German Environment Agency

Umwelt Bundesamt

CEWEP Waste-to-Energy Congress 2025 – Technical Seminar: PFAS

PFAS in Different Waste Treatment Streams

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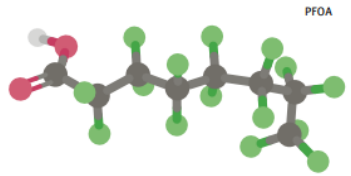
Definition of PFAS

PFAS – per- and polyfluorinated alkyl substances (also PFC – per- and polyfluorinated chemicals)

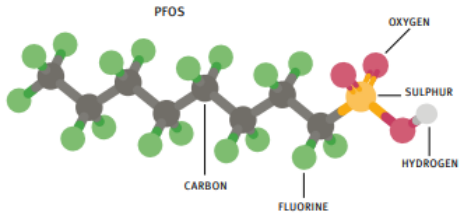
- Anthropogenically produced organic substances
- completely (per-) or partially (poly-) fluorinated organic compounds
- group of substances comprises more than 4,700 different substances

Classification of PFAS

- **PFASs**
  - **Non-polymers**
    - **Perfluoroalkyl acids (PFAAs)** $C_nF_{2n+1}R$
      - Perfluoroalkyl carboxylic acids (PFCAs)
      - Perfluoroalkane sulfonic acids (PFSAs)
      - Perfluoroalkyl phosphonic acids (PFPAs)
      - Perfluoroalkyl phosphinic acids (PFPIAs)
    - **Perfluoroalkane sulfonyl fluoride (PASF)** $C_nF_{2n+1}SO_2F$ → **PASF-based derivatives** $C_nF_{2n+1}SO_2$-R, R = NH, $NHCH_2CH_2OH$, etc.
    - **Perfluoroalkyl iodides (PFAIs)** $C_nF_{2n+1}I$ → **Fluorotelomer iodoes (FTIs)** $C_nF_{2n+1}CH_2CH_2I$ → **FT-based derivatives** $C_nF_{2n+1}CH_2CH_2$-R, R = NH, $NHCH_2CH_2OH$, etc.
    - **Per- and polyfluoroalkyl ethers (PFPEs)-based derivatives** – Polyfluoroalkyl ether carboxylic acids
  - **Polymers**
    - **Fluoropolymers** — Polytetrafluoroethylene (PTFE), Polyvinylidene fluoride (PVDF), Fluorinated ethylene propylene (FEP), Perfluoroalkoxyl polymer (PFA), etc.
    - **Side-chain fluorinated polymers** — Fluorinated (meth)acrylate polymers, Fluorinated urethane polymers, Fluorinated oxetane polymers
    - **Perfluoropolyethers**



PFOA (perfluorooctanoic acid)



PFOS (perfluorooctane sulphonic acid)

Source: OECD "Synthesis paper on per- and polyfluorinated chemicals (PFCS)"

Properties and use of PFAS

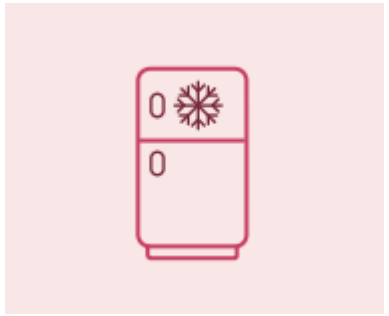
Properties

- Water-, oil- and dirt-repelllent
- Flame retardant or non-flammable
- Low frictional resistance, high surface activity
- High biological, chemical and thermal stability

Risks

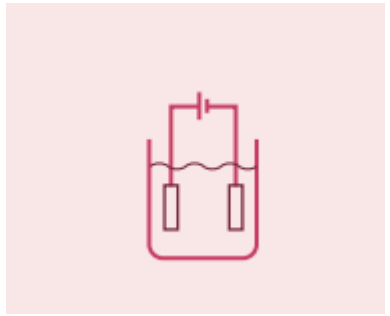
- Linked to: accelerated puberty, bone variations and behavioral changes, interference with the hormone system (thyroid, cholesterol levels), carcinogenic, impairment of immune system
- Transferred through placenta

Examples for use:



