	76.4
TOTAL	777	702	1840	769

Other emerging pollutants



D. Gutierrez et al. Occurrence of emerging contaminants in Norwegian Sewage Sludge and E-waste (Under preparation)

Conclusions

- Emerging pollutants and other hazardous organic substances are ubiquitous during the different stages of the sludge treatment.
- Anaerobic digestion (AD) is not effective enough to remove these chemicals.
- Lime addition leads to the mobility of some compounds and thus, their transformation.

Take home message

Data presented today points out to the necessity of assessing systematically the presence of emerging pollutants and other HOCs to fully comprehend their mass balance in the WWTPs, and to evaluate the potential risks associated with the reintroduction of those into the terrestrial environment during the application of sludge as agricultural fertilizer.

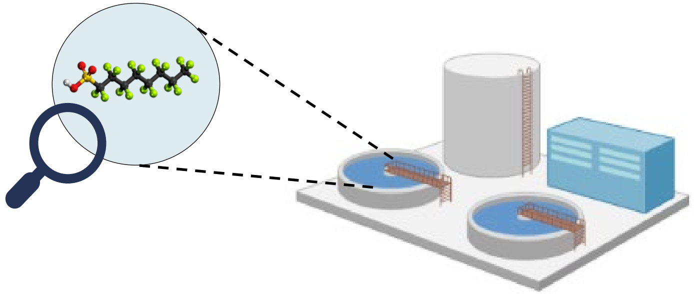
Acknowledgements

Many thanks…

- Trondheim Kommune, VEAS and Lindum for providing us with the most important thing of SLUDGEFFECT, the samples ☺
- Envirochemistry Lab at NTNU for helping us with the analysis.
- All the students related to the SLUDGEFFECT project for the great job.

SLUDGEFFECT

Sludge Concentrations and Removal efficiencies in Norwegian WWTPs



Gabriela Castro
9th April 2024

Gabriela.c.varela@usc.es

NTNU
Department of Chemistry

NGI

The Research Council of Norway

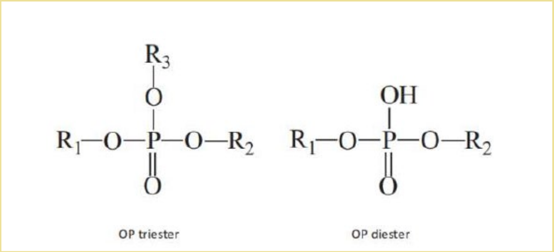
Sludge Contaminant Mass Flow in Norway

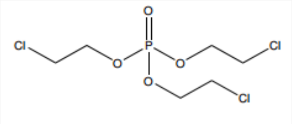
Hans Peter Arp, Heidi Knutsen, Håkon Langberg

SLUDGEFFECT Symposium
April 9, 2024

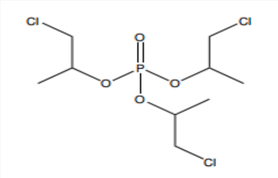
Intro to OPFRs and PFAS – persistent and toxic

OPFRs

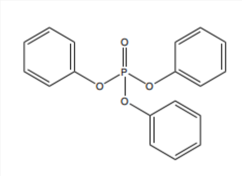




TCEP



TClPP

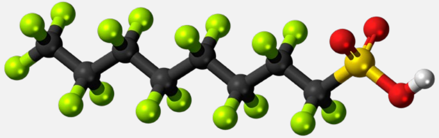


TPhP

- Chlorinated OPFRs are the most persistent of the OPFRs
- Not widely discussed in sludge management

PFAS

- *EFSA PFAS*
  - *perfluorooctanoic acid (PFOA)*
  - *perfluorooctane sulfonate (PFOS)*
  - *perfluorononanoic acid (PFNA)*
  - *perfluorohexane sulfonic acid (PFHxS)*
- *Thousands of other known and unknown substances*



- Upcoming Drinking Water Directive to limit the total sum of EFSA PFAS to 4 ng/L

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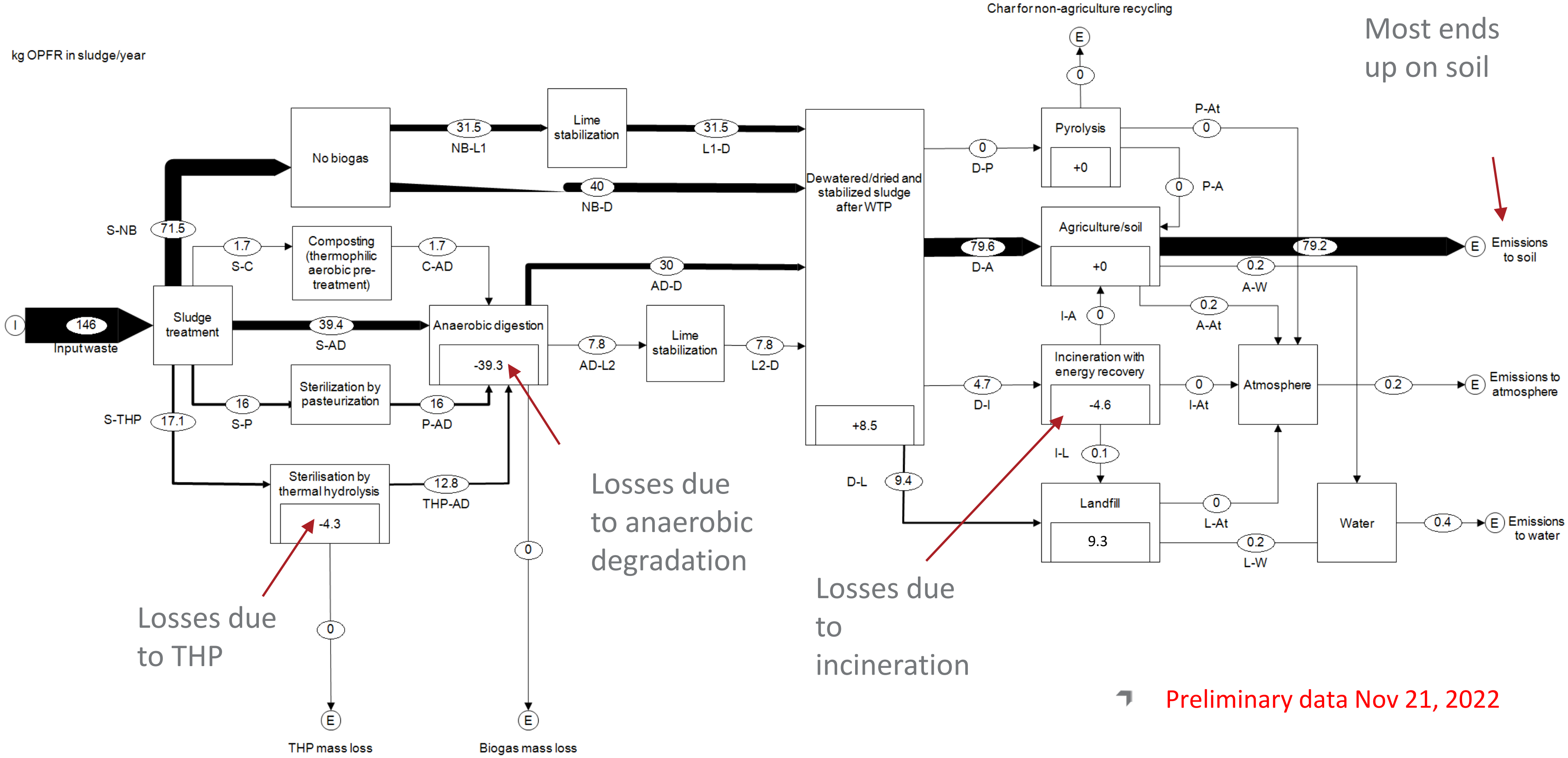
Mass flow of OPFRs in Norway



Most ends up on soil

Losses due to anaerobic degradation

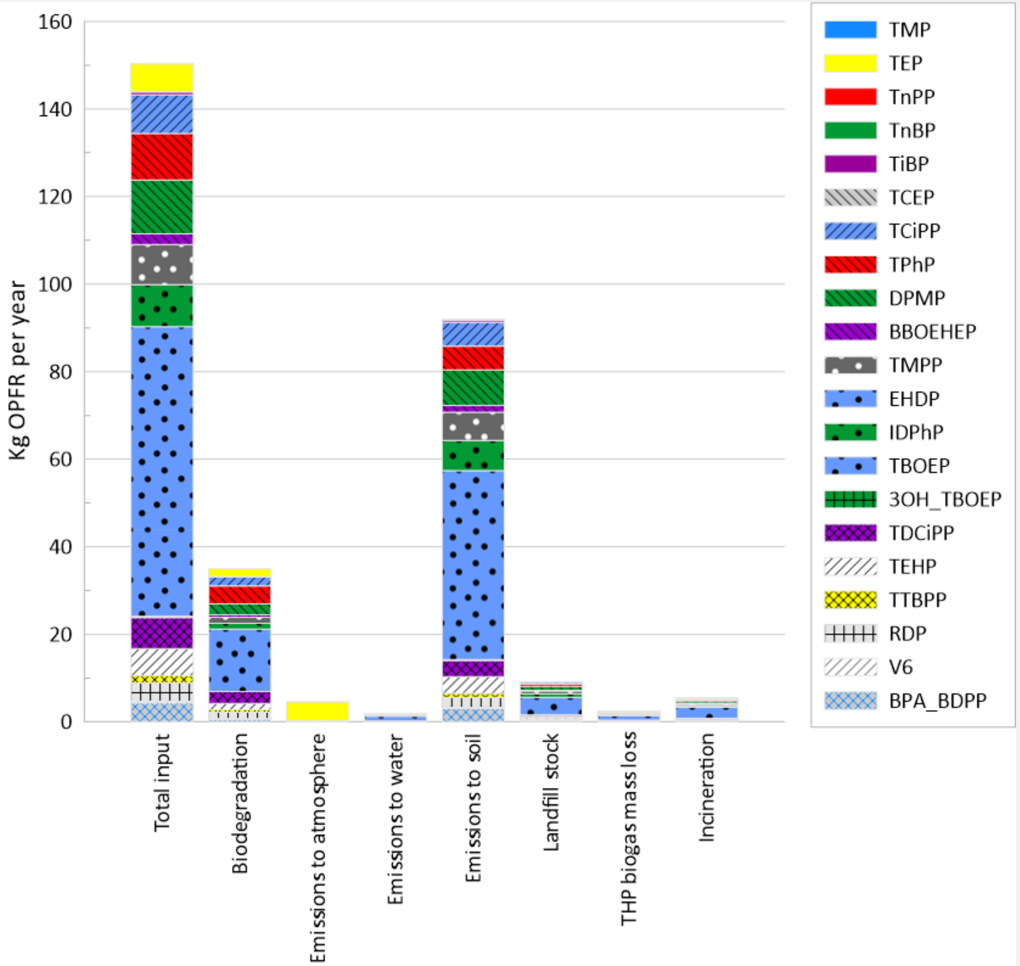
Losses due to THP

Losses due to incineration

Preliminary data Nov 21, 2022

Break down of analysed OPFRs

- Dominated by non-chlorinated OPFRs
- The chlorinated Cl-OPFR only detected in one sample



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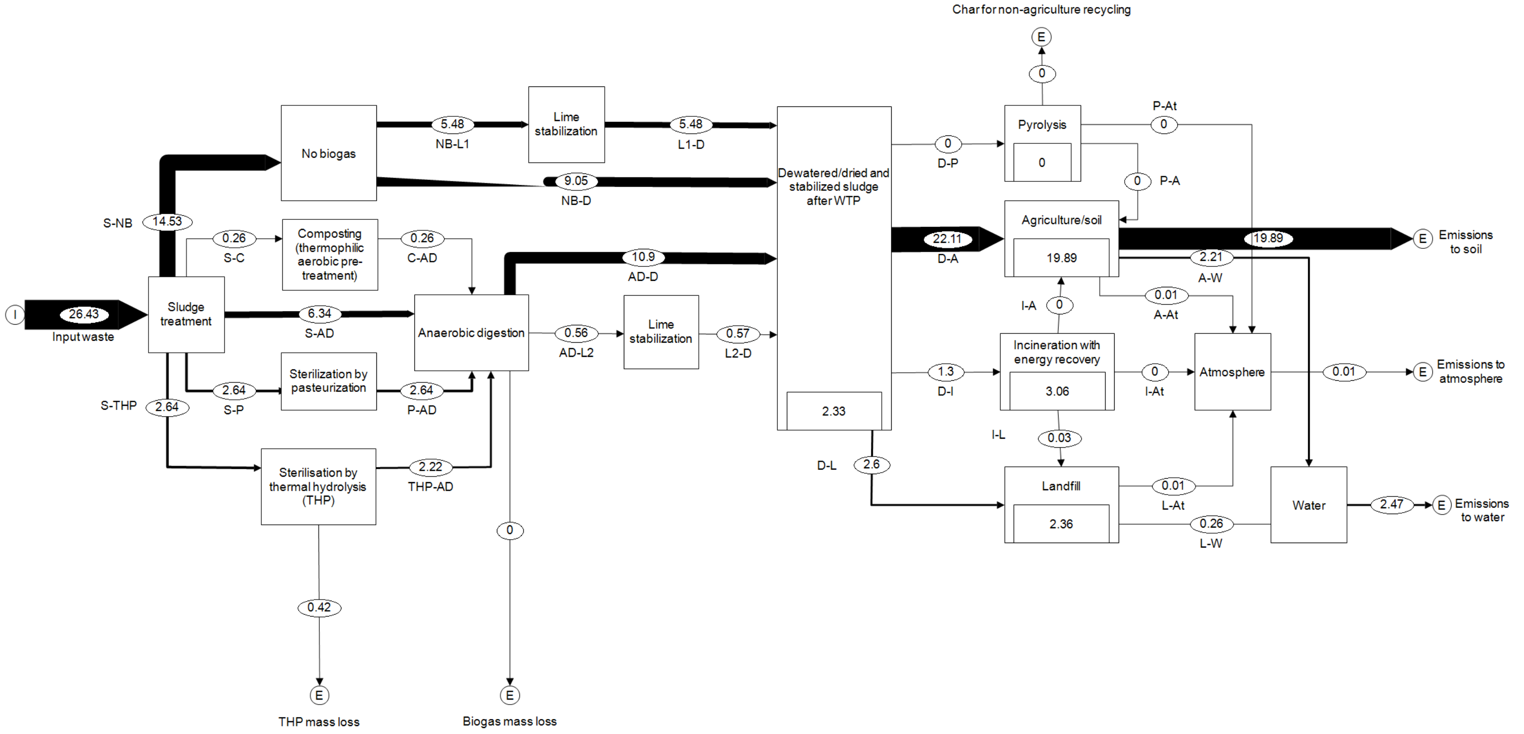
Mass Flow of EFSA – PFAS in Norway



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PFNA and PFOA dominates

Futuristic scenarios….

Ca 40% of sludge in Norway sent to pyrolysis…

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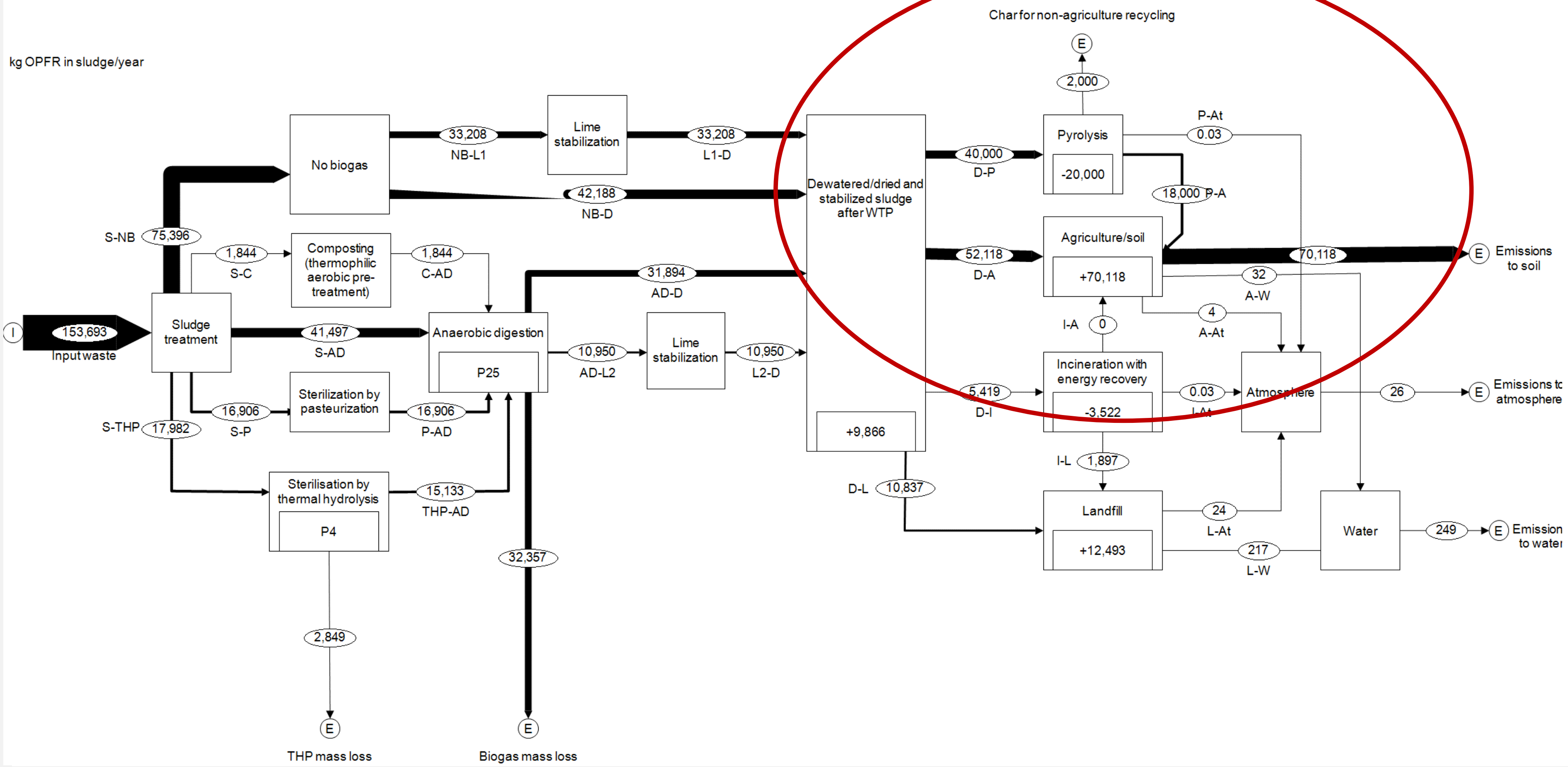
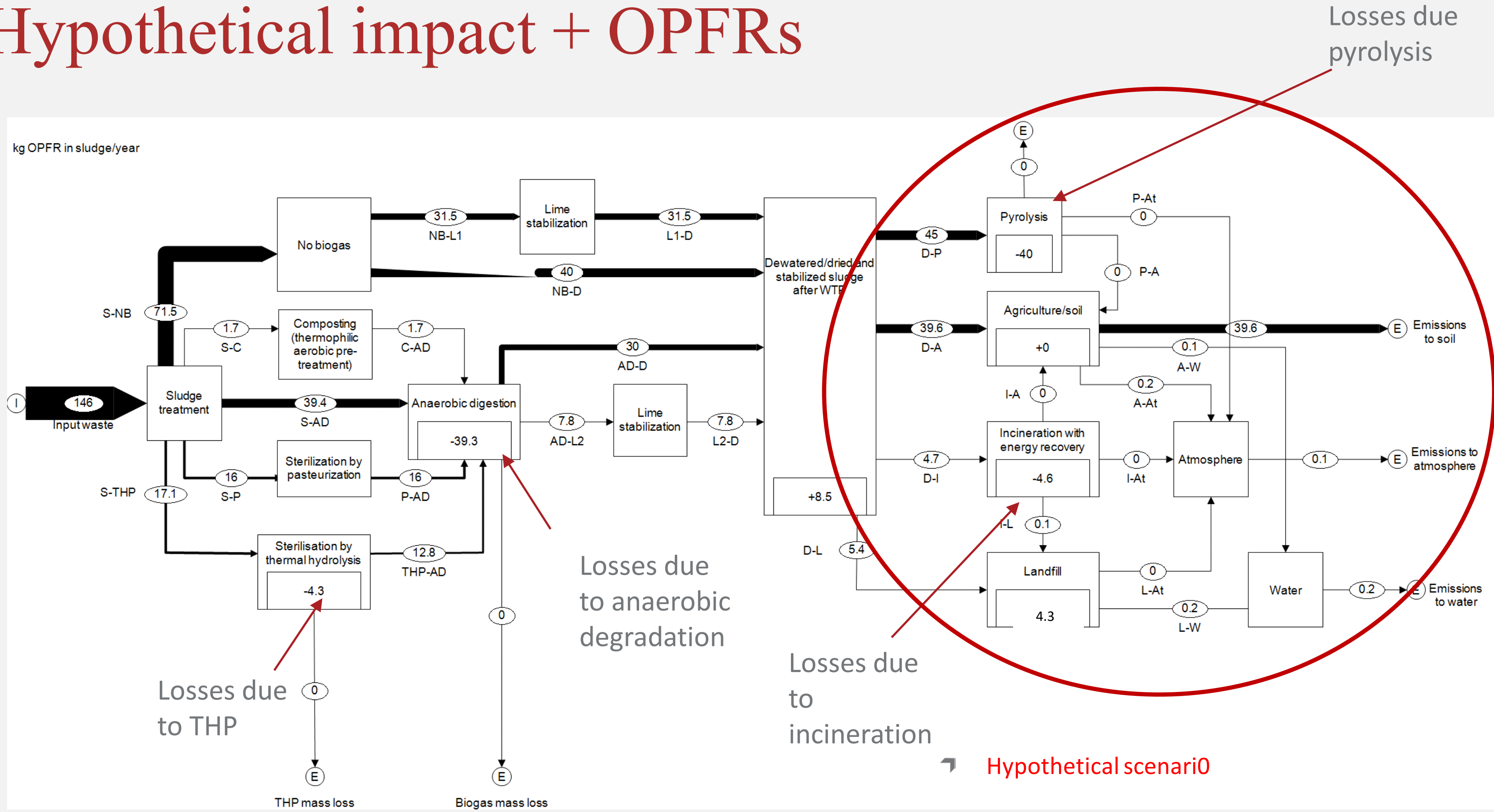
Imagine a future with pyrolysis …

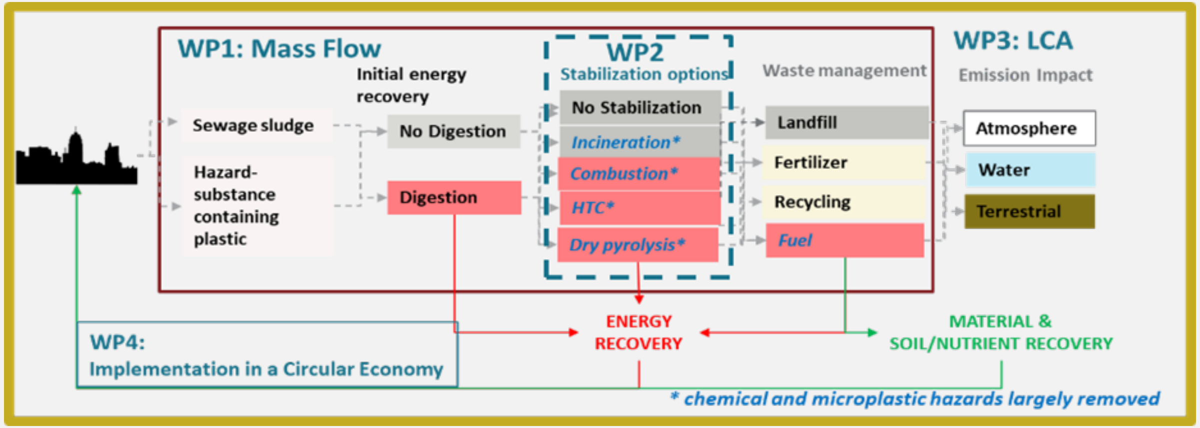


Hypothetical impact + OPFRs



Hypothetical scenari0

To do next



11:00-11:45 **Part 2. Effect of Pyrolysis on concentrations**

6. **What happens to PFAS and other contaminants in organic waste when pyrolyzed into biochar? – 35 min** Erlend Sørmo, NGI and Gabriela Castro
7. **Discussion –** 15 min

NGI

Discussion (example topics)

- Emerging unknown contaminants (e.g. total PFAS)
- upstream source control of pollutants
- Variations in sludge management practices on contaminant exposure

Thank you!

#onsafeground

NORWEGIAN GEOTECHNICAL INSTITUTE
NGI.NO

What happens to PFAS and other contaminants in organic waste when pyrolyzed into biochar?

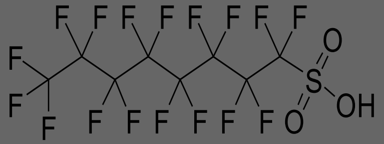
Erlend Sørmo, Gabriela Castro, Gerard Cornelissen, Junjie Zhang, Alexandros G. Asimakopoulos, Katinka Krahn, Gudny Flatabø, Clara Lade, Hans H. Peter Arp

SLUDGEFFECT Symposium, Trondheim, 09.04.24

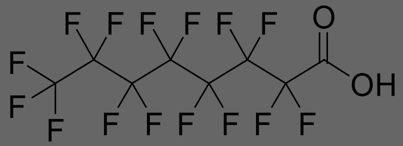
Per and polyfluorinated alkylsubstances (PFAS)
- a massive environmental threat

- Persistent, mobile, toxic (PMT)[1]
- >5000 compounds[2]
- Countless applications[2,3]

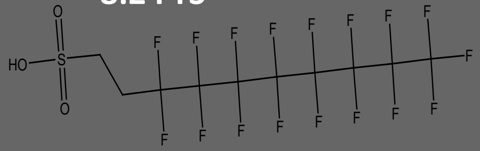
PFOS



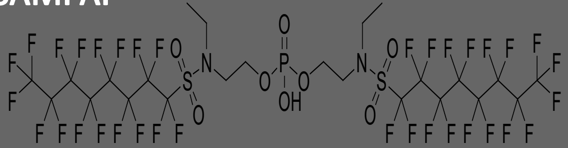
PFOA

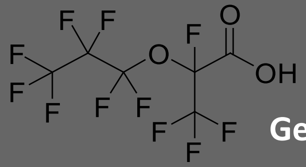


8:2 FTS



diSAMPAP





GenX

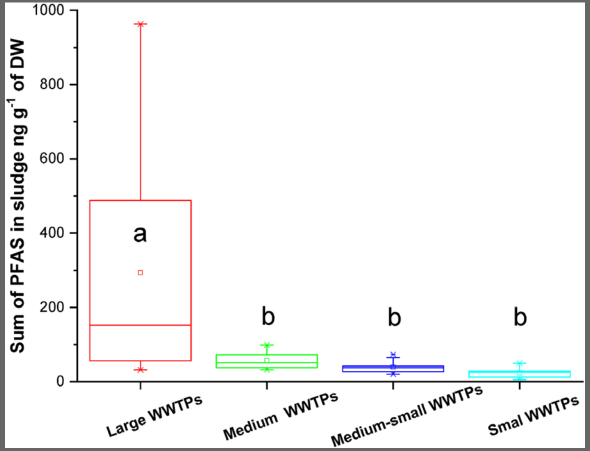


Figure: Semerád et al (2020) Chemos https://doi.org/10.1016/j.chemosphere.2020.128018

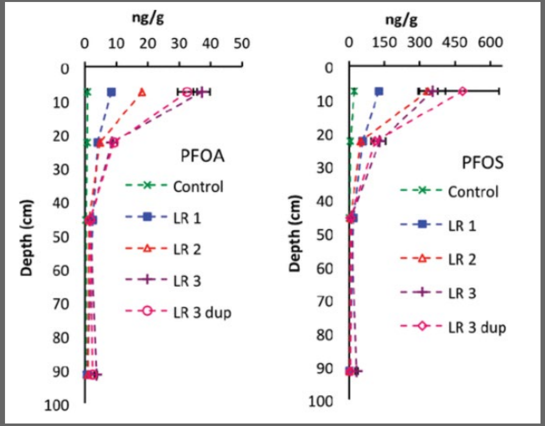


Figure: Sepulvado et al (2011) ES&T https://doi.org/10.1021/es103903d

1) Hale et al (2020) Env Sci Europe https://doi.org/10.1186/s12302-020-00440-4
2) Rudin et al (2023) STOTEN https://doi.org/10.1016/j.scitotenv.2023.162618
3) Glüge et al (2020) Env Sci Pros Imp https://doi.org/10.1039/D0EM00291G

How can we reduce PFAS emissions from waste handling?

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

Photo: Ove Dahl, Lindum.no

Photo: NGI

NGI

1) Berg et al (2021) Jrn. Air & Waste Management Association
2) Stoiber et al (2020) Chemosphere

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

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

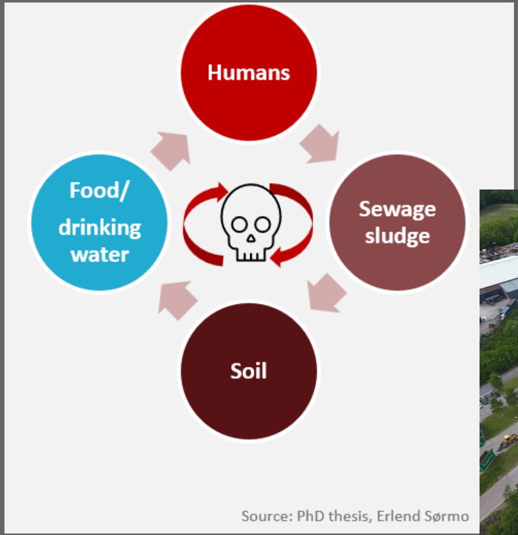


Photo: Ove Dahl, Lindum.no

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 - thermal treatment with benefits

- Energy recovery[1]
- Drying needed[1]
- Carbon storage[1,2]
- Multiple applications for sludge biochars:
  - Soil amendment[1]
  - Sorbents for contaminants[3]
  - Substitute in cement kiln[1]

Photo: Lindum AS

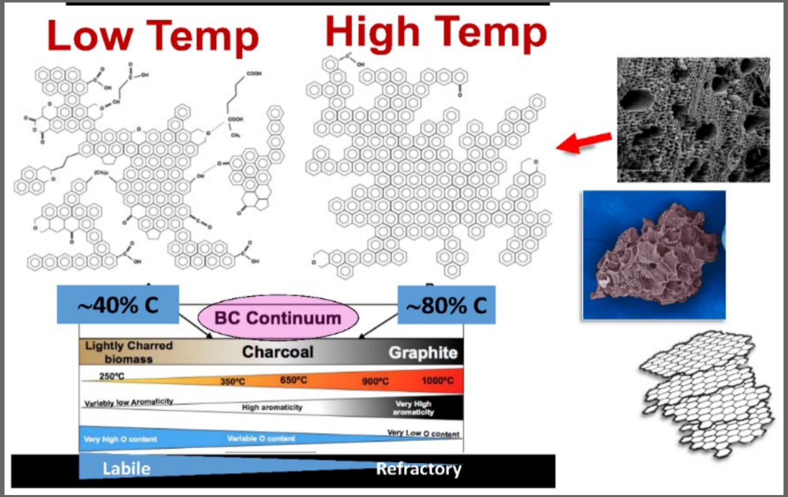

Figure: Adapted from Zimmerman & Ouyang (2019) Soil Biol. and Biochem. https://doi.org/10.1016/j.soilbio.2018.12.011

1) Barry et al (2019) Biomass & Bioenergy https://doi.org/10.1016/j.biombioe.2019.01.041
2) Lehmann et al (2006) Mitig. Adapt. Strateg. Glob. Chang https://doi.org/10.1007/s11027-005-9006-5
3) Krahn et al (2022) Jrn Haz Mat https://doi.org/10.1016/j.jhazmat.2022.130449

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

Boiling points deciding factor → volatilized or decomposed[2]

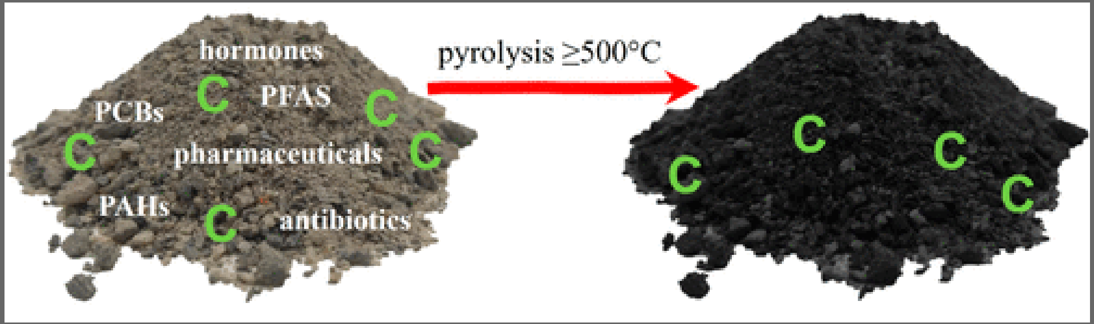

Figure: Buss (2021) ACS Sust Chem. Eng.
https://doi.org/10.1021/acssuschemeng.1c03651

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

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)

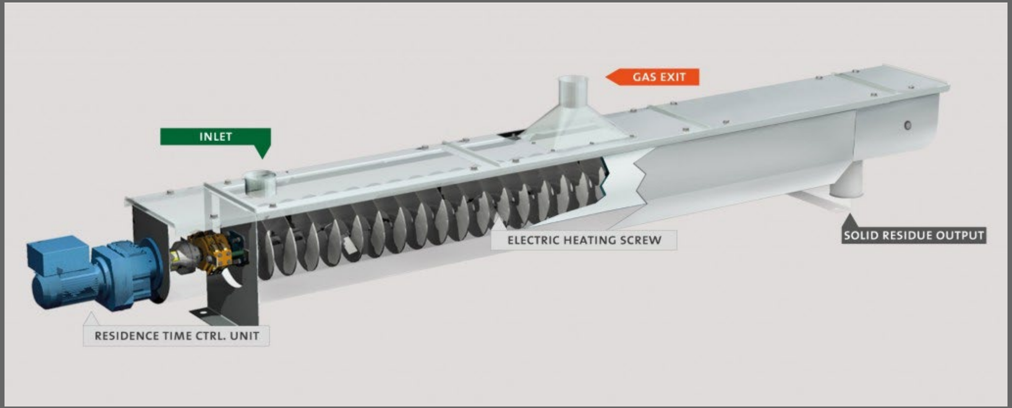

Figure: http://www.biogreen-energy.com/spirajoule/

Photo: NGI

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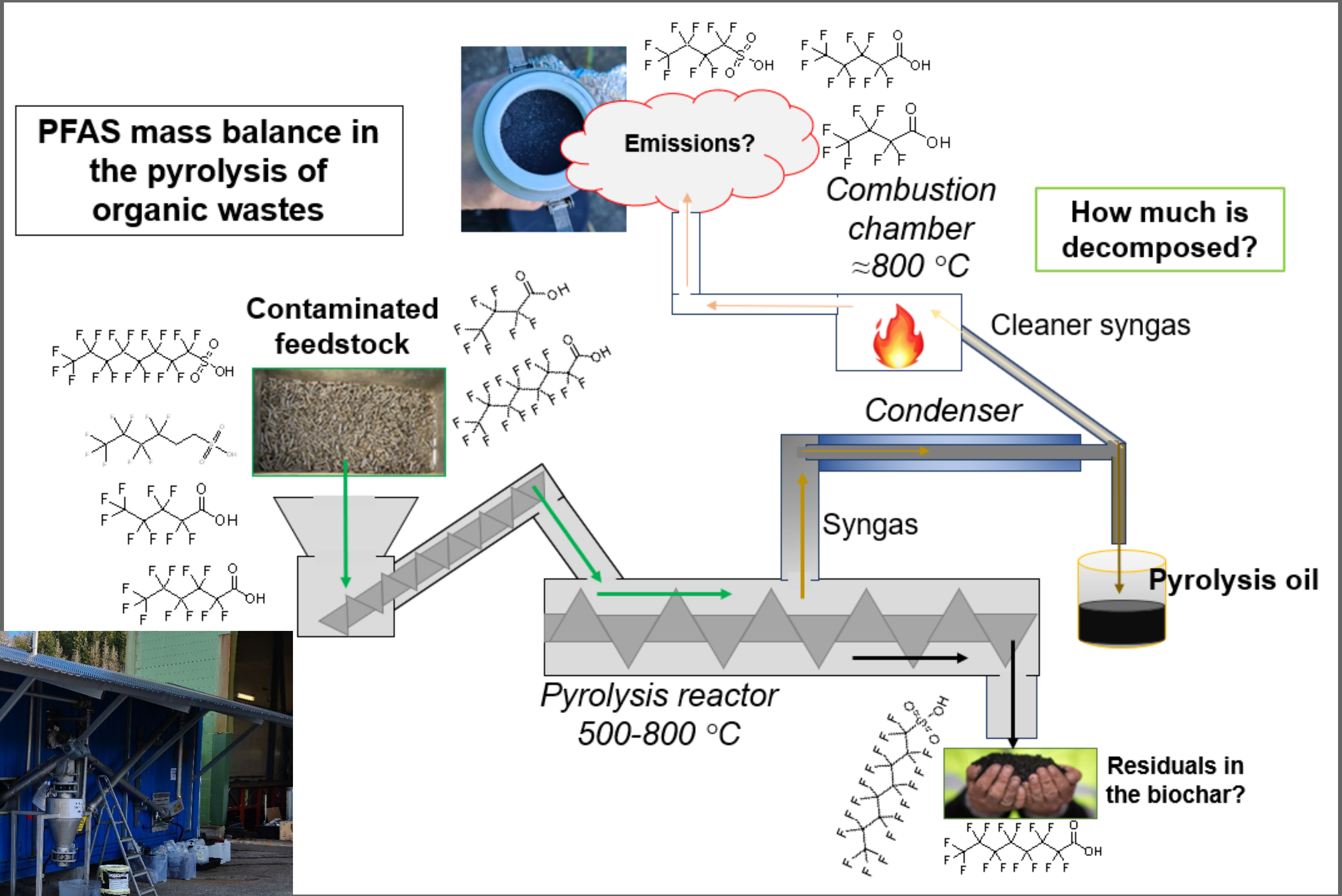
What happens to PFAS and other organic contaminants in full-scale pyrolysis?



Source: Sørmo et al (2023) JHazMat

Photo: NGI

Waste fractions[1]

- **Sewage sludge – 134 000 t yr^{-1}**
  - **Sewage sludge and food waste digestate (Cambie) (DSS-1)**
  - **Anaerobically digested sewage sludge (DSS-2)**
  - **Anaerobically digested and lime stabilized sewage sludge (LSS)**
  - **De-watered and hydrolysed sewage sludge (DWSS)**
- Food waste reject (FWR) – 65 000 t yr^{-1}
- Waste timber (WT) – 786 000 t yr^{-1}
- Garden waste (GW) – 212 000 t yr^{-1}
- Wood chips from forestry (CWC) – 3 700 000 t yr^{-1}

1) www.ssb.no – Norwegian Waste Budget 2021

No standard method available for PFAS in biochars

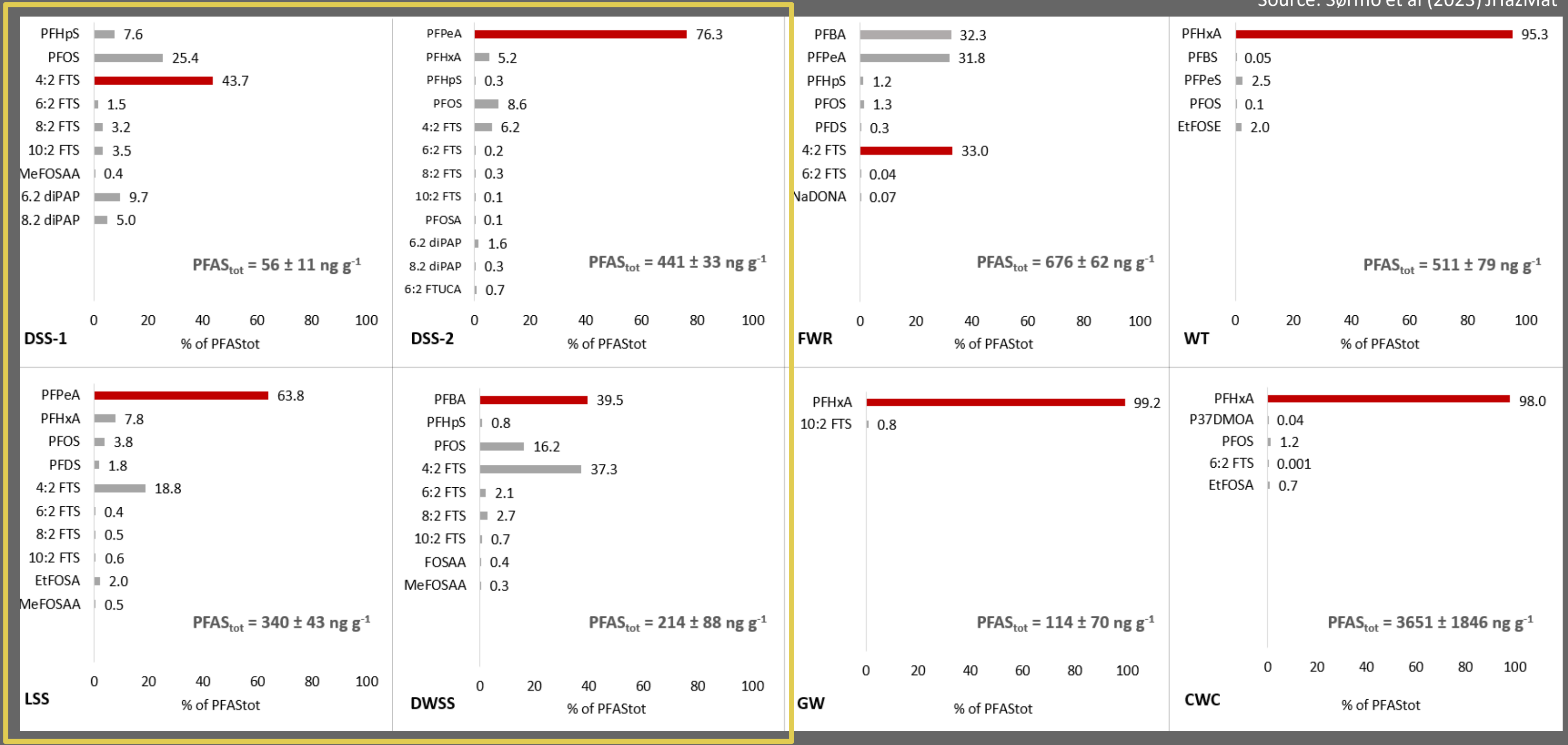
- Room temp. MeOH-extraction gave poor recoveries
  - **Approach used by commercial labs**
- More comprehensive extraction protocols needed
- 56 congeners targeted
  - 41 common congeners (9 PFSA, 15 PFCA, 4 FTS, 8 FSA, & 5 substitutes)[1]
  - 4 ultrashort chain PFAS (1 PFSA & 3 PFCA)[2]
  - 11 additional PFAS precursor compounds (7 FTUCA, 2 FTEOC, & 2 diPAP)[3]

1) Asimakopoulos et al. (2014) Jrn of Chromatography A
2) Neuwald et al (2022) ES&T
3) Ahmadireskety (2021) STOTEN

NGI

High PFAS-concentrations in all investigated wastes!

