ZerOPM

aragorn

Funded by the European Union

Confront the threat of PFAS and TFA by focusing on prevention not removal

Hans Peter H. Arp
Norwegian Geotechnical Institute (NGI)
Norwegian University of Science and Technology (NTNU)
Contact: hans.peter.arp@ngi.no

NGI

NTNU



The Flow

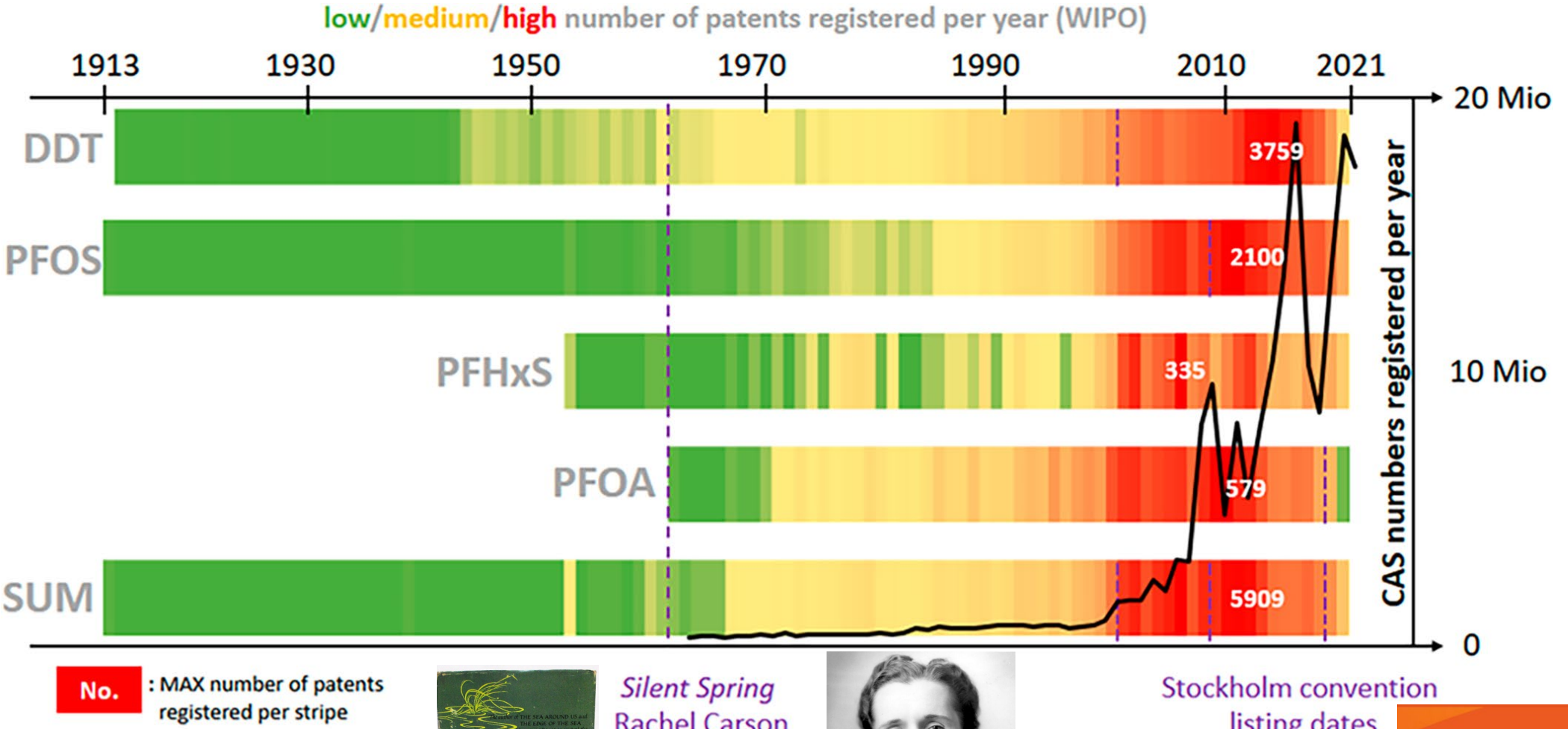
- The rise of PFAS pollution
- The increasing impacts
- The solutions