Refrigerants and foam blowing agents

Fire fighting foams



Electroplating

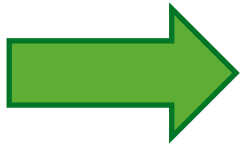
Textiles

Paper and printed matter

PFAS in EU market and waste streams

PFAS placed on the EU market

- Intermediates: <10.000 t/a
- Direct polymer production: <500 t/a
- Surfactants C6: < 500 t/a; C4: <200 t/a
- Surfactants for firefighting: 1,500-3,000 t/a
- Paper: <300 t/a
- Textile treatment: <1,200 t/a
- Surface treatment of hard materials: <2,000t/a



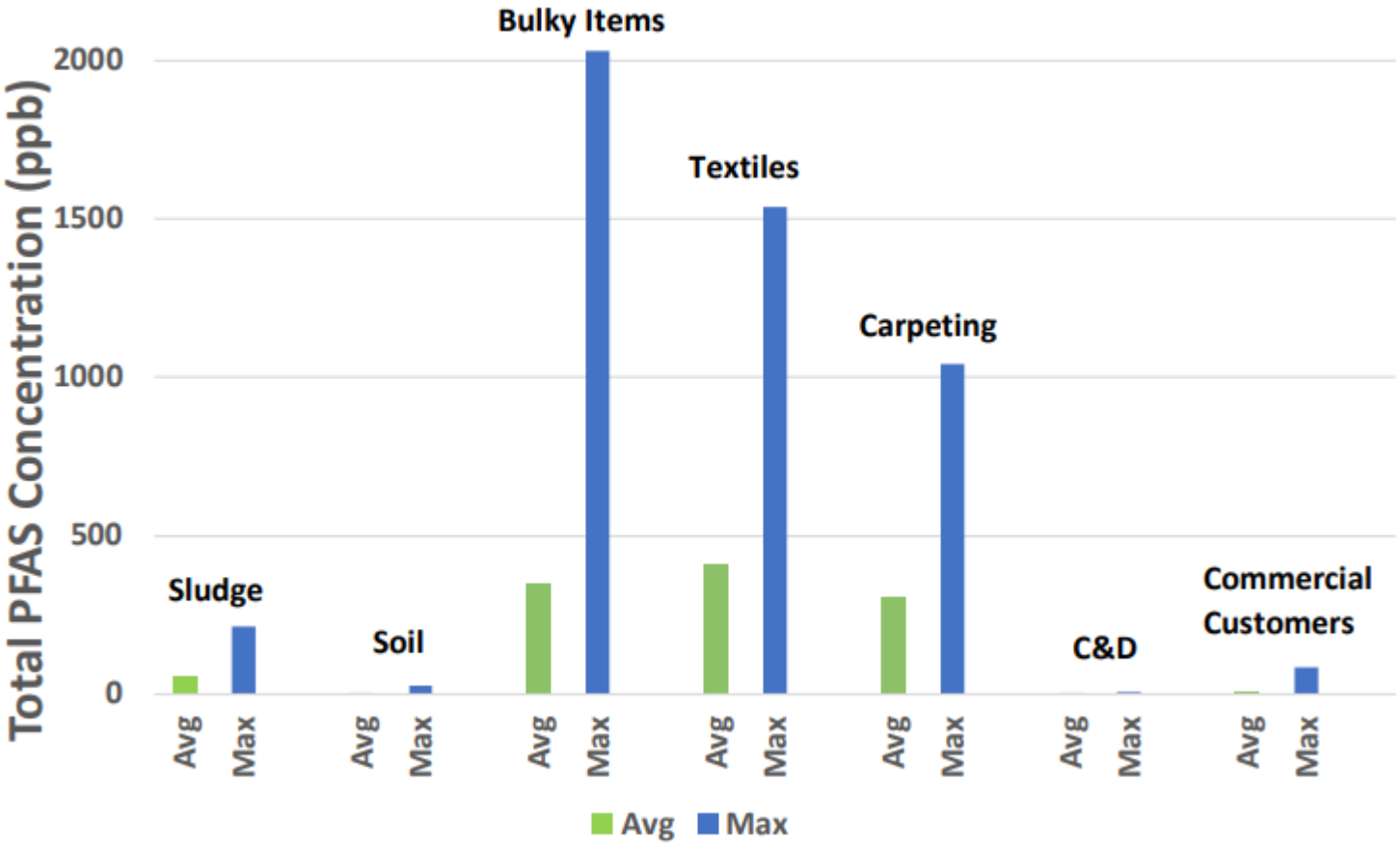
Largest PFAS-relevant waste streams in terms of volume