Source: Sørmo et al (2023) JHazMat



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)

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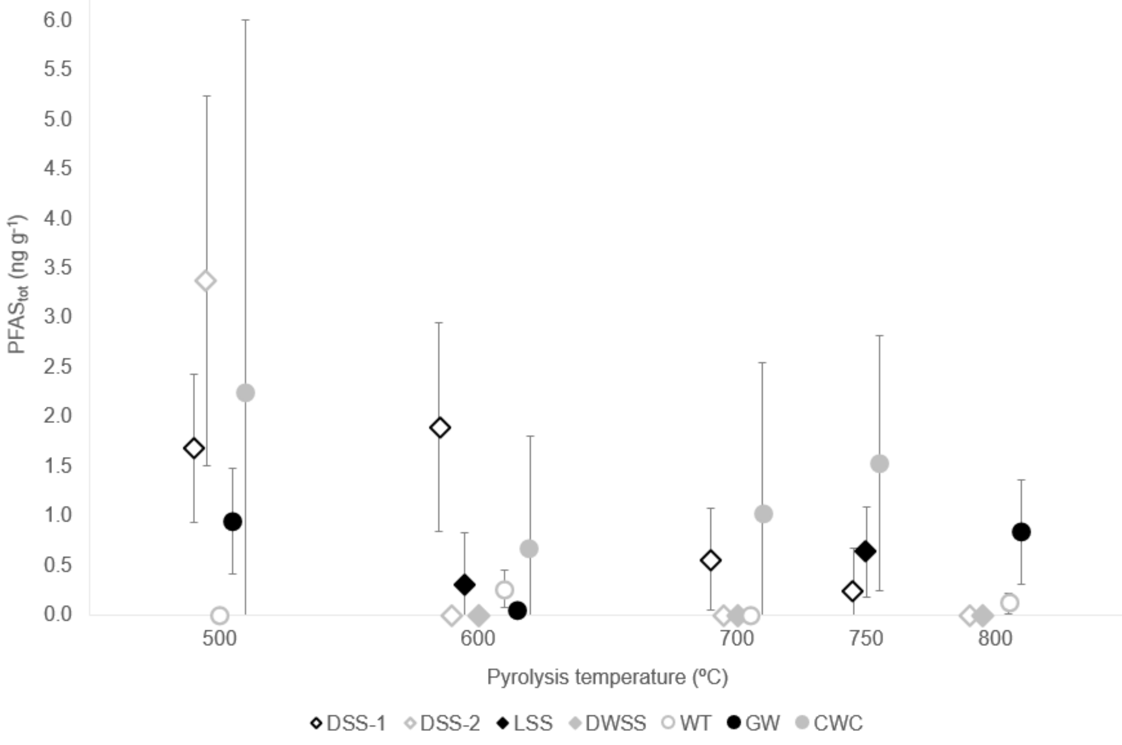
PFAS-residuals were found in the biochar

Source: Sørmo et al (2023) JHazMat

- 1-3 oom. conc. drop
- 60-100% fewer congeners
- Shift towards long chain PFAS (>6xCF_2)
- **Accounts for up to 2% of TA total mass**



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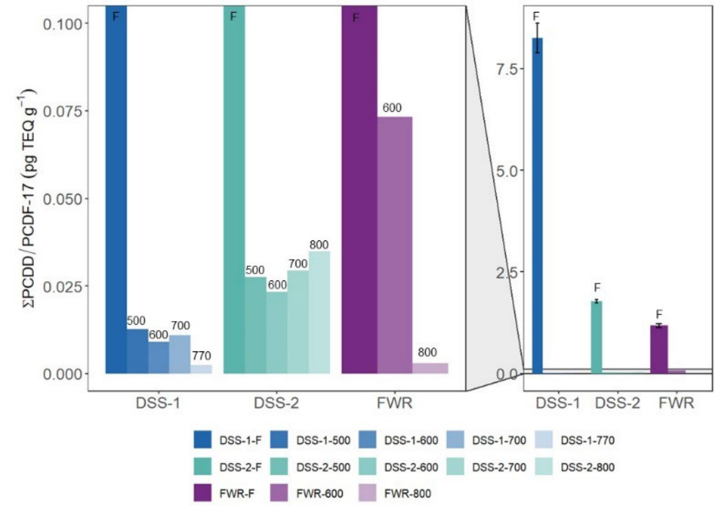
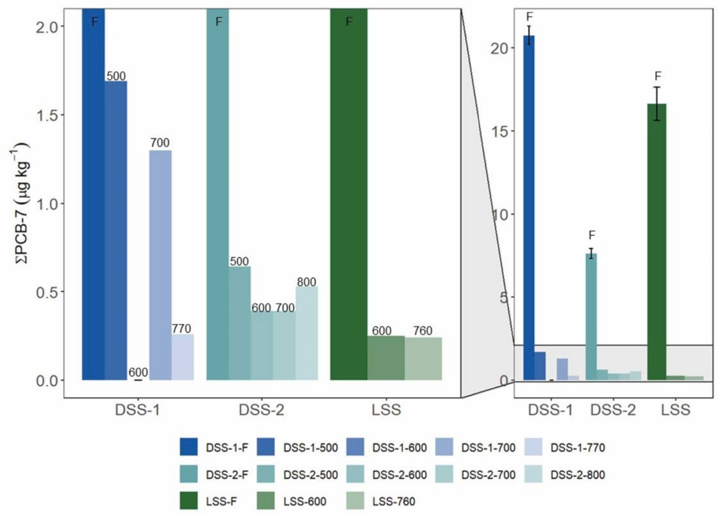
Digested sewage sludge (DSS-1 and DSS-2), limed sewage sludge (LSS), de-watered sewage sludge (DWSS), food waste reject (FWR), waste timber (WT), garden waste (GW), & wood chips from forestry (CWC)

PCDD/Fs and PCBs are almost completely volatilized!

- PCBs and PCDD/Fs
  - REs >99%
- Partial dichlorination
- Mainly volatilized and trapped in pyrolysis condensate





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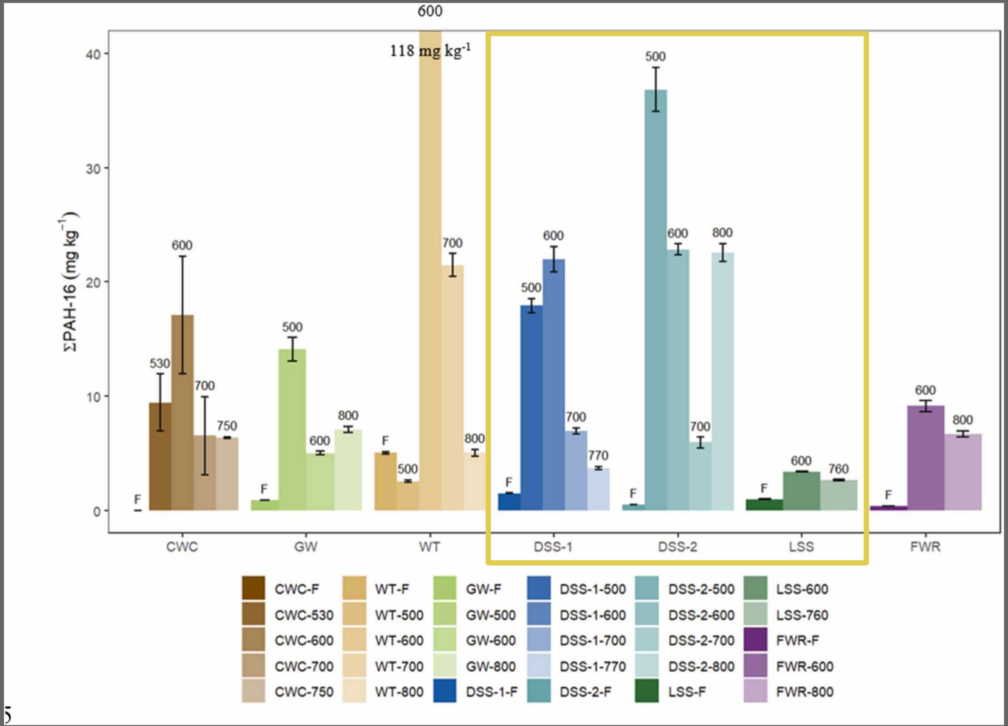
Source: Sørmo et al (2024) JHazMat https://doi.org/10.1016/j.jhazmat.2023.132546

PAHs are more unpredictable..

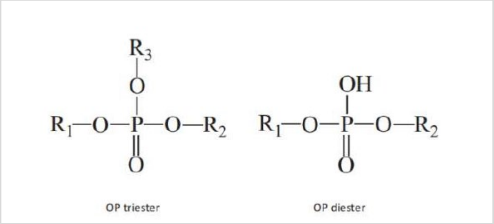
- Net generation of PAHs
- No clear correlation with pyrolysis temperature
- PAH generation linked to feedstock composition
- Most likely an issue that can be solved through technology optimization

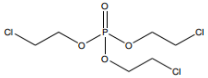


Source: Sørmo et al (2024) JHazMat https://doi.org/10.1016/j.jhazmat.2023.132546

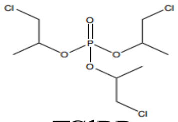
Organophosphate flame retardants (OPFRs)

- ❖ Chemical additives widely used in combustible materials to prevent fire or delay combustion processes.
- ❖ High volume production chemicals.

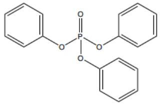




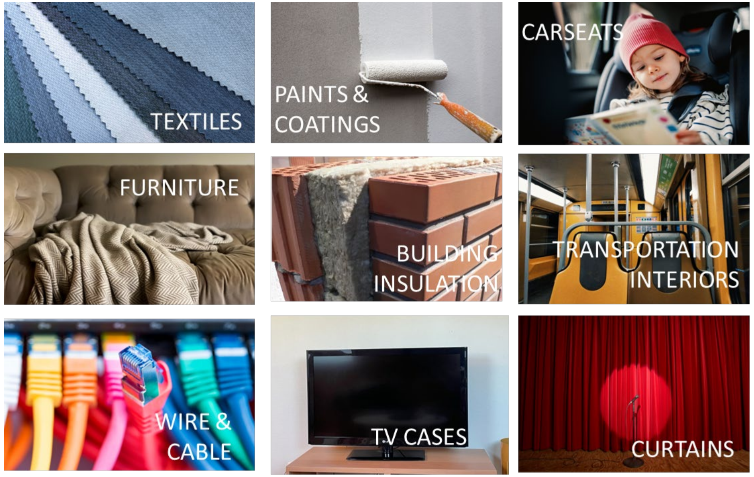
TCEP



TClPP

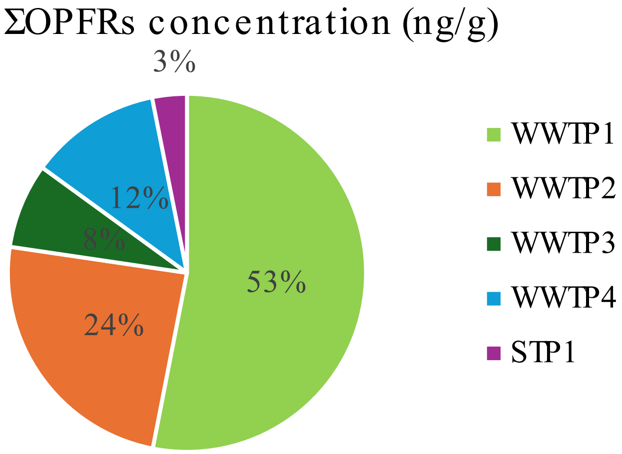


TPhP



Organophosphate flame retardants (OPFRs)

- Occurrence of OPFRs in Norwegian digested sludge



100% DF for TnBP, TiBP, TBOEP and BPA-BDPP in digested sludge.
Higher concentrations were detected in the WWTPs with primary treatment (WWTP1 and WWTP2).

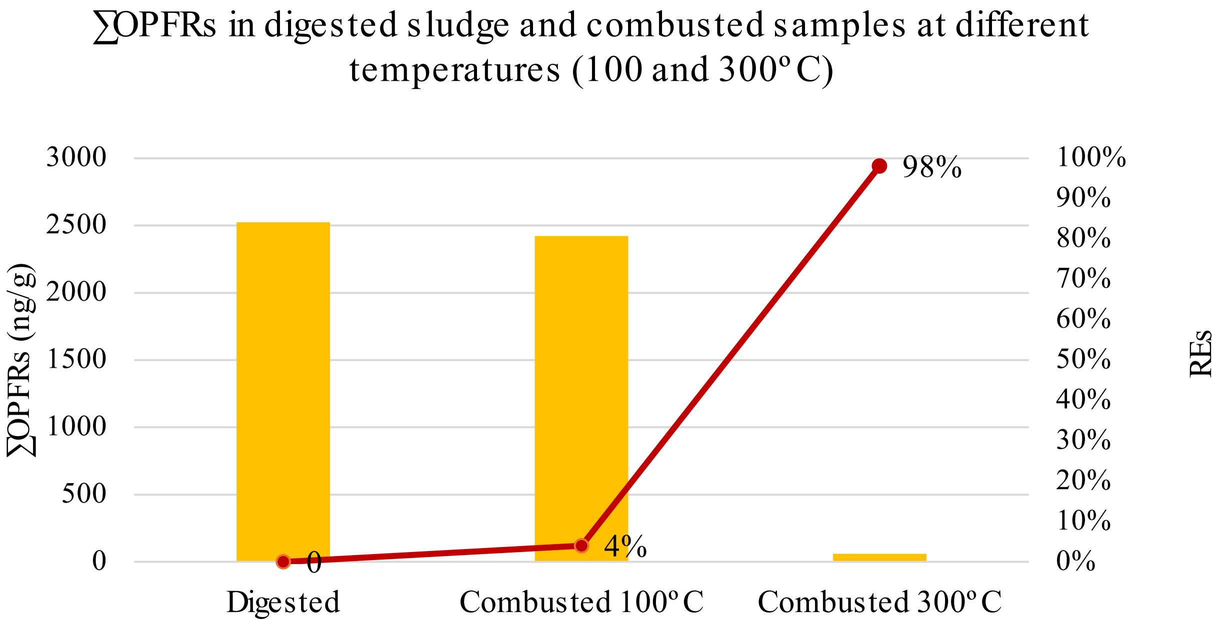
Combustion

Combustion was carried out in an oven at 100 and 300 °C in digested sludge from WWTP1.

Digested WWTP1

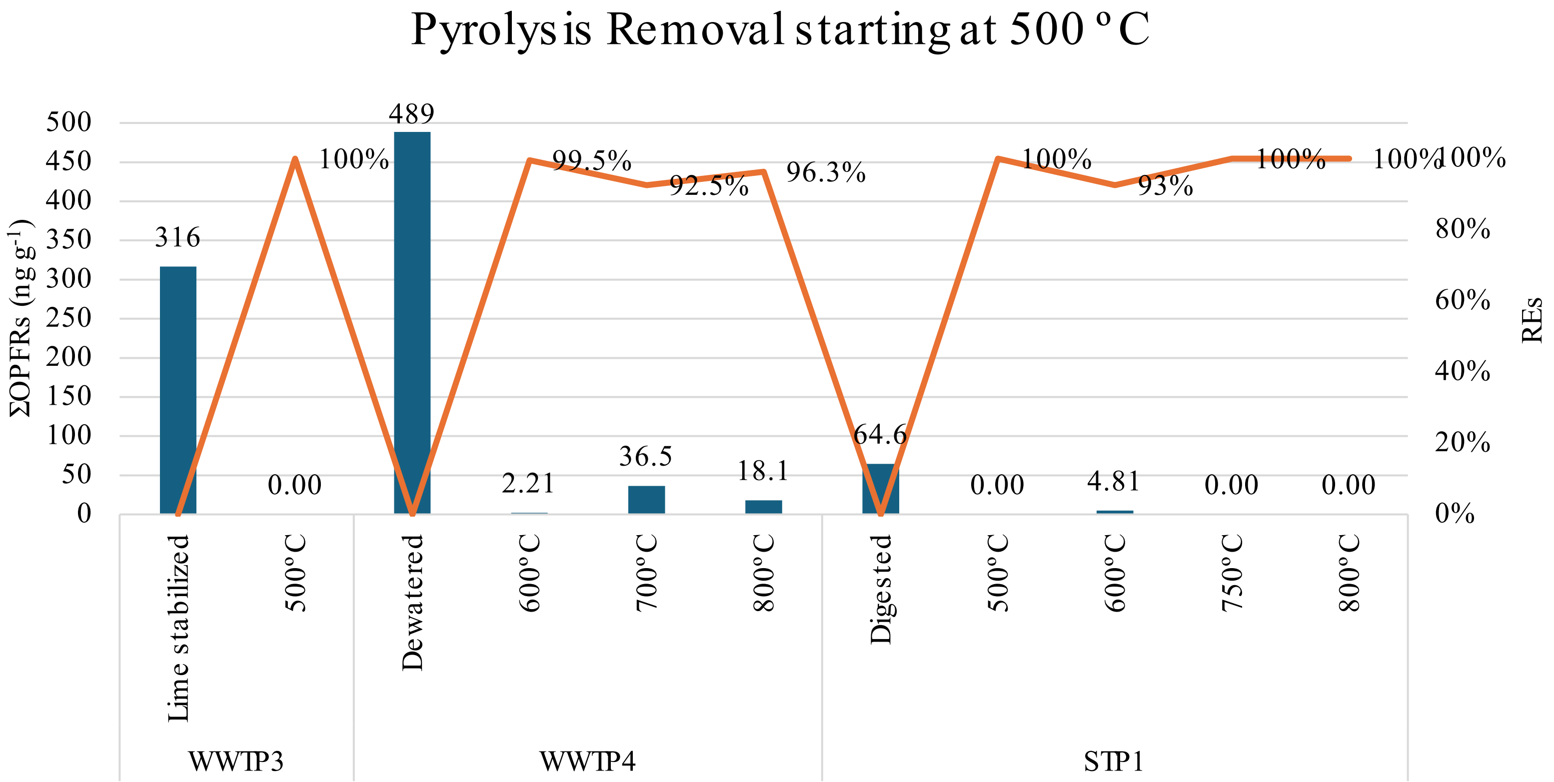
Digested WWTP1
Combusted 100º C

Digested WWTP1
Combusted 300º C



G. Castro et al. (2023). Analysis, Occurrence and Removal Efficiencies of Organophosphate Flame Retardants (OPFRs) in Sludge undergoing Anaerobic Digestion followed by diverse Thermal Treatments, Science of the Total Environment 870, 161856

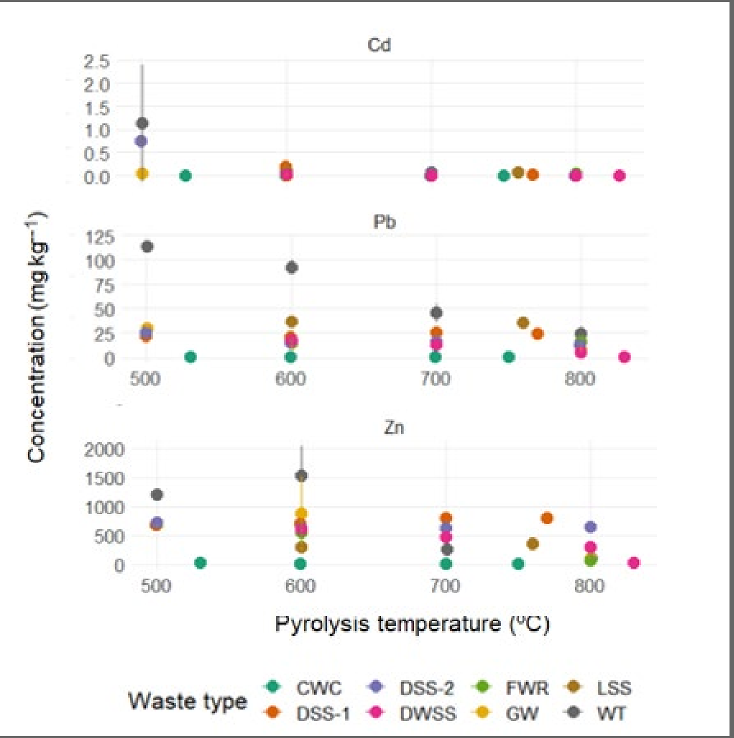
Pyrolysis



Pyrolysis Removal starting at 500 °C
ΣOPFRs (ng g-1)
REs
500
450
400
350
300
250
200
150
100
50
0
100%
80%
60%
40%
20%
0%
316
0.00
489
2.21
36.5
18.1
64.6
0.00
4.81
0.00
0.00
100%
99.5%
92.5%
96.3%
100%
93%
100%
100%
Lime stabilized
500°C
Dewatered
600°C
700°C
800°C
Digested
500°C
600°C
750°C
800°C
WWTP3
WWTP4
STP1

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)

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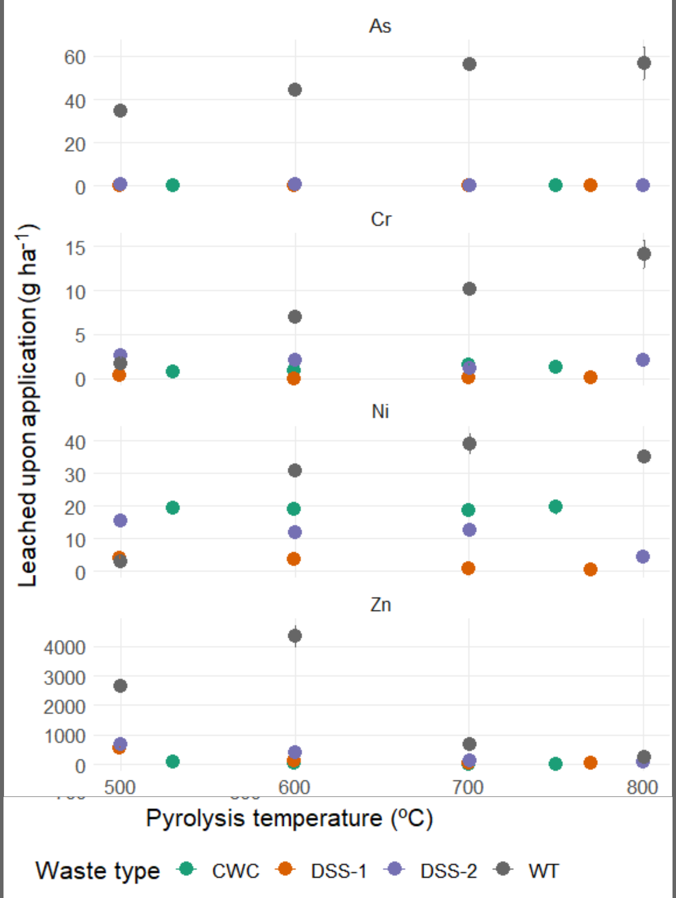
Heavy metals are immobilized at the same high temperatures

- 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: Sørmo et al (submitted)

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So, pyrolysis does solve the issue of contaminants in sewage sludge..

- Pyrolysis temperature is key!
  - **≥600 °C**
- Feedstock composition matters
  - Upstream actions important

But

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PFAS survives pyrolysis + combustion

		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

- Some PFAS are emitted
  - Account for up to 2.8 % of TA total mass
  - Dominated by short chain PFAS

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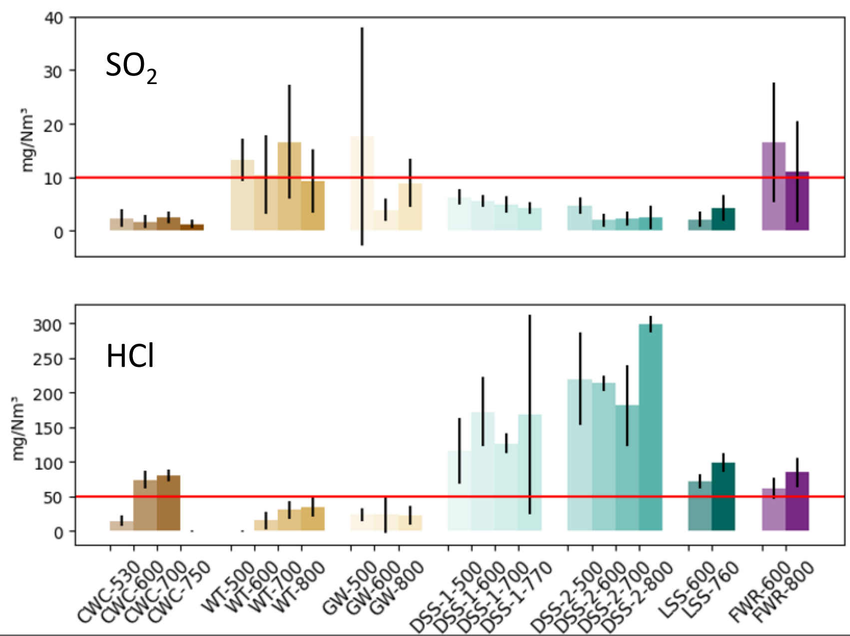
Digested sewage sludge (DSS-1 and DSS-2) & limed sewage sludge (LSS)

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: Flatabø et al (2023) Jrn Cleaner Prod.

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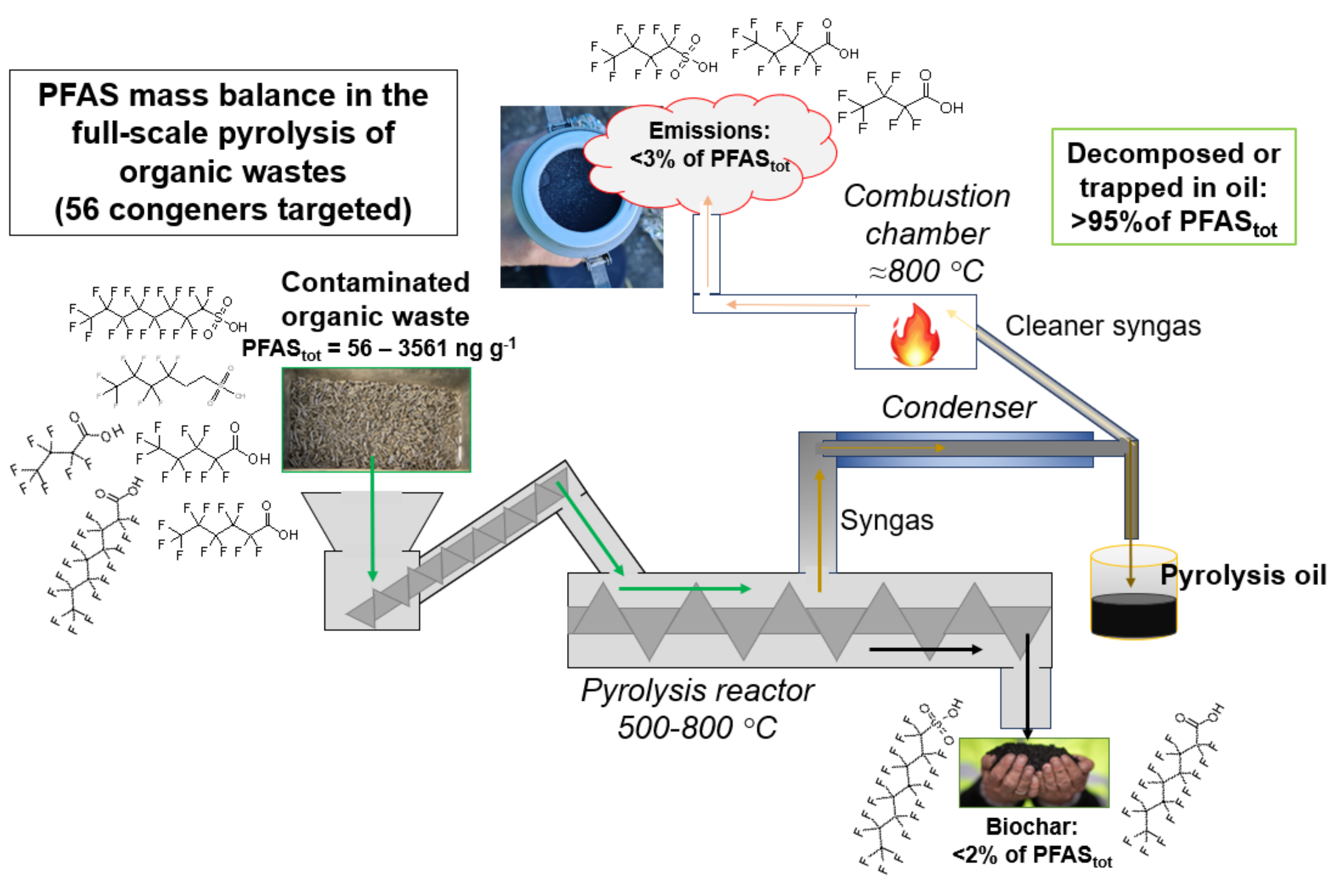
To condense or not to condense?

- 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

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

Mass balance for PFAS



Source: Sørmo et al (2023) JHazMat

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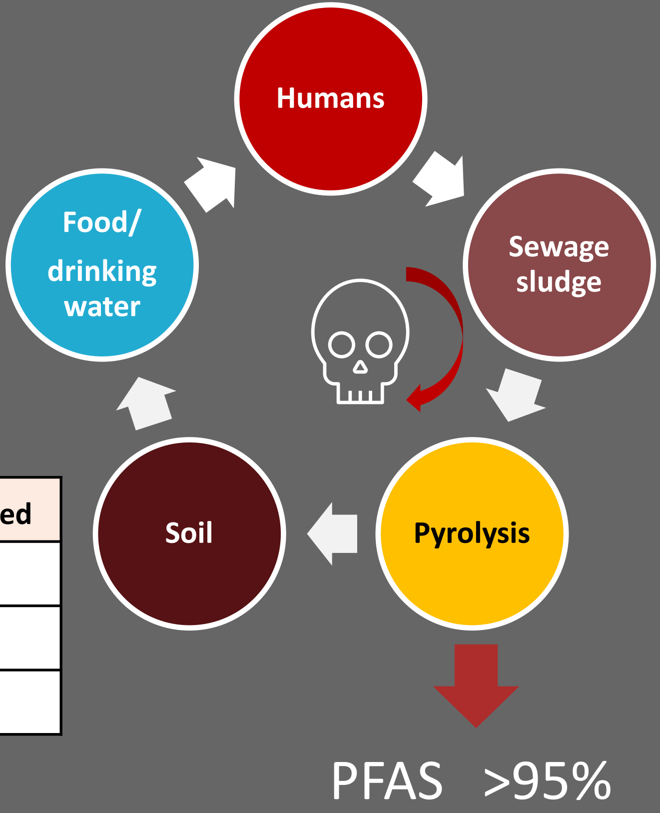
Flue gas emissions vs. taking contaminants out of circulation

- 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]

Compounds	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

Remaining uncertainties…

- PFAS in pyrolysis oil
  - Significant amounts could accumulate in oil[1]
- Fate and presence of non-targeted compounds in flue gas
  - Per and polyfluorinated alkanes, alkenes, alcohols detected in lab studies[2]
- Effect of flue gas cleaning and/or improvement of combustion chamber

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1) McNamara et al (2023) Env. Sci. Water Research & Technology
2) Yao et al (2022) JHazMat

Bonus section

Sewage sludge biochars as sorbents for PFAS

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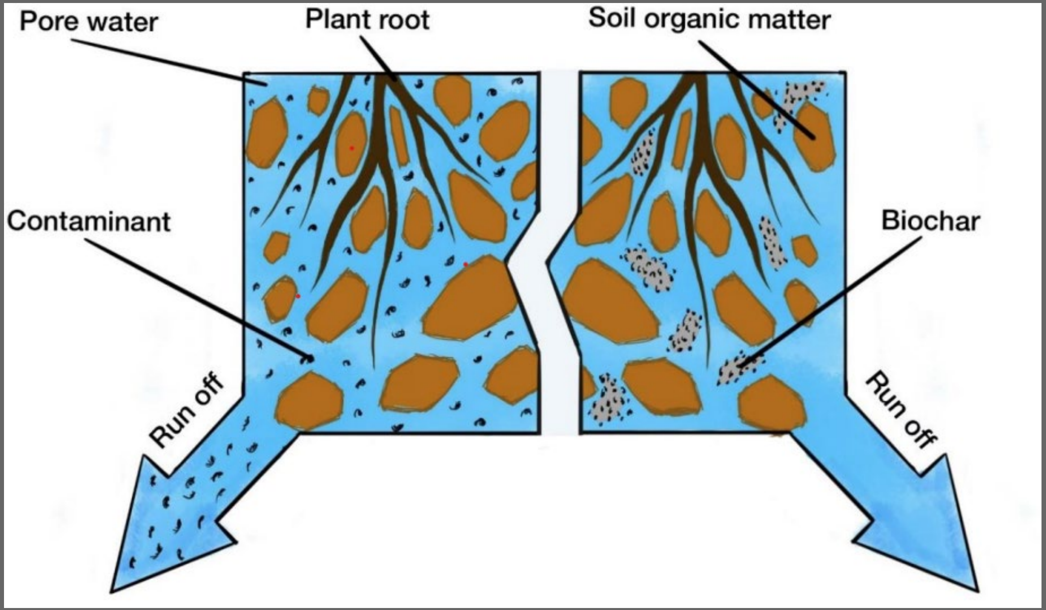
What is a sorbent?

- A material that binds a contaminant strongly
  - Activated carbon (AC)
  - **Biochar**
- Some current uses:
  - Wastewater
  - Landfill leachate
  - Drinking water
  - Air filters
  - **Soil remediation**



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

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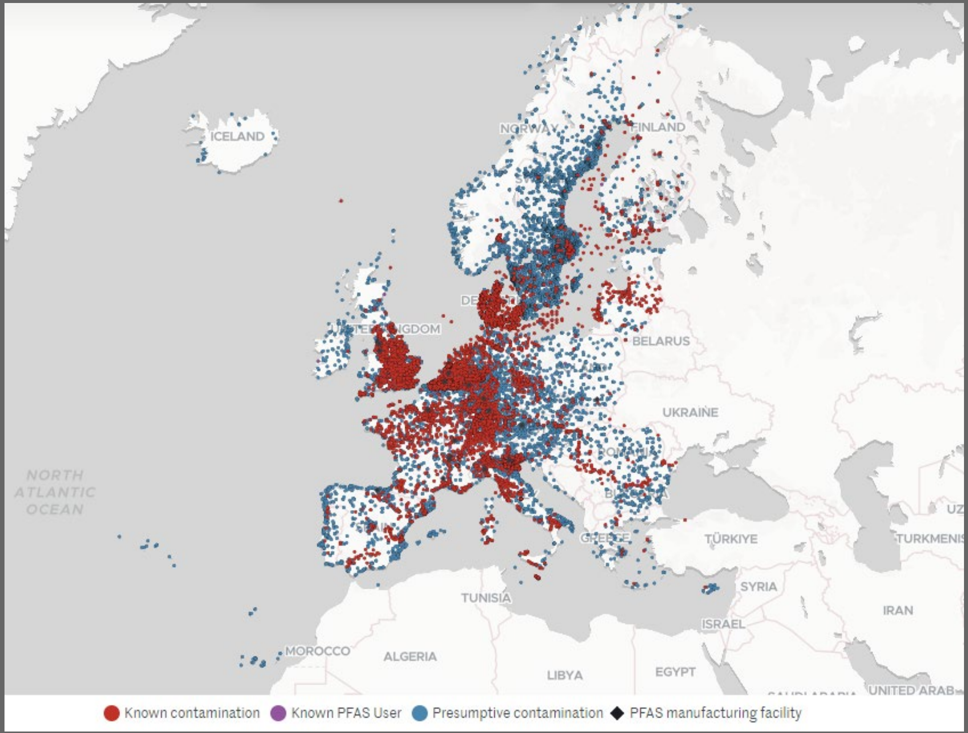
Remediation of PFAS-contaminated sites needed!

- 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)

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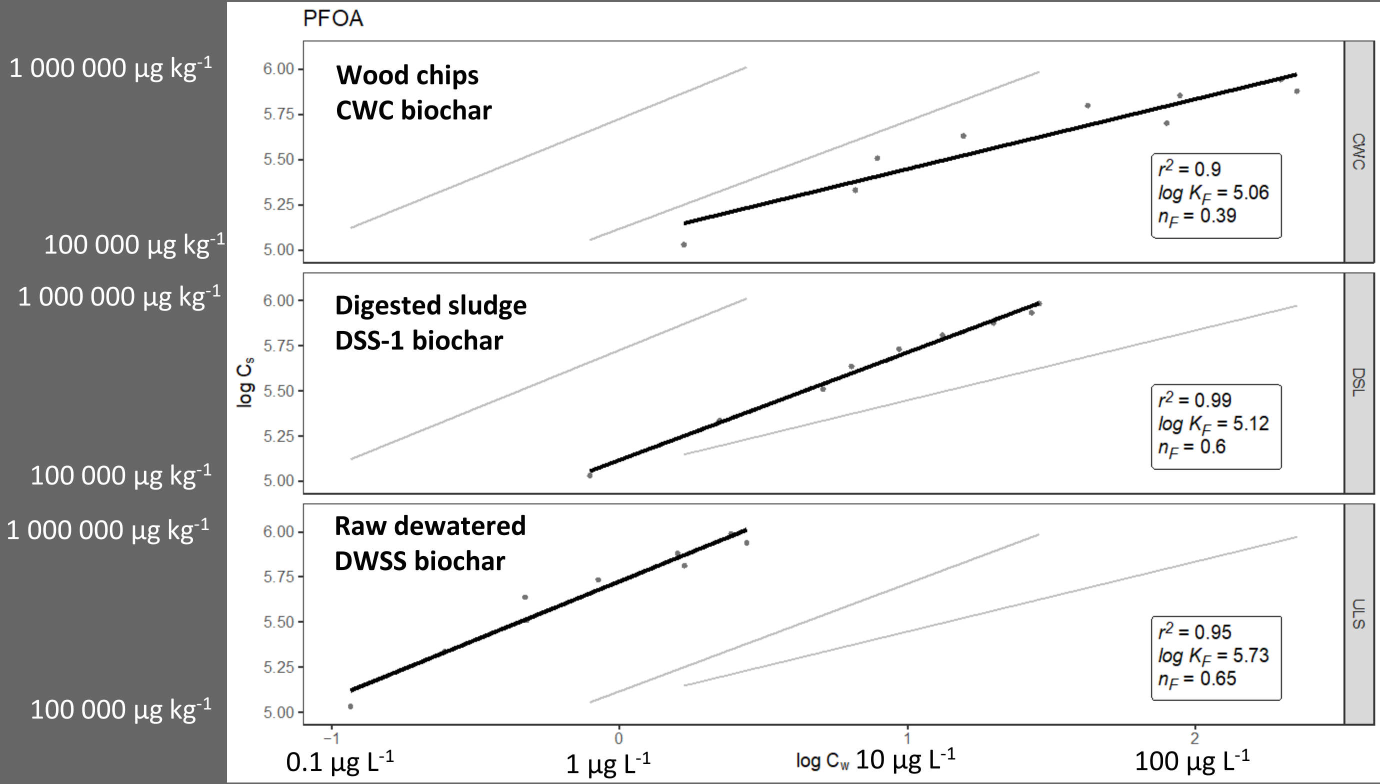
1) Ruyle et al (2023) ES&T https://doi.org/10.1021/acs.est.3c00675
2) Sörengård et al (2019) Jrn Env Man https://doi.org/10.1016/j.jece.2020.103744
3) Navarro et al (2023) Env Pol https://doi.org/10.1016/j.envpol.2023.121249

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]



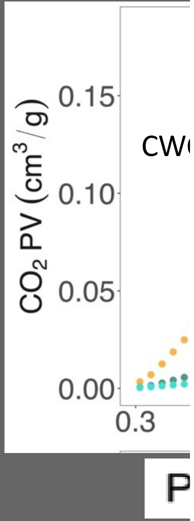
Source: Krahn et al (2023) JHazMat https://doi.org/10.1016/j.jhazmat.2022.130449

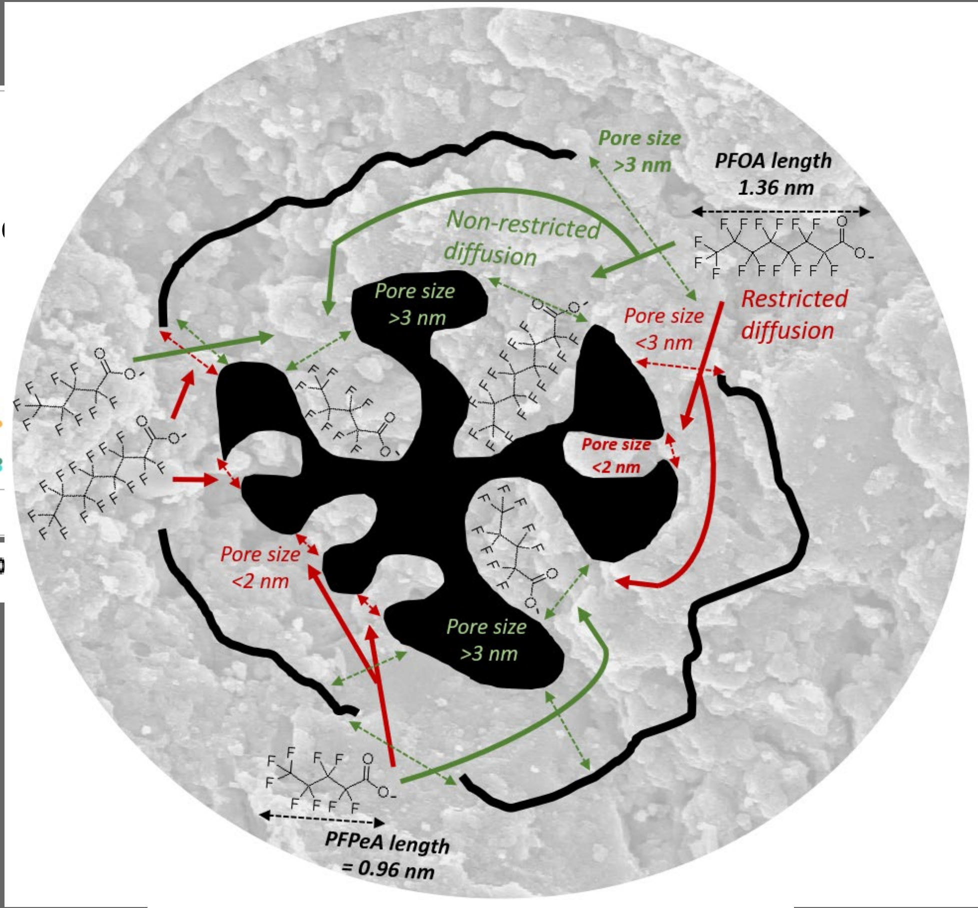
1) Kupryianchyk et al. (2016), Chemosphere https://doi.org/10.1016/j.chemosphere.2015.04.085
2) Silvani et al. (2019), STOTEN https://doi.org/10.1016/j.scitotenv.2019.133693

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!