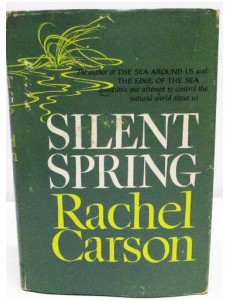


The rise of PFAS pollution



The rise of PFAS





Silent Spring
Rachel Carson

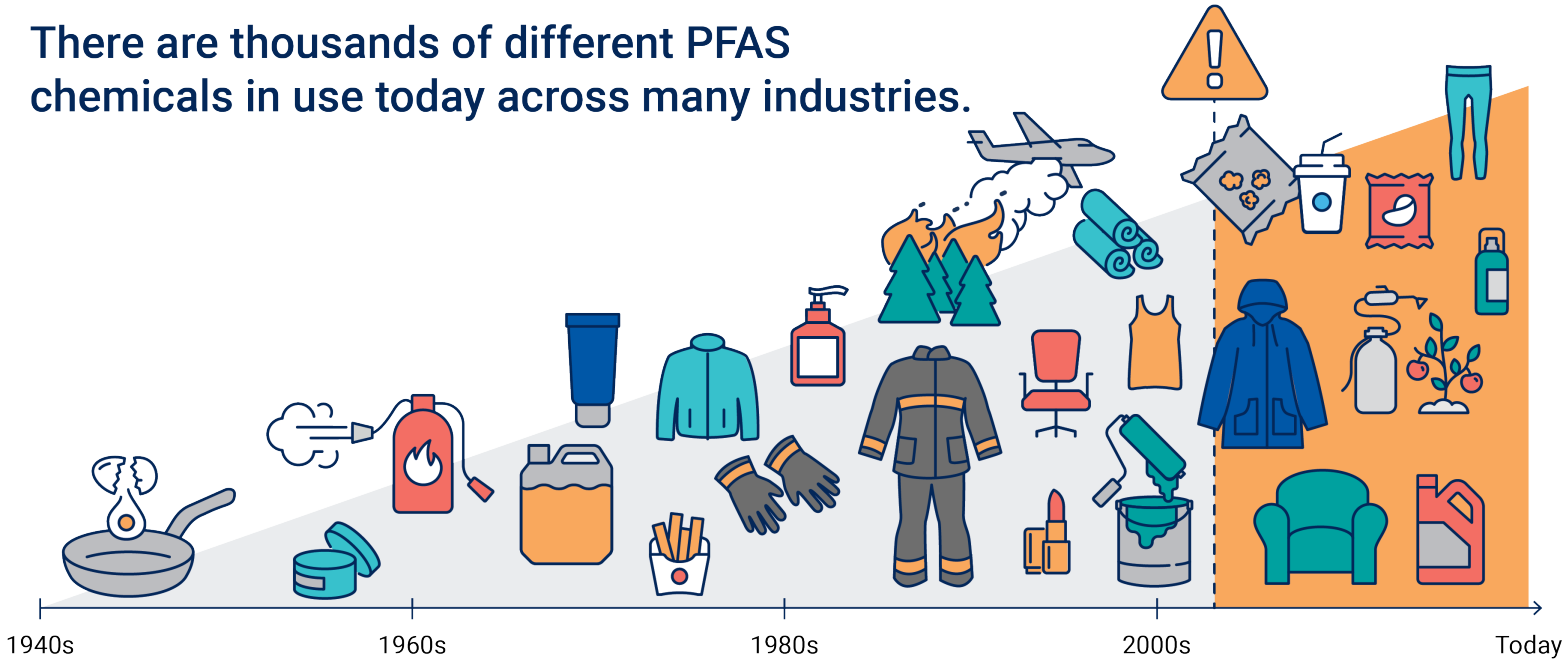


Freons discovered -1928
PTFE discovered -1938
Manufacture PFOS – 1949

STOCKHOLM CONVENTION
UNEP
Protecting human health and the environment from persistent organic pollutants

Arp et al. *Environ. Sci. Technol.* (2023) 57 (16): 6355–6359.

Increases in uses and hotspots



Fire-fighting foams used at
- Chemical Manufacture
- Airports
- Military airports
- Oil and gas
- Chemical industry

Waste areas
- Grease-proof paper sludge
- Industial landfills

Agriculture areas:
- PFAS contaminated sludge
- PFAS pesticides

https://chemicalinsights.org/pfas/

Browsing PFAS on Pubchem

Emma Schymanski



ZeroPM

Are there really 6 million PFAS in PubChem?

Luxembourg National Research Fund

uni.lu | LCSB

NIH U.S. National Library of Medicine National Center for Biotechnology Information

ZeroPM Webinar
22 March 2023

2021

ZeroPM

No…it's already 7 million!

- PFAS and Fluorinated Compounds in PubChem ? 20,929
  - OECD PFAS definition ? 6,370,077
  - Organofluorine compounds ? 19,963,719
  - Other diverse fluorinated compounds ? 122,266
  - PFAS and fluorinated compound collections ? 1,78
  - PFAS breakdowns by chemistry ? 7,299,804
  - Regulatory PFAS collections ? 26,965