- textiles (incl. upholstery, leather, clothing and carpets),
- food packaging,
- metal coatings,
- refrigerants,
- hydraulic oils,
- medical applications,
- electronic devices,
- energy sector,
- building materials and
- sewage sludge

PFAS in waste streams - USA

Waste Category	Description
Sludge	WWTP, Industrial, Paper, & Sewer Grit
Contaminated Soil	Soils contaminated with petroleum, PAH, PCB, and tire fire residue
Furniture/Bulky Items	Textiles from mattresses, furniture, and other bulky items
Textiles and Leather	Clothing and miscellaneous textiles
Carpet	Mixed carpet
C&D	C&D waste materials other than carpet (e.g., roofing shingles, vinyl siding, flooring, fiberglass insulation, drywall)
Commercial Customers	Waste materials from 20 customers

Exhibit 8 – Average and Maximum Total PFAS Concentration by Waste Type



Source: PFAS WASTE SOURCE TESTING REPORT by Sanborn, Head and Associates, Inc.

PFAS in waste streams - EU

PFAS in waste streams	EU	Denmark			
	PFAS inkl. Polymere	PFAS and precursors	polymere PFAS	sum PFAS	Share of EU amount
	t/a	t/a	t/a	t/a	
Textiles (incl. Upholstery, leather, colthing, carpets	69'118	172	920	1'092	1.1%
Food packaging	26'566	50	230	280	1.1%
Metal coatings	954	0.4	10	10.4	1.1%
Transport sector	12'850	7	140	147	1.1%
Medical applications	5'901	30	100	130	2.2%
Electronics	3'752	15	40	55	0.6%
Energy sector	2'995	4	40	44	0.7%
Building sector	6'495	22	90	112	1.2%

Source: PFAS in Abfallströmen; Literaturstudie im Auftrag des VBSA, Stand Oktober 2024

PFAS in waste streams – what may be found where?

Examples of certain PFAS expected in waste streams:

- **Fluorinated polymers** are most widly used in consumer products and industry applications
  - Market: PTFE 65 %, PVDF 22 %, PFA, FKM and FEP each 4-5 %
  - FKM is used e.g. for sealing materials an tubes
  - -> **commercial waste, household waste**
- **sidechain fluorinated polymers (SCFP)** are often polymers of the acrylic acid with side chainslike of polyfluorinated alkyl substance, mainly FTOH (fluorotelomer alcohols) and FTAc (fluorotelomer acrylates): are **used e.g. in coatings** (food contact materials, upholstered furniture, carpets, clothing etc.) due to their water-, oil- and grease repellency -> **textile waste, paper waste, bulky waste**
- Capstone A, Capstone B are derivates of 6:2-fluorotelomer sulfonic acid: **fire fighting agents** after banning PFOA and PFOS
- perfluorinated carbonic acids und fluorotelomer sulfonic acids: **fire fighting agents** after banning PFOA and PFOS
- perfluoropolyether or polyfluorinated polyether (PFPE) are PFAS polymers/polymerlike substance: e.g. **lubricating grease in industry and cosmetics** -> **commercial and household waste**

PFAS in waste treatments

- The various waste streams are distributed across different treatment routes:
  - waste incineration (household and industrial waste, shredded material, sewage sludge and hazardous waste),
  - recycling (textiles, paper, batteries and construction waste) and
  - composting/fermentation (biogenic waste).