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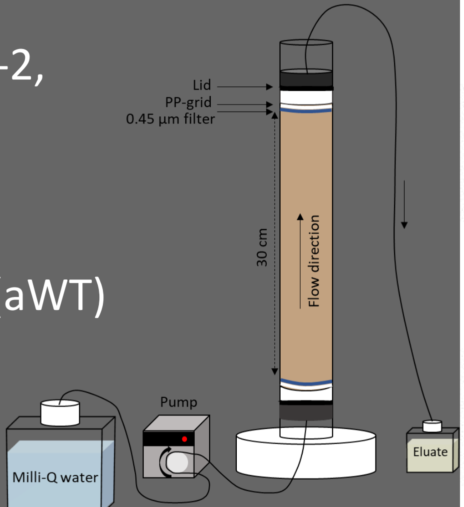
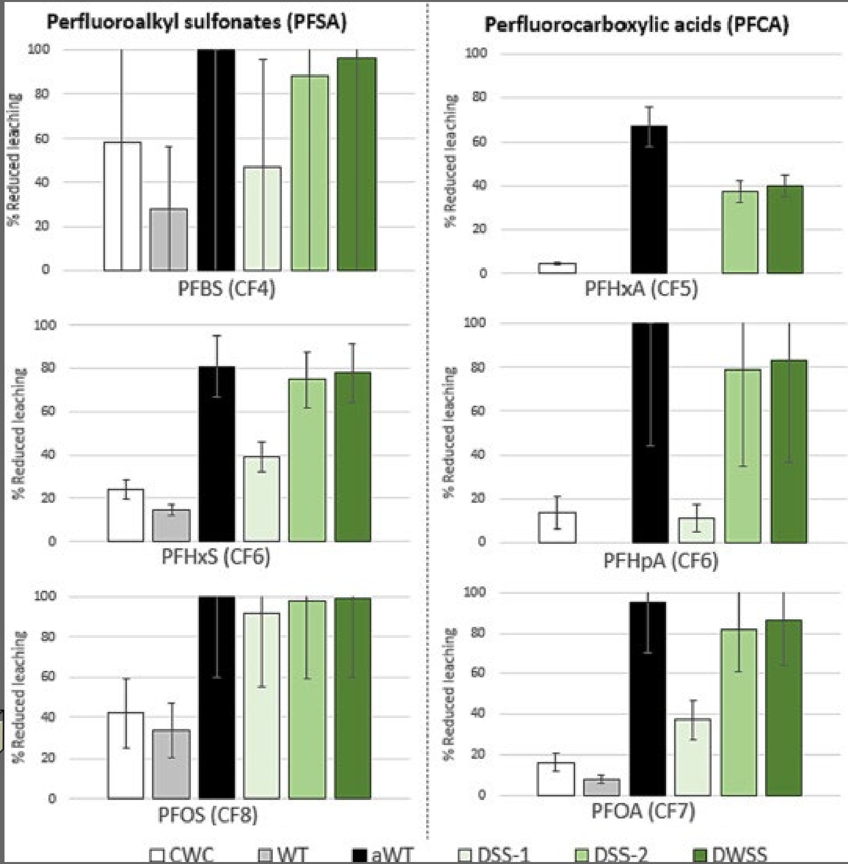
Source: Paper VIII

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





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

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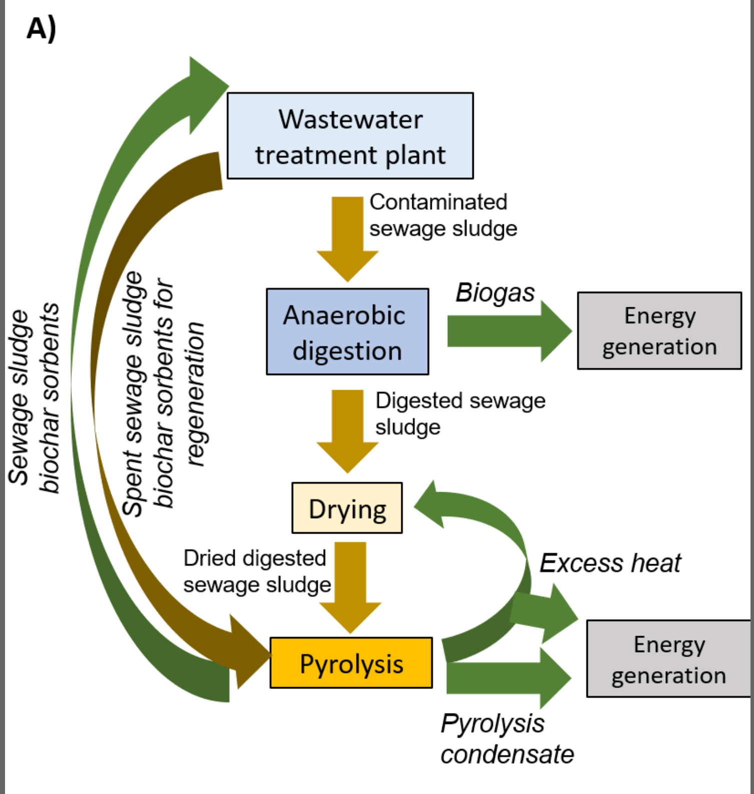
1) Sørmo et al. (2024) STOTEN https://doi.org/10.1016/j.scitotenv.2024.170971

Future outlook

- Close F-balance
- Compare emissions with and without condensation
- Investigate long term release of heavy metals from sludge biochars in soil
- Integration of pyrolysis into waste handling processes
- LCIA to study overall impact of pyrolysis for waste handling and sorbent application



Source: PhD thesis, Erlend Sørmo

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- VOW project
- SLUDGEEFFECT project

Forskningsrådet
The Research Council of Norway

Photo: NGI

Photo: Lindum AS

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#onsafeground

NORWEGIAN GEOTECHNICAL INSTITUTE
NGI.NO

NTNU
Norwegian University of Science and Technology

Industrial Ecology Programme

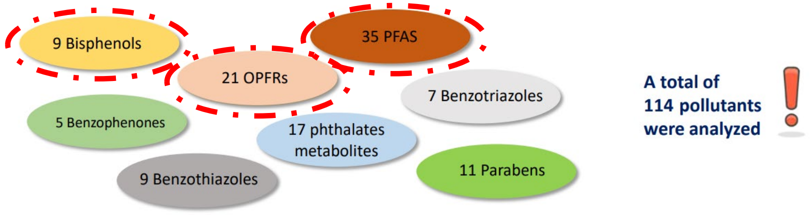
Eco-toxicological and climate change effects of sludge thermal treatments:

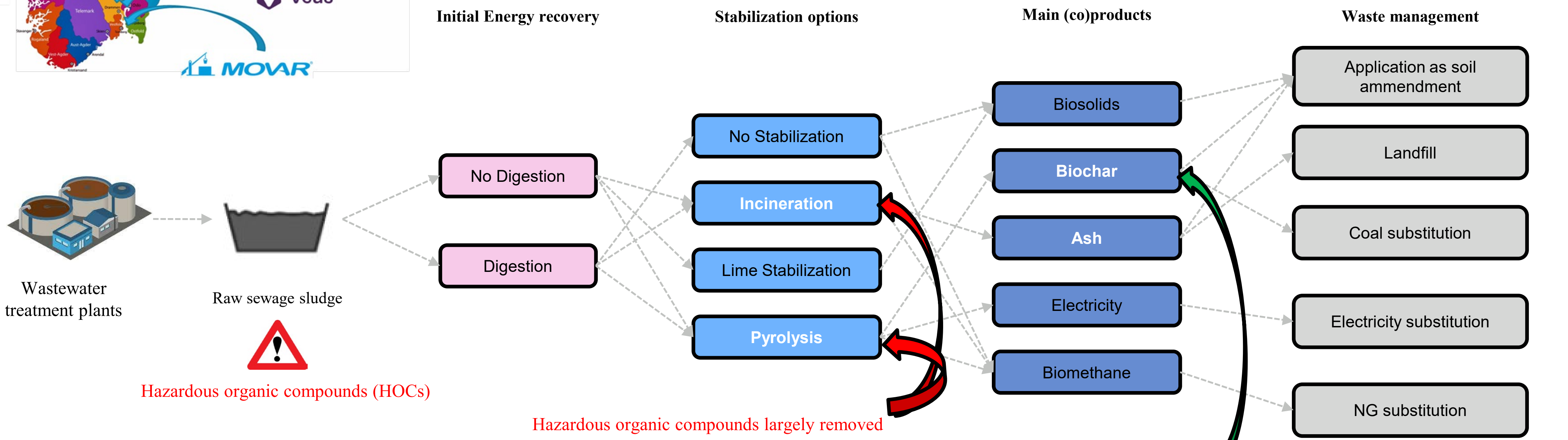
Comparison of alternative sludge handling scenarios in Norway

SLUDGEFFECT Project – *mitigate hazardous substances of sewage sludge within a circular economy*

Morales, Marjorie; Arp, Hans Peter H.; Castro, Gabriela; Asimakopoulos, Alexandros G.; Sørmo, Erlend; Peters, Gregory; Cherubini, Francesco

Sludge management





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

Content

Part I : LCA of thermal treatments for removing hazardous organic substances and metals.

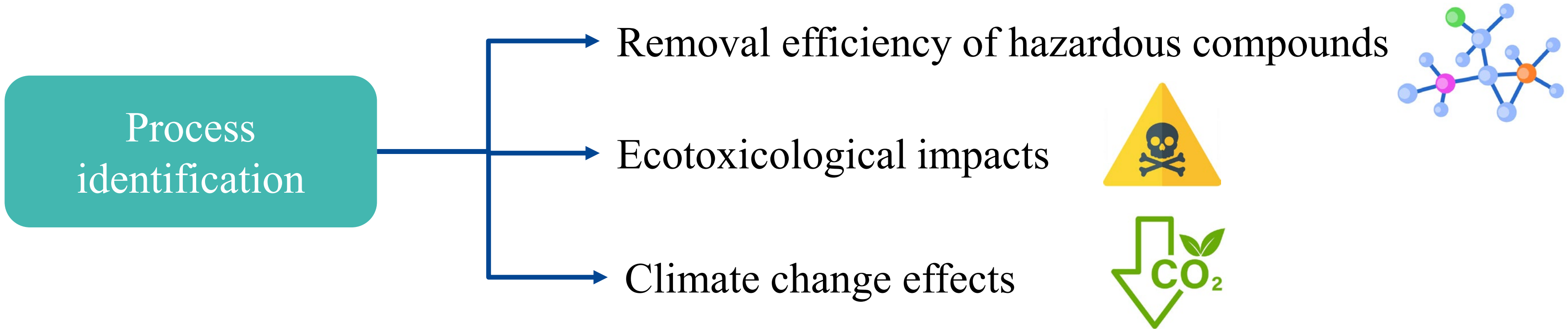
- Mapping emissions of hazardous substances and metals.
- Eco-toxicological and climate change effect of sludge thermal treatments.

Part II: LCA of large-scale sludge handling scenarios in Norway.

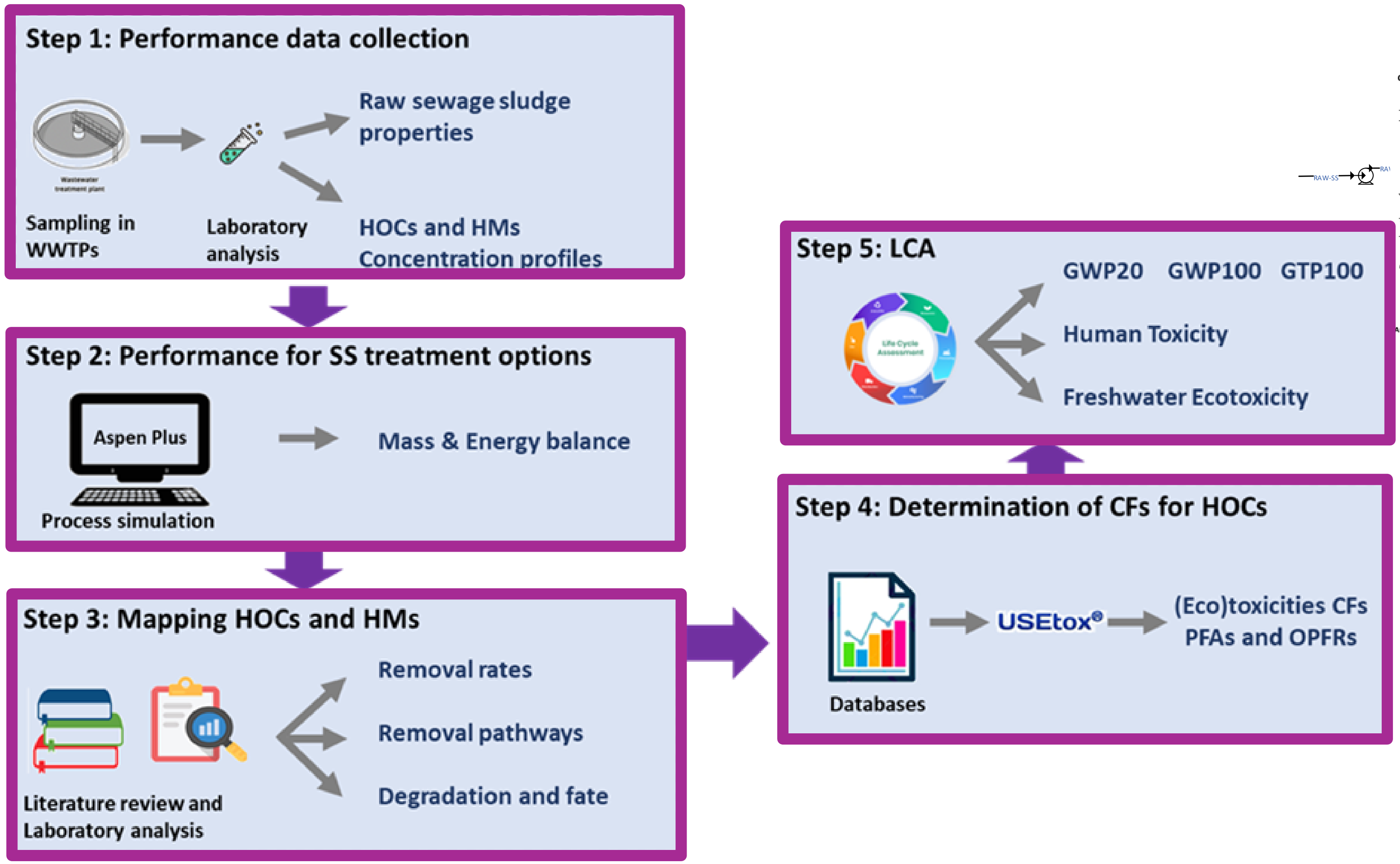
- MFA for PFAS, OPFRs and hazardous metals at National scale.
- Eco-toxicological effects of large-scale sludge handling scenarios.
- Potential Biochar and Biomethane production at National scale.

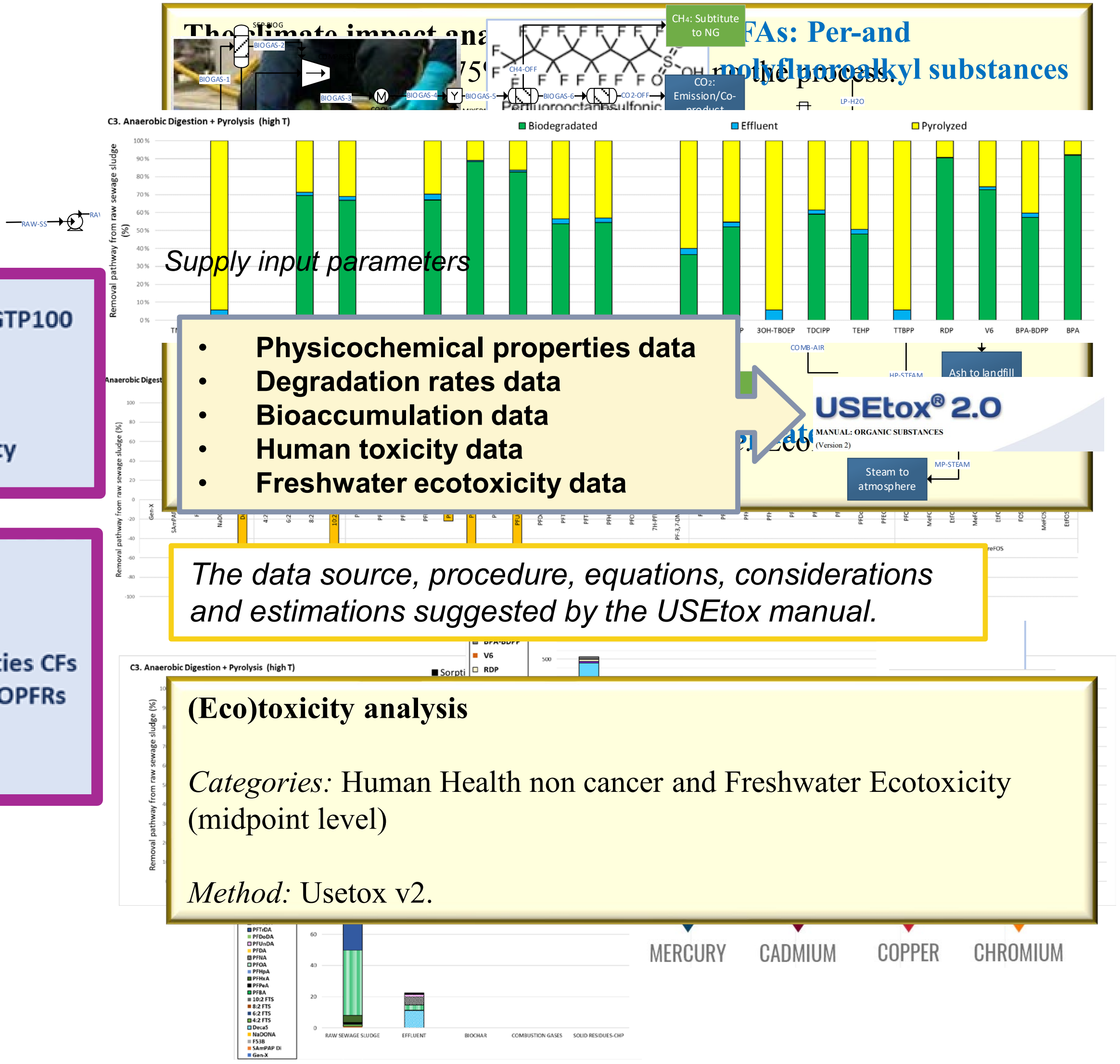
Part I :

LCA of thermal treatments for removing hazardous organic substances and metals.



Methodology





Supply input parameters

- Physicochemical properties data
- Degradation rates data
- Bioaccumulation data
- Human toxicity data
- Freshwater ecotoxicity data

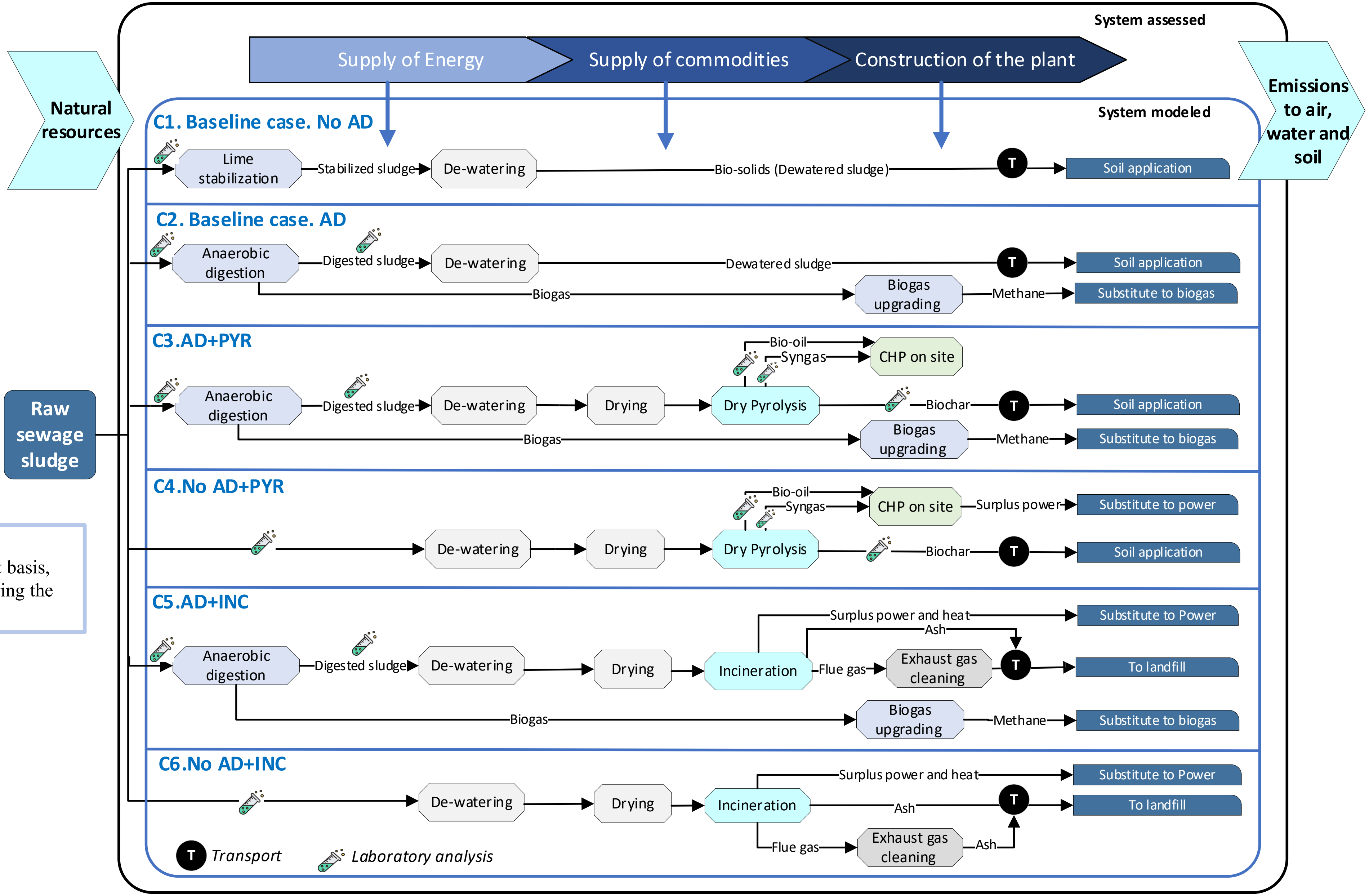
The data source, procedure, equations, considerations and estimations suggested by the USEtox manual.

(Eco)toxicity analysis

Categories: Human Health non cancer and Freshwater Ecotoxicity (midpoint level)

Method: Usetox v2.

System Boundary and Functional unit



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

NTNU

Hazardous Organic compounds (HOCs) and Heavy metals evaluated

OPFRs
(Organosphosphate flame retardants)
21 OPFRs included

Bisphenols
1 Bisphenol included

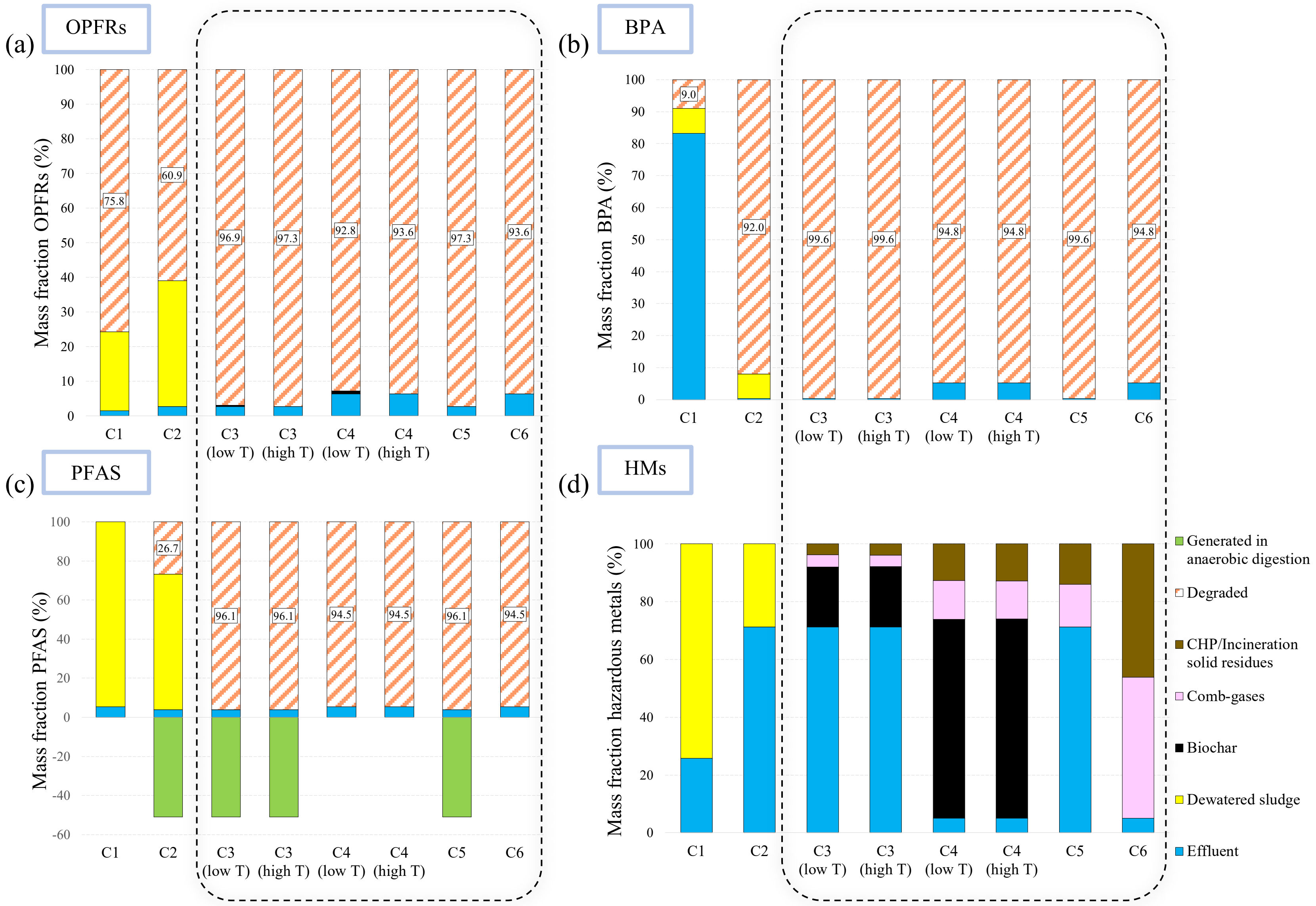
PFAs
(Poly-and perfluoroalkylated substances)
41 PFAs included

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

Results: Degradation and fate HOCs and HMs

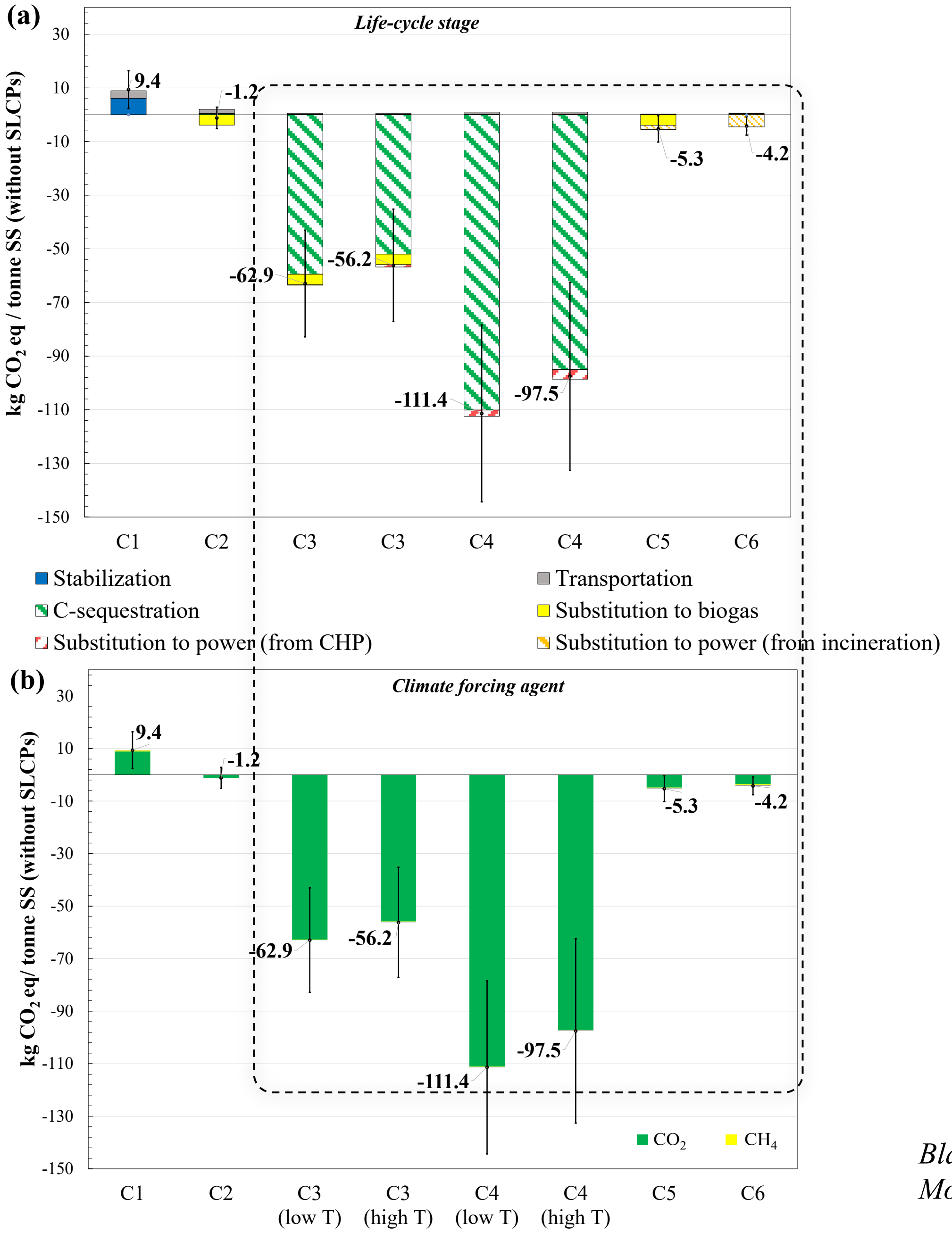


Percentage degradation and fate of hazardous organic compounds and heavy metals

Mass fraction (%) relative to total initial loading (100%) in the raw sewage sludge.

	BPA	OPFRs	PFAs
Conventional (C1-C2)	9-92%	61-76%	0-18%
Pyrolysis (C3-C4)	> 95%	93-97%	95-96%
Incineration (C5-C6)	> 95%	94-97%	91-96%

Climate change (GWP100)

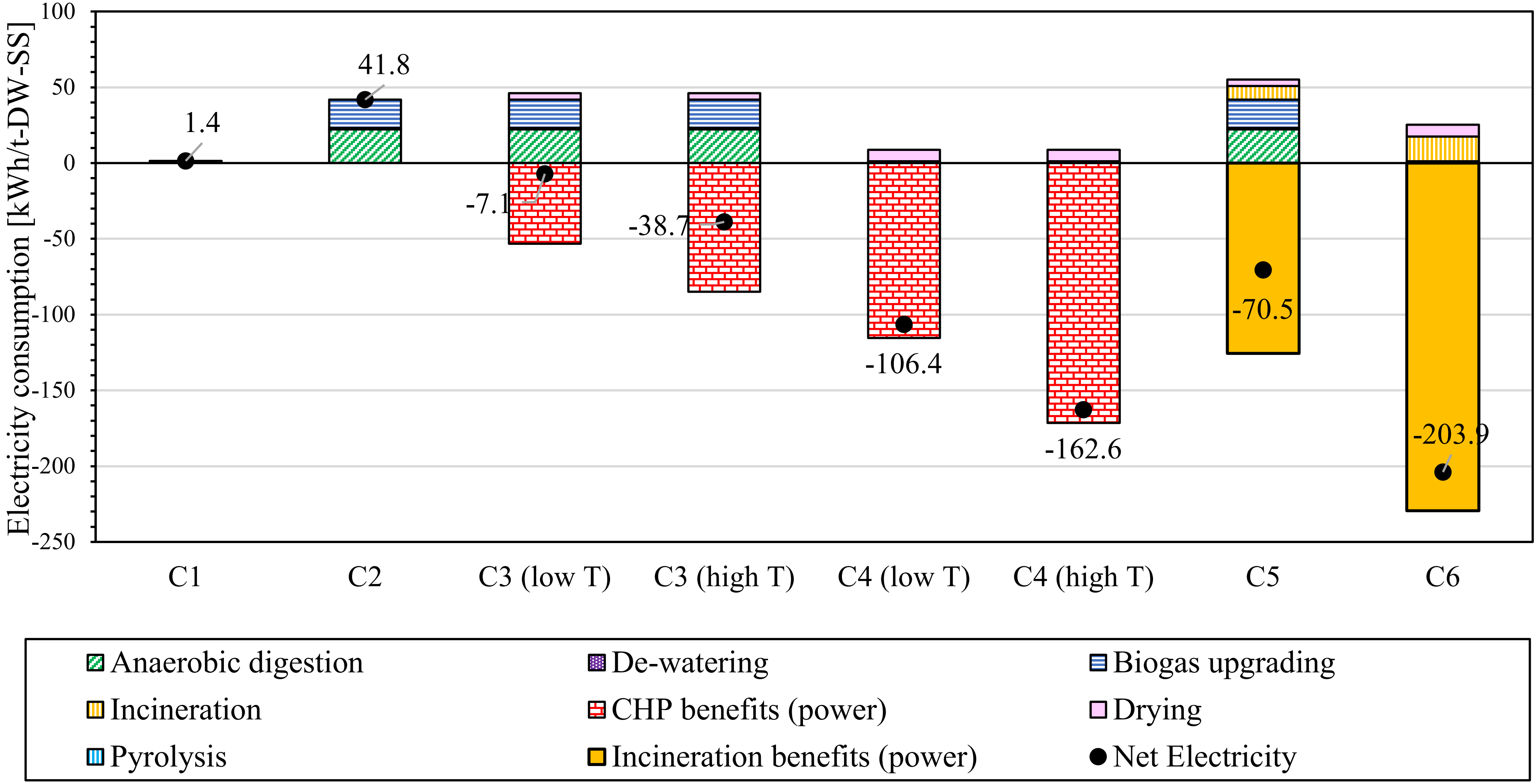


Pyrolisis benefits

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

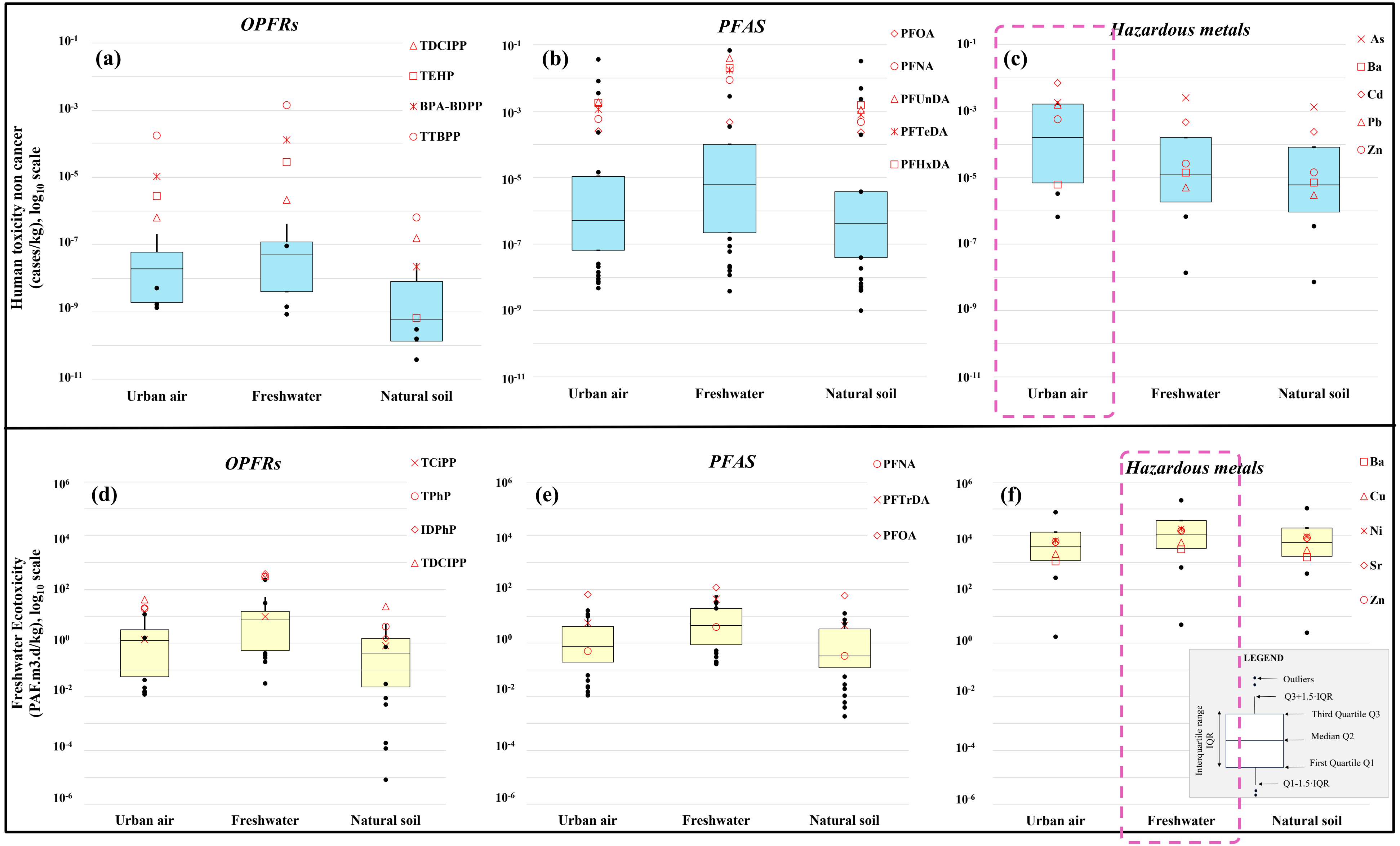
Black dots represent the net GWP100 impacts, and the whiskers show uncertainty range from Monte-Carlo analysis (± Standard deviation).