2023

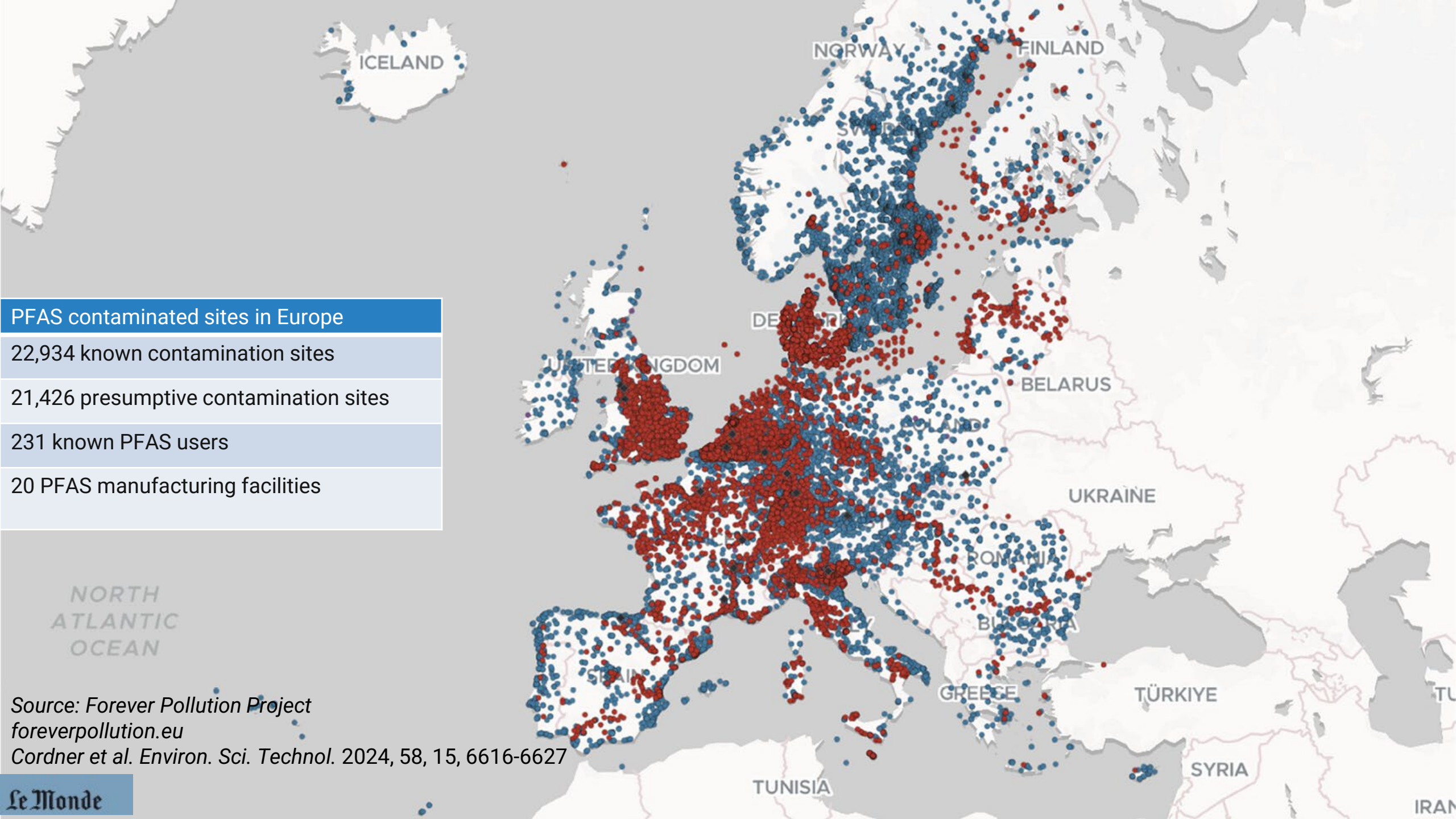
You guessed it - already >8 million!

Browse PFAS and Fluorinated Compounds in PubChem

- PFAS and Fluorinated Compounds in PubChem 23,490,216
  - OECD PFAS definition 7,315,072
  - Organofluorine compounds 22,344,979
  - Other diverse fluorinated compounds 184,992
  - PFAS and fluorinated compound collections 1,790,104
  - PFAS breakdowns by chemistry 8,418,495
  - Regulatory PFAS collections 26,994

2026

Schymanski *et al* (2023) DOI: 10.1021/acs.est.3c04855
https://pubchem.ncbi.nlm.nih.gov/classification/#hid=120
Schymanski & Bolton (2023) ZeroPM Webinar, Zenodo. DOI: 10.5281/zenodo.7756622
Schymanski (2026) PFAS Fwd Action Summit. Zenodo. DOI: 10.5281/zenodo.19039034