- Amount of waste in treatment route depends on waste
- But also on waste management system

PFAS in waste streams - EU

PFAS in waste streams	EU	Denmark				
	PFAS inkl. Polymere	PFAS and precursors	polymere PFAS	sum PFAS	Share of EU amount	Waste treatment
	t/a	t/a	t/a	t/a		
Textiles (incl. Upholstery, leather, colthing, carpets	69'118	172	920	1'092	1.1%	60-100% KVA 39% Recycling (Kleidersammlung)
Food packaging	26'566	50	230	280	1.1%	80% KVA 20% Recycling (Papiersammlung)
Metal coatings	954	0.4	10	10.4	1.1%	100% Recycling
Transport sector	12'850	7	140	147	1.1%	63% KVA 27% Deponie 10% Recycling
Medical aplications	5'901	30	100	130	2.2%	100% Sonderabfall
Electronics	3'752	15	40	55	0.6%	100% Recycling
Energy sector	2'995	4	40	44	0.7%	80% KVA 20% Recycling
Building sector	6'495	22	90	112	1.2%	80% KVA 20% Deponie

KVA = WtE
Deponie = Lanfills
Sonderabfall = hazardous waste
Kleidersammlung = seperate textile collection
Papiersammlung = seperate paper collection

This report points out that **no reliable data** on the **distribution of PFAS loads from the individual applications/products in the respective disposal category** (landfilling/composting/incineration/recycling) is available to date. Very **general assumptions** were made for this distribution.

Source: PFAS in Abfallströmen; Literaturstudie im Auftrag des VBSA, Stand Oktober 2024

Examples of different waste and waste treatment streams

Following data taken from:

Refoplan – “Investigation of the occurrence of PFAS in waste streams”

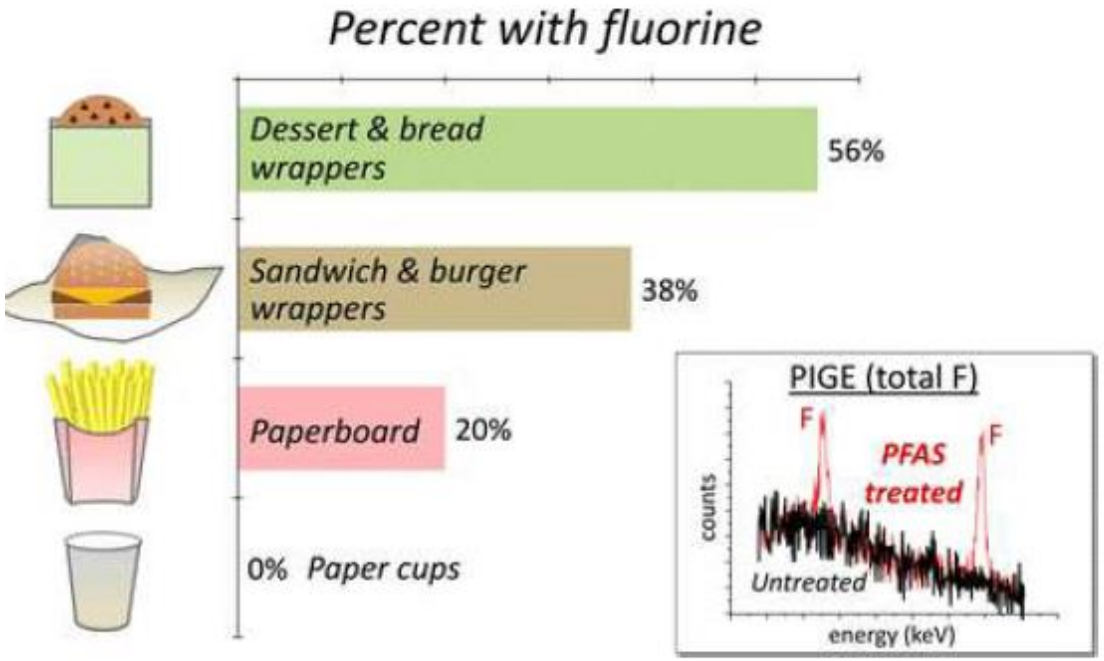
Carried out on behalf of the German Federal Environment Agency

by
Federal Institute for Materials Research and Testing, Berlin
Ramboll Deutschland GmbH

Project No. (FKZ) 3719 34 307 0
Published as TEXTE 86/2024

Waste stream - paper

- Main sources of PFAS in paper
  - water- and grease-repellent specialty papers, e.g. food contact paper material
  - paper tablecloth



Source: Schaider *et al.* (2017) *Environ. Sci. Technol. Lett.* 2017, **4**, 3, 105–111