Energy



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

Characterization factors



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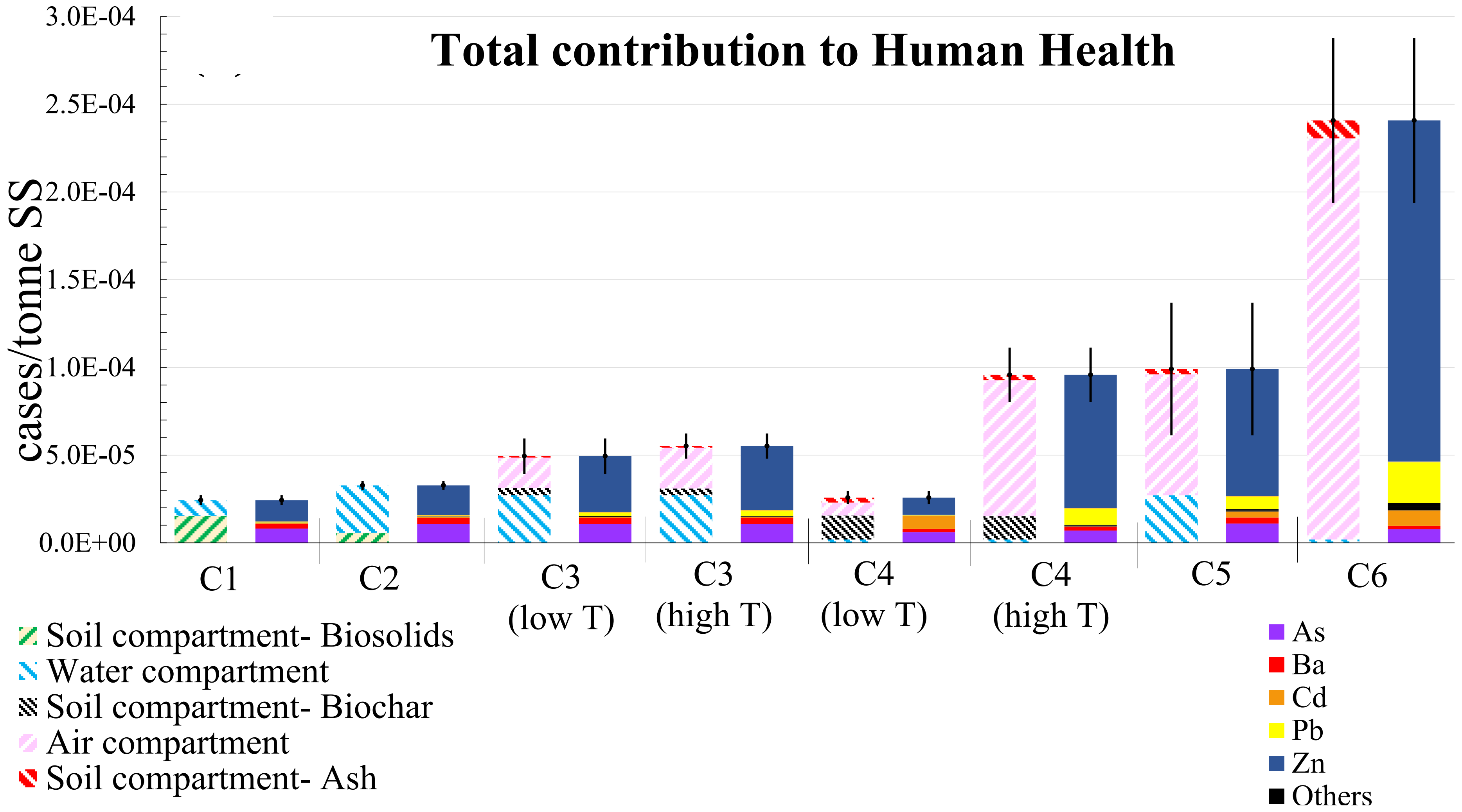
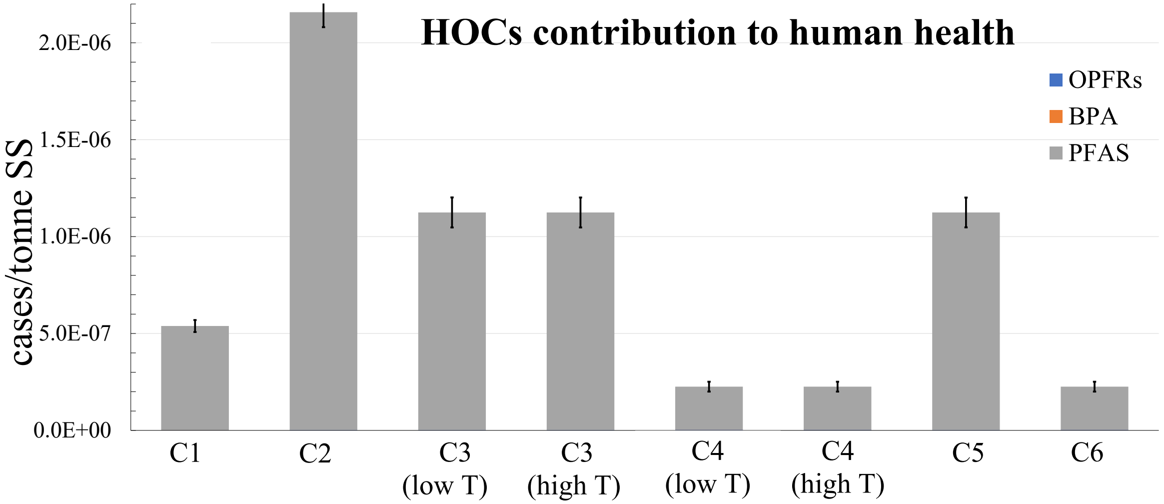
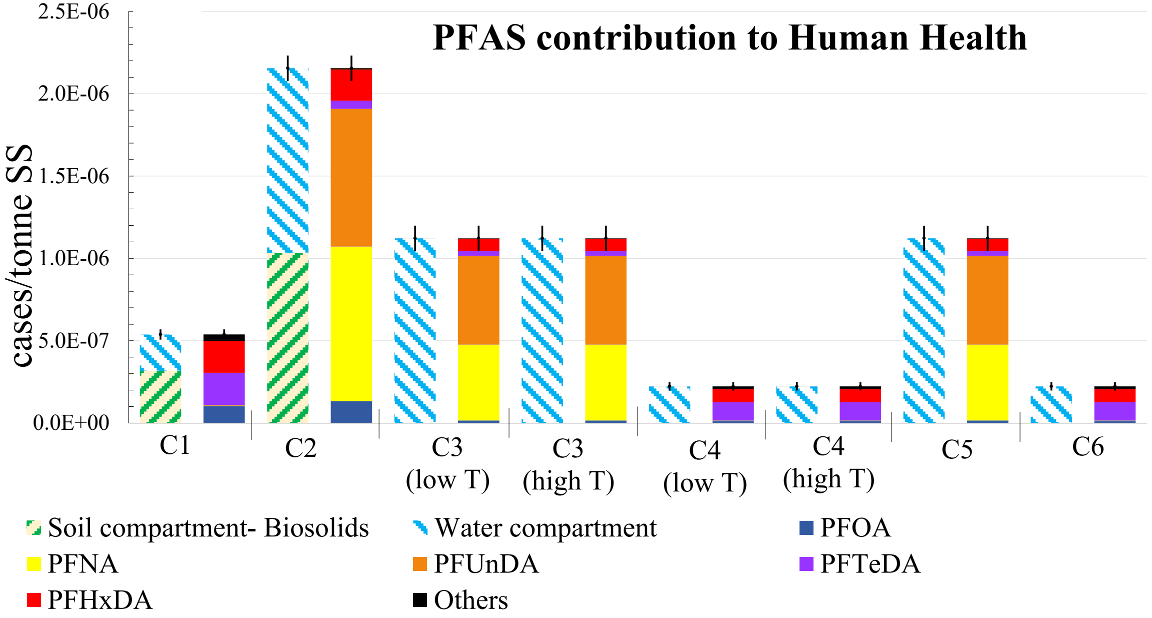
Toxicity to Human Health (non-cancer effects)

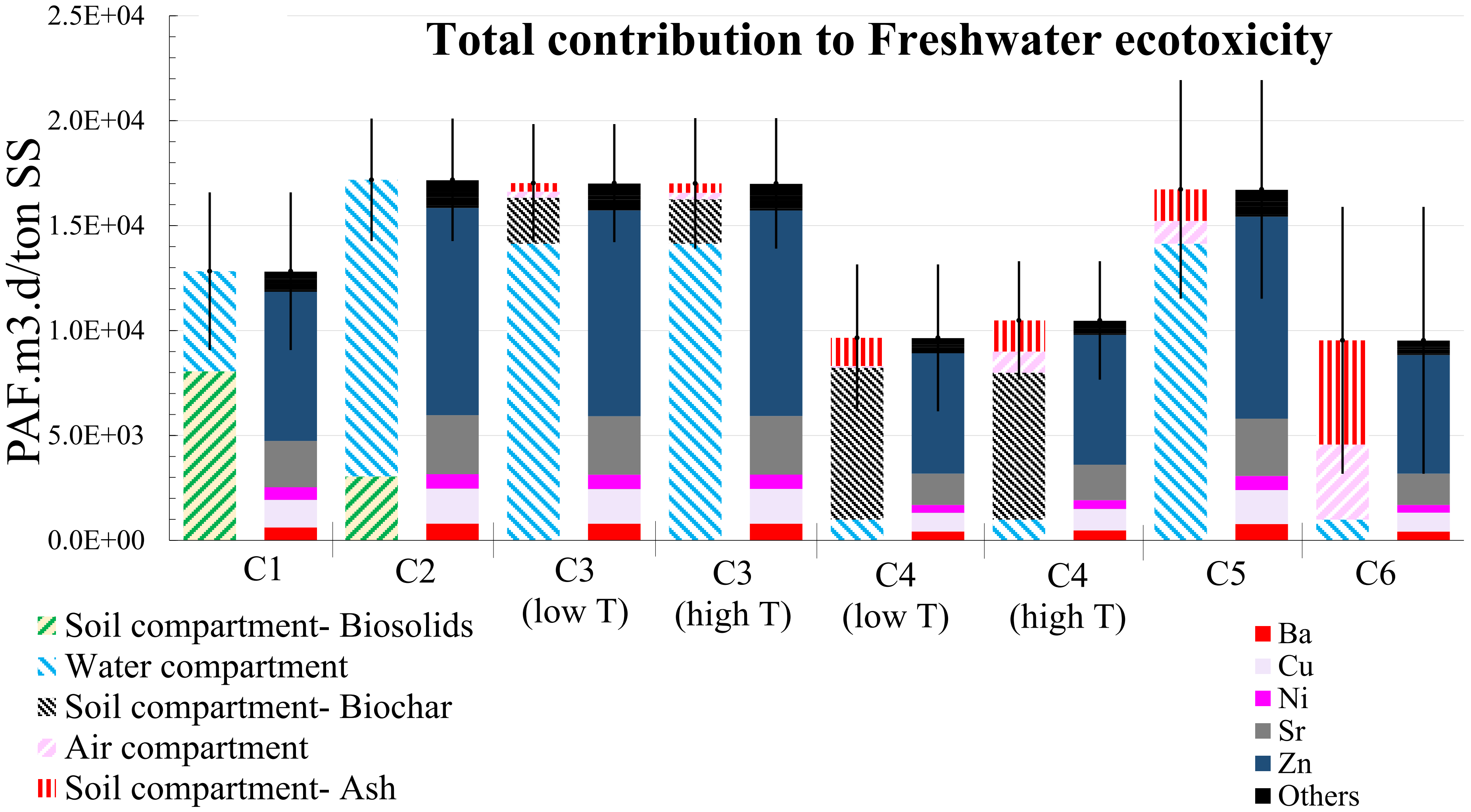


Toxicity to Human Health (non-cancer effects)

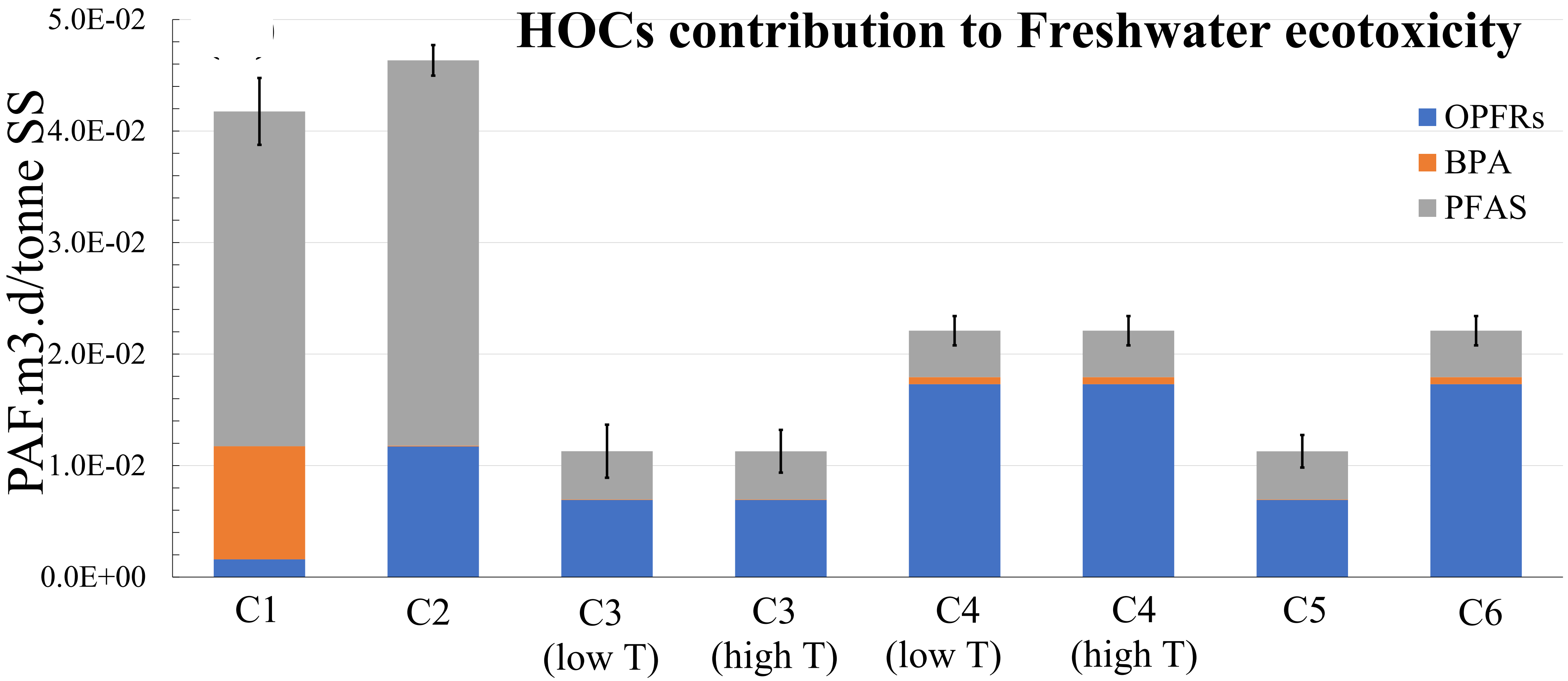




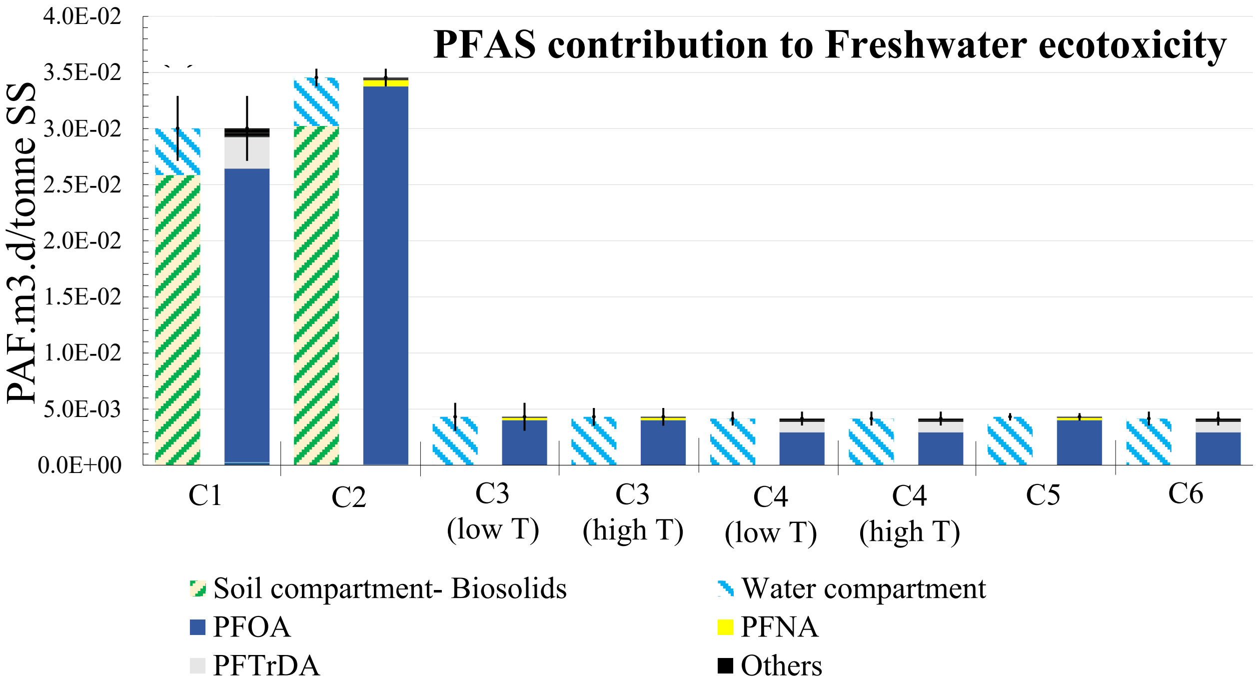
Freshwater Ecotoxicity

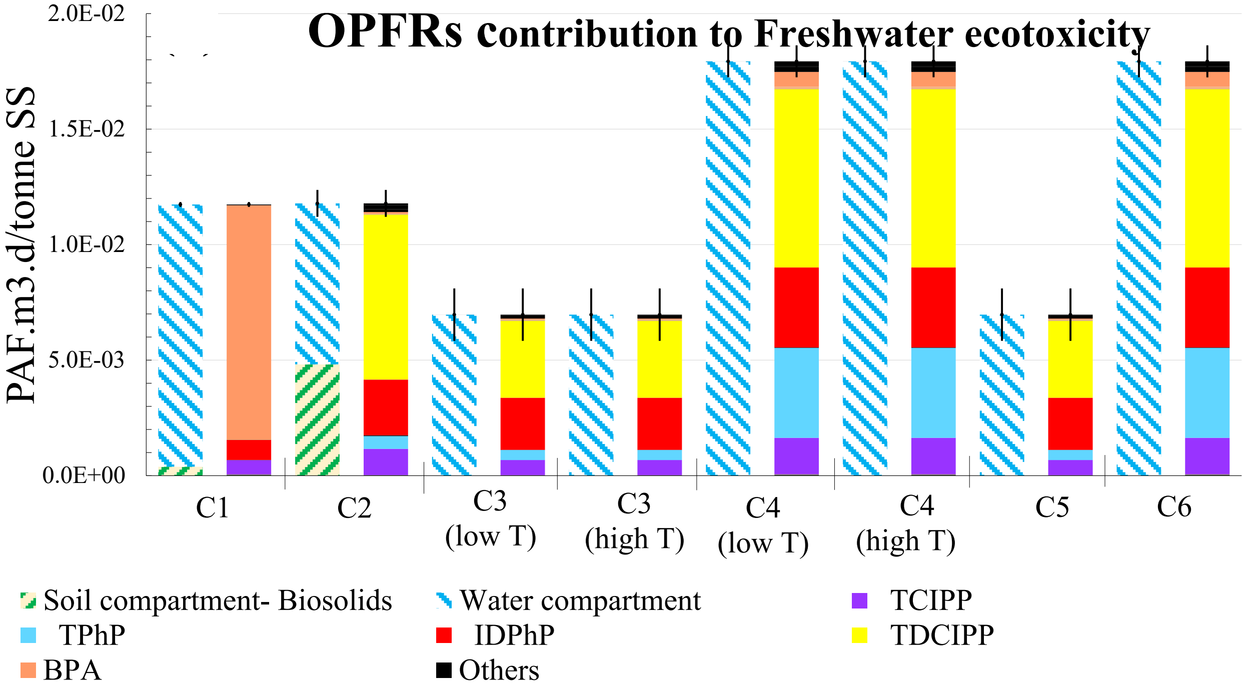


Freshwater Ecotoxicity



Freshwater Ecotoxicity





Summary

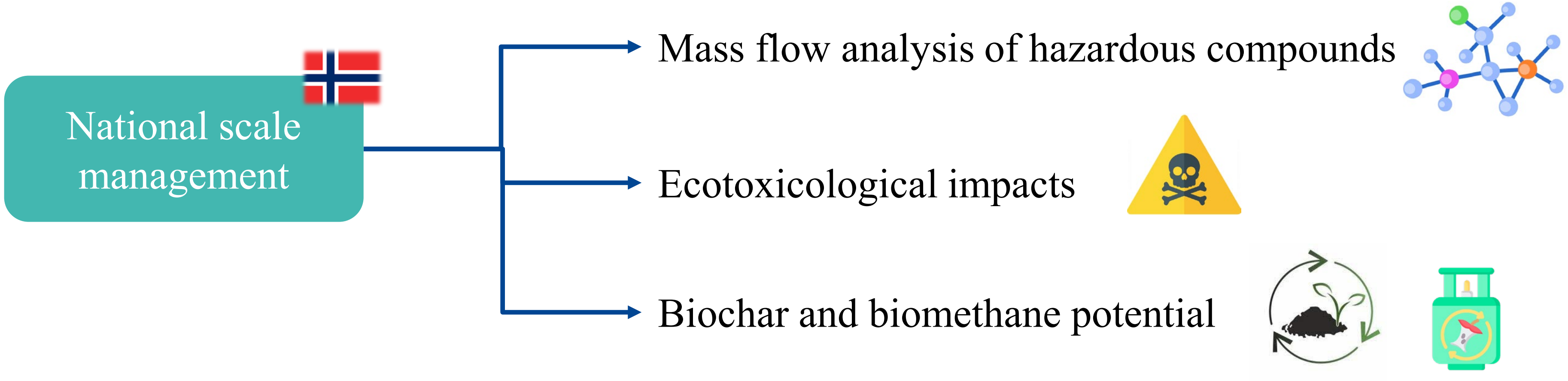
Pyrolysis at low temperature without AD represents the eco-friendler treatment for SS:

- Negative climate change impacts.
- C-storage
- Energy benefits
- Reduce contaminants and ecotoxicological impacts.

National scale management

Part II :

LCA of large-scale sludge handling scenarios in Norway.



Proposed scenarios for evaluation

Current sludge managdement in Norway

versus

Pyrolysis at low Temp

AD + Pyrolysis at low Temp

Current sludge managdement in 6 main WWTPs in Norway

versus

Pyrolysis at low Temp

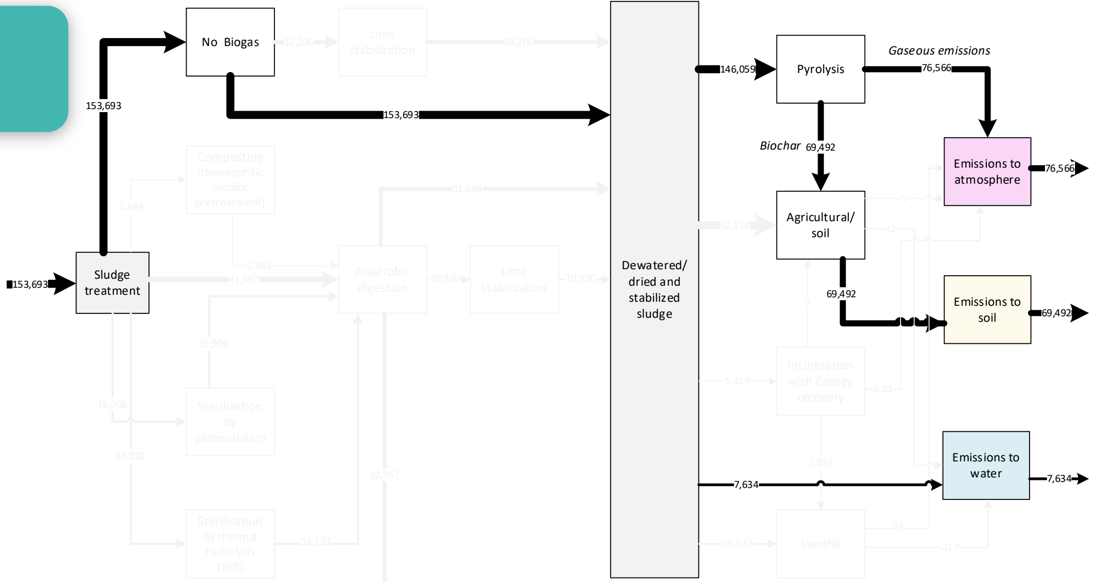
AD + Pyrolysis at low Temp

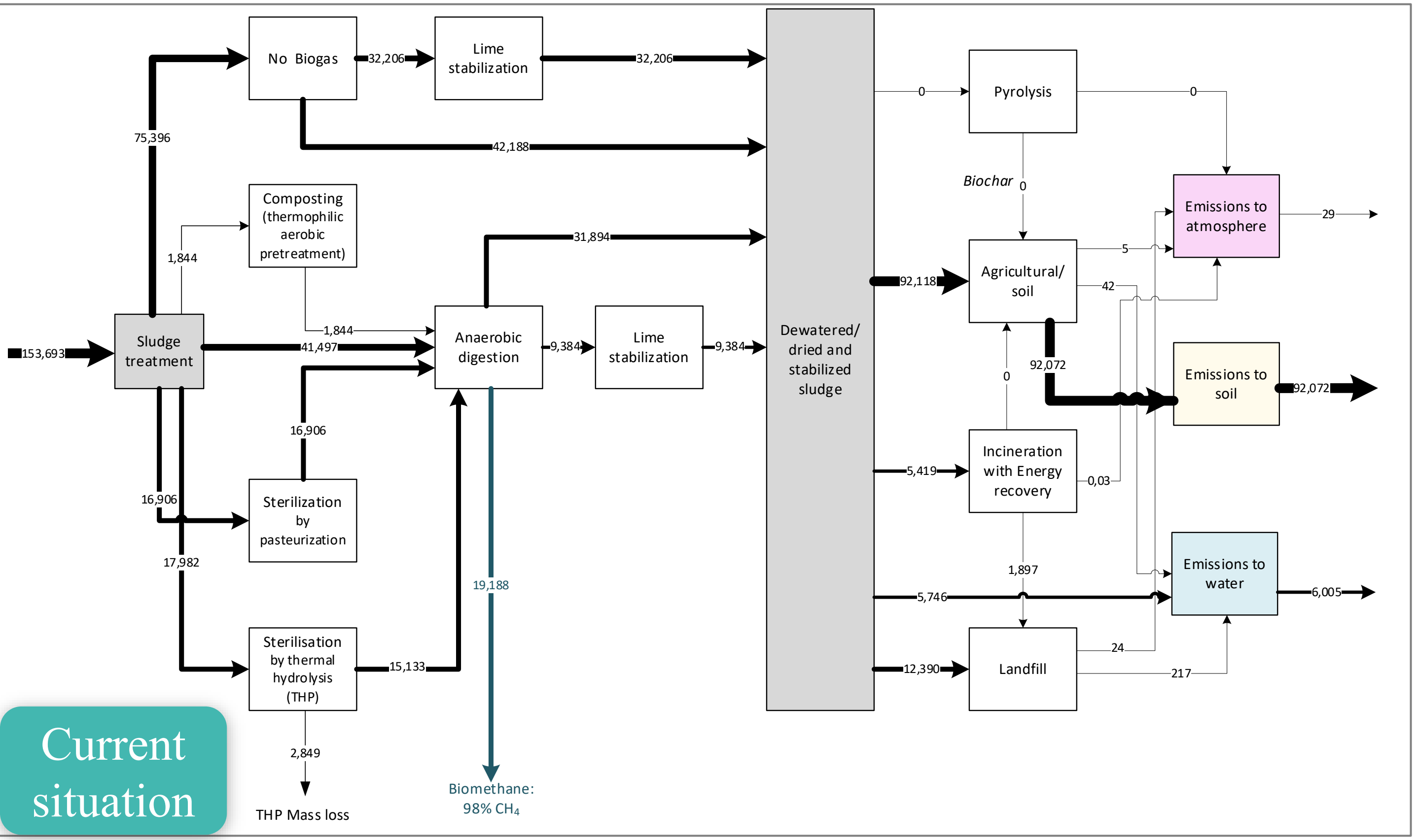
	Total Norway	WWTPs in project	% of total Norway
Number plants	18	6	
Total Capacity (PE)	3 004 150	1 177 400	**41 %**
Total sludge (tonnes TS/year)	62 829	25 789	**39.2%**

Mass flow of sludge in all Norway (2020)

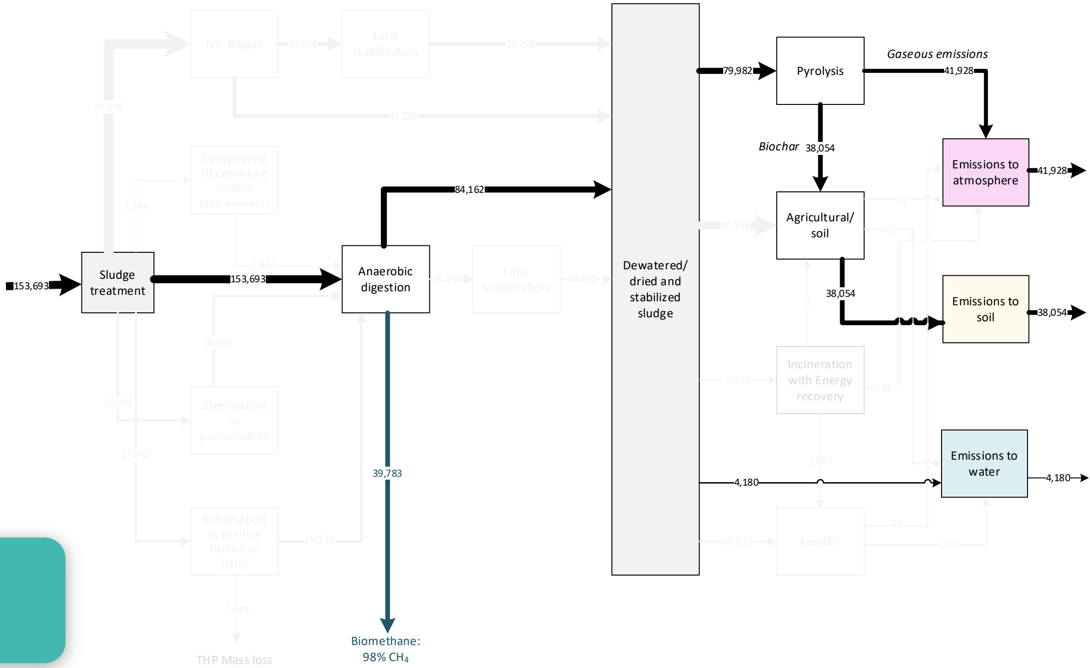
[tonn DW/year]

Pyrolysis at low Temp





Current situation



AD + Pyrolysis at low Temp

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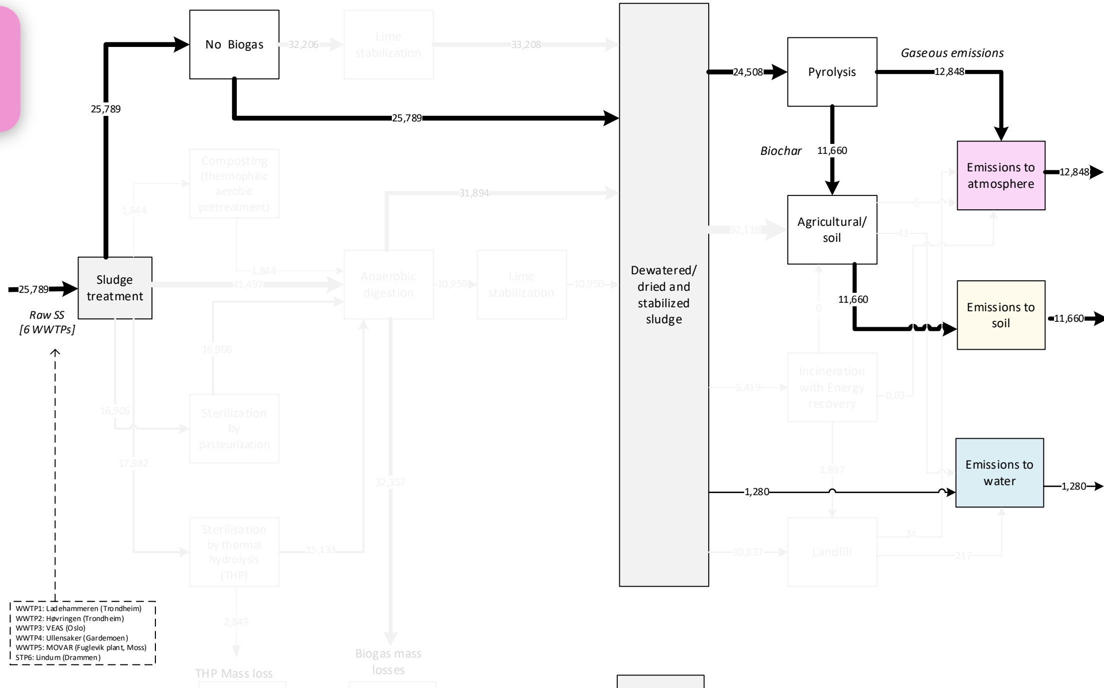
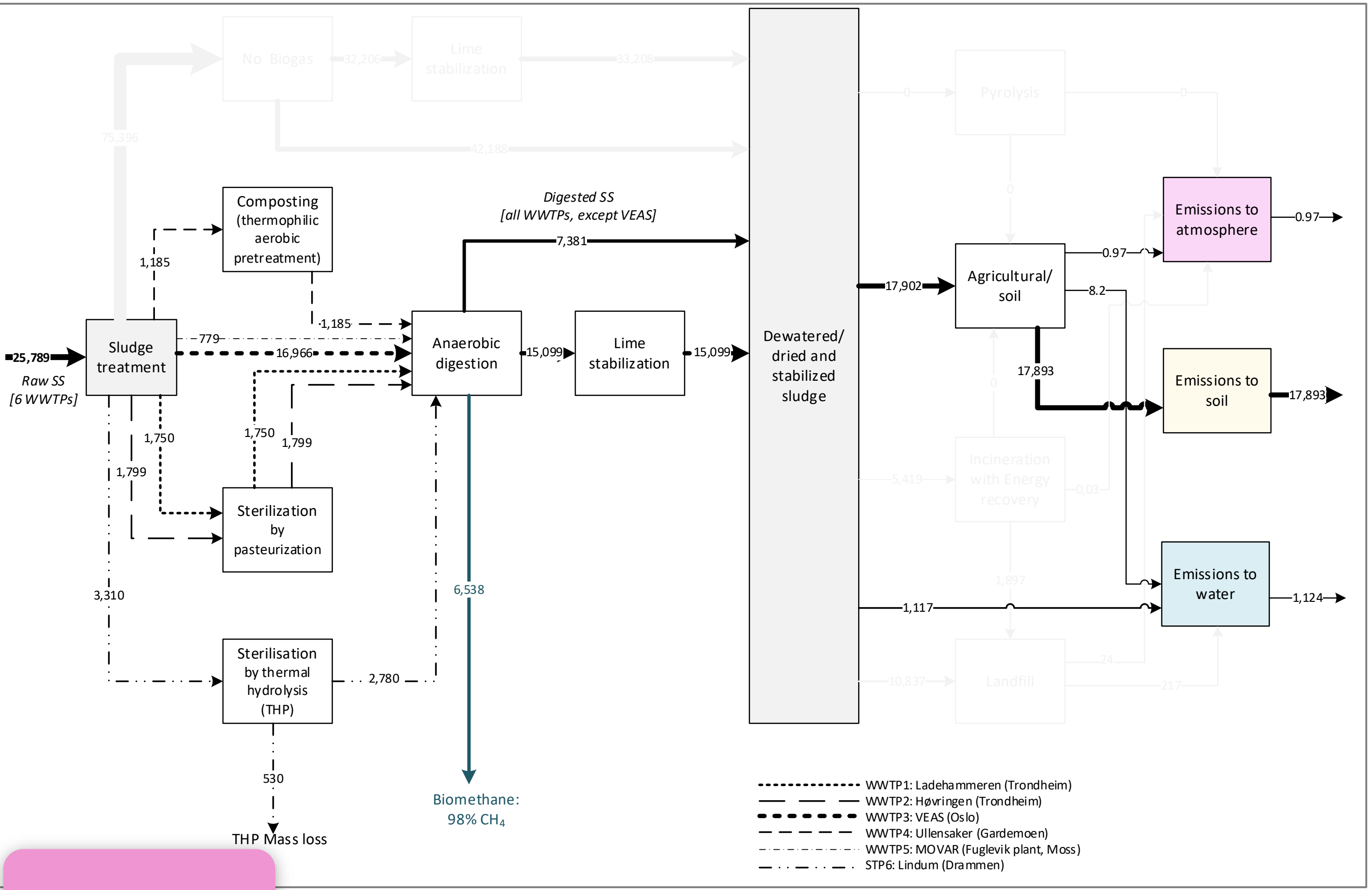
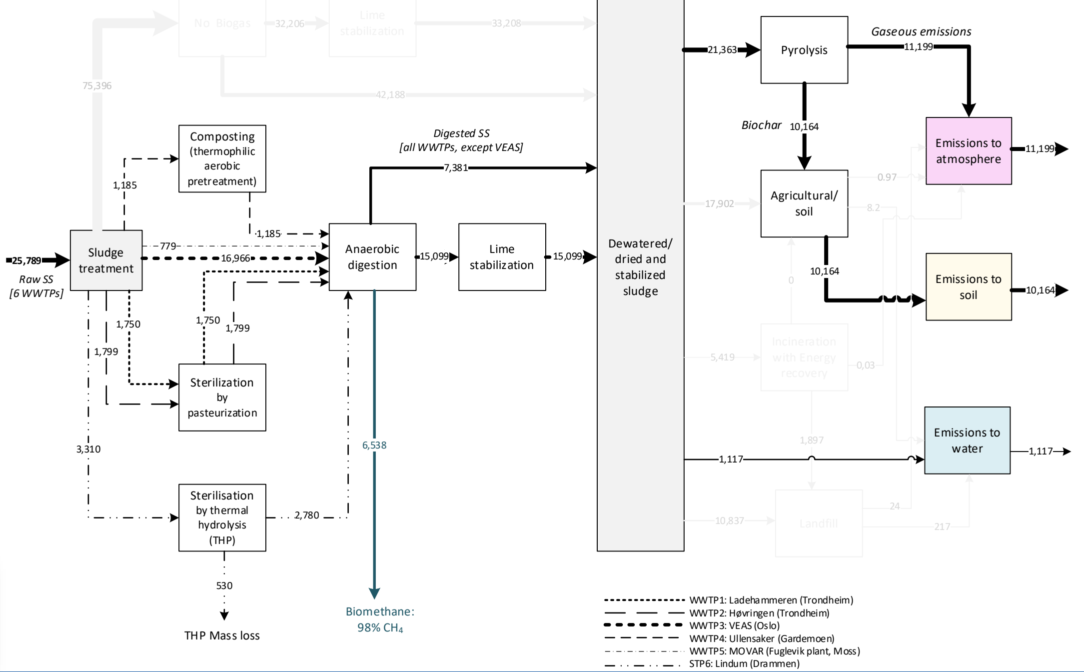
Mass flow of sludge in 6 WWTPs Norway (2020)

[tonn DW/year]

Pyrolysis at low Temp





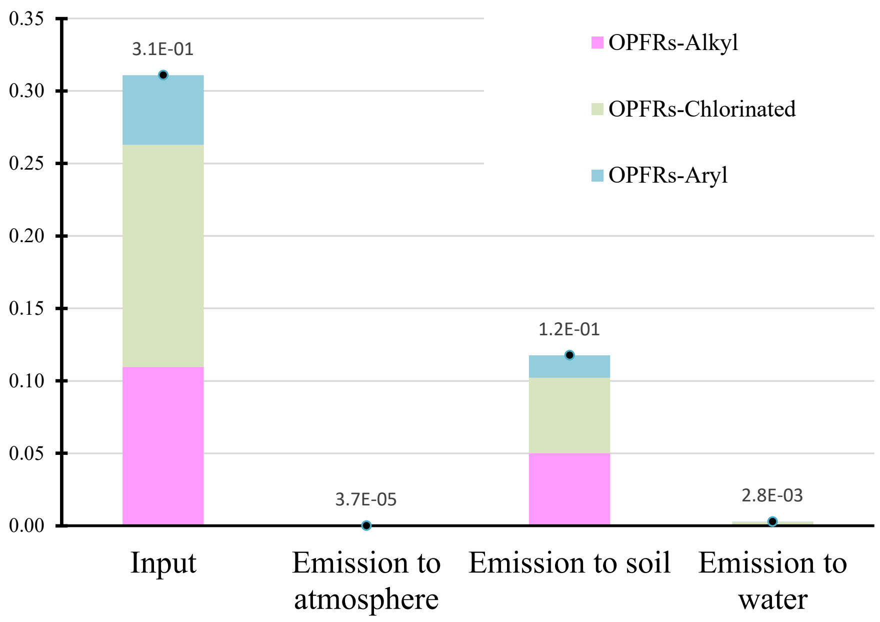


6 WWTPs

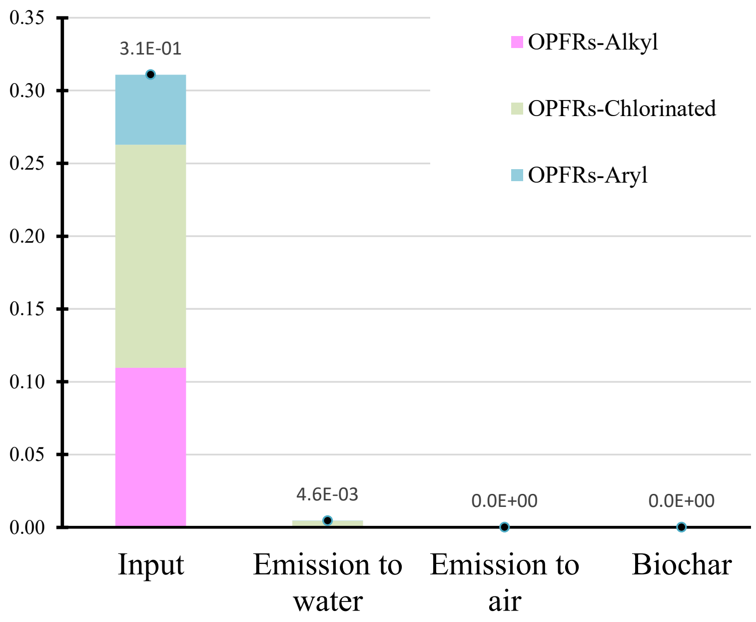
AD+ Pyrolysis at low Temp

OPFRs

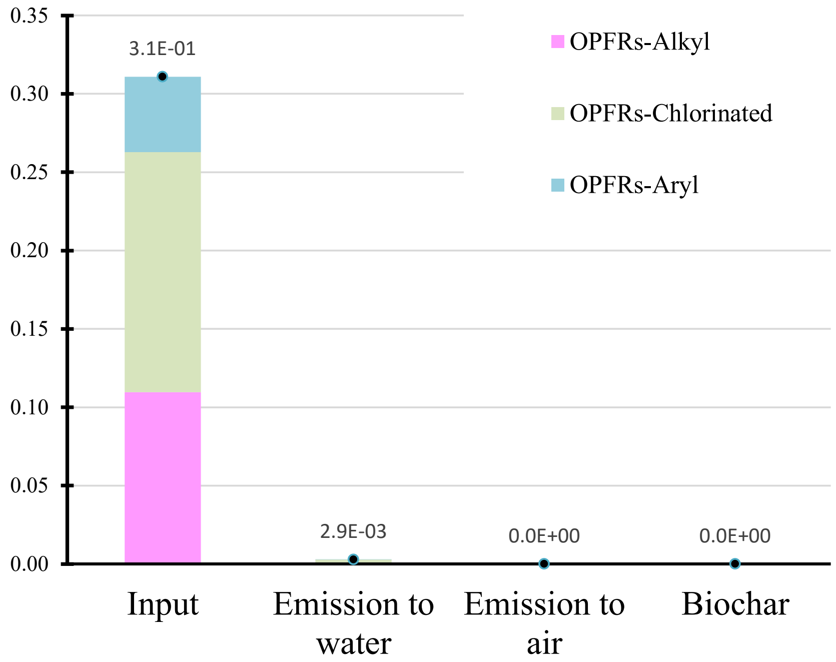
Total Norway: Current situation



Pyrolysis (low Temp)



AD+ Pyrolysis (low Temp)