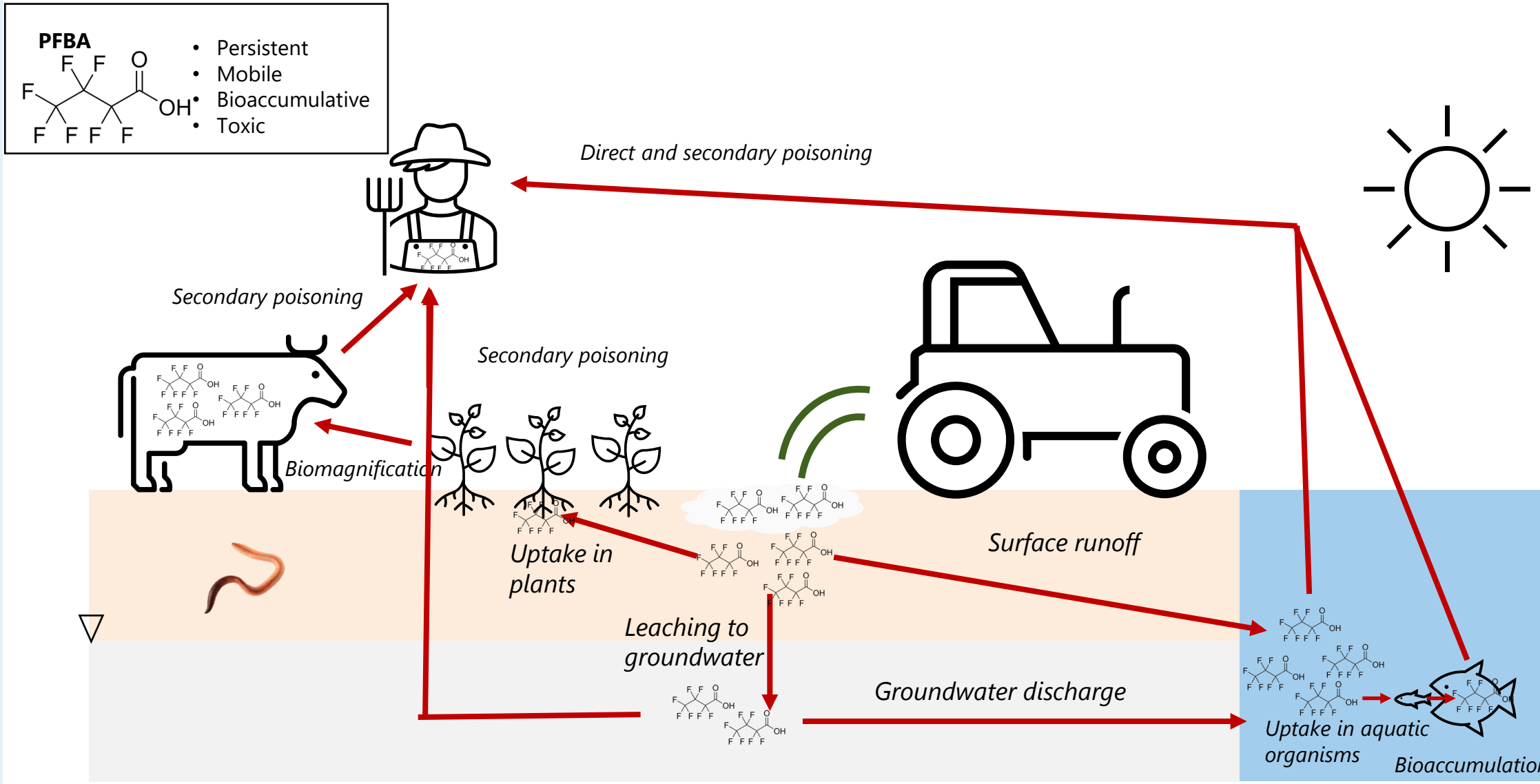


PFAS contaminated sites in Europe
22,934 known contamination sites
21,426 presumptive contamination sites
231 known PFAS users
20 PFAS manufacturing facilities

Source: Forever Pollution Project
foreverpollution.eu
Cordner et al. Environ. Sci. Technol. 2024, 58, 15, 6616-6627