Waste stream - paper

- Main sources of PFAS in paper
  - water- and grease-repellent specialty papers, e.g. food contact paper material
  - paper tablecloth
- A German Federal Institute for Risk Assessment (BfR) recommendation* applies to papers, cartons and cardboards for food contact, in which 21 PFAS compounds are listed with maximum permissible amounts
- Contamination of the paper cycle takes place via the entry of PFAS contaminated papers into the wastepaper cycle
- Direct wastewater or the consumer product at the end of its life cycle may lead to emissions

Source: Refoplan – “Investigation of the occurrence of PFAS in waste streams”;
*(Recommendation XXXVI. Papers, cartons and cardboards for food contact; and Recommendation XXXVI/2. Papers, cartons and cardboards for baking purposes 2019)

Waste stream - paper

Substance	Wastepaper volume [t]	Recycling [80%]	Energy recovery [19.69%]	Landfill [0.31%]
	14,468,000	11,574,400	2,849,200	44,400
PFAS quantities from mean value [kg].				
∑PFCA	2,255.06	1,804.05	444.09	6.92
∑PFSA	21,36	17,09	4,21	0,07
∑PFPA				
∑Precursors	1,685.03	1,348.03	331.84	5.17
∑PFAS	**3,961.46**	**3,169.17**	**780.13**	**12.16**
PFAS quantities from median [kg].				
∑PFCA	8.68	6.94	1.71	0.03
∑PFSA	10.13	8.10	1.99	0.03
∑PFPA				
∑Precursors				
∑PFAS	**150.47**	**120.37**	**29.63**	**0.46**

Estimated PFAS material flows in paper in 2018 in Germany

PFCA - perfluorocarboxylic acids
PFSA - perfluorosulfonic acid
PFPA - perfluorophosphoric acids

Source: Refoplan – “Investigation of the occurrence of PFAS in waste streams”

Waste stream - paper

- total PFAS load is ~3961 kg (mean) and ~150 kg (median) → Large difference between mean and median values
- 80% of paper is recycled in Germany → recycling does not destroy PFAS -> high percentage of PFAS are kept in the cycle and is distributed to non-food papers; also accumulation in waste water and fiber sludge
- ~20% are incinerated → ~20% are incinerated -> assumption that a large portion of PFAS are destroyed (>99.9%)
- 0.3% disposed of in landfills → 0.3% landfilled -> no destruction of PFAS

! PFAS in waste paper are likely overestimated
Only food contact paper where investigated and considered for PFAS concentration but waste paper contains large amount of Non-PFAS or low-PFAS contaminated other papers (newspaper, books etc)

Source: Refoplan – “Investigation of the occurrence of PFAS in waste streams”

Waste stream - textiles

- Main sources of PFAS in textiles
  - waterproof and dirt-repellent agent
  - other finishes for include flame retardancy, wrinkle resistance
  - production of (outdoor) jackets is one of the main applications for PFAS in this sector
  - other applications like commercial clothing for emergency services such as police and firefighters and in hospital clothing
- direct wastewater or the consumer product at the end of its life cycle can provide an emission
- slow release due to repeated washing cycles and repeated impregnation is important
- strong dependence of PFAS concentration found with the "history" (age, storage conditions, etc.) of the product

Source: Refoplan – “Investigation of the occurrence of PFAS in waste streams”

Waste stream - textiles

Substance	Total textile waste [t]	Recycling (69%) [t]	Thermal treat-ment (28.4%) [t].	Other disposal (2.6%) [t].
	1,950,.867	1,346,669	553,348	50,850
PFAS quantities from mean value [kg].				
∑PFCA	170.83	117.92	48.45	4.45
∑PFSA	40.29	27.81	11.43	1.05
∑PFPA	0.00	0.00	0.00	0.00
∑Precursors	547.60	378.00	155.32	14.27
∑PFAS	**758.71**	**523.74**	**215.20**	**19.78**
PFAS quantities from median [kg].				
∑PFCA	16.31	11.26	4.63	0.43
∑PFSA	0.00	0.00	0.00	0.00
∑PFPA	0.00	0.00	0.00	0.00
∑Precursors	6.76	4.67	1.92	0.18
∑PFAS	**144.47**	**99.73**	**40.98**	**3.77**

Source: Refoplan – “Investigation of the occurrence of PFAS in waste streams”