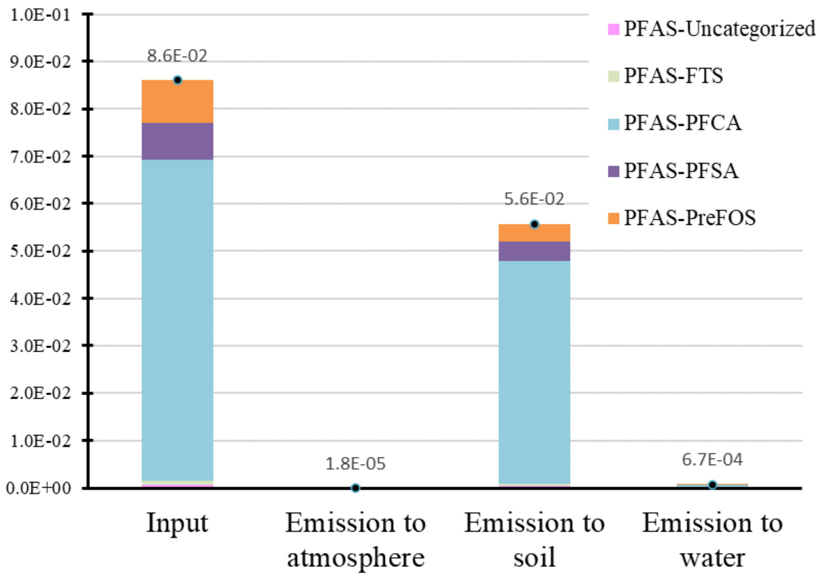
Unit: Tonne/year

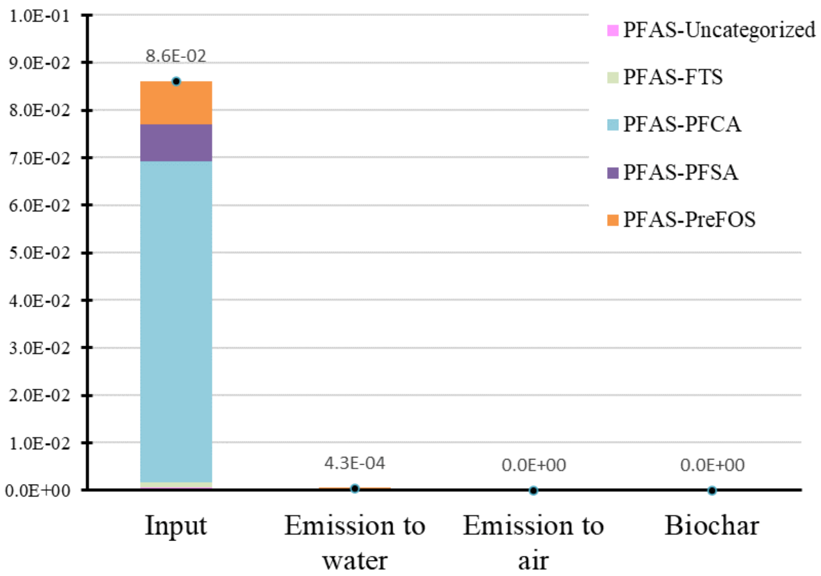
PFAS

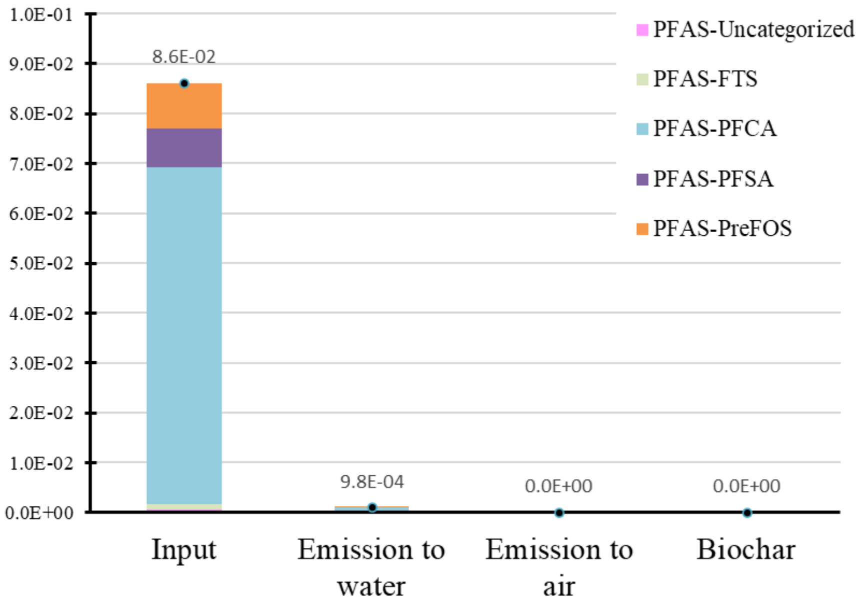
Total Norway: Current situation

Pyrolysis (low Temp)

AD+ Pyrolysis (low Temp)







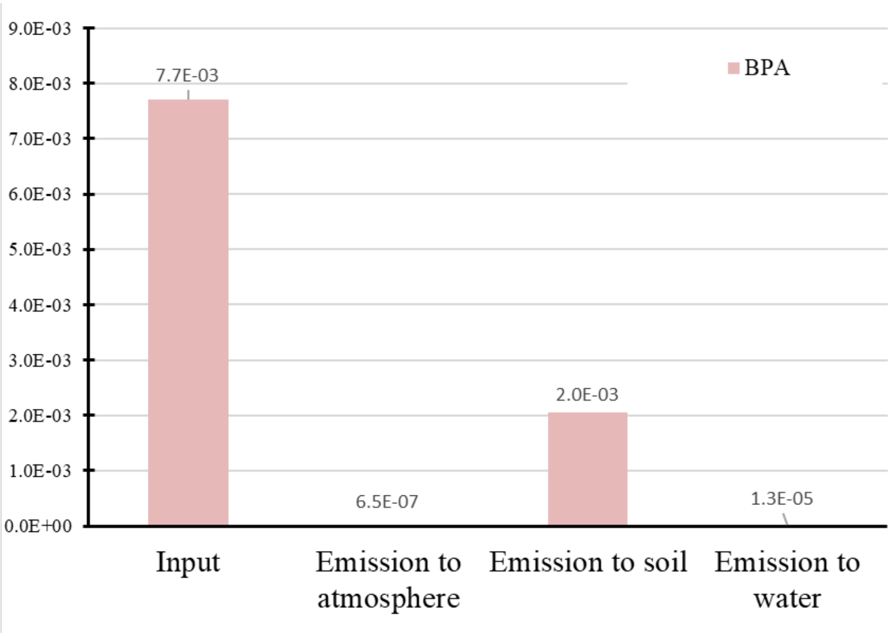
Unit: Tonne/year

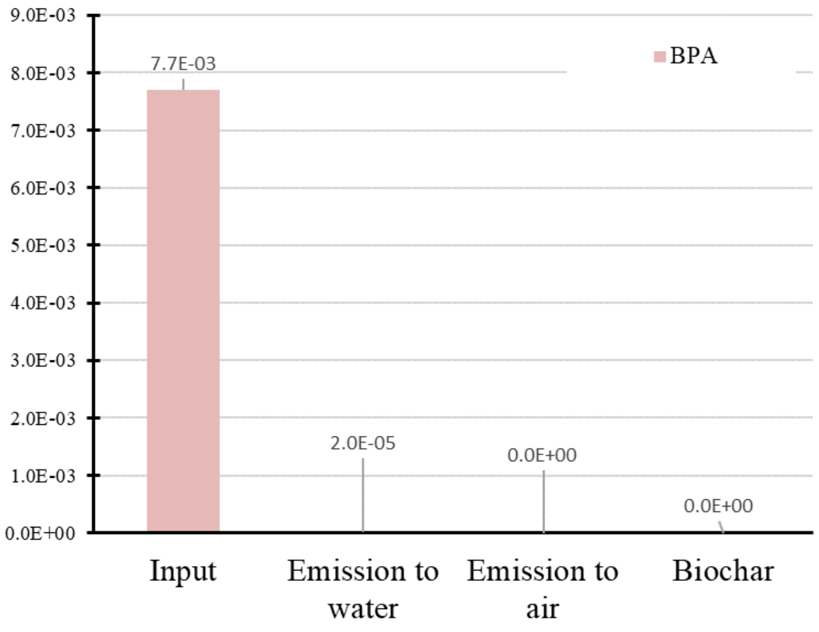
BPA

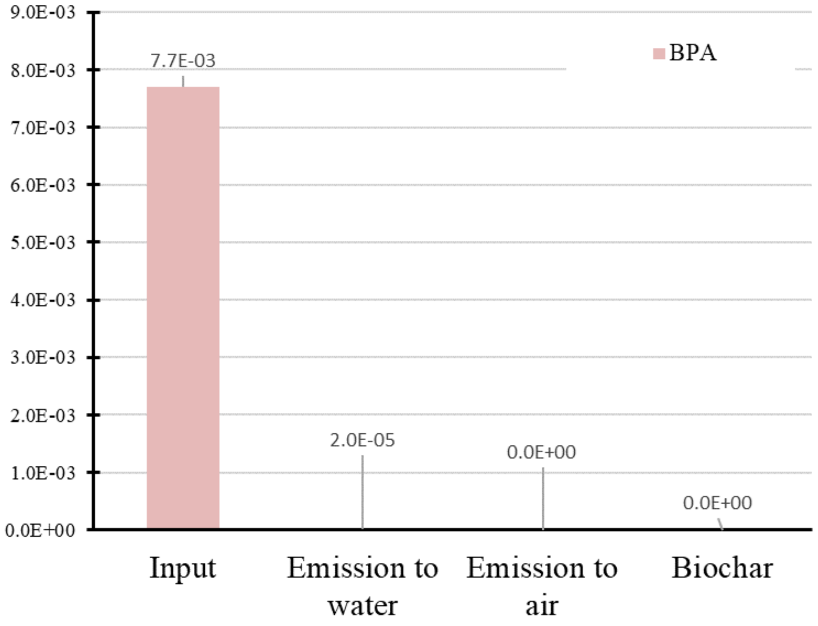
Total Norway: Current situation

Pyrolysis (low Temp)

AD+ Pyrolysis (low Temp)







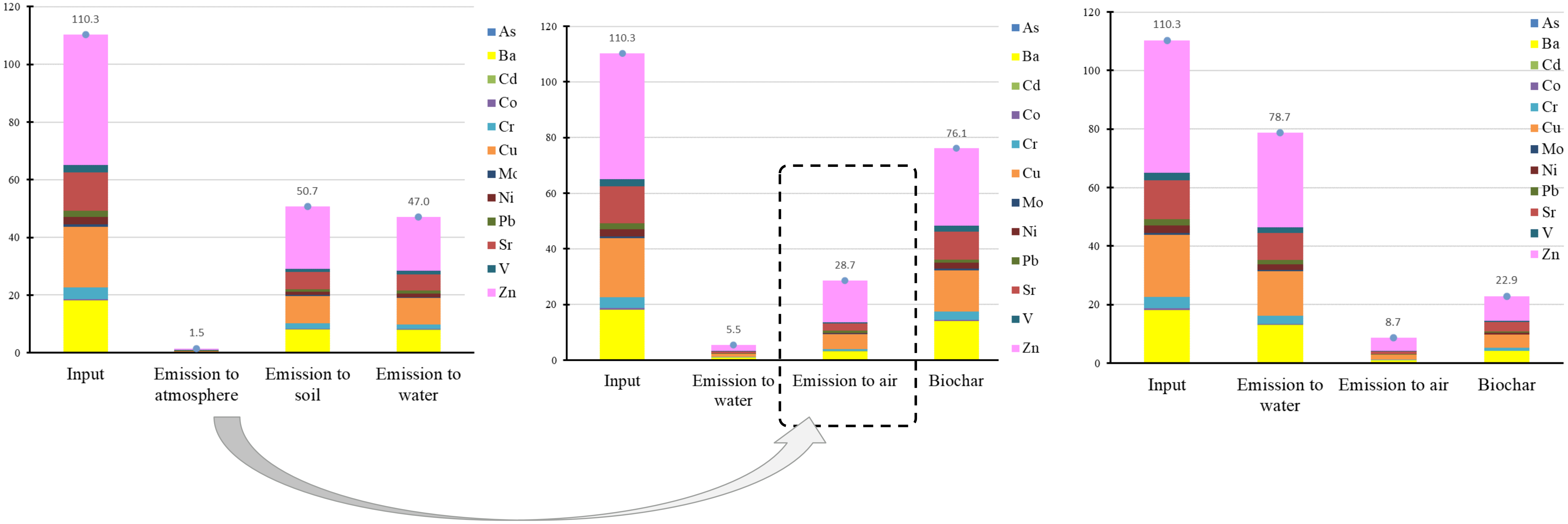
Unit: Tonne/year

Hazardous metals

Total Norway

No AD+ Pyrolysis (low Temp)

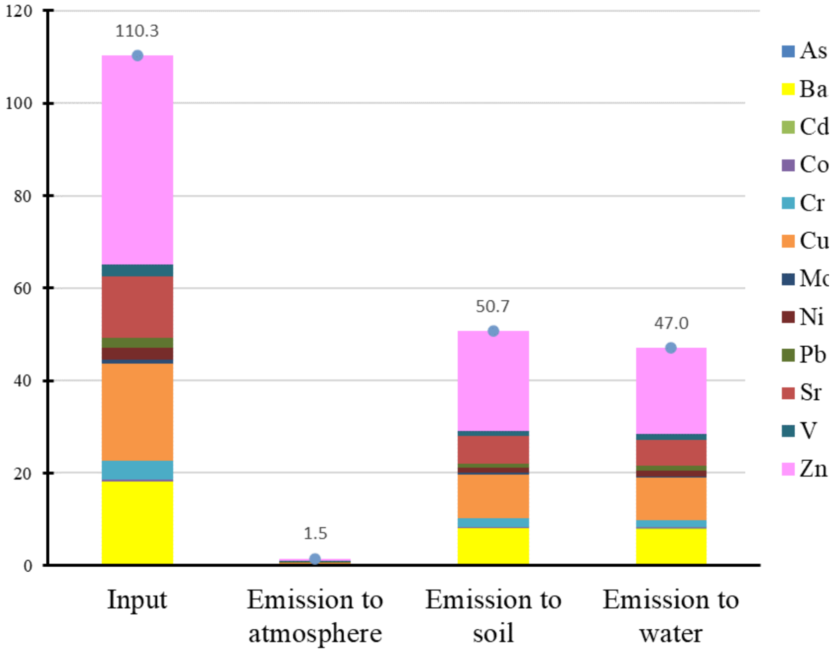
AD+ Pyrolysis (low Temp)



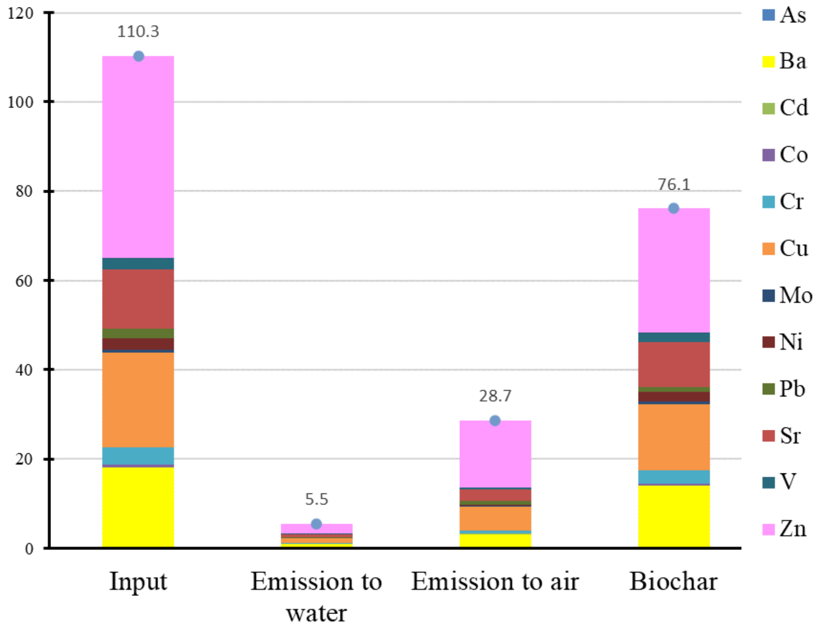
Unit: Tonne/year

Hazardous metals

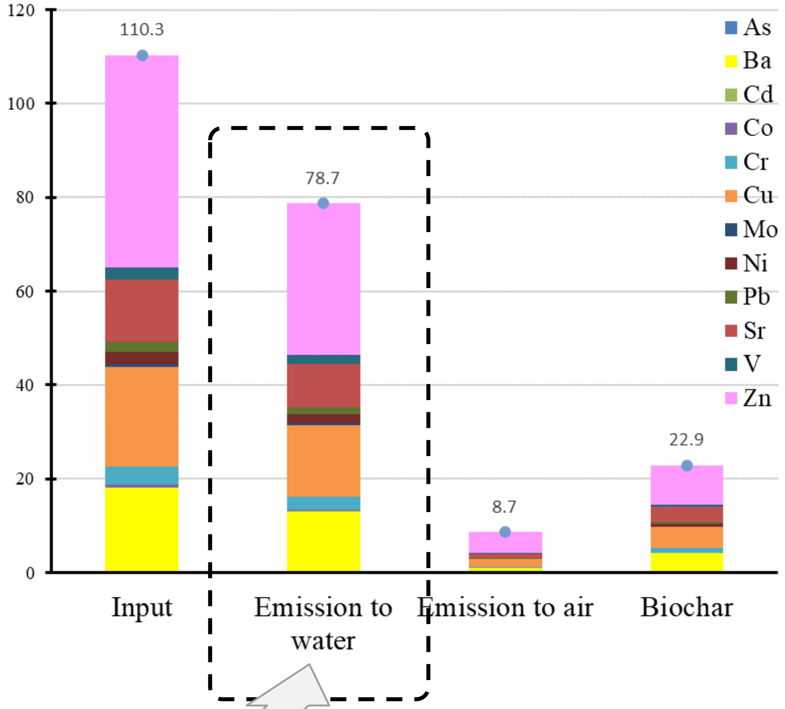
Total Norway



No AD+ Pyrolysis (low Temp)



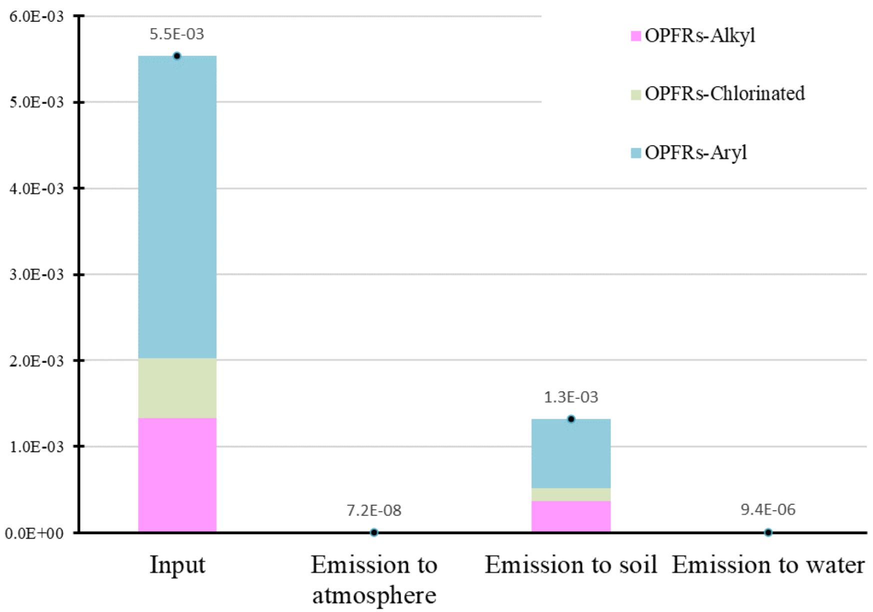
AD+ Pyrolysis (low Temp)



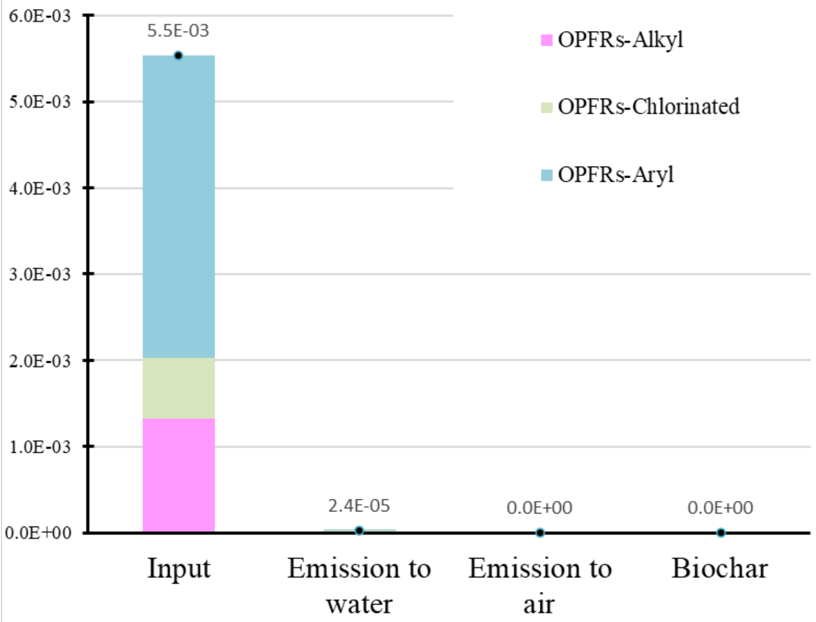
Unit: Tonne/year

OPFRs

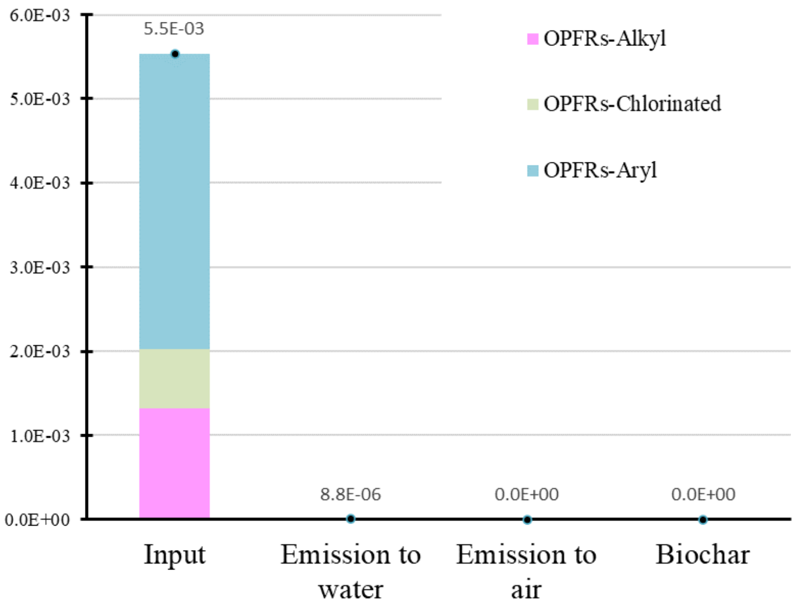
6 WWTPs: current situation



Pyrolysis (low Temp)

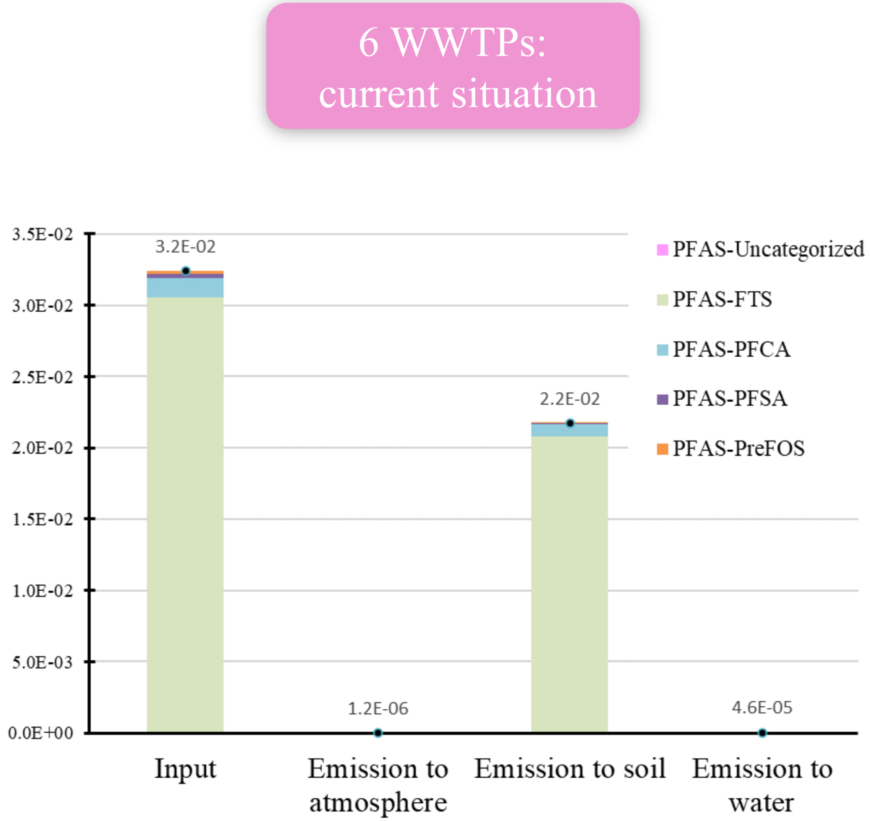


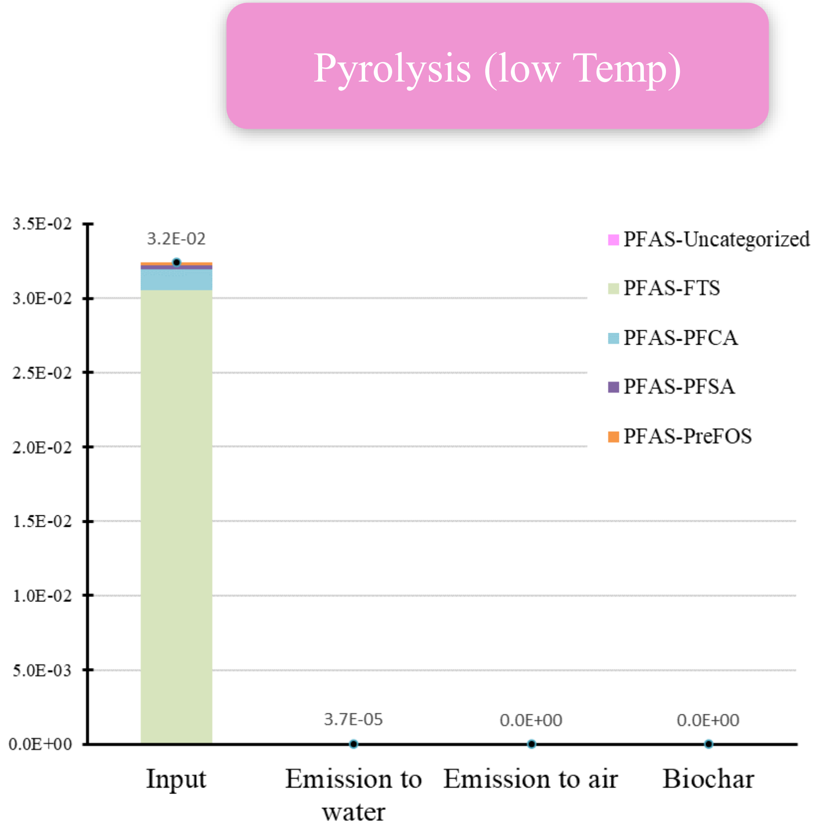
AD + Pyrolysis (low Temp)

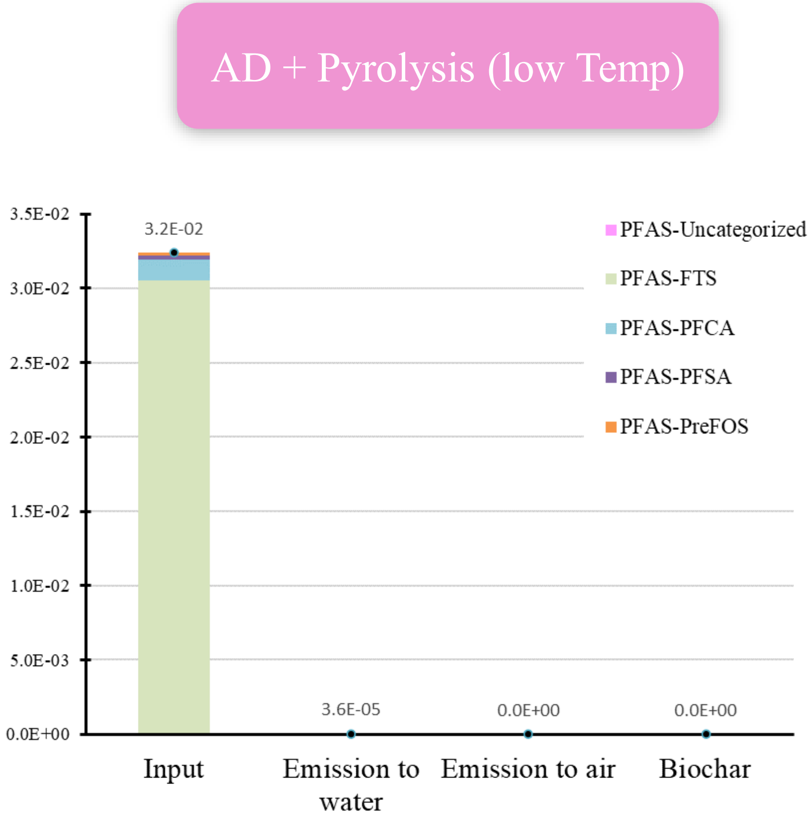


Unit: Tonne/year

PFAS

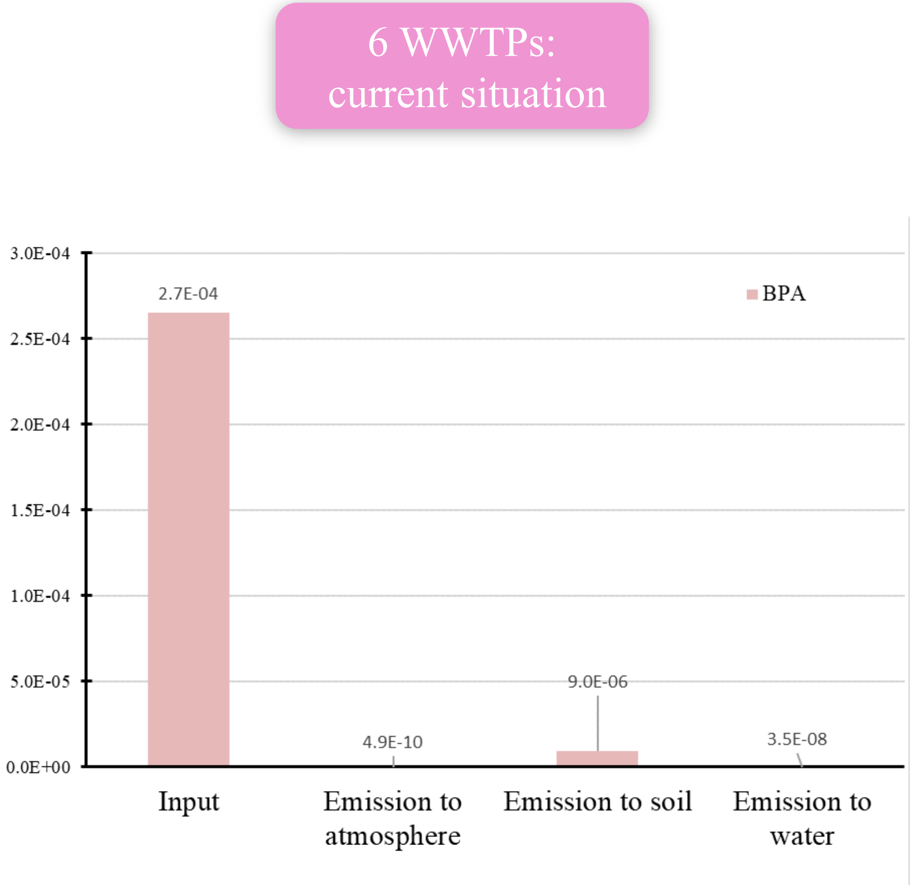


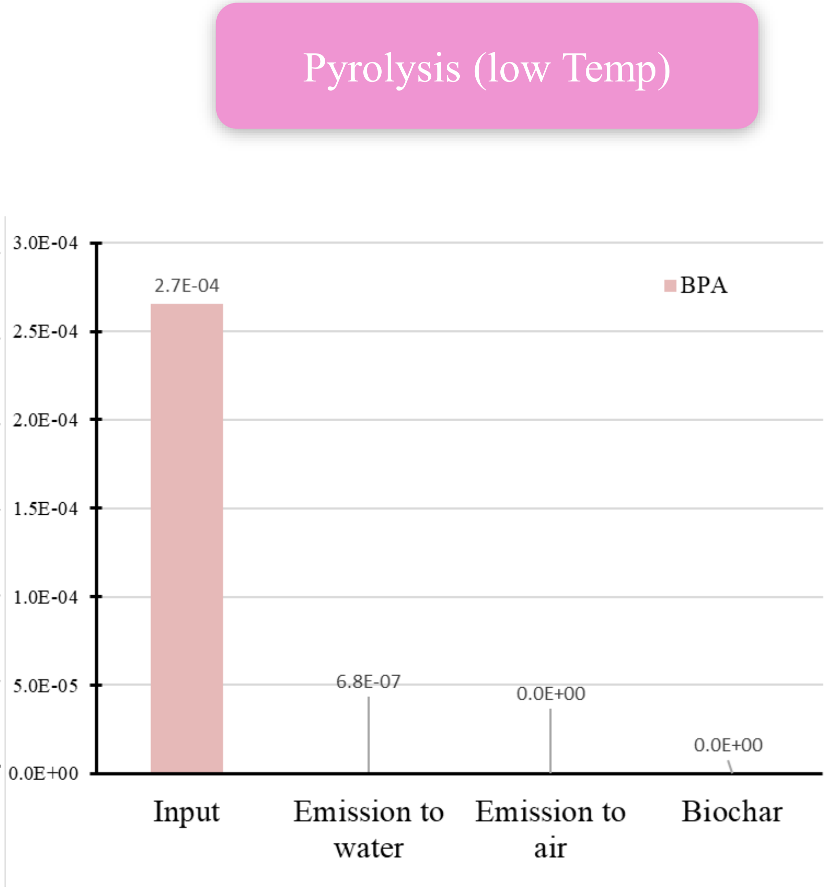


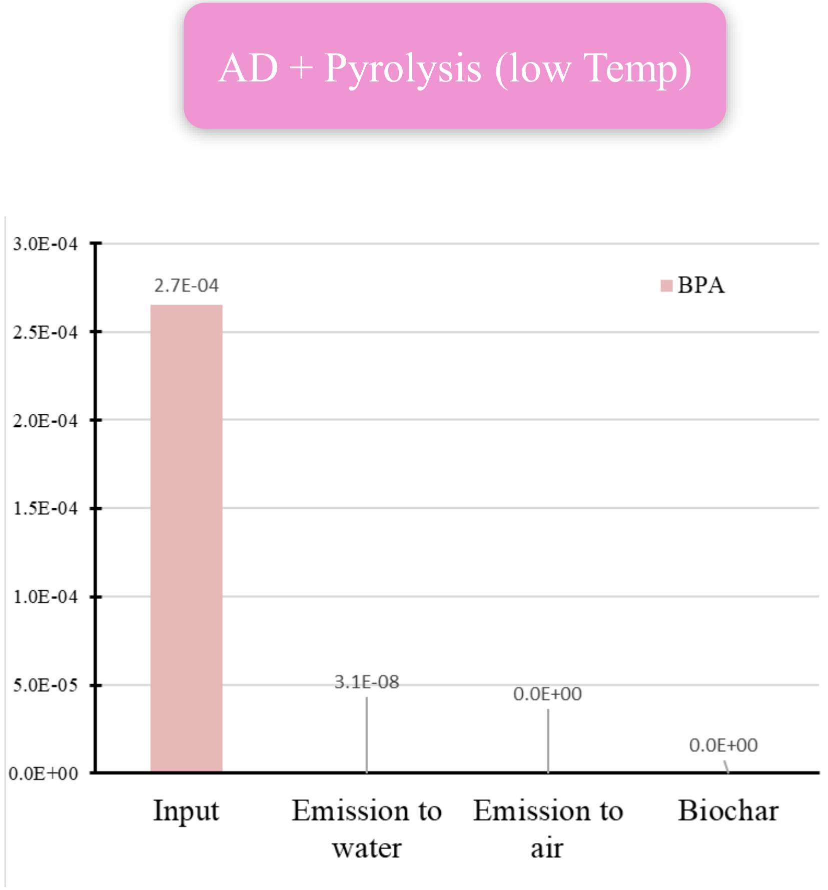


Unit: Tonne/year

BPA







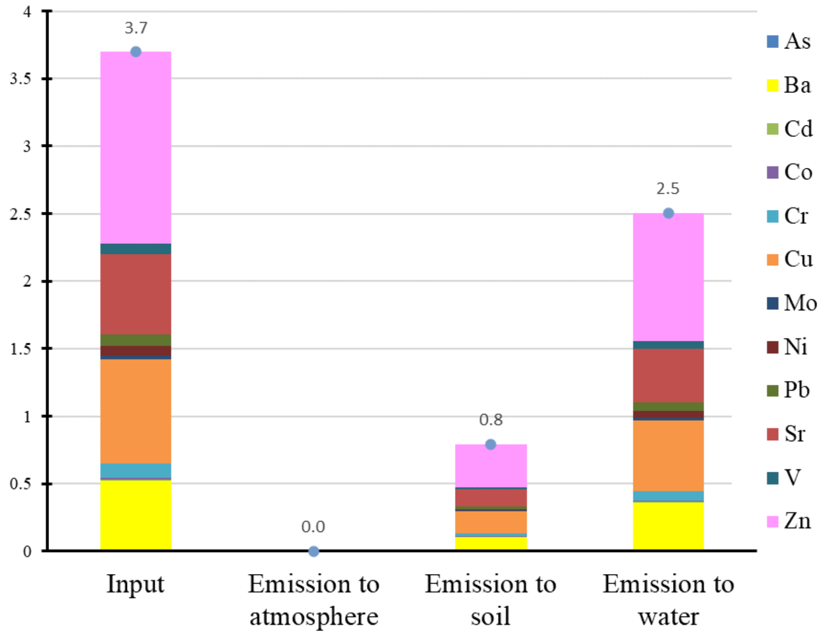
Unit: Tonne/year

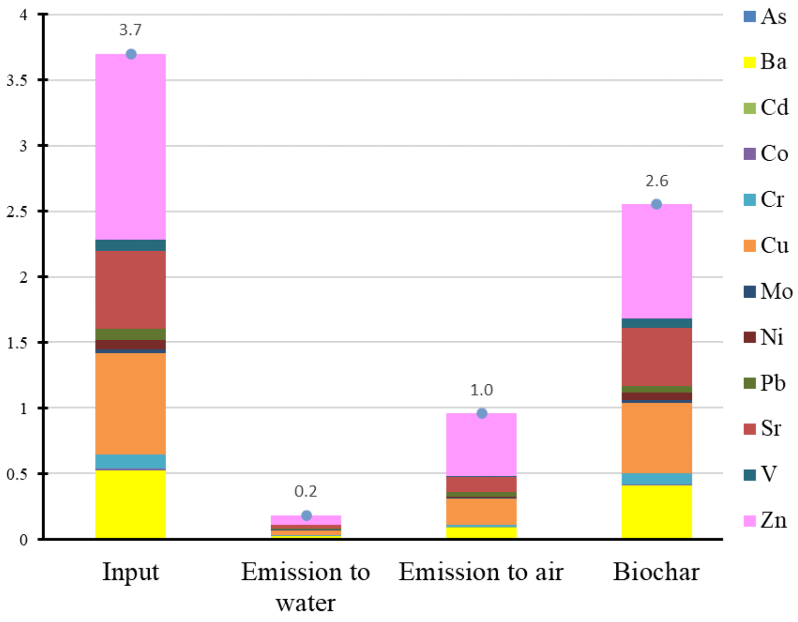
Hazardous metals

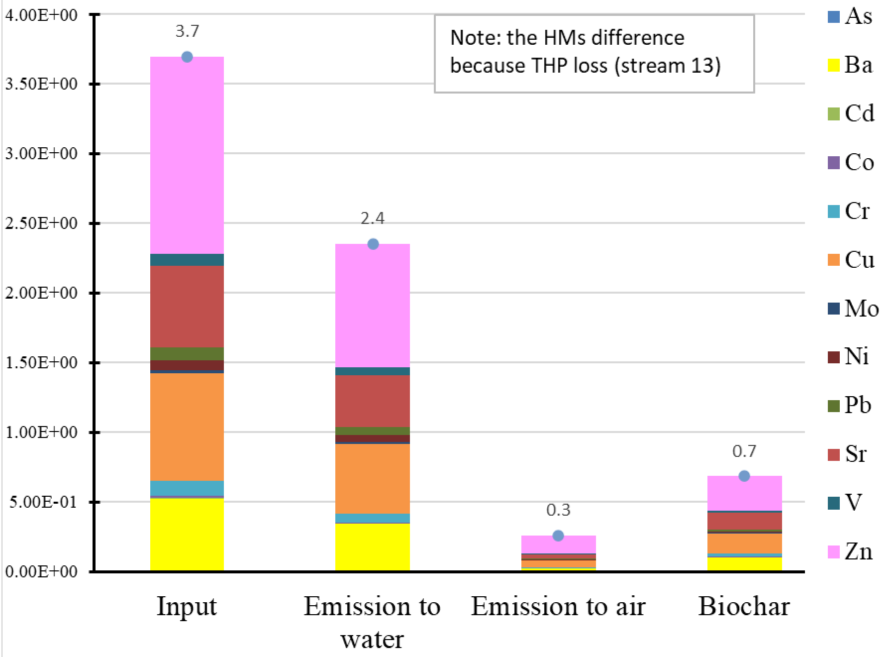
6 WWTPs:
current situation

Pyrolysis (low Temp)

AD + Pyrolysis (low Temp)