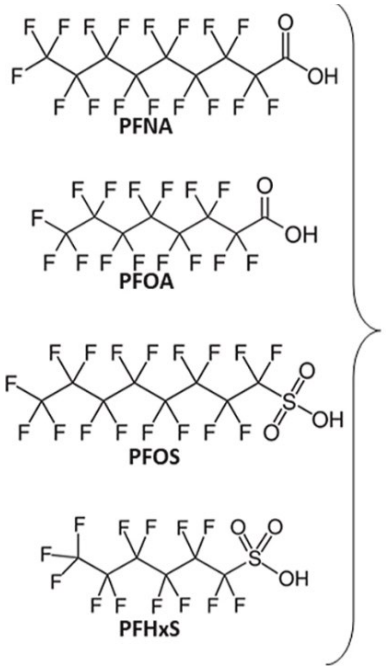
Le Monde

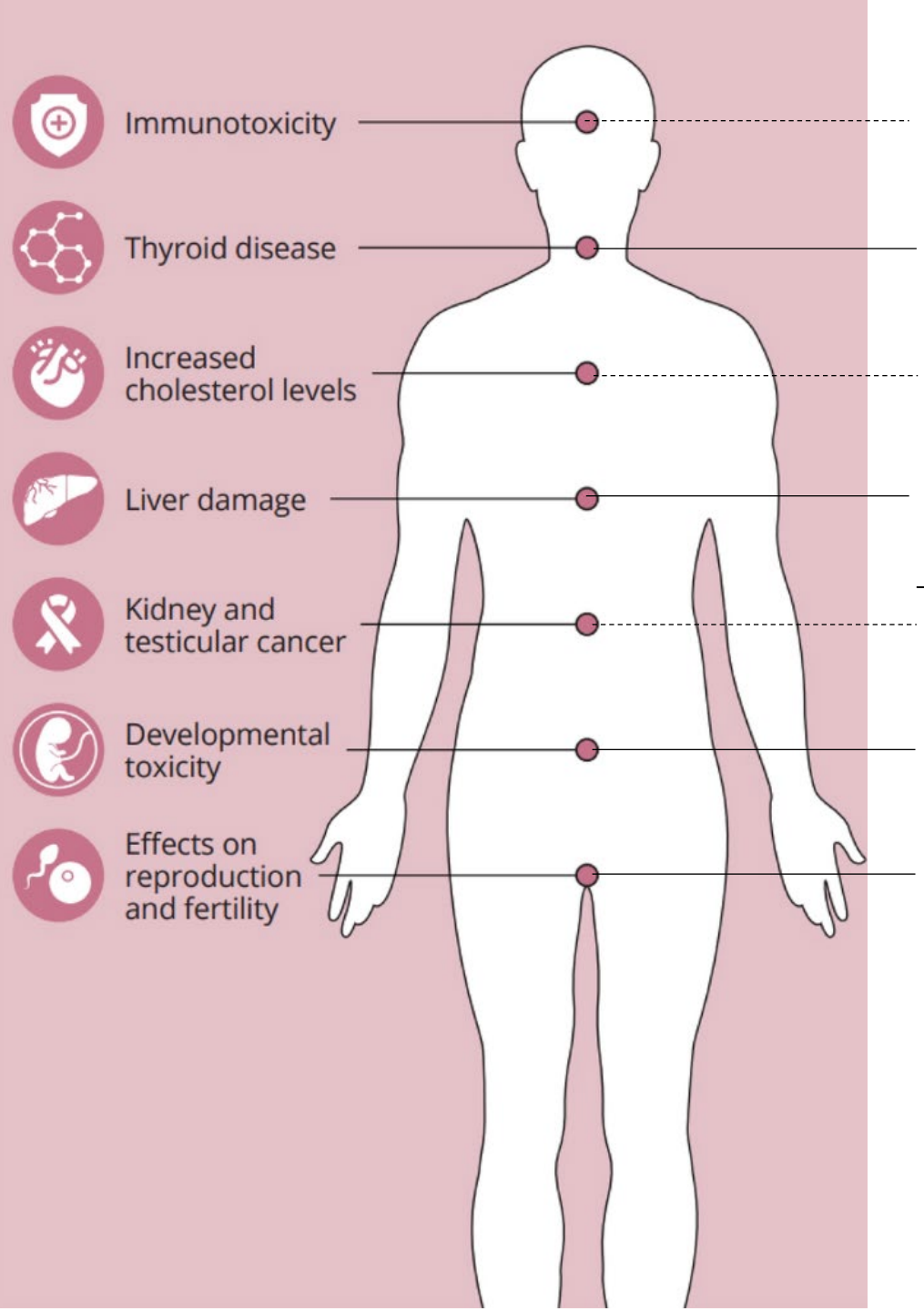
No dilution to this persistent and mobile pollution



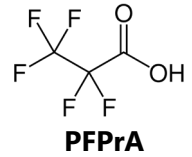
Zhang et al (2021) Eng Int. https://doi.org/10.1016/j.envint.2021.106856