Estimated PFAS material flows in textiles in 2018 in Germany

PFCA - perfluorocarboxylic acids
PFSA - perfluorosulfonic acid
PFPA - perfluorophosphoric acids

Waste stream - textiles

- total PFAS load is ~760 kg (mean) and ~145 kg (median)

• 69% is recycled or otherwise reused	→	• recycling does not destroy PFAS -> 69% of PFAS are kept in the cycle
• 28% are incinerated	→	• assumption that a large portion of PFAS are destroyed (>99.9%)
• 3% disposed of elsewhere	→	• no information found about type of treatment/disposal

Source: Refoplan – “Investigation of the occurrence of PFAS in waste streams”

Waste stream – sewage sludge

- PFAS in sewage sludge are entering through waste water from households and industry
- In Germany, since 2015, sewage sludge used for soil-related purposes has been subject to the requirements of the Fertiliser Ordinance (DüMV) and may not exceed a PFAS concentration of 100 µg/kg (sum of PFOA and PFOS) in the dry substance
- Otherwise it must undergo thermal treatment (i.e. usually incinerated as waste).

Source: Refoplan – “Investigation of the occurrence of PFAS in waste streams”

Waste stream – sewage sludge

Substance	Total direct sewage sludge disposal [t].	Thereof								
		Material recovery				Thermal disposal				Other direct disposal [t]
		Total [t]	In agriculture [t]	For landscaping measures [t].	Other recycling [t]	Total [t]	Mono-incineration [t]	Co-incineration [t]	Unknown [t]	
	1,740,556	388,886	259,851	25,181	103,854	1,334,994	507,929	795,819	31,246	16,676
PFAS quantity from mean value [kg].										
∑PFCA	31.38	7.01	4.68	0.45	1.87	24.06	9.16	14.35	0.56	0.30
∑PFSA	84.94	18.98	12.68	1.23	5.07	65.14	24.79	38.83	1.52	0.81
∑PFPA	-	-	-	-	-	-	-	-	-	-
∑Precursors	0.63	0.14	0.09	0.01	0.04	0.48	0.18	0.29	0.01	0.01
∑PFAS	**116.94**	**26.13**	**17.46**	**1.69**	**6.98**	**89.69**	**34.13**	**53.47**	**2.10**	**1.12**
PFAS quantity from median [kg].										
∑PFCA	28.89	6.46	4.31	0.42	1.72	22.16	8.43	13.21	0.52	0.28
∑PFSA	54.48	12.17	8.13	0.79	3.25	41.79	15.90	24.91	0.98	0.52
∑PFPA	-	-	-	-	-	-	-	-	-	-
∑Precursors	-	-	-	-	-	-	-	-	-	-
∑PFAS	**82.50**	**18.43**	**12.32**	**1.19**	**4.92**	**63.28**	**24.08**	**37.72**	**1.48**	**0.79**

Estimated PFAS material flows in sewage sludge in 2020 in Germany

PFCA - perfluorocarboxylic acids
PFSA - perfluorosulfonic acid
PFPA - perfluorophosphoric acids

Source: Refoplan – "Investigation of the occurrence of PFAS in waste streams"

Waste stream – sewage sludge

- total PFAS load is ~117 kg (mean) and ~83 kg (median)

- 77% is incinerated in Germany
- 22% are recycled (agricultural use)
- 1% disposed of elsewhere (e.g. composting)

→ assumption that a large portion of PFAS are destroyed (>99.9%)