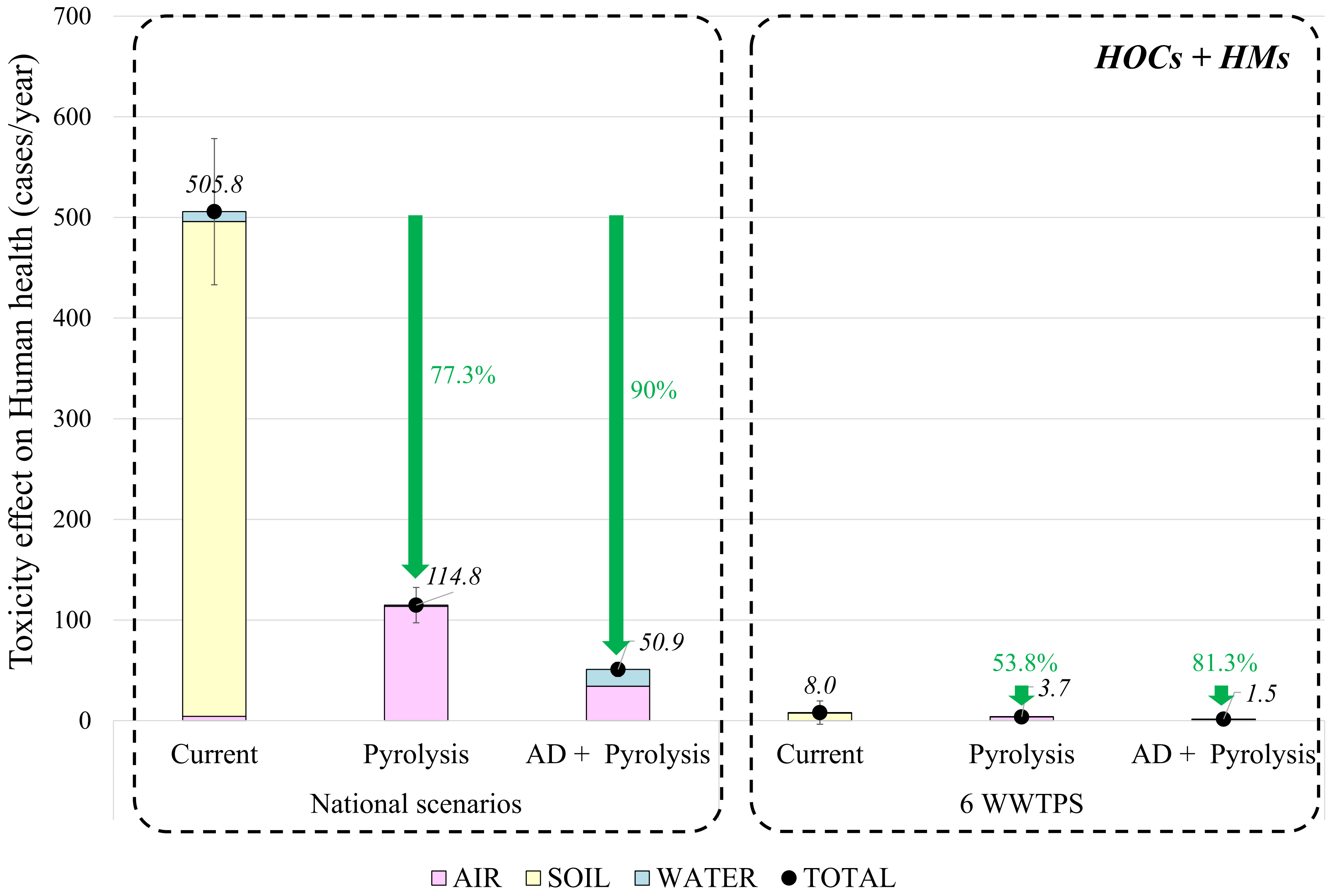




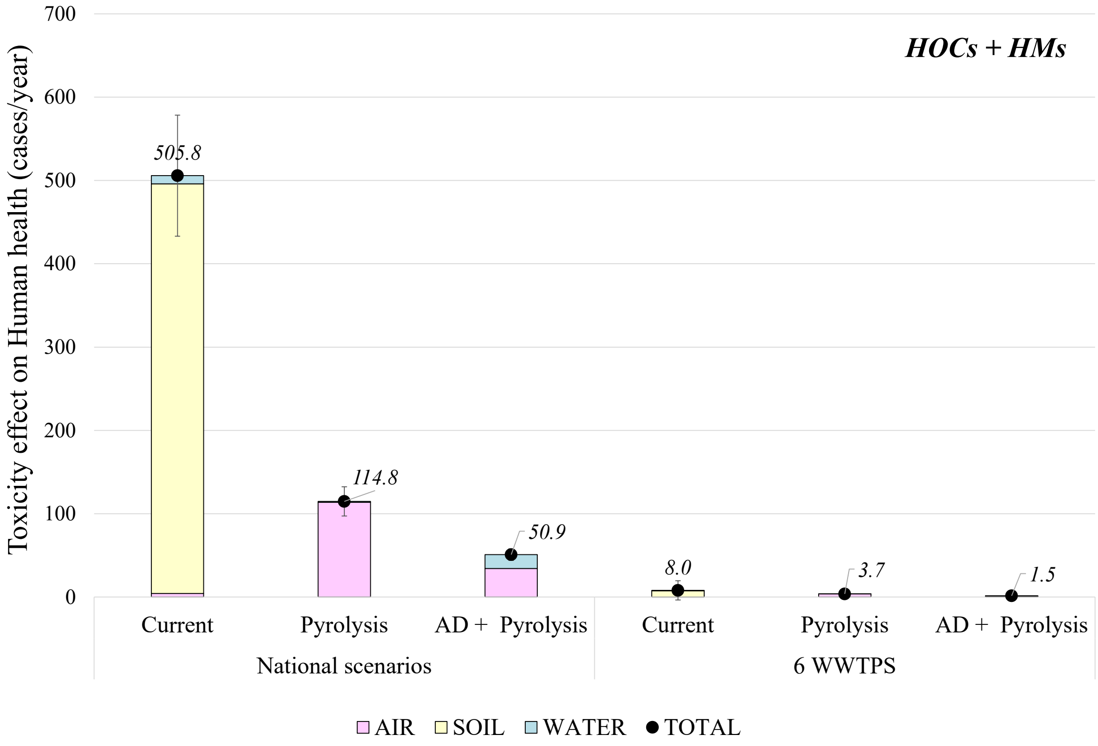


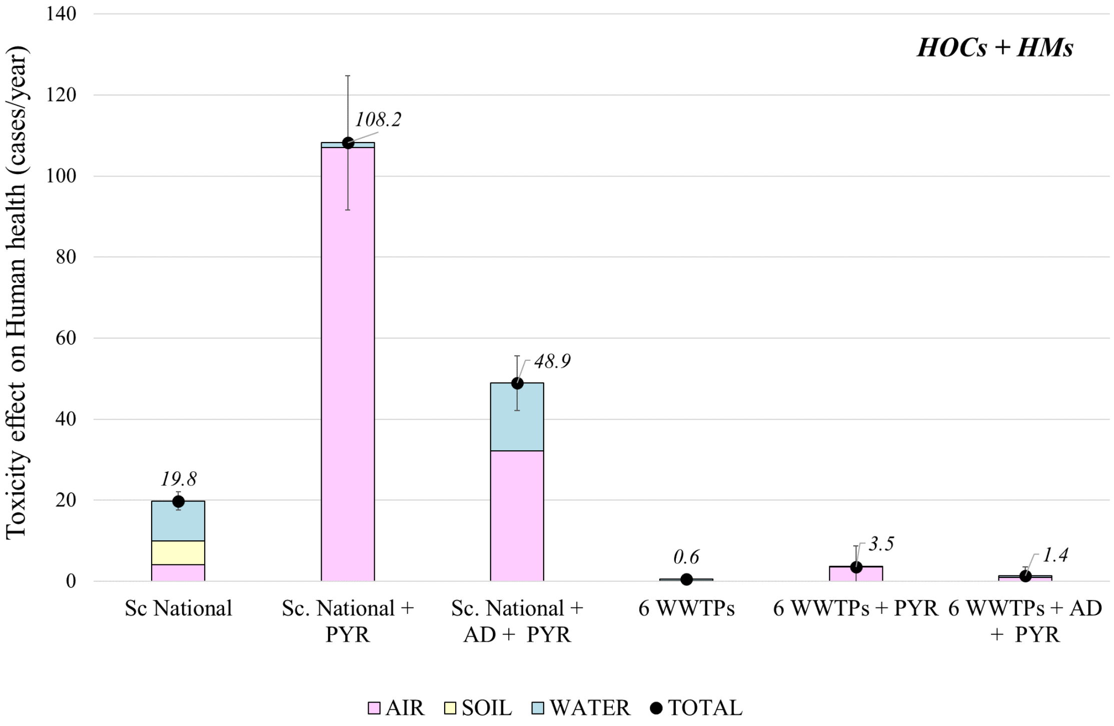
Unit: Tonne/year

Ecotoxicological effects: Human health



Compartment emission on Human health



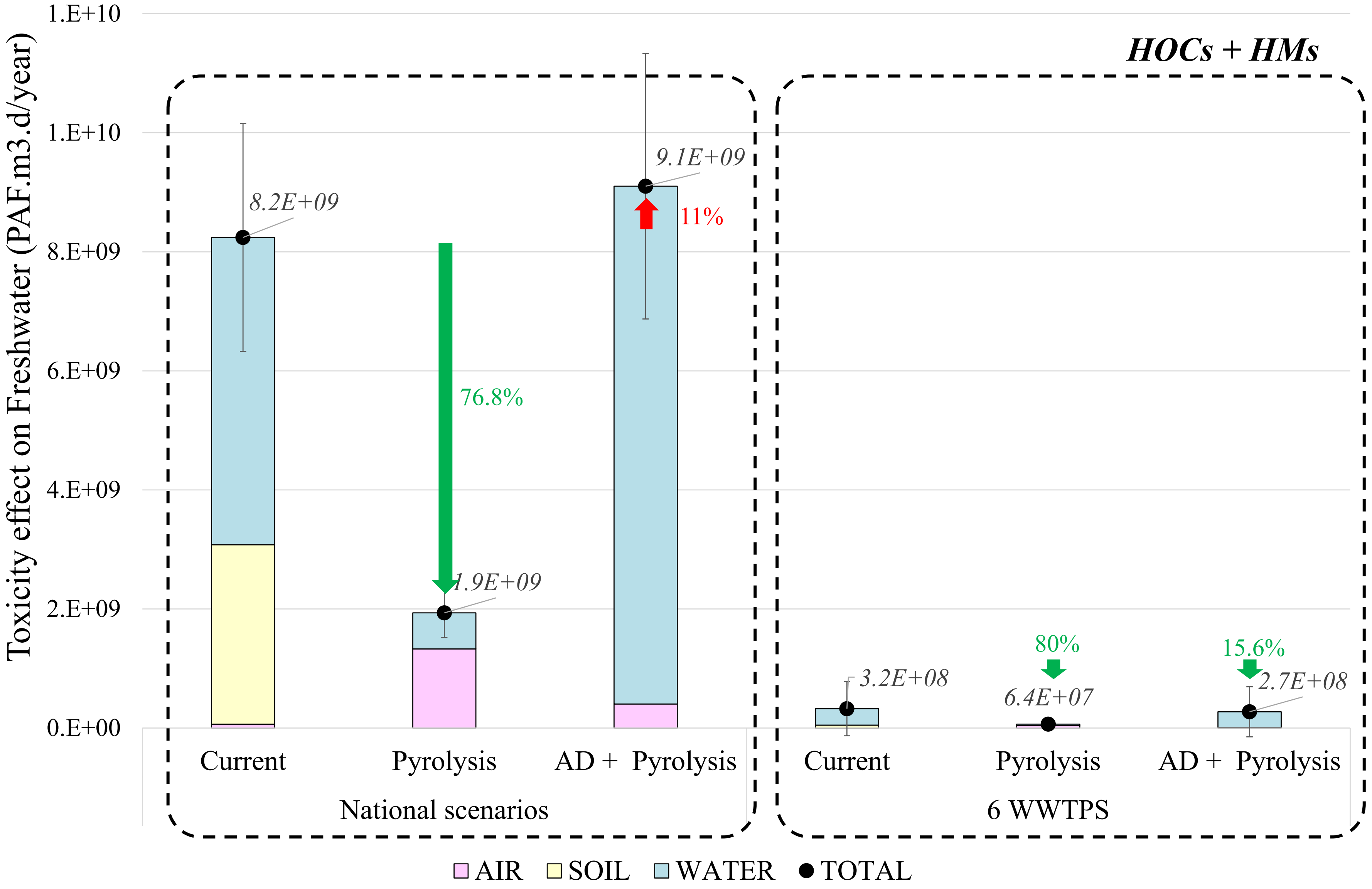


Biochar + Sewage sludge → Agricultural soil > Natural Soil

Process emissions + Soil emissions → Rural air < Urban air

NTNU

Ecotoxicological effects: Freshwater

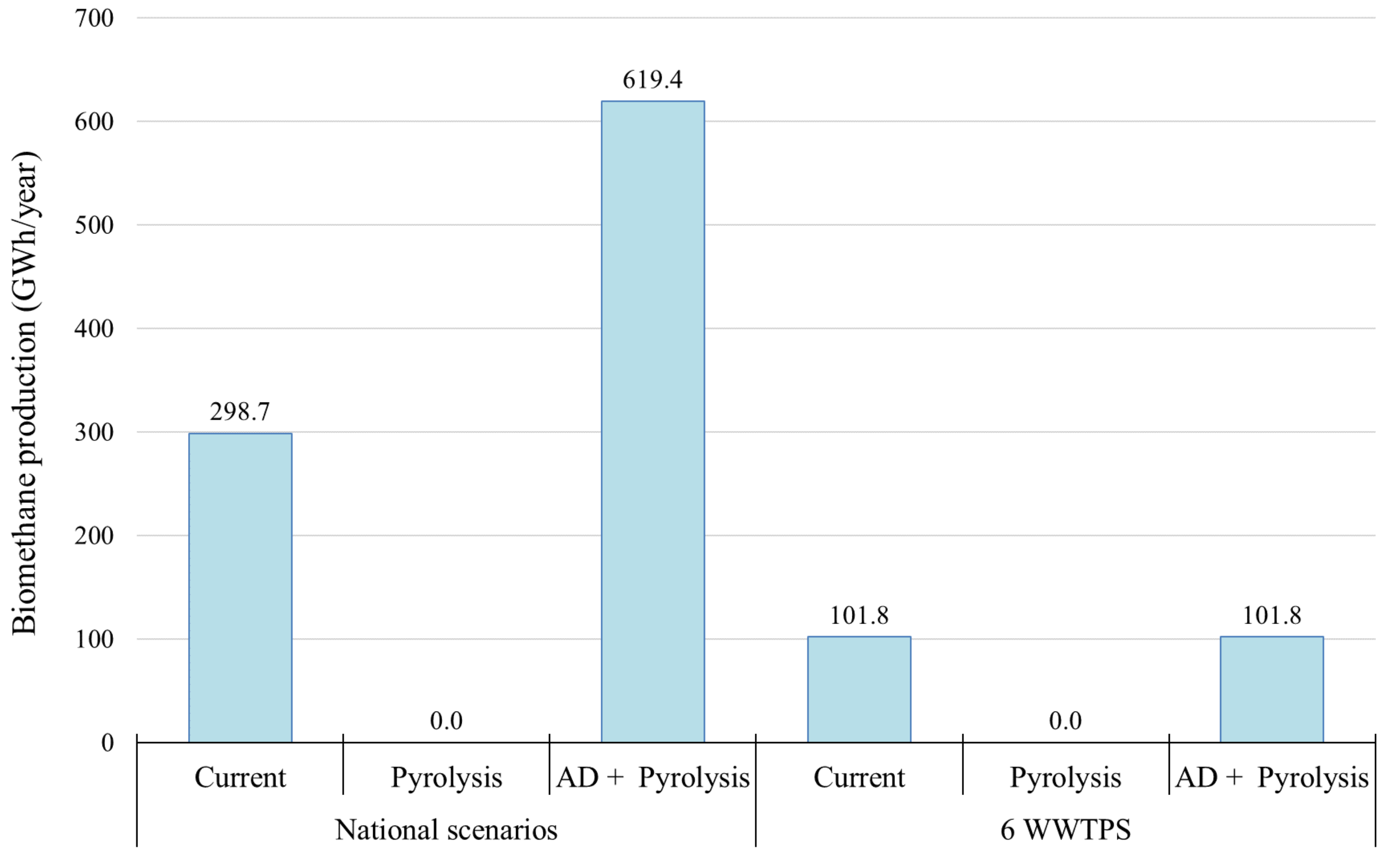


Biomethane potential → Biogas upgraded: 98% CH_4 + 2% CO_2

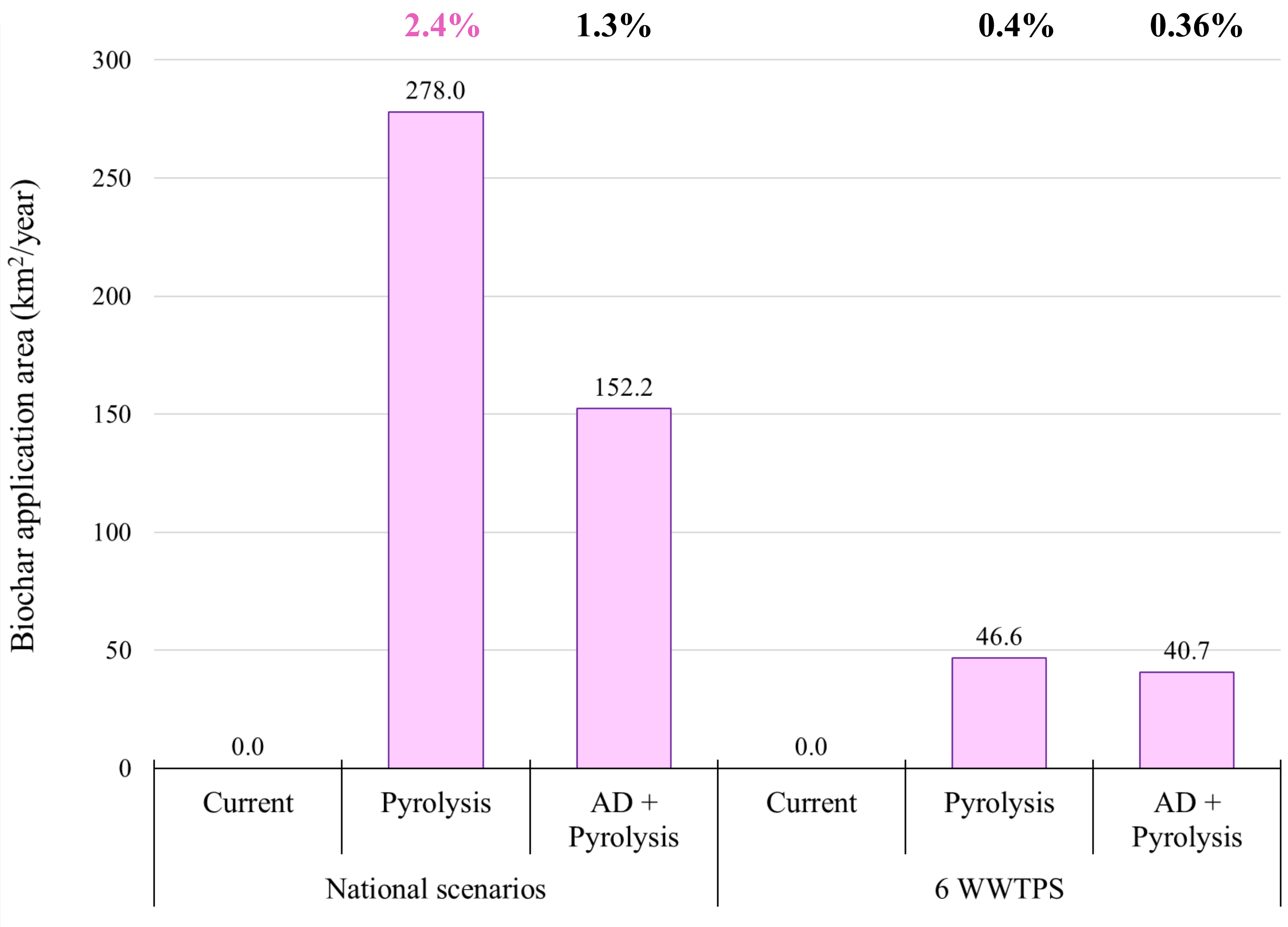
NOTE: 40% of total biogas loss as CO_2 emissions

25.8% **53.5%** **8.8%** **8.8%** → ***Fractions of natural gas currently used in transport sector in Norway***

Source: Statistics Norway, 2022



Biochar potential



Assuming and application rate to agricultural soils of 2.5 tonnes/ha.
Tisserant et al., 2022

Key messages

Pyrolysis and incineration cases can both degrade between 94% to 99% of HOCs.
PFAS degraded up to 96% in pyrolysis cases , while current technologies leaves all PFAS available.

Pyrolysis without AD shows the lowest impacts on climate change, because more biomass goes to the biochar production, and the lowest impacts on Human toxicity (non-cancer) and Freshwater Ecotoxicity.

Heavy metals switch the emission compartments (moistly from soil to air).
Higher impacts in ecotoxicity are caused by heavy metals, mainly Zinc.

Pyrolysis without AD represents the eco-friendler treatment for SS:

- Negative climate change impacts.
- C-storage (Biochar)
- Energy benefits
- Reduce contaminants and ecotoxicological impacts.

Key messages

At National scale, pyrolysis (without AD)

Almost complete removal of **organic hazardous compounds**.

No degradation of **hazardous metals** :

Emitted to solids (biochar) → Pyrolysis

Emitted to water → AD + Pyrolysis

Up to 77% reduction on ecotoxicological effect on freshwater and human health (non-cancer).

Potential production of biochar to be applied on 2.4% of agricultural lands per year.

Anaerobic digestion has the potential to produce biomethane replacing up to 54% of the natural gas used in the transport sector.

NTNU
Norwegian University of Science and Technology

Industrial Ecology Programme

Thank you!

Eco-toxicological and climate change effects of sludge thermal treatments:

Comparison of alternative sludge handling scenarios in Norway

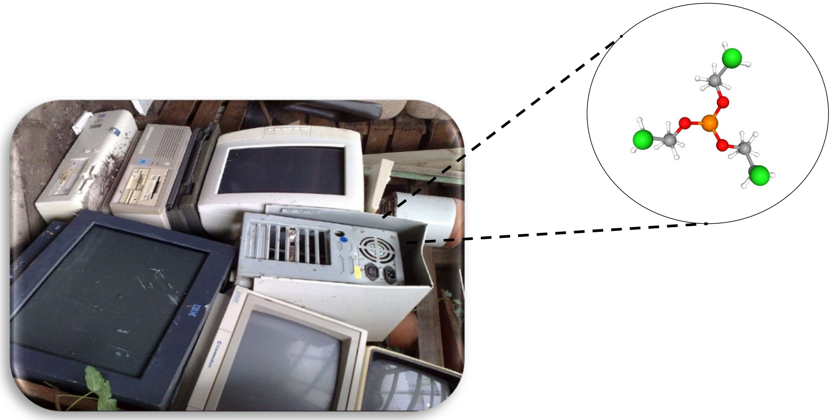
SLUDGEFFECT Project – ***mitigate hazardous substances of sewage sludge within a circular economy***

Morales, Marjorie; Arp, Hans Peter H.; Castro, Gabriela; Asimakopoulos, Alexandros G.; Sørmo, Erlend; Peters, Gregory; Cherubini, Francesco

marjorie.morales@ntnu.no

SLUDGEFFECT

Concentrations in WEEE



Gabriela Castro

9th April 2024

NTNU
Department of Chemistry

NGI

The Research Council of Norway

What is WEEE?

- Waste of electric and electronic equipment
- End-of-life equipment
- WEEE contains
  - Glass
  - Plastic
  - Metals
  - Cables
  - Toxic substances

Sampling

Recycling of cooling appliances

Pre-treatment

- Radioactive smoke detector
- Mercury
- Oil and other fluids
- Batteries
- Light tubes and bulbs

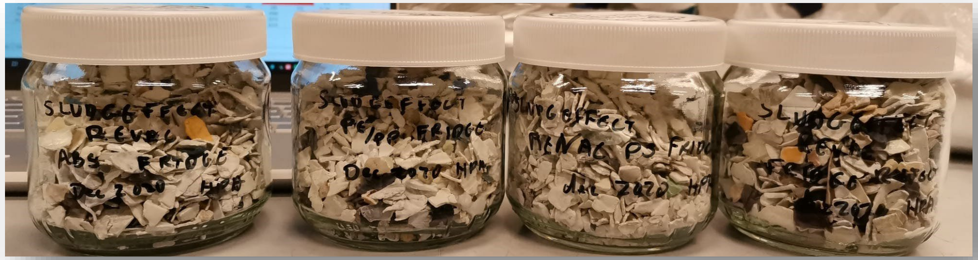
Treatment

1. Machining process removing:
- Oil and cooling gas
- Printed circuit board
- Condensator

2. Machining process:
- Cooling appliances is shredded
- Blowing agent gas is removed and CFC/HCFC gas is collected
- PUR-foam is pelletized

Sorting

- Sorting out:
  - Iron
  - Aluminum
  - Copper
  - Plastic



REVAC

Recycling of WEEE

Pre-treatment

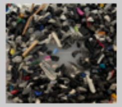
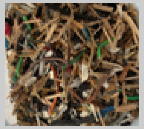
- Radioactive smoke detector
- Mercury
- Oil and other fluids
- Batteries
- Light tubes and bulbs

Treatment

- Printed circuit board
- Condensator
- Batteries
- Other dangerous waste

Sorting

- Sorting out:
  - Iron
  - Aluminum
  - Copper
  - Plastic

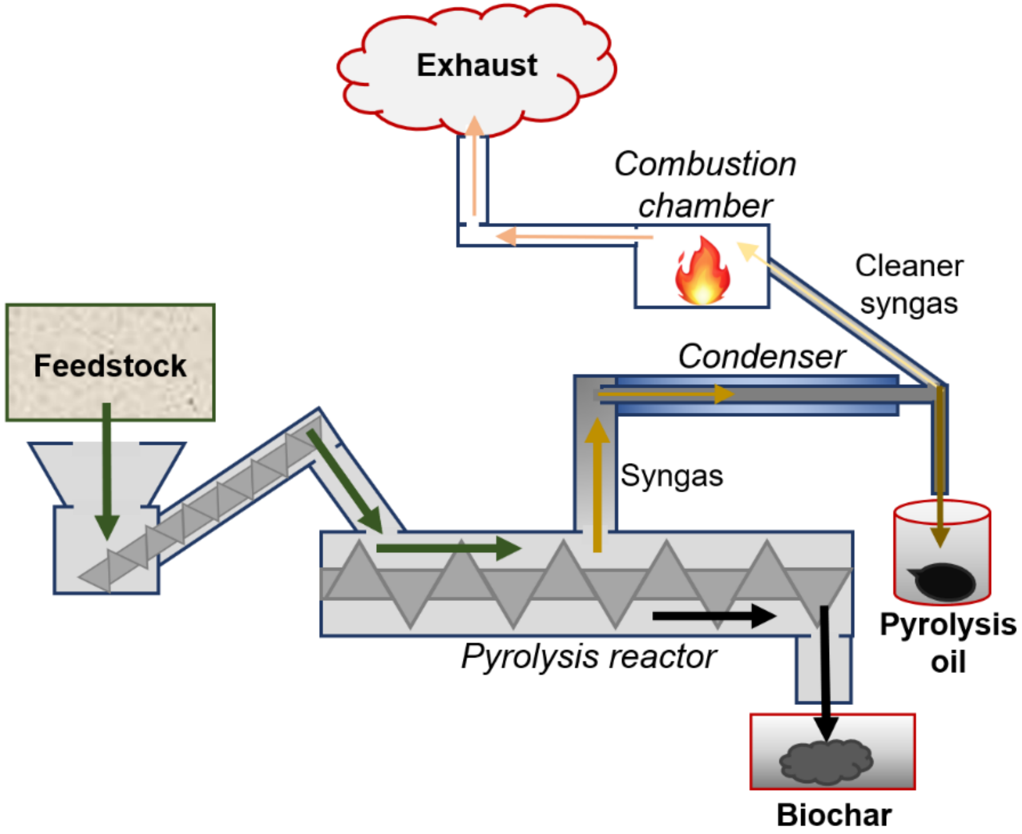
Code	Picture	Description	Plastic type	Waste category
R1		ABS SDA	ABS	Small equipment
R2		PP/PE SDA	PP/PE	Small equipment
R3		PS SDA	PS	Small equipment
R4		ABS Fridge	ABS	Temperature exchange equipment
R5		PP/PE Fridge	PP/PE	Temperature exchange equipment
R6		PS Fridge	PS	Temperature exchange equipment
R7		SDA reject	mixed grinds	Small equipment
R8		Reject Fridge	mixed grinds	Temperature exchange equipment
R9		PUR pellets	PUR	Temperature exchange equipment / Large equipment

Scanship and ETIA

Companies specialised in ecotechnologies working together to find solutions for processing biomass, food products and industry residues.

PYROLYSIS

Code	Appearance	Origin	Characteristics	Contributor
Q1		Cable granulate	PVC and/or PE	A Norwegian e-waste recycling facility
Q2		Pyrolysed bottle char	90% PET 10% PE and/or PP	Scanship and ETIA
Q3		Bottles	PET	Scanship and ETIA
Q4		Bottles cap	PET and/or PP	Scanship and ETIA
Q5		Green plastic	70% PE or PET from plastic bags "Biodegradable plastic"	The Magic Factory
Q6		Reject/ solid fraction	Mix of materials	The Magic Factory



Target analytes

- 9 Bisphenols
- 41 PFAS
- 21 OPFRs
- 7 Benzotriazoles
- 5 Benzophenones
- 17 monoester phthalate
- 11 Parabens
- 9 Benzothiazoles

Organophosphate flame retardants (OPFRs)

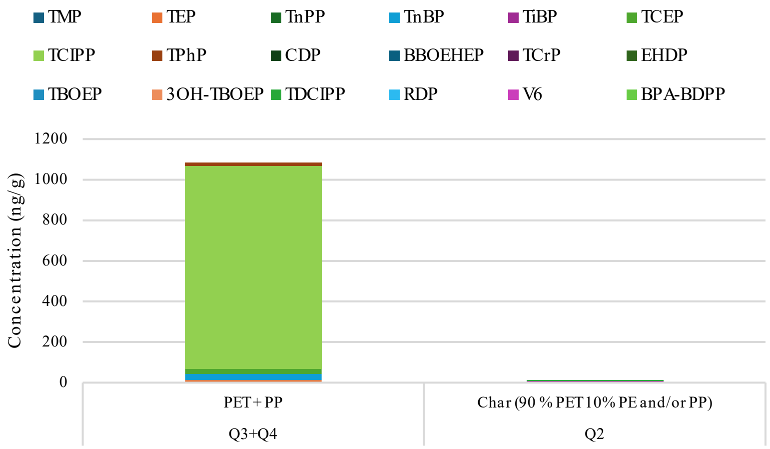
Code	Material	TMP	TEP	TnPP	TnBP	TiBP	TCEP	TCIPP	TPhP	CDP	BBOEHEP	TCrP	EHDP	TBOEP	3OH-TBOEP	TDCIPP	RDP	V6	BPA-BDPP	ΣOPFRs (ng/g)
R1	ABS	n.d.	322	n.d.	47.9	27.0	608	2761	33188	2236	n.d.	720	n.d.	48.7	n.d.	116	1446	8.7	455	41984
R2	PP/PE	n.d.	56.4	n.d.	31.4	51.4	254	1426	3298	1984	n.d.	530	325	269	n.d.	653	788	12.6	267	9945
R3	PS	n.d.	116	n.d.	16.3	7.4	125	635	9540	364	n.d.	116	n.d.	20.4	n.d.	n.d.	573	6.1	39.4	11558
R4	ABS	n.d.	45.7	n.d.	37.3	39.8	92.1	2043	513	34.9	n.d.	229	n.d.	<LOQ	n.d.	n.d.	n.d.	6.4	n.d.	3042
R5	PP/PE	n.d.	147	n.d.	33.4	37.6	528	1509	99.0	198	n.d.	936	n.d.	<LOQ	n.d.	n.d.	n.d.	9.9	43.7	3542
R6	PS	n.d.	33.5	n.d.	<LOQ	17.5	22.3	315	39.5	<LOQ	n.d.	38.9	n.d.	n.d.	n.d.	n.d.	n.d.	3.1	n.d.	470
R7	mixed grinds	52.9	1053	n.d.	137	54.4	4244	30492	278617	279218	n.d.	12040	n.d.	41.1	n.d.	75.5	2384	4.4	1485	609898
R8	mixed grinds	n.d.	235	n.d.	304	157	1036	7419	10572	828	n.d.	109	n.d.	<LOQ	n.d.	n.d.	n.d.	4.9	n.d.	20666
R9	PUR pellet	34.1	12687	n.d.	264	36.2	89600	61848	1819	6531	n.d.	2085	7156	20.3	n.d.	1543	<LOQ	1.7	680	184307
Q1	PVC and/or PE	n.d.	8.5	n.d.	59.4	23.3	791	1295	324	517	n.d.	n.d.	n.d.	n.d.	n.d.	1489	n.d.	n.d.	n.d.	4508
Q3	PET	n.d.	13.0	n.d.	8.1	n.d.	25.8	158	16.3	n.d.	n.d.	n.d.	<LOQ	<LOQ	n.d.	n.d.	n.d.	n.d.	n.d.	222
Q4	PET and/or PP	n.d.	n.d.	n.d.	21.5	8.2	n.d.	841	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	33.9	n.d.	n.d.	n.d.	905
Q5	70% PE or PET from plastic bags	n.d.	14.6	n.d.	23.3	17.2	<LOQ	n.d.	118	215	n.d.	<LOQ	n.d.	80.9	n.d.	n.d.	n.d.	n.d.	n.d.	470
Q6	Mix of materials	n.d.	16.4	n.d.	26.3	16.7	n.d.	<LOQ	30.5	<LOQ	n.d.	41.5	n.d.	131	n.d.	n.d.	n.d.	n.d.	n.d.	262

Pyrolysis Q3+Q4 (9:1) 800ºC, 15 min ϒ= 6%


Q2


Q3


Q4



RE (%) 99%

G. Castro et al. Occurrence of organophosphate flame retardants (OPFRs) in e-waste plastic and vehicle fluff (Under preparation)

Per- and polyfluoroalkyl substances (PFAS)

Code	Uncategorized	∑FTS	∑PFCA	∑PFSA	∑PreFOS	ΣPFAS (ng/g)
R1	11.8	0.47	2.84	35.6	-	50.7
R2	-	-	3.35	4.07	-	7.4
R3	-	-	6.95	4.13	-	11.1
R4	9.64	-	16.3	2.53	-	28.5
R5	-	0.45	-	-	-	0.45
R6	-	-	-	-	-	-
R7	-	-	-	22.5	-	22.5
R8	-	0.44	176	3.57	-	180
R9	-	-	27.3	-	-	27.3
Q1	-	-	-	-	-	-
Q3	-	-	472	-	-	472
Q4	-	1.15	80.2	-	-	81.3
Q5	-	14.9	32.2	4.80	-	51.9
Q6	-	9.74	250	11.1	-	271

D. Gutierrez et al. Occurrence of emerging contaminants in Norwegian Sewage Sludge and E-waste (Under preparation)

Q2 Q3 Q4

Pyrolysis Q3+Q4 (9:1) 800°C, 15 min ϒ= 6%

Pyrolysis removal of PFAS in plastics (CHAR)

		Uncategorized	∑FTS	∑PFCA	∑PFSA	∑PreFOS	ΣPFAS
Q3+Q4	PET+ PP	0.0	1.1	552.6	0.0	0.0	553.8
Q2	Char (90 % PET 10% PE and/or PP)	0.0	0.0	0.0	0.0	0.0	0.0
RE (%)		-	100%	100%	-	-	100%

Bisphenols

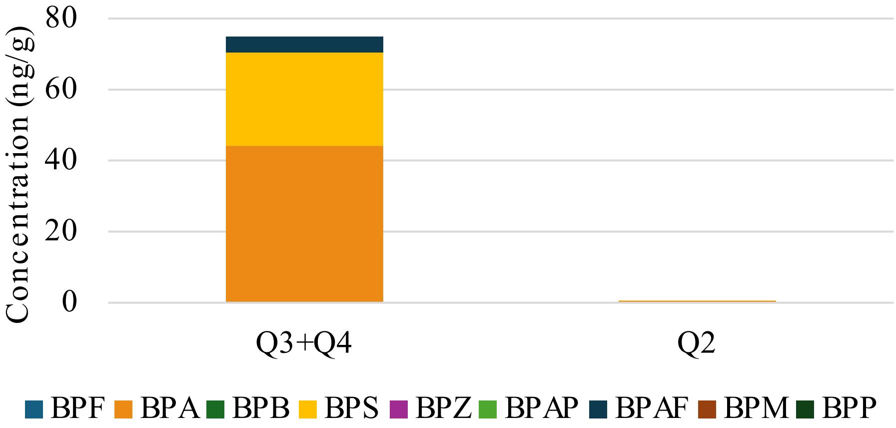
Code	BPF	BPA	BPB	BPS	BPZ	BPAP	BPAF	BPM	BPP	∑BPs (ng/g)
R1	522	2157	n.d.	7.40	n.d.	n.d.	0.48	n.d.	n.d.	2686
R2	34.4	130	n.d.	2.13	n.d.	n.d.	n.d.	n.d.	n.d.	166
R3	38.8	724	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	763
R4	n.d.	136	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	136
R5	n.d.	33.6	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	33.6
R6	n.d.	83.0	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	83.0
R7	2824	6428	n.d.	14.3	n.d.	n.d.	n.d.	n.d.	n.d.	9266
R8	36028	4644	140	1.54	n.d.	n.d.	n.d.	n.d.	n.d.	40814
R9	31.7	780	n.d.	2.75	n.d.	n.d.	n.d.	n.d.	n.d.	814
Q1	n.d.	3204	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	3204
Q3	n.d.	14.4	n.d.	1.39	n.d.	n.d.	n.d.	n.d.	n.d.	15.8
Q4	n.d.	29.8	n.d.	25.0	n.d.	n.d.	4.39	n.d.	n.d.	59.2
Q5	36.2	161	n.d.	454	n.d.	n.d.	n.d.	n.d.	n.d.	652
Q6	89.3	671	n.d.	658	n.d.	n.d.	n.d.	n.d.	n.d.	1419


Q2


Q3


Q4

Pyrolysis Q3+Q4 (9:1) 800°C, 15 min ϒ= 6%



RE (%) 99%

D. Gutierrez et al. Occurrence of emerging contaminants in Norwegian Sewage Sludge and E-waste (Under preparation)

Other emerging pollutants

		Concentration (ng/g)				
Code	Material	Σparabens	ΣBenzophenones	ΣBenzothiazoles	ΣBenzotriazoles	ΣmPHTs
R1	ABS	598	3.07	45.6	25.6	812
R2	PP/PE	841	53.4	20.5	13.0	1096
R3	PS	143	3.93	12039	22.0	956
R4	ABS	3709	1.59	26.9	5.66	1387
R5	PP/PE	219	n.d.	74.7	5.26	481
R6	PS	63.4	n.d.	1.5	2.59	347
R7	mixed grinds	5419	128	175	87.1	3403
R8	mixed grinds	2554	9.22	17.9	366	1518
R9	PUR pellet	258	6.71	69.3	49.8	5026
Q1	PVC and/or PE	106	2.6	30.1	26.4	1485
Q3	PET	42.6	14.5	14.1	8.3	1887
Q4	PET and/or PP	n.d.	41.7	9363	124	1519
Q5	70% PE or PET from plastic bags	33168	77.6	109	235	553
Q6	Mix of materials	24374	175	145	284	457

Pyrolysis removal of emerging contaminants in plastics (CHAR)

Pyrolysis Q3+Q4 (9:1) 800°C, 15 min ϒ= 6%


Q2


Q3


Q4

	Concentration (ng/g)	Σparabens	ΣBenzophenones	ΣBenzothiazoles	ΣBenzotriazoles	ΣmPHTs
Q3+Q4	PET+PP	42.6	56.1	9377	132	3406
Q2	Char (90 % PET 10% PE and/or PP)	3.71	-	3.0	0.20	54.0
	RE (%)	91%	100%	100%	100%	98%

Conclusions

- Emerging pollutants and other hazardous organic substances are ubiquitous in e-waste collected in Norway.
- Highest concentrations were detected for flame retardants (OPFRs), particularly TPhP and TClPP (DF> 80%).
- Pyrolysis at 800ºC could constitute an option in the treatment of these materials as it is able to remove more than 90% of the studied pollutants.
- Analysis of pyrolysis oil and gas phase is required to fully comprehend the behaviour of these substances during the treatment.

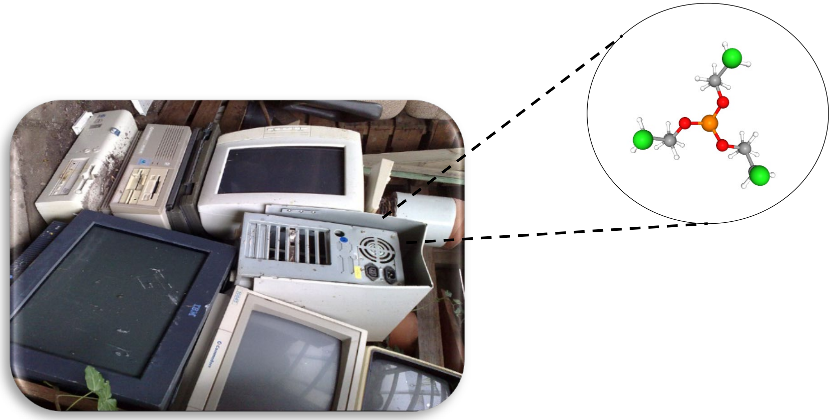
Acknowledgements

Many thanks…

- REVAC, Scanship and ETIA for the samples ☺
- Envirochemistry Lab at NTNU for helping us with the analysis.
- All the students related to the SLUDGEFFECT project for the great job.

SLUDGEFFECT

Concentrations in WEEE



Gabriela Castro
9th April 2024

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Department of Chemistry

NGI

The Research Council of Norway

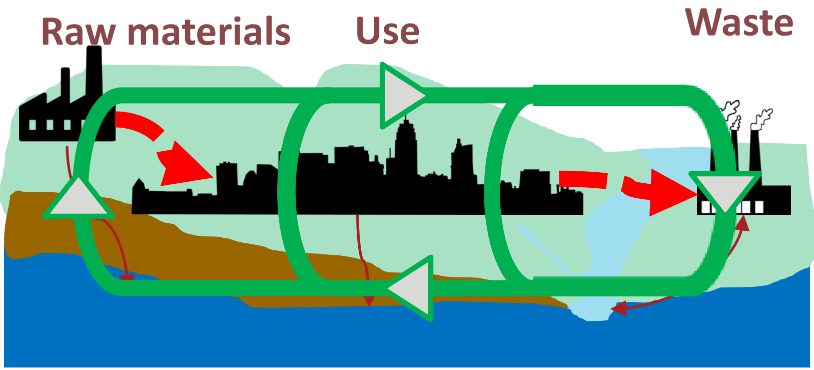
MFA and emissions of microplastic and bisphenols from waste electric and electronic equipment plastic (WEEEP) in Norway

Mari E. Løseth[1]. Heidi Knutsen[1]. Gabriela Castro[2]. Alexandros G. Asimakopoulos[2]. Sarah Hale[1] and Hans Peter H. Arp[1.2]

[1] Norwegian Geotechnical Institute. Oslo; [2] Norwegian. University of Science and Technology. Trondheim

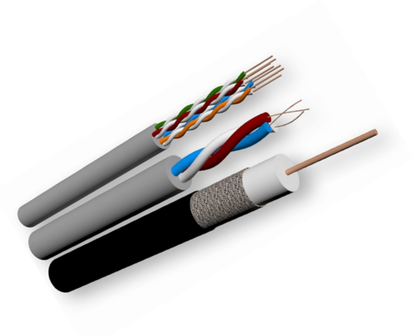
Email: mari.loseth@ngi.no

Circular Economy vs. bisphenols in plastic

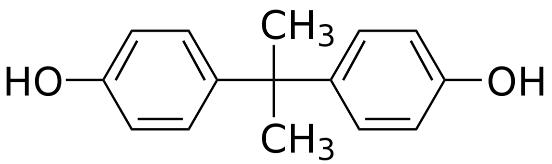


Circular Economy

vs.