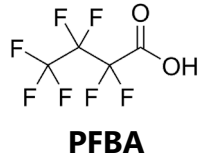
Legacy PFAS

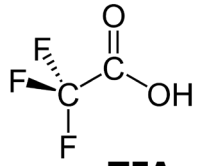




Emerging PFAS

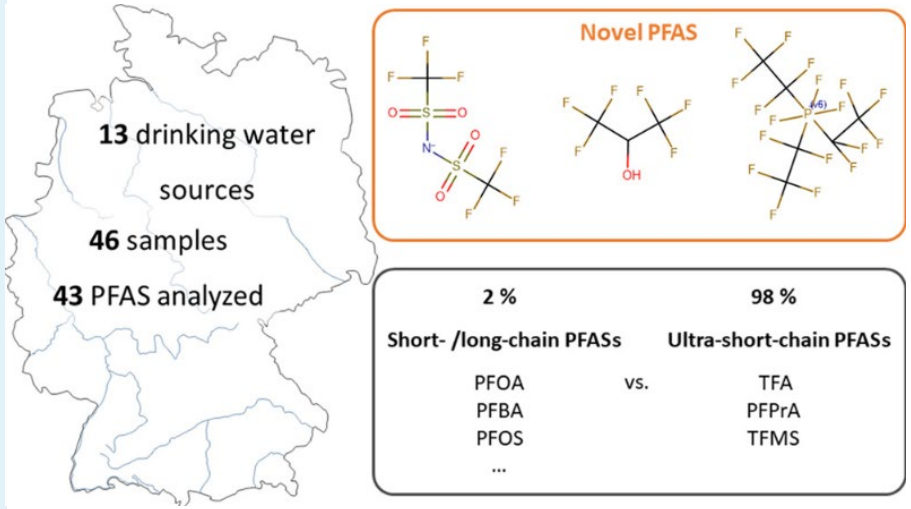




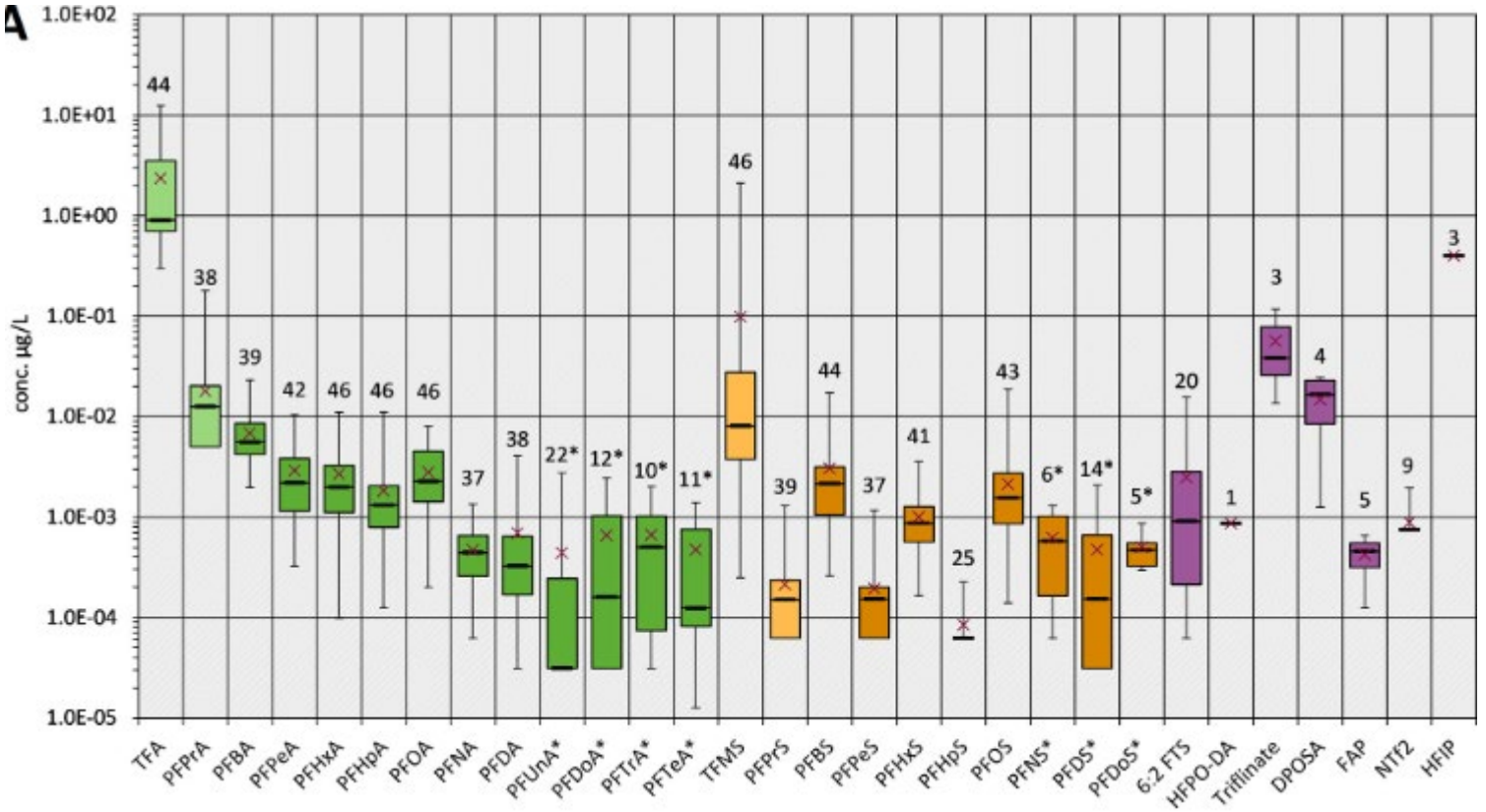


Brunn, H., Arnold, G., Körner, W. *et al.* . *Environ Sci Eur* **35**, 20 (2023). https://doi.org/10.1186/s12302-023-00721-8

What is the most abundant of the PFAS in water resources legacy or emerging?