→ 22% of PFAS will be directly brought into environment

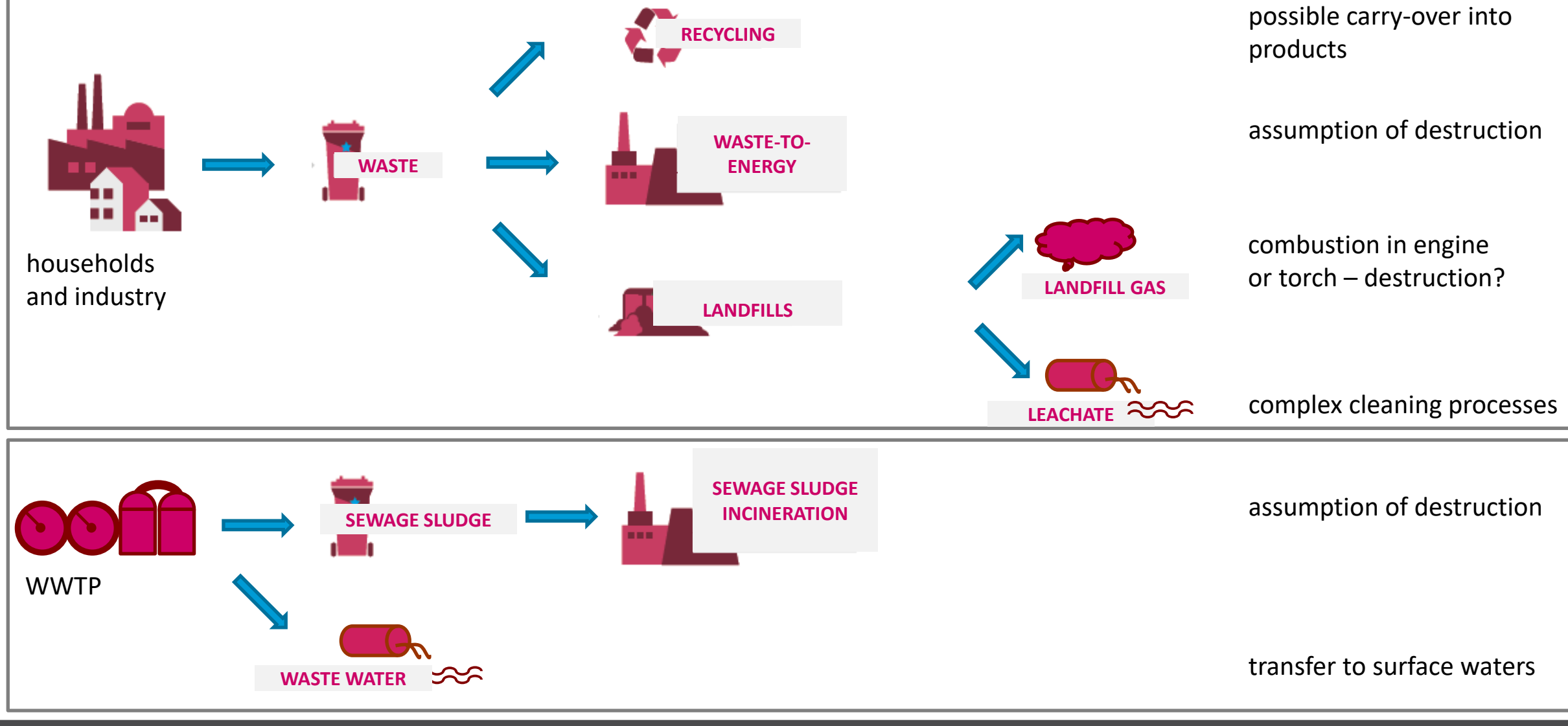
→ 1% of PFAS will also most likely enter the environment

Source: Refoplan – “Investigation of the occurrence of PFAS in waste streams”

Waste streams – others

- Compost can be contaminated by food packaging (e.g. from municipal green waste collection), which has been identified as the main source of PFAS in compost ⇨ These PFAS can enter soils through the spreading of compost on arable and garden land.
- In building materials, PFAS can be found in many different products, e.g., paints and varnishes, to protect against soiling of house facades, and in sealants and adhesives ⇨ Direct release of PFAS from building materials is possible e.g. through rain on facades or at end of life.
- Soils are mainly contaminated through contaminated fertilizer (e.g. sewage sludge) or illegal dumping of contaminated sludges ⇨ Release of PFAS to groundwater, contamination of crops etc.

Potential pathways to the environment from waste treatment



Conclusions

- Major waste streams contaminated by PFAS
- Quantity PFAS contamination of waste streams are just rough estimates
- Multiple pathways from waste treatment to environment
- Only incineration shows destruction potential (and chemical-physical waste treatment in case of hazardous waste)

- Sampling and measurements necessary for better estimation of PFAS contamination in waste streams (Difficult!)
- Measurements to determine destruction efficiency of waste incineration

- Waste treatment alone cannot solve PFAS contamination problem!
- Restrictions in use are vital!

Thank you for your attention!

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www.uba.de