Hazardous substances



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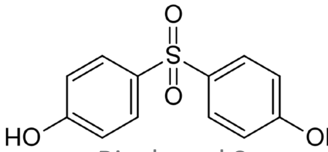
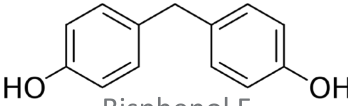
Bisphenols

- Additive or antioxidant in PVC plastic and epoxides
- Also used in printing lables
- Not chemically bound – easily released
- Several bisphenol analogues

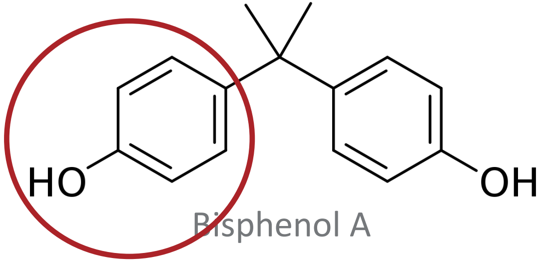
- Endocrine disruptive properties
  - Weakly bind to ER receptor
  - BPA banned from baby bottles, restricted in toys.
  - BPA and BPS on ECHAs SVHC candidate list



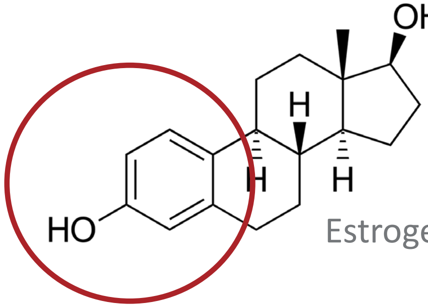
Bisphenol S



Bisphenol F



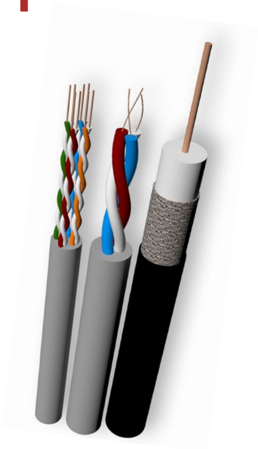
Bisphenol A



Estrogen

Focus on three WEEEP material types

- Cable plastic (contain ca. 55 % plastic: PE. PP. PVC[1.2])
- Brominated Flame Retardant (BFR) containing plastic (i.e. dense plastic)
- Other WEEE plastic



Collection → Sorting and separation → Metal recovery → Density separation of plastic → Sanitizing or recycling

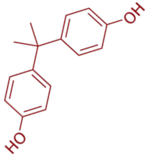
NGI

[1]Pita and Castilho 2018. Minerals. 10.3390/min8110517
[2]Mepex. 2013. TA-2956/2012

Methods and data collection

Mass flow data collection via the Norwegian Environment Agency – Extended producer responsibility (EPR) scheme

Literature review to collect information on plastic % in WEEE categories



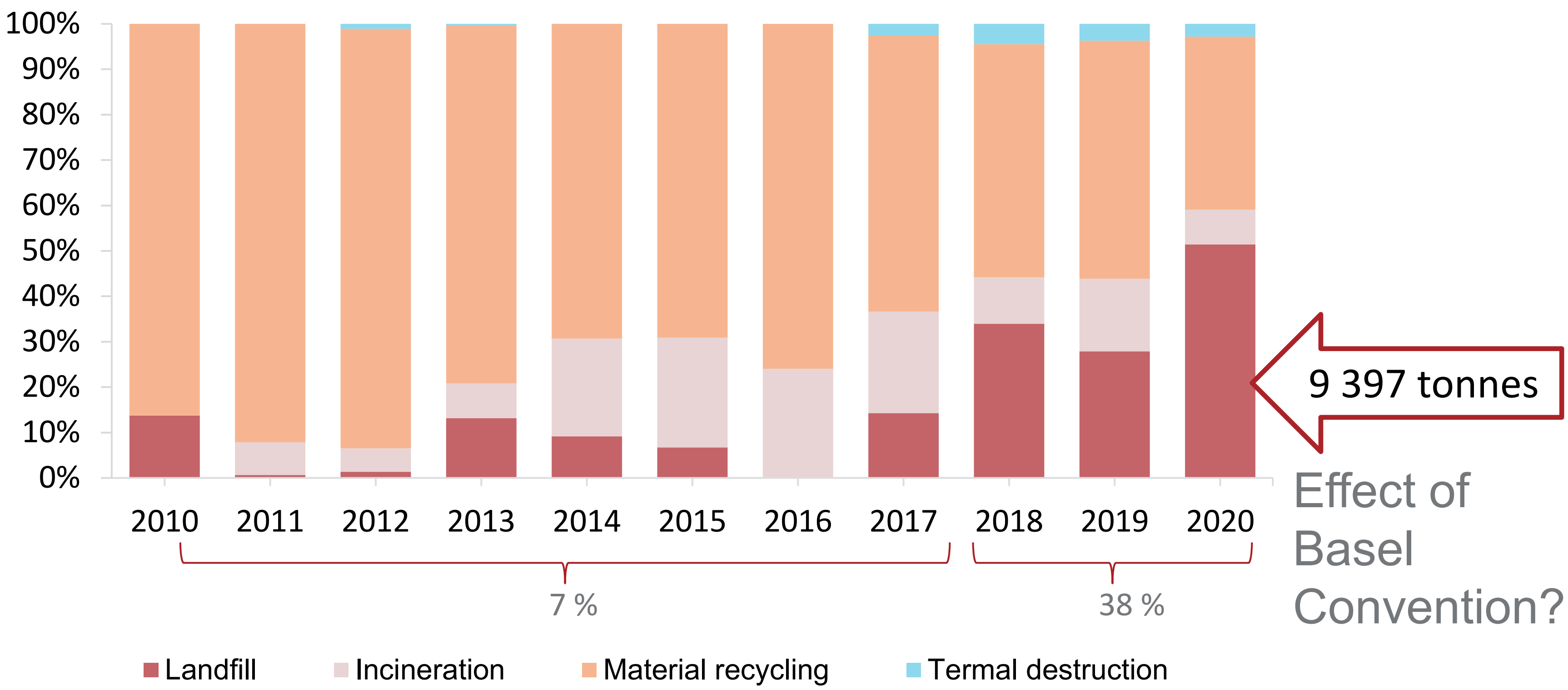
Use emission factors from Arp et al. (2017) multiplied by 0.007 and 0.021 – thus assumed that 2% of particles are emitted as microplastics[3], ~ 1 tonne/year from landfills

Analysis of bisphenols in plastic collected from WEEE recyclers in South Eastern Norway by ammonium acetate, ethyl acetate extraction and UPLC-MS/MS[4]

Data processing using STAN 2.7 for MFA, Excel and R

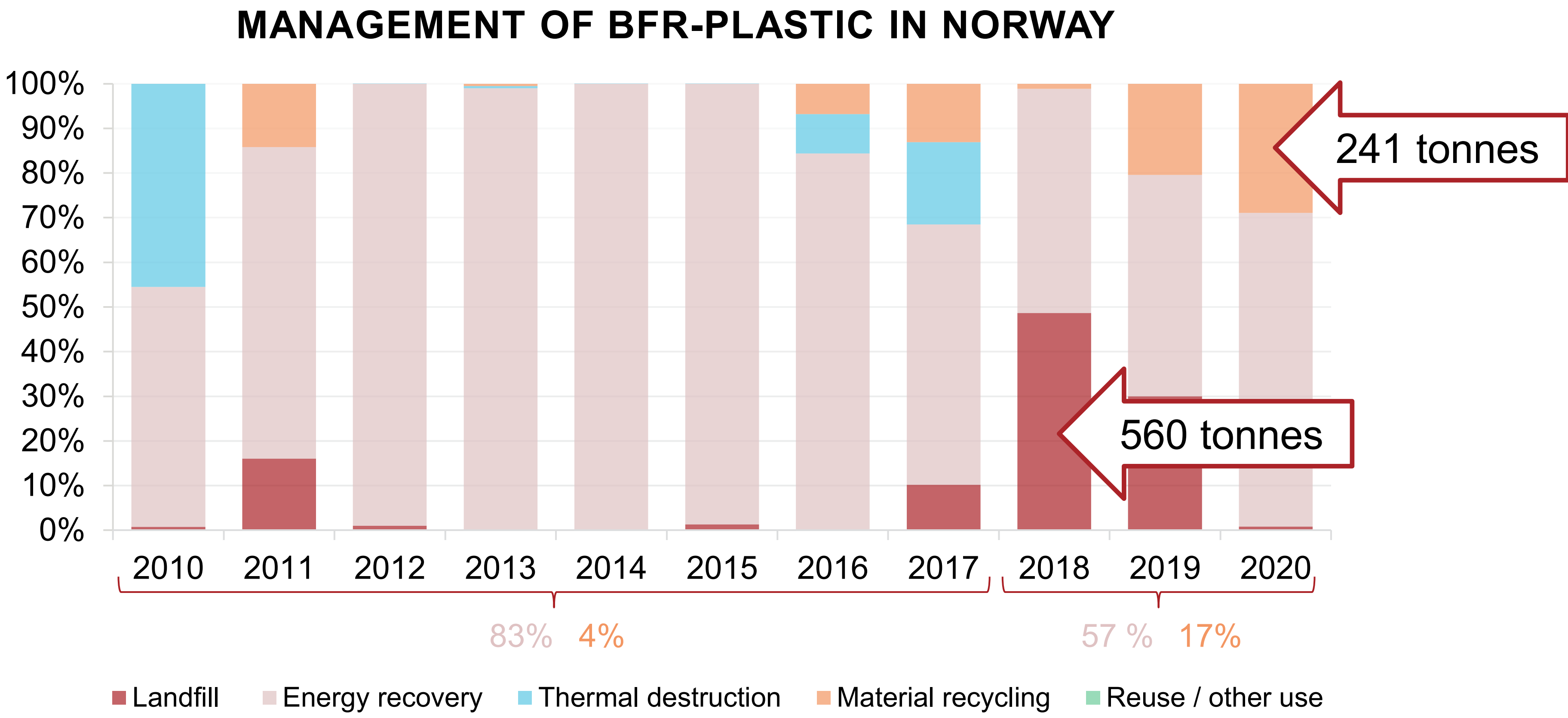
[3]Narevski et al.. 2021. Environ. Sci. Pollut. Res.10.1007/s11356-021-13705-z
[4]Runde et al.. 2022. J Haz Mat 10.1016/j.jhazmat.2021.127814

MANAGEMENT OF ELECTRICAL WHOLE CABLES IN NORWAY



Effect of Basel Convention?

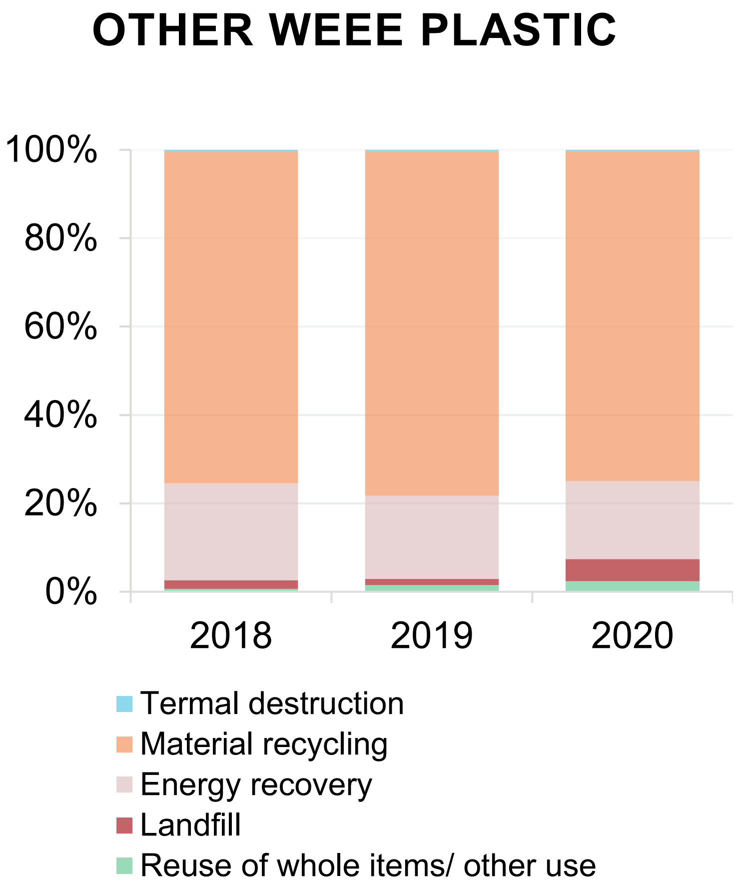
Resource: Norwegian Environment Agency. 2021



MANAGEMENT OF BFR-PLASTIC IN NORWAY
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
241 tonnes
560 tonnes
83% 4%
57 % 17%
Landfill
Energy recovery
Thermal destruction
Material recycling
Reuse / other use

Other WEEEP

- 75 % of WEEEP in Norway
- PP, PE, PS, ABS and other
- Mainly recycled or incinerated



Bisphenols detected in WEEEP

Compounds used as:

- Plastic monomers and plasticizers in the production of PC and epoxy resins.
- Additive and antioxidant in PVC for cable insulation
- Thermal printing paper as developer for heat reactive dye

			BPA (kg/ton)		**BPF** (kg/ton)		**BPS** (kg/ton)		**Sum BPs** (kg/ton)	
For MFA of WEEEP	**Sample material**	n	mean	SD	mean	SD	mean	SD	mean	SD
Totalt WEEEP	All samples	14	2.7E-02	6.2E-02	4.9E-03	9.8E-03	3.0E-05	8.46E-05	0.03	0.06
BFR plastic	BFR plastic. reject from SDA and Fridge	3	1.8E-02	8.5E-03	1.0E-02	5.2E-03	1.2E-04	1.52E-04	0.03	0.004
Cable plastic	PVC. PE and PP granulates	4	7.6E-02	9.9E-02	2.1E-05	3.5E-05	1.1E-05	1.79E-05	0.08	0.09
Other WEEEP	Grined PP. PS. ABS from SDA and Fridge. mixed e-waste	7	1.7E-03	2.5E-03	5.6E-03	1.2E-02	2.8E-06	4.75E-06	0.007	0.01

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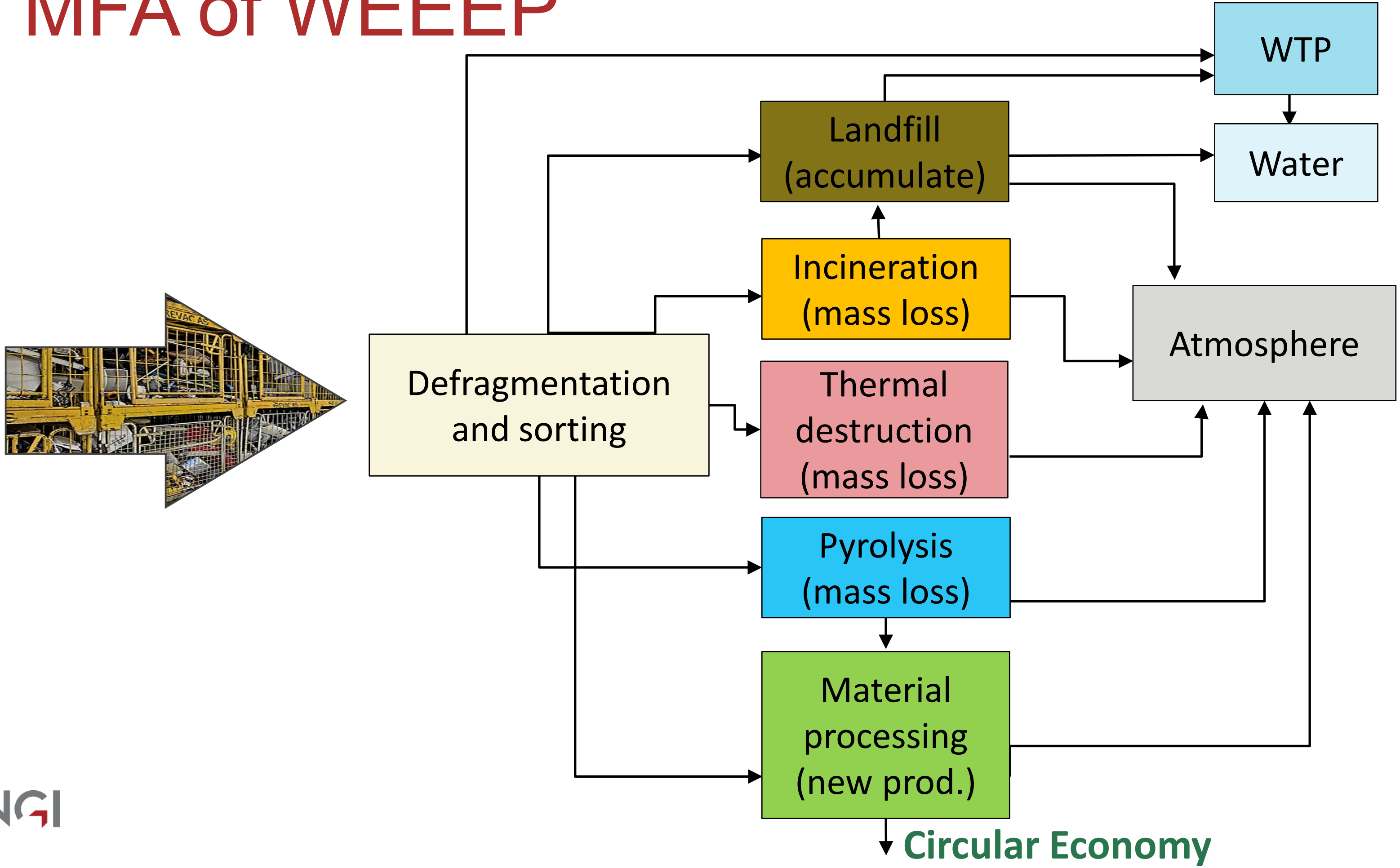
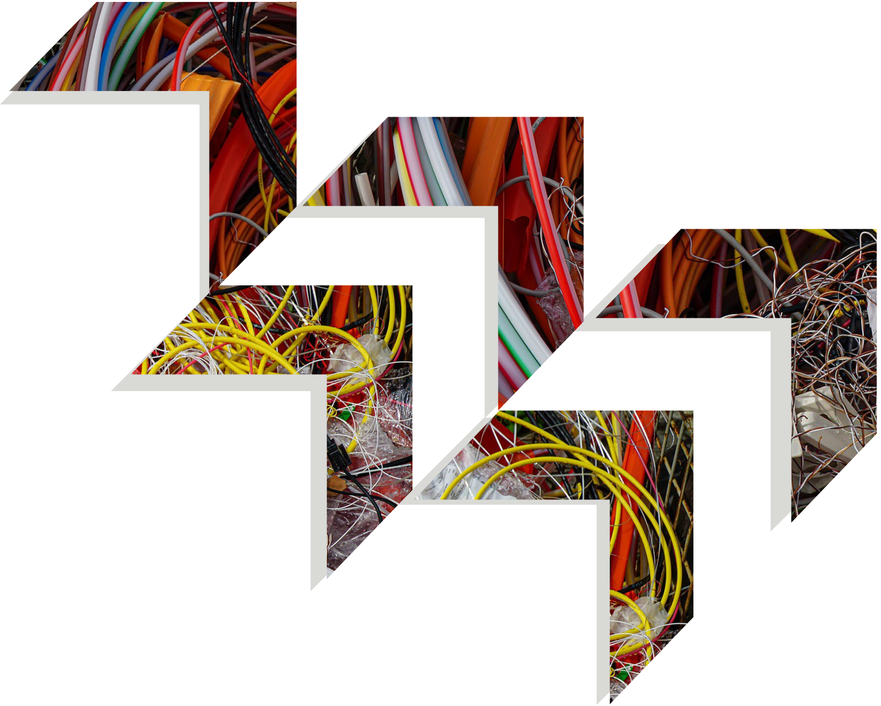
Combined data from Runde et al. 2021 and samples received from REVAC analysed by Gabriela Castro

MFA of WEEEP

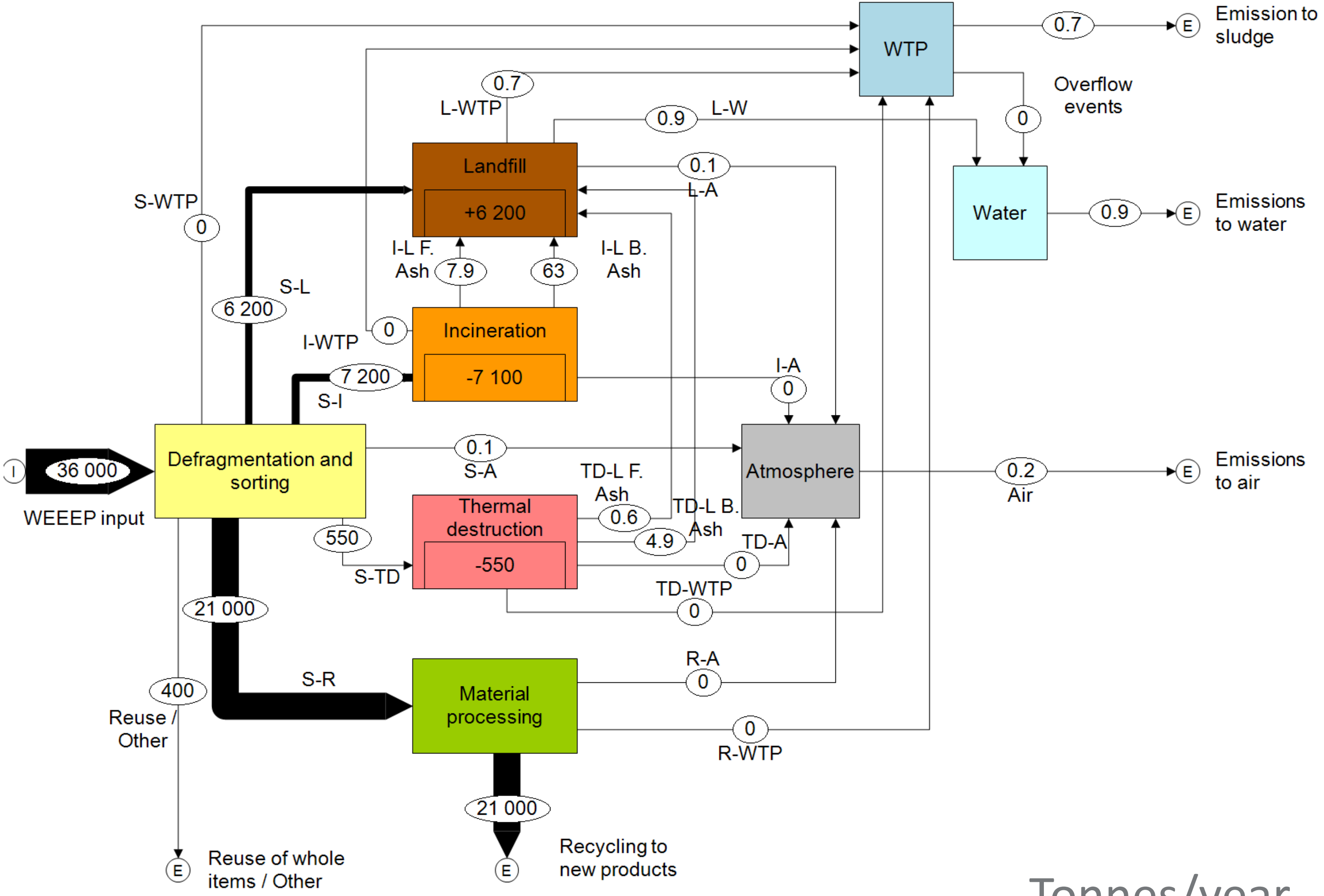


WTP
Landfill (accumulate)
Water
Incineration (mass loss)
Atmosphere
Defragmentation and sorting
Thermal destruction (mass loss)
Pyrolysis (mass loss)
Material processing (new prod.)
Circular Economy



Results

Total WEEEP 2018 to 2020



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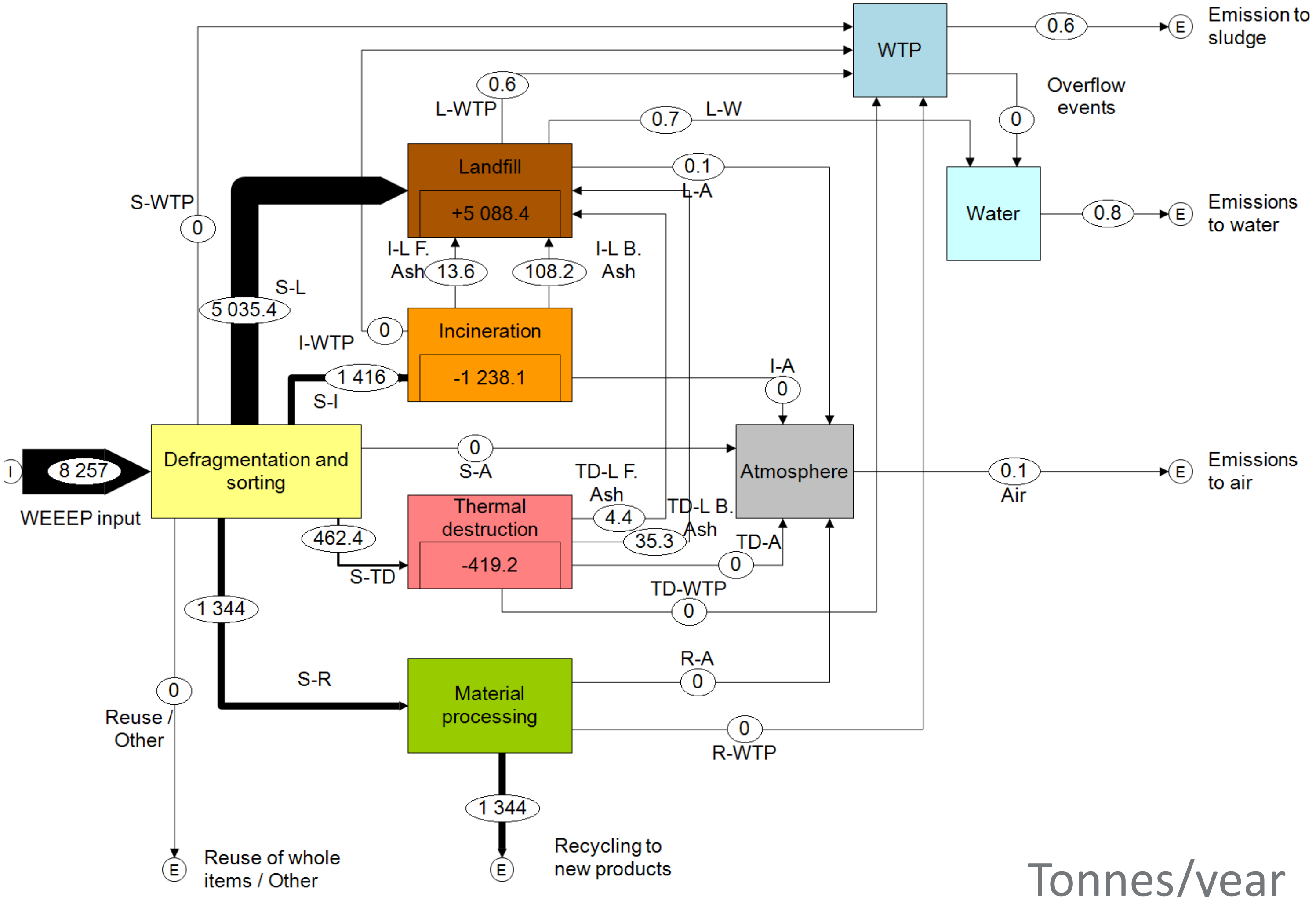
Tonnes/year

Cable plastic 2018 to 2020



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Tonnes/year

MFA of BPs in WEEEP 2018 – 2020

Plastic type	Total WEEEP		BFR-plastic		Cable plastic		Other WEEEP	
(kg BPs / year)	Mean	±SE	Mean	±SE	Mean	±SE	Mean	±SE
Waste (tonnes/year)	35 575	1370	1 305	327.5	8 257	884.37	26 012	727.7
kg BPs input waste	1 121.79	43.20	36.79	9.23	631.2	67.60	197.30	5.52
Landfill (stock)	168.58	6.49	9.34	0.36	333.4	12.84	4.95	0.19
Energy recovery (mass loss)	225.76	8.69	19.91	0.77	108.1	4.16	38.22	1.47
Thermal destruction (mass loss)	17.47	0.67	0.00	0.00	35.3	1.36	0.70	0.03
Recycling to new products	671.35	9.74	6.09	3.12	102.73	38.88	149.65	3.00
Reuse / other use	12.46	4.41	0	0.00	0	0.00	3.00	1.06
Emission to sludge	14.22	3.71	0.79	0.38	27.97	8.25	0.44	0.18
Emission to water	11.97	3.14	0.66	0.33	23.67	7.00	0.35	0.15
Emission to air	8.6E-02	0.01	2.7E-03	0.00	6.9E-02	0.01	1.3E-02	5.7E-04

MFA of BPs and microplastics under two potential future scenarios

Scenario 1

Cable and **BFR plastic**: Reduce BPs use by 50%.

Other WEEEP: no changes.

Scenario 2

Cable plastic: 75% incineration, 25% recycling

BFR-plastic: 100% incineration

Other WEEEP: no changes

Current scenario

Cable plastic:

17% incineration, 16% recycling, 61% landfilling, 5.6% thermal destruction

BFR-plastic:

54% incineration, 17% recycling, 29% landfilling

Other WEEEP:

19% incineration, 76% recycling, 3% landfilling, 0.4% thermal destruction, 2% reuse

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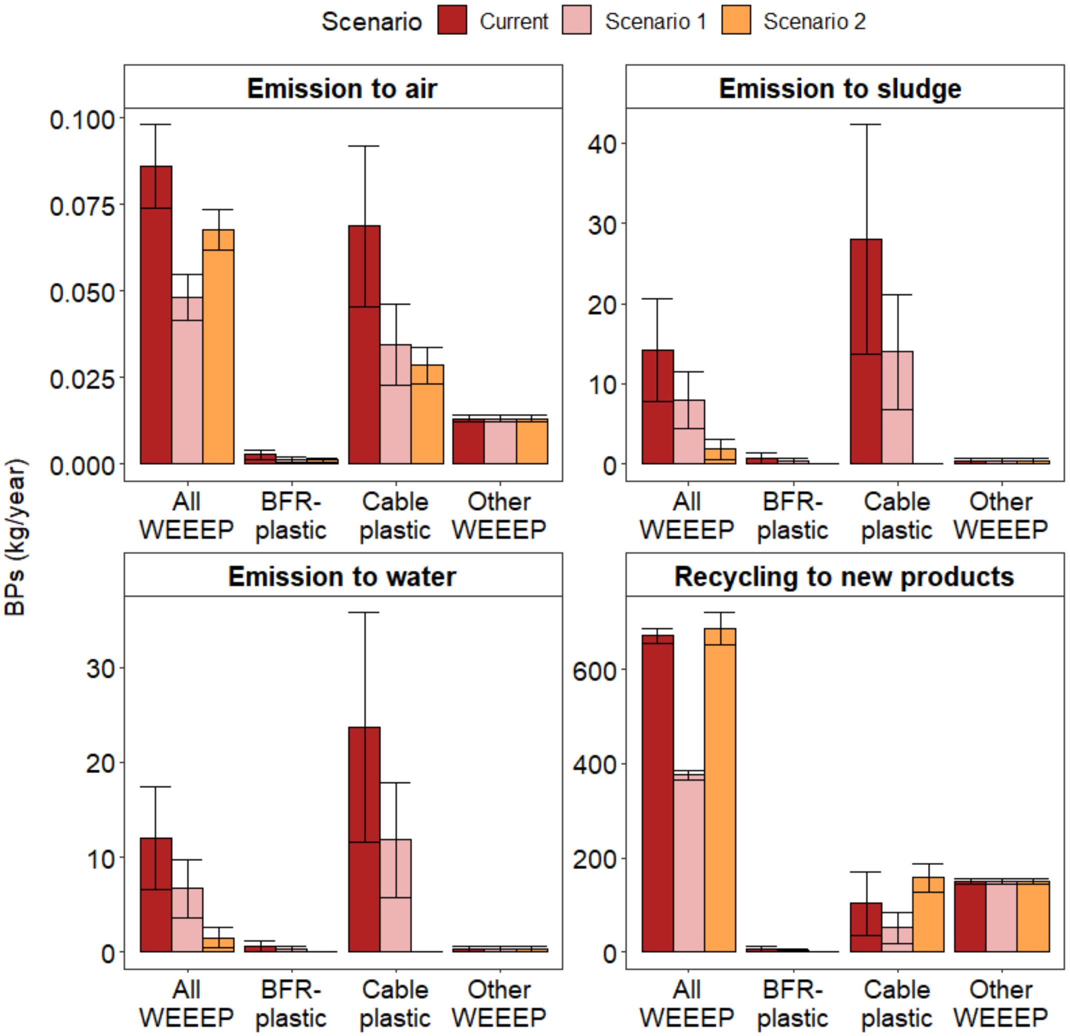
Emissions of BPs under two potential future scenarios



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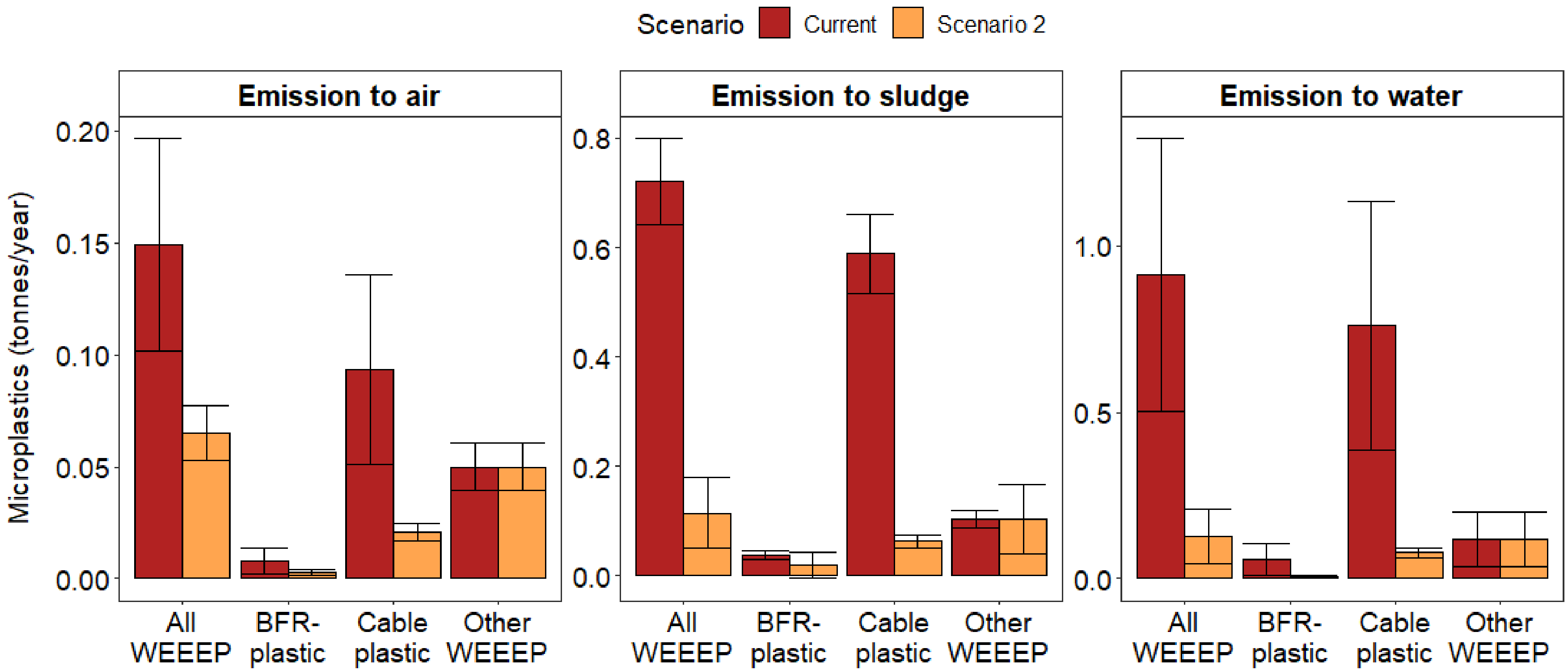
Emissions of MPs under two potential future scenarios



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Scenario 1: Recommendation for future design of cables and BFR-plastics

- PE and PP are more recyclable than PVC and PC
- Evaluate if BPs are essential for WEEE plastic
- Other safer alternatives to BPs
- Improve recyclability and re-use of cables
- More universal cable design (e.g. USB-C)
- Closed loop recycling
- Explore chemical pyrolysis

Conclusion

- Landfilling = major contributor of BPs and MPs from WEEEP to environment
- Need for improvement of waste management of cable and BFR-plastic
  - Will have a major reduction on environmental impact by BPs and MPs from WEEE
- Include removal of bisphenols and other hazardous substances as part of safe and sustainable design of future WEEE plastic
- Løseth et al. in prep. ***Material flow analysis of WEEE plastic in Norway: emissions of bisphenols and microplastics under three management scenarios***

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Thank you for the attention!

#onsafeground

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SLUDGEFFECT - Implementation in a Circular Economy and General Discussion

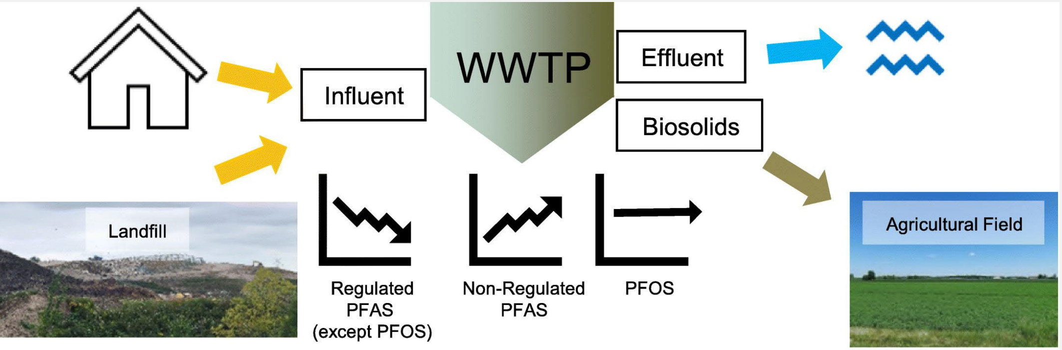
Hans Peter Arp and Erlend Sørmo

SLUDGEFFECT Symposion
April 9, 2024

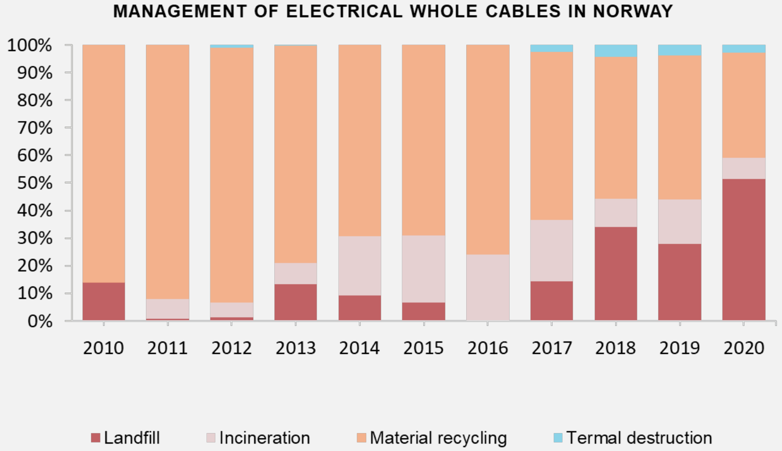

The European Green Deal
Horizon2020 + ICT4Water
sludge
Climate Adaptation Strategy
sludge
Energy systems integration strategy
sludge
Methane strategy
sludge WEEE
Circular Economy Action Plan 2.0
Renovation wave
Increasing the EU's Climate ambition for 2030 and 2050
sludge
Supplying clean, affordable and secure energy
WEEE
Mobilising industry for a clean and circular economy
Building and renovating in an energy and resource efficient way
Transforming the EU's economy for a sustainable future
The European Green Deal
And leave No one behind
Financing the transition
Leave no one behind (Just Transition)
The EU as a global leader
Mobilising research and fostering innovation
sludge WEEE
A zero pollution ambition for a toxic-free environment
Preserving and restoring ecosystems and biodiversity
From 'Farm to Fork': a fair, healthy and environmentally friendly food system
WEEE
Accelerating the shift to sustainable and smart mobility
sludge
Strategic Approach to Pharma in the environment
sludge
Zero Pollution Action Plan for air, water & soil
sludge
Integrated Nutrient Management Action Plan
WEEE
Plastics Strategy
Biodiversity Strategy
sludge
Farm to Fork Strategy
WEEE
sludge
Chemicals Strategy
Pharmaceuticals Strategy
A European Climate Pact

Upstream regulations for WWTP and e-waste design matter

Sludge



E-waste plastic



- 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

Sludge

EU-level discussions on sludge

- Several policy domains consider sludge and contaminants within:
  - EU Green Deal (Circular Economy (CE), the Zero Pollution Action plan (ZPA), Chemical strategy), the fertilizer directive, waste and food, chemical monitoring and risk management
  - The EU Sewage Sludge Directive (SSD) 86/278/EEC sets quality standards for seven metals, and restricts the application of biosolids to pastures, or agricultural land for growing vegetables and fruit
  - The EU Joint Research Commission (JRC) was highly critical of sewage sludge in any form as fertilizer based on the precautionary principle, but is ok with nutrients «extracted» from sewage sludge or its ashes (though this is not yet economical).