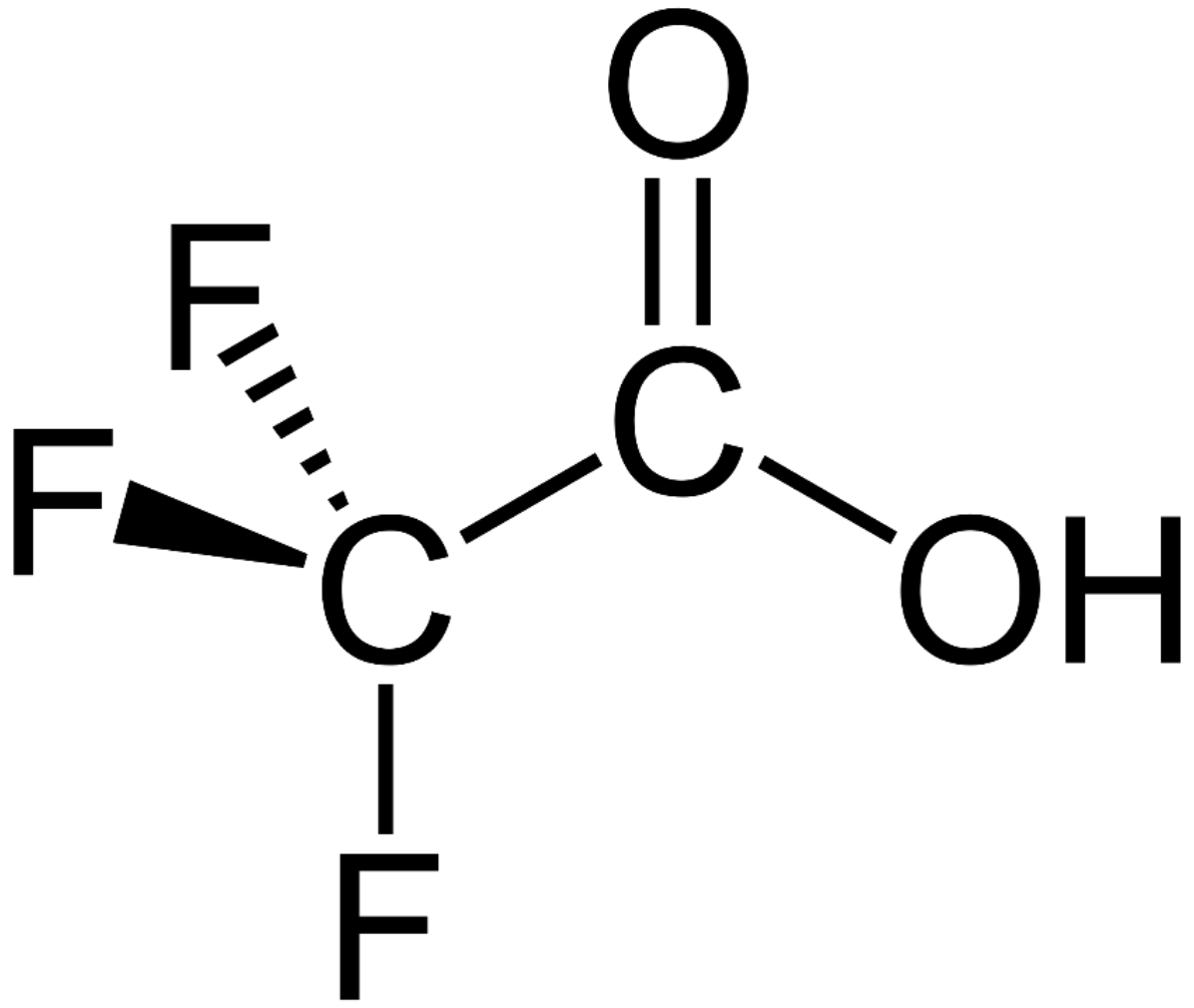


2 %		98 %
Short- /long-chain PFASs		Ultra-short-chain PFASs
PFOA	vs.	TFA
PFBA		PFPrA
PFOS		TFMS
...		



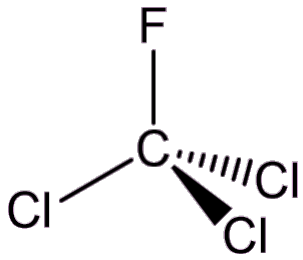
Environmental Science & Technology **2022** *56* (10), 6380-6390

Why is this PFAS now everywhere?



A precautionary tale….

James Lovelock (1919 – 2022)

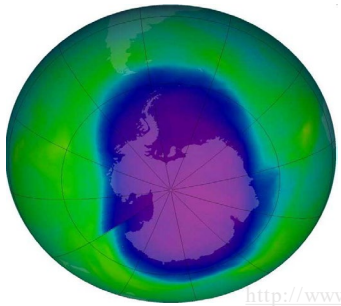




- **Invented the Electron Capture Detector (ECD)**
- **First to detect chlorofluorocarbons (CFCs) in the atmosphere**

- CFCs pose "no conceivable hazard"

Lovelock J (1988). The Ages of Gaia: A Biography of Our Living Earth



http://www.nasa.gov/vision/earth/environment/ozone_resource_page.html

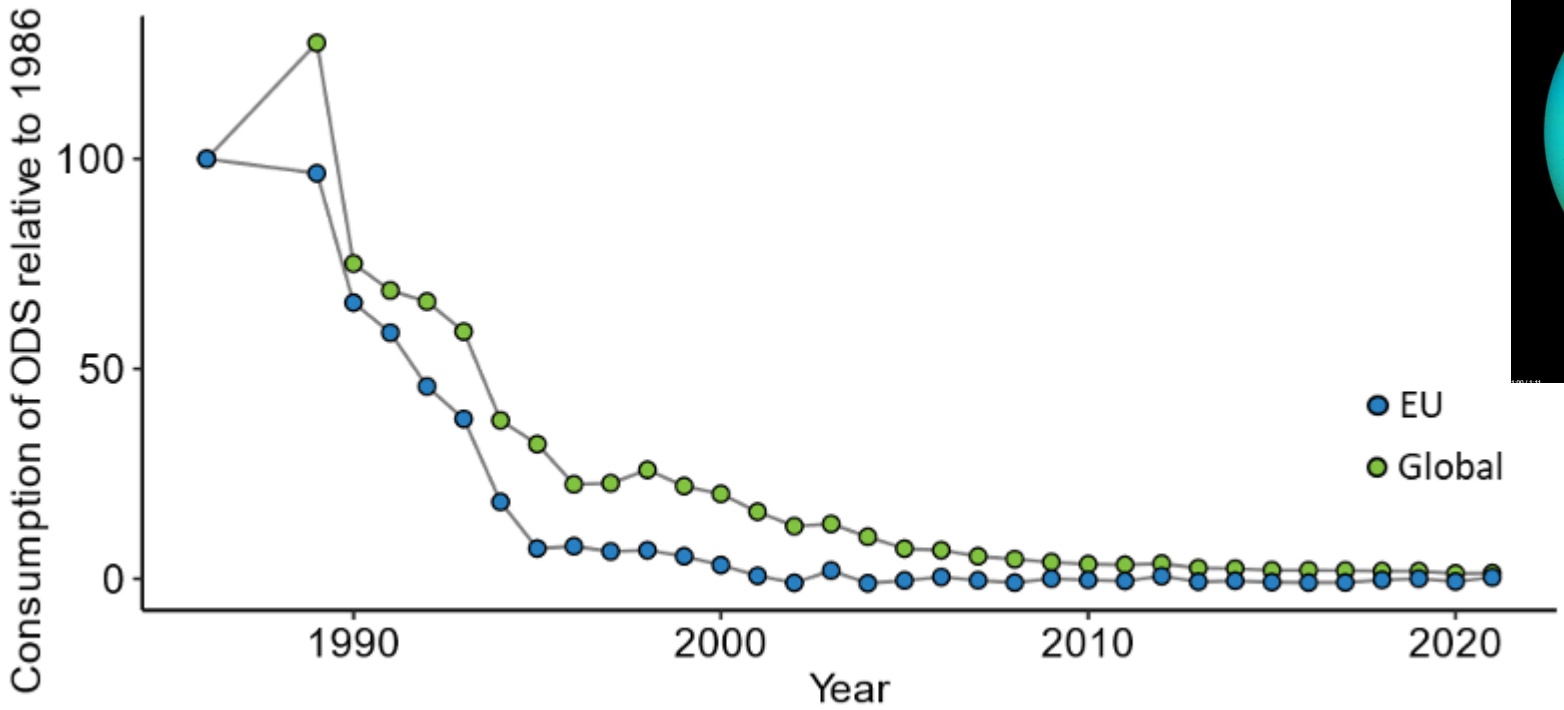


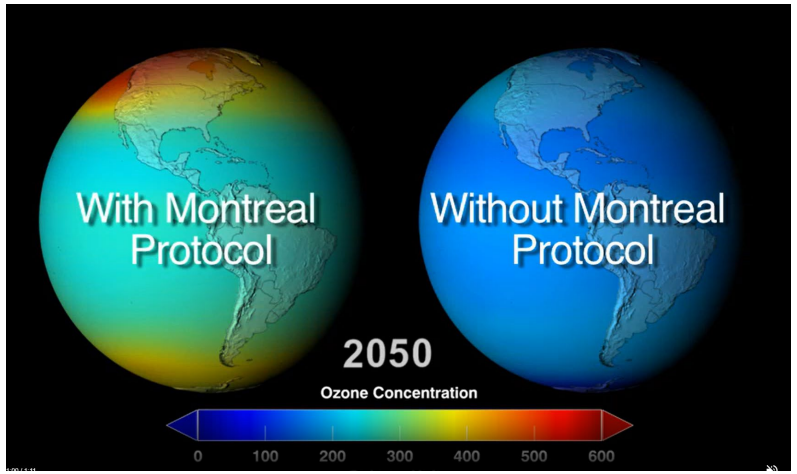
- CFCs pose "no conceivable toxic hazard"

Lovelock J (2000). Homage to Gaia: The Life of an Independent Scientist

https://en.wikipedia.org/wiki/James_Lovelock

The Montreal Protocol saved the planet. without it there would be no photosynthesis





EU and global relative consumption of ozone depleting substances (ODS, like chlorofluorocarbons) since 1986, showing the reduction the consumption of ODS due to the Montreal Protocol.

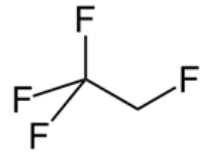
Chirsir, Palm *et al.* (2024 in press), ESEU, DOI: 10.26434/chemrxiv-2024-tn5t5

EEA (2023) EU and global consumption of controlled ozone-depleting substances — European Environment Agency. In: European Environmental Agency. 826

https://svs.gsfc.nasa.gov/cgi-bin/details.cgi?aid=10824

The history of the Montreal Protocol is a history of burden shifting via «drop in substitution»

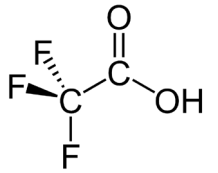
- 1st Gen: Chlorofluorocarbons (**CFCs**) – *Ozone depletion*
- 2nd Gen: Hydrochlorofluorocarbons (**HCFCs**)– less ozone depleting, but *green house gases*
- 3rd Gen: Saturated hydrofluorocarbons (**HFCs**) -> green house gases, *mild formation of TFA*



1,1,1,2-Tetrafluoroethane
(HFC-134a, Norflurane)

$h \cdot \upsilon$

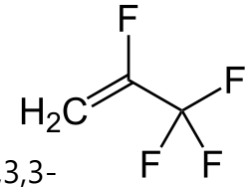
high global warming potential



Triflouroacetic acid (TFA) Yield between 7- 23%

Extremely persistent and mobile
Accumulates in the environment

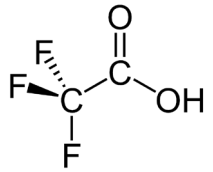
- 4th Gen: F-gases after Kigali amendment (2019): Unsaturated hydrofluoroolefins (**HFOs**), less global warming potential, ***increased formation of TFA***



2,3,3,3-
Tetrafluoropropene
(µHFC-1234yf)

$h \cdot \upsilon$

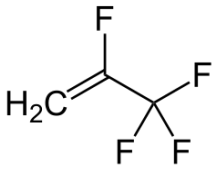
low global warming potential



TFA Yield = 100% !