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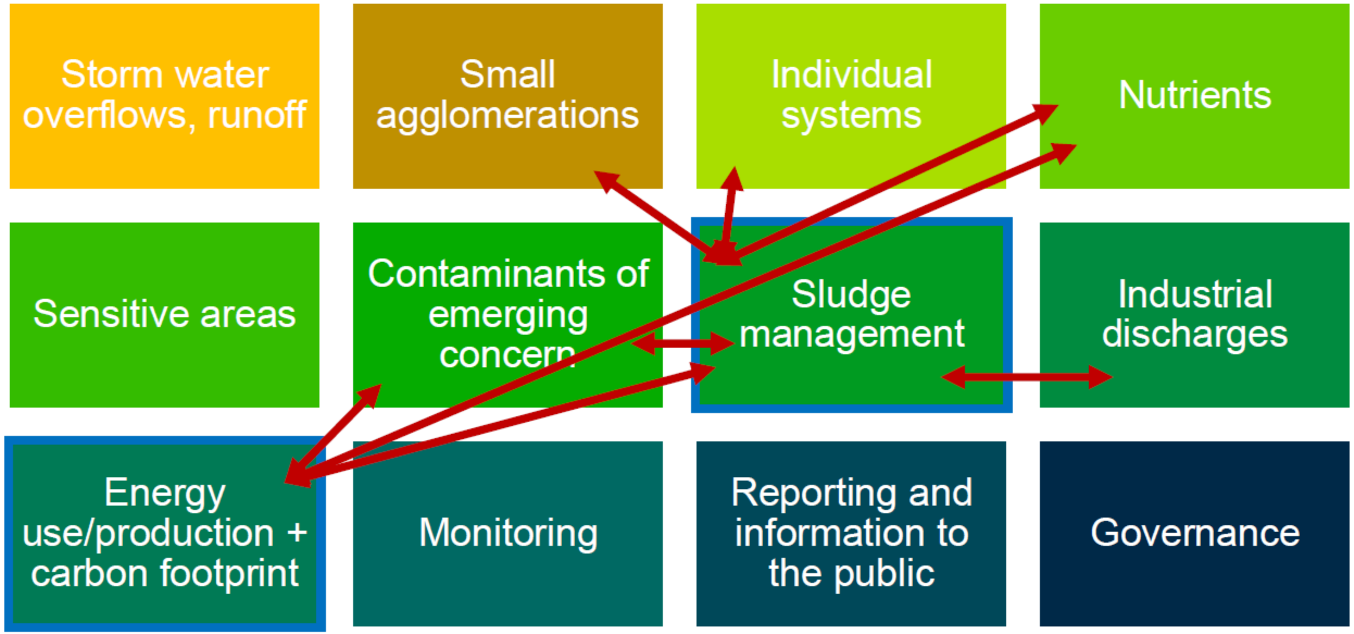
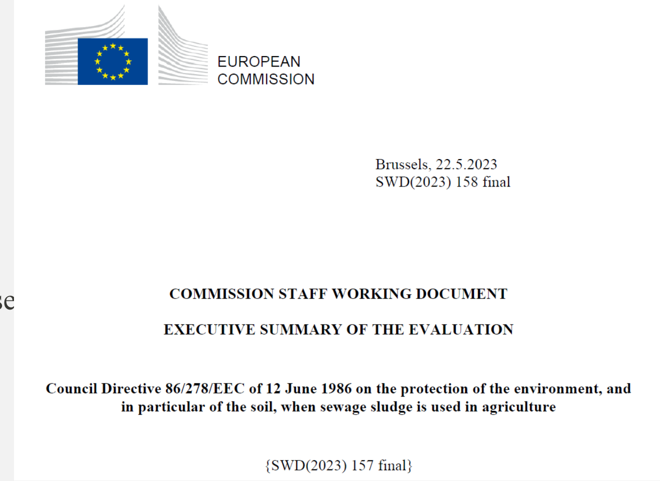
Synergies and trade-offs between policy measures for energy, contaminant and food protection



Sewage Sludge Directive

- The EU Sewage Sludge Directive (SSD) 86/278/EEC sets quality standards for seven metals, and restricts the application of biosolids to pastures, or agricultural land for growing vegetables and fruit
- Evaluated to be still relevant for the EU
  - sole legal instrument providing an EU wide framework for soil protection from sludge use in agriculture,
  - minimum level of harmonisation for control of pollution and health risks.
  - Acknowledges different country regulations (e.g. for organic contaminants)
- *"The level of heavy metals in sludge used in agriculture significantly decreased over time, to level below the limits set by the SSD, very often 10 times lower. While it can be partly attributed to the Directive, it is challenging to distinguish its effect from that of national action or of legislation controlling the emission of these pollutants at source."*
- Not yet updated, to be done after related Directives (e.g. Urban waste water treatment directive(



EUROPEAN
COMMISSION

Brussels, 22.5.2023
SWD(2023) 158 final

COMMISSION STAFF WORKING DOCUMENT

EXECUTIVE SUMMARY OF THE EVALUATION

Council Directive 86/278/EEC of 12 June 1986 on the protection of the environment, and in particular of the soil, when sewage sludge is used in agriculture

{SWD(2023) 157 final}

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Provisional Agreement to the Urban Wastewater Treatment Directive – Jan 29, 2024

- New article 8 on **Quaternary treatment**: obligation to apply additional treatment to urban wastewater in order to eliminate the broadest possible spectrum of micro-pollutants.
- New Article 9 on **Extended producer responsibility**: obligation for producers (including importers) of certain products (pharmaceuticals and personal care products only) to contribute to the costs of the quaternary treatment.
- Revision of Article 15 on water reuse: Paragraph 1 has been amended so that Member States will be required to systematically **promote the reuse of treated wastewater** from all urban wastewater treatment plants.
- New Article 17 Urban wastewater surveillance : establishes a **national urban wastewater monitoring system** to monitor relevant public health parameters in urban wastewater.

- Quaternary treatment => many options for water, but pyrolysis is relevant for sludge

Provisional Agreement to the Urban Wastewater Treatment Directive – Jan 29, 2024

- **New Article 18 on Risk assessment and management: obligation for Member States to assess the risks caused by urban wastewater discharges to the environment and human health** (at least in relation to the quality of a water body used for the abstraction of water intended for human consumption - as defined in DWD -, the quality of bathing water falling in the scope of the BWD, the good ecological status of a water body as defined in the WFD, the quality of a water body where aquaculture activities take place).
- Revision of Article 20 on sludge: **sludge will have to be treated, recycled and recovered whenever appropriate and disposed of in accordance with the requirements of the Waste Framework Directive and the Sludge Directive.**
- **Revision of article 21 on monitoring**: For all agglomerations of above 10 000 population equivalent, Member States must monitor at the inlets and outlets of urban wastewater treatment plants, the concentration and loads in the urban wastewater of **pollutants listed in EQSD, Groundwater Directive, E-PRTR, Sewage sludge Directive and the presence of microplastics including in the sludge**. -> This includes PFAS

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Environmental Quality Standard (EQS) Directive Draft

- Utilized by many directives for deriving PFAS threshholds
- Annex I: ***23 new substances are added to the list of priority substances including pharmaceuticals, industrial substances, pesticides and metals***. The Annex also indicates the substances that are hazardous, those that are ubiquitous PBTs as well as those that require long-term trend assessment. Among the 23 new substances, **an EQS is defined for the sum of the concentrations of the 24 PFAS expressed as PFOA-equivalents : 0.0044 µg/l (surface water and ground water) and 0.077 µg/kg wet weight (biota).** List of substances is in attached Annexes (Annex V). The EQS is in line with the opinion of the SCHEER of August 2022.

The 24 PFAS and relative potency factors (RPF)

(6) This refers to the following compounds, listed with their CAS number, EU number and Relative Potency Factor (RPF): Perfluorooctanoic acid (PFOA) (CAS 335-67-1, EU 206-397-9) (RPF 1), Perfluorooctane sulfonic acid (PFOS) (CAS 1763-23-1, EU 217-179-8) (RPF 2), Perfluorohexane sulfonic acid (PFHxS) (CAS 355-46-4, EU 206-587-1) (RPF 0,6)), Perfluorononanoic acid (PFNA) (CAS 375-95-1, EU 206-801-3) (RPF 10), Perfluorobutane sulfonic acid (PFBS) (CAS 375-73-5, EU 206-793-1) (RPF 0,001), Perfluorohexanoic acid (PFHxA) (CAS 307-24-4, EU 206-196-6) (RPF 0,01), Perfluorobutanoic acid (PFBA) (CAS 375-22-4, EU 206-786-3) (RPF 0,05), Perfluoropentanoic acid (PFPeA) (CAS 2706-90-3, EU 220-300-7) (RPF 0,03), Perfluoropentane sulfonic acid (PFPeS) (CAS 2706-91-4, EU 220-301-2) (RPF 0,3005), Perfluorodecanoic acid (PFDA) (CAS 335-76-2, EU 206-400-3) (RPF 7), Perfluorododecanoic acid (PFDoDA or PFDoA) (CAS 307-55-1, EU 206-203-2) (RPF 3), Perfluoroundecanoic acid (PFUnDA or PFUnA) (CAS 2058-94-8, EU 218-165-4) (RPF 4), Perfluoroheptanoic acid (PFHpA) (CAS 375-85-9, EU 206-798-9) (RPF 0,505), Perfluorotridecanoic acid (PFTrDA) (CAS 72629-94-8, EU 276-745-2) (RPF 1,65), Perfluoroheptane sulfonic acid (PFHpS) (CAS 375-92-8, EU 206-800-8) (RPF 1,3), Perfluorodecane sulfonic acid (PFDS) (CAS 335-77-3, EU 206-401-9) (RPF 2), Perfluorotetradecanoic acid (PFTeDA) (CAS 376-06-7, EU 206-803-4) (RPF 0,3), Perfluorohexadecanoic acid (PFHxDA) (CAS 67905-19-5, EU 267-638-1) (RPF 0,02), Perfluorooctadecanoic acid (PFODA) (CAS 16517-11-6, EU 240-582-5) (RPF 0,02), Ammonium perfluoro (2-methyl-3-oxahexanoate) (HFPO-DA or Gen X) (CAS 62037-80-3) (RPF 0,06), Propanoic Acid / Ammonium 2,2,3-trifluoro-3-(1,1,2,2,3,3-hexafluoro-3-(trifluoromethoxy)propoxy)propanoate (ADONA) (CAS 958445-44-8) (RPF 0,03), 2- (Perfluorohexyl)ethyl alcohol (6:2 FTOH) (CAS 647-42-7, EU 211-477-1) (RPF 0,02), 2-(Perfluorooctyl)ethanol (8:2 FTOH) (CAS 678-39-7, EU 211-648-0) (RPF 0,04) and Acetic acid / 2,2-difluoro-2-((2,2,4,5-tetrafluoro-5-(trifluoromethoxy)-1,3-dioxolan-4-yl)oxy)- (C6O4) (CAS 1190931-41-9) (RPF 0,06).

- RPF = toxcity relevant to PFOA
- SLUDGEFFECT measured them all, except C6O4

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Norwegian Sludge contexts

- Ongoing discussions in Norway, reflecting those happening at the EU level
- Norskvann (an organisation representing drinking water and waste water producers in Norway) are worried that uncertainty/extra regulations around contaminants in sludge and waste water will disrupt sludge as a fertilizer
- Fertilizer regulation (2003) was opened for revision in 2009, and there is still discussion about this, mostly related to amounts of phosphorous that can be applied and environmental contaminants
- The role of contaminants in sewage sludge has made this revising much more complicated, with key reports from COWI and NIBIO regarding maximum contaminant levels of selected contaminatns

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

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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/

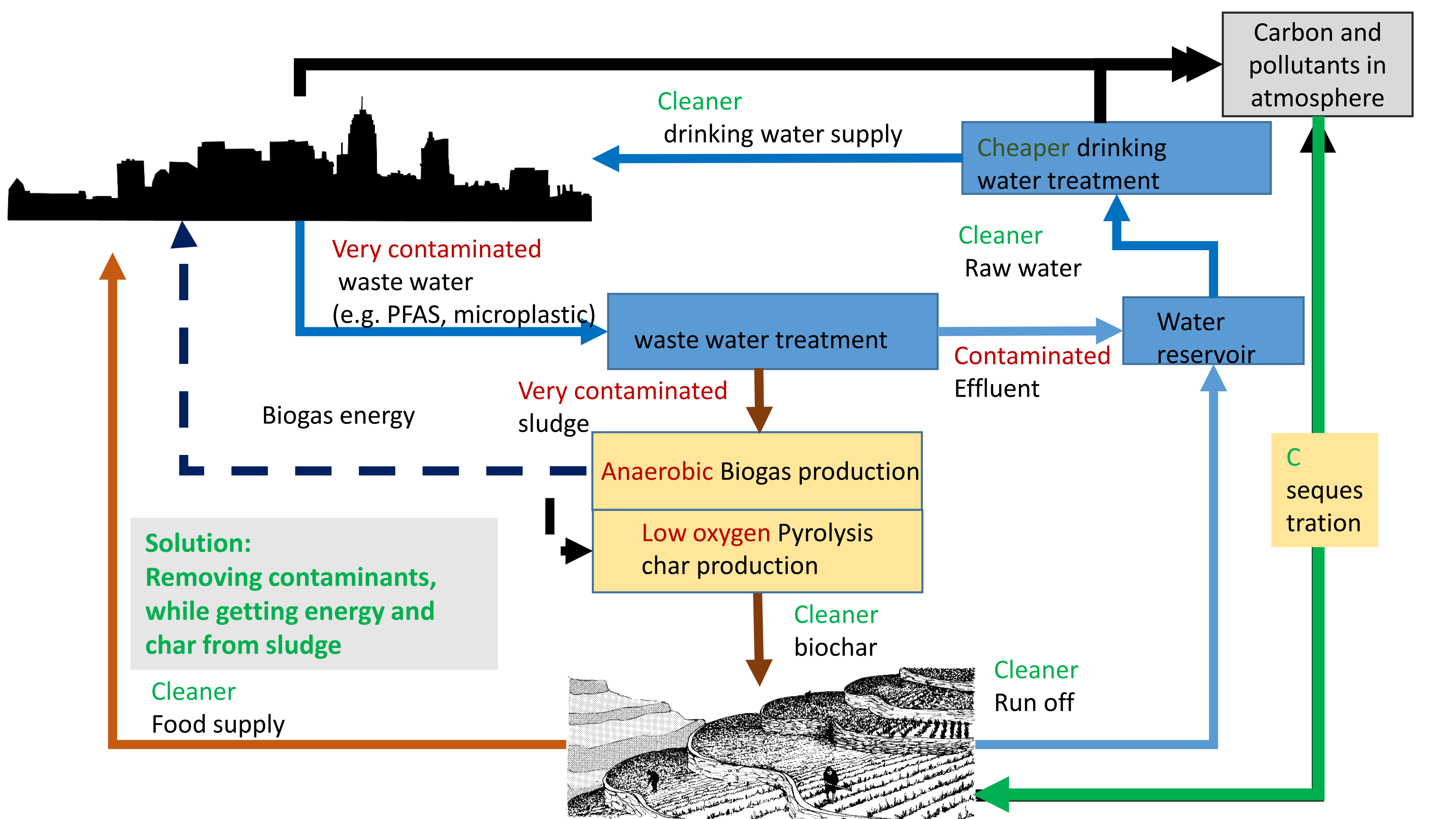
EurEau recommendations for sludge management in a circular economy

The best solution is local, and depends on contaminants in the sludge, need for phosphorous, climate mitigation targets and goals towards zero pollution. 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

Zero Pollution Action Plan

- *Proposal for a Regulation on reporting of environmental data from industrial installations and establishing an Industrial Emissions Portal*
- Article 14 empowers the Commission to adopt delegated acts to amend Annexes I and II - adding new industrial or agricultural activities to Annex I and adding pollutants which are subject to specific regulatory controls under EU chemicals, water and air quality legislation to Annex II (SVHCs, priority substances under WFD and EQSD, substances included in the watch list of the GWD and EQSD, substances subject to limit values under air quality Directives and GWD).


Carbon and pollutants in atmosphere
Cleaner drinking water supply
Cheaper drinking water treatment
Very contaminated waste water (e.g. PFAS, microplastic)
Cleaner 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
Cleaner Run off
Cleaner Food supply

Different views and Different Tradeoffs for Thermal Treatments

Negative

Commission

JRC SCIENCE FOR POLICY REPORT

Technical proposals for selected new fertilising materials under the Fertilising Products Regulation (Regulation (EU) 2019/1009)

Process and quality criteria, and assessment of environmental and market impacts for precipitated phosphate salts & derivates, thermal oxidation materials & derivates and pyrolysis & gasification materials

Huygens D, Saveyn HGM, Tonini D, Eder P, Delgado Sancho L

2019

- JRC recommends mono-incineration and nutrient extraction (fertilizer regulation)
- *Precautionary principle*: unknown chemical hazards- do not use sludge for fertilizer, pyrolyzed or otherwise

Positive

3.2.6.4 **Life Cycle Impact Assessment**

Barry, Devon J., "Pyrolysis as an Economical and Ecological Treatment Option for Solid Anaerobic Digestate and Municipal Sewage Sludge" (2018).

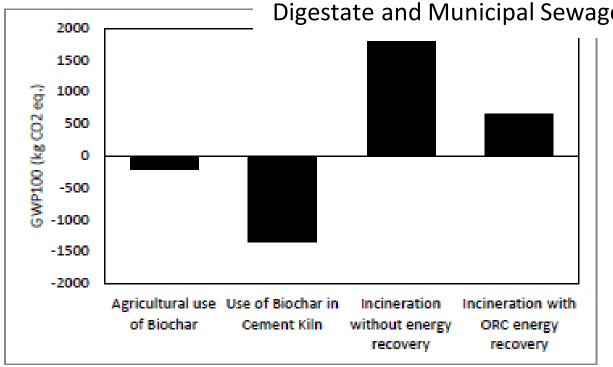


Figure 3.25: LCA Global Warming Potential Results

- Incineration worse than pyrolysis from an LCA perspective
- Dry pyrolysis is carbon negative in agriculture
- Sewage sludge biochar for co-combustion in cement kilns is even more carbon negative

What is the best sludge treatment scenario?

Global warming potential
Contaminant removal
Toxicity effects

- Toxicity effects:
  - Removal of organic contaminants offset by heavy metal emissions
  - Need for flue gas cleaning?
  - Source control measures
- **Overall:**
  - **Pyrolysis with no AD the best alternative**

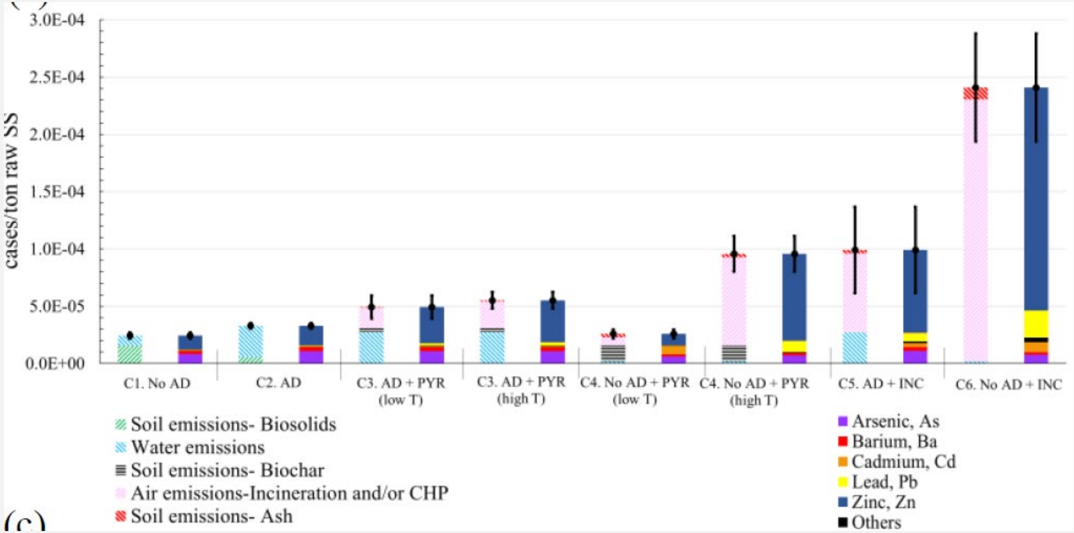


Figure: Morales et al (submitted) *Eco-toxicological and climate change effects of sludge thermal treatments: pathways towards ero pollution and negative emissions*

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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

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The way forward

"There is no such an ultimate disposal scheme for sludge that can be called the optimal scheme without any environmental damage. Each scheme is more or less suitable for specific situations"[1]

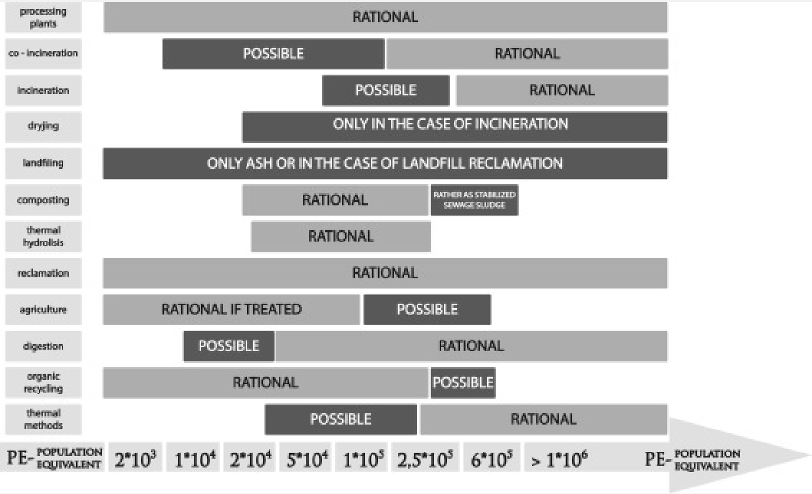
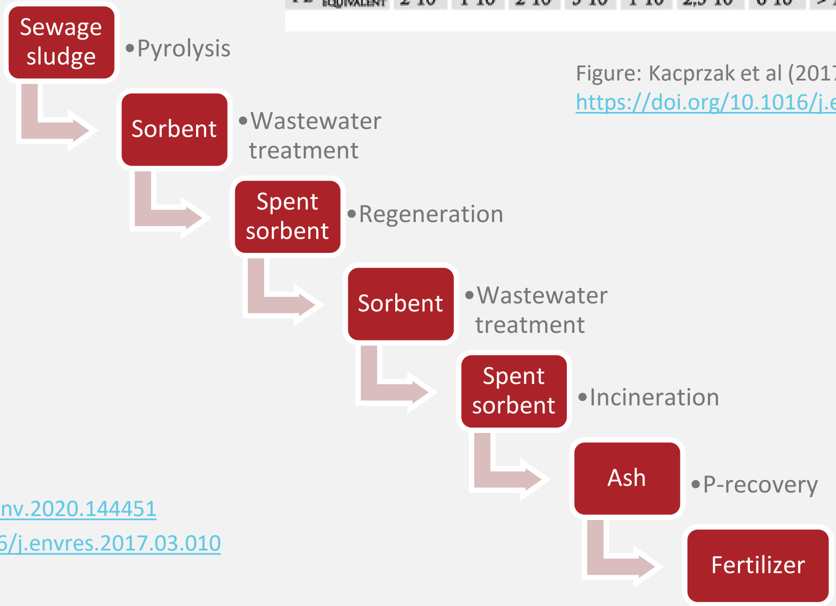


Figure: Kacprzak et al (2017) Env Research https://doi.org/10.1016/j.envres.2017.03.010

- Design processes suited for local conditions[2]
- Integrate processes to lower costs[1]
- Sequential uses[3]



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1) Ding et al (2021) STOTEN https://doi.org/10.1016/j.scitotenv.2020.144451
2) Kacprzak et al (2017) Env Research https://doi.org/10.1016/j.envres.2017.03.010
3) Wurzer et al (2019) GreenCarbon ETN Book, Chapter 12.

E-waste

- Circular Economy Action Plan (CEAP) will address increased recycling/reuse of E-waste through
  - Directive 2012/19/EU on Waste from Electrical and Electronic Equipment (WEEE)
  - Directive 2011/65/EU (RoHS Directive) on Restriction of Hazardous Substances in Electrical/Electronic Equipment

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EU-level discussions on WEEE in the Circular Economy Action Plan (2020)

- **with current annual growth rates of 2%. It is estimated that less than 40% of electronic waste (total) is recycled in the EU. *NEED MORE!***

- **Circular Electronics Initative (circular)**
  - Ecodesign Directive so that devices are designed for energy efficiency and durability, reparability, upgradability, maintenance, reuse and recycling of selected products (e.g. mobile phones, tablets and laptops)
  - Right to repair
  - Improving recycling collection
  - Review of EU rules on restrictions of hazardous substances (RoHS) in electrical and electronic equipment23 and provide guidance to improve coherence with relevant legislation, including REACH24 and Ecodesign

- **What about the waste plastics?**
  - Depends on RoHS level and recycling stream

WEEE in the circular economy

- **WEEE directive 2012/19/EU** is to promote re-use, recycling and other forms of recovery of waste electrical and electronic equipment (WEEE) in order to reduce the quantity of such waste to be disposed and to improve the environmental performance of the economic operators involved in the treatment of WEEE.

- **Restriction of Hazardous Substances (RoHS)** Directive (2002/95/EC) defines levels of certain hazardous substances that can be used. These cannot be exceeded for re-use in a circular economy

Current RoHS

- Cadmium(Cd): 0.01%
- Mercury: 0.1%
- Lead(Pb) : 0.1%
- Hexavalent chromium (Cr^{6+}) : 0.1%
- Polybrominated biphenyls (PBB): 0.1 %;
- Polybrominated diphenyl ethers (PBDE): 0.1 %
- Bis(2-Ethylhexyl) phthalate (DEHP): 0.1% (added in 2015);
- Benzyl butyl phthalate (BBP): 0.1% (added in 2015);
- Dibutyl phthalate (DBP): 0.1% (added in 2015);
- Diisobutyl phthalate (DIBP): 0.1% (added in 2015).

RoHS revision

- The Commission will consider the coherence between the RoHS Directive and the **REACH** and **Ecodesign Regulation** in view of ensuring better delineation between them and avoid overlaps - the option of repealing RoHS and incorporating its provisions into REACH will be considered. The review will also consider the introduction of provisions related to recycled material and critical raw materials.
- Focus is on changing design requirements for a) more consistent pathways to add restricted substances, b) stricter design requirements for traceability of contaminants and better recycling/reuse
- WEEE should be «greener» and more recycleable
- Draft out soon!!
- Review: Restriction of the use of hazardous substances in electronics (europa.eu)

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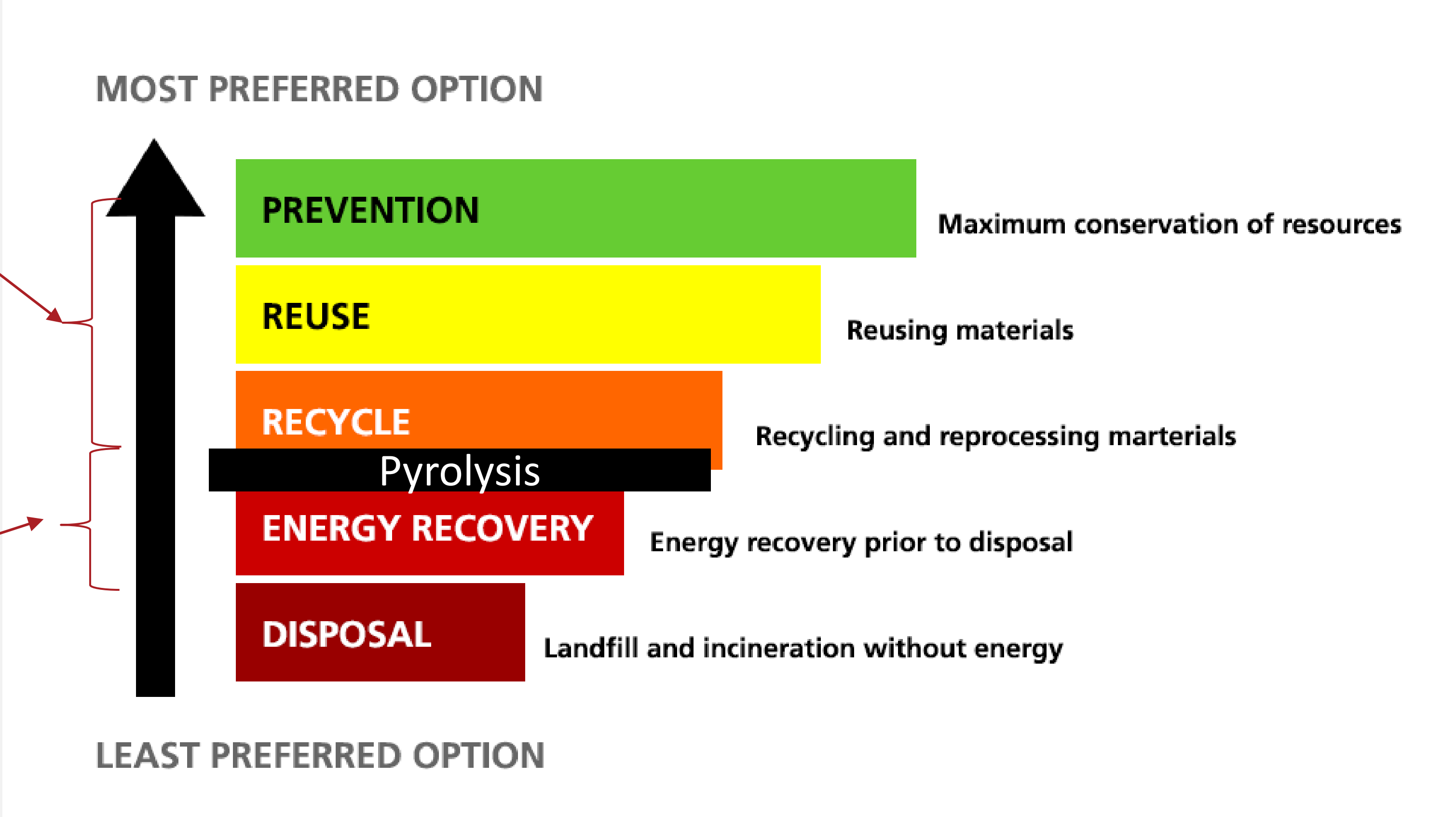
Pyrolysis of Hazardous E-waste plastic?

< RoHS levels

> RoHS levels



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EcoDesign updates

- Article 5 lays down the product aspects for which eco-design requirements can be set**, such as product durability and reliability, reparability, products' carbon and environmental footprints etc**. The list of aspects includes the presence of substances of concern in products.
- The Regulation defines substances of concern as: 1) **substances identified as SVHC under REACH,** 2) **substances classified under CLP as CMR 1 and 2, respiratory sensitisation category 1, skin sensitisation category 1, chronic hazard to the aquatic environment categories 1 to 4, hazardous to the ozone layer, specific target organ toxicity – repeated exposure categories 1 and 2, specific target organ toxicity – single exposure categories 1 and 2, and, when included in CLP Persistent, Bioacumulative, Toxic (PBTs), very Persistent very Bioaccumulative (vPvBs), Persistent, Mobile and Toxic (PMT), very Persistent very Mobile (vPvM), Endocrine disruption, and 3)** substances that negatively affects the re-use and recycling of materials in the product in which it is present.
- Article 7 set minimum information requirements related to the product aspects listed in Article 5 with which product must comply. These information requirements must enable the tracking of all substances of concern throughout the life cycle of products and contain the mame, location, concentration of the substances of concern.

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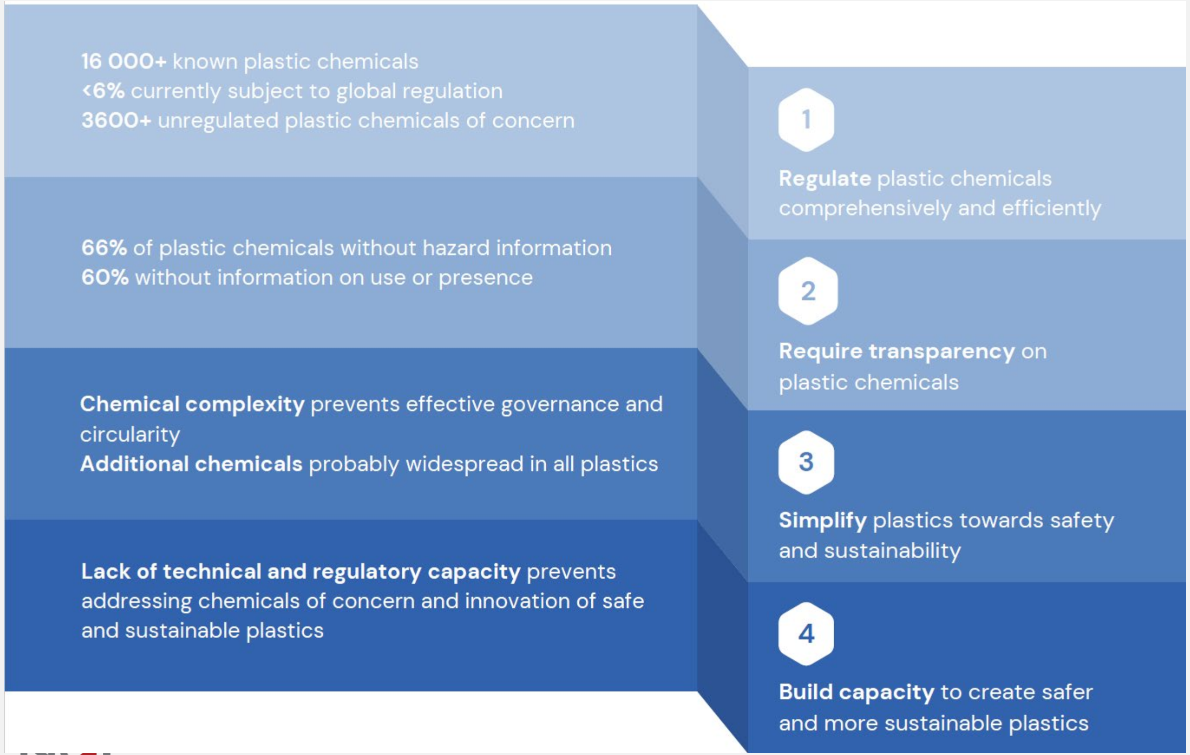
Plastchem recommendations for hazardous substances in Plastic

https://plastchem-project.org/



- Removing hazardous substances facilitates all parts of the waste heirarchy

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Key messages From SLUDGEFFECT

- Source control and regulations the best strategy for reducing impacts of pollutant in sludge, regardless of treatment
- Several win-win strategies for pyrolysing sludge, particularly when having high pollutant carbon reductions
  - Lowers hazardous substance concentrations
  - Carbon sequestration
  - Production of biochar for valuation
  - Pyrolysis without AD the best at LCA impacts, allows for phosphorous recycling, carbon sequestration and hazard substance reduction
  - THOUGH tradeoffs of metal impacts need to be managed

Key guidance needed going forward for sludge

- Regulatory considerations to be devloped for pyrolysing sludge
- New markets for sludge biochar to be explored beyond fertilizers (see the VOW research project)
  - Sorbents for use in WTPs (e.g. use sludge from PFAS contaminated WTPs to make biochar that is ues in same WTP to sorb PFAS)
  - Use of sludge biochar as ingredient/fuel source to cement/metallurgy
- Several benefits to pyrolyzing sludge, even in the absence of contaminants; though the benefits become clearer for heavily contaminated sludge.

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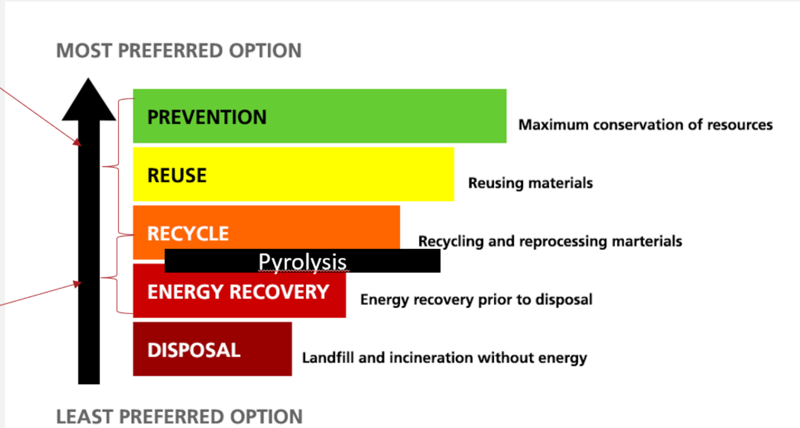
Key guidance needed going forward for e-waste plastic

- For plastics – pyrolysis can have a role in the circular economy, but less than more preferred actions on the waste heirarch (repair, reuse, mechanical recycling without hazarous substances).
- Pyrolysis worth further exploring for plastics not suitable for the circular economy (exception – high chlorine content, e.g. PVC, due to corrosion caused by Cl radicals)

Pyrolysis of E-waste plastic with hazardous chemicals?

- < RoHS levels
- > RoHS levels



In a nut shell

- Sludge – reduce pollutants upstream, pyrolyse more, lots of potential for investment but needs regulatory clarity

- Plastic – reduce pollutants upstream, pyrolysis needs further investigation for non reusable/recycleable plastics due to hazard chemical concentration

General Discussion

SLUDGEFFECT publications so far (1 of 2)

- **PFAS in sludge/environment**

  - Høisæter, Å., Arp, H. P. H., Slinde, G., Knutsen, H., Hale, S. E., Breedveld, G. D., & Hansen, M. C. (2021). Excavated vs novel in situ soil washing as a remediation strategy for sandy soils impacted with per-and polyfluoroalkyl substances from aqueous film forming foams. *Science of The Total Environment*, *794*, 148763.
  - Hubert, M., Arp, H. P. H., Hansen, M. C., Castro, G., Meyn, T., Asimakopoulos, A. G., & Hale, S. E. (2023). Influence of grain size, organic carbon and organic matter residue content on the sorption of per-and polyfluoroalkyl substances in aqueous film forming foam contaminated soils-Implications for remediation using soil washing. Science of the Total Environment, 875, 162668.

- **Environmental concerns of plastic and microplastic in the environment/agriculture**

  - MacLeod, M., Arp, H. P. H., Tekman, M. B., & Jahnke, A. (2021). The global threat from plastic pollution. *Science*, *373*(6550), 61-65.
  - Yao, S., Cao, H., Arp, H. P. H., Li, J., Bian, Y., Xie, Z., ... & Song, Y. (2021). The role of crystallinity and particle morphology on the sorption of dibutyl phthalate on polyethylene microplastics: Implications for the behavior of phthalate plastic additives. *Environmental Pollution*, *283*, 117393.
  - Yao, S., Li, X., Wang, T., Jiang, X., Song, Y., & Arp, H. P. H. (2023). Soil metabolome impacts the formation of the eco-corona and adsorption processes on microplastic surfaces. Environmental Science & Technology, 57(21), 8139-8148.
  - Rummel, C. D., Schäfer, H., Jahnke, A., Arp, H. P. H., & Schmitt-Jansen, M. (2022). Effects of leachates from UV-weathered microplastic on the microalgae Scenedesmus vacuolatus. *Analytical and bioanalytical chemistry*, *414*(4), 1469-1479.
  - Estoppey, N., Castro, G., Slinde, G. A., Hansen, C. B., Løseth, M. E., Krahn, K. M., ... & Cornelissen, G. (2024*). Exposure assessment of plastics, phthalate plasticizers and their transformation products in diverse bio-based fertilizer*s. Science of The Total Environment, 918, 170501.
  - Groh, K. J., Arp, H. P. H., MacLeod, M., & Wang, Z. (2023). Assessing and managing environmental hazards of polymers: historical development, science advances and policy options. Environmental Science: Processes & Impacts, 25(1), 10-25.

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SLUDGEFFECT publications so far (2 of 2)

- **Sludge pyrolysis, sorption and biochar**
  - Krahn, K. M., Cornelissen, G., Castro, G., Arp, H. P. H., Asimakopoulos, A. G., Wolf, R., ... & Sørmo, E. (2023). Sewage sludge biochars as effective PFAS-sorbents. Journal of Hazardous Materials, 445, 130449.
  - Castro, G., Sørmo, E., Yu, G., Sait, S. T., González, S. V., Arp, H. P. H., & Asimakopoulos, A. G. (2023). Analysis, occurrence and removal efficiencies of organophosphate flame retardants (OPFRs) in sludge undergoing anaerobic digestion followed by diverse thermal treatments. Science of the Total Environment, 870, 161856.
  - Sørmo, E., Castro, G., Hubert, M., Licul-Kucera, V., Quintanilla, M., Asimakopoulos, A. G., ... & Arp, H. P. H. (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.
  - Sørmo, E., Krahn, K. M., Flatabø, G. Ø., Hartnik, T., Arp, H. P. H., & Cornelissen, G. (2024). Distribution of PAHs, PCBs, and PCDD/Fs in products from full-scale relevant pyrolysis of diverse contaminated organic waste. Journal of Hazardous Materials, 461, 132546.
  - Sørmo, E., Lade, C. B. M., Zhang, J., Asimakopoulos, A. G., Åsli, G. W., Hubert, M., ... & Cornelissen, G. (2024). Stabilization of PFAS-contaminated soil with sewage sludge-and wood-based biochar sorbents. Science of The Total Environment, 170971.

- **Plastic/WEEE plastic recycling issues**
  - Knutsen, H., & Arp, H. P. H. (2021). Preventing brominated flame retardants from occurring in recycled expanded polystyrene: comparing Norwegian visual sorting with advanced screening methods. *Journal of Hazardous Materials Letters*, *2*, 100016.
  - Runde, K., Castro, G., Vike-Jonas, K., González, S. V., Asimakopoulos, A. G., & Arp, H. P. H. (2021). Occurrence and Sorption Behaviour of Bisphenols and Benzophenone UV-filters in e-waste Plastic and Vehicle Fluff. *Journal of Hazardous Materials*, 127814.
- **LCA**
  - Liu, W., Iordan, C. M., Cherubini, F., Hu, X., & Fu, D. (2021). Environmental impacts assessment of wastewater treatment and sludge disposal systems under two sewage discharge standards: A case study in Kunshan, China. *Journal of Cleaner Production*, *287*, 125046
  - Morales, M., Arp, H. P. H., Castro, G., Asimakopoulos, A. G., Sørmo, E., Peters, G., & Cherubini, F. Eco-Toxicological and Climate Change Effects of Sludge Thermal Treatments: Pathways Towards Zero Pollution and Negative Emissions. Journal of Hazardous Materials. *Accepted*

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Thank-you!

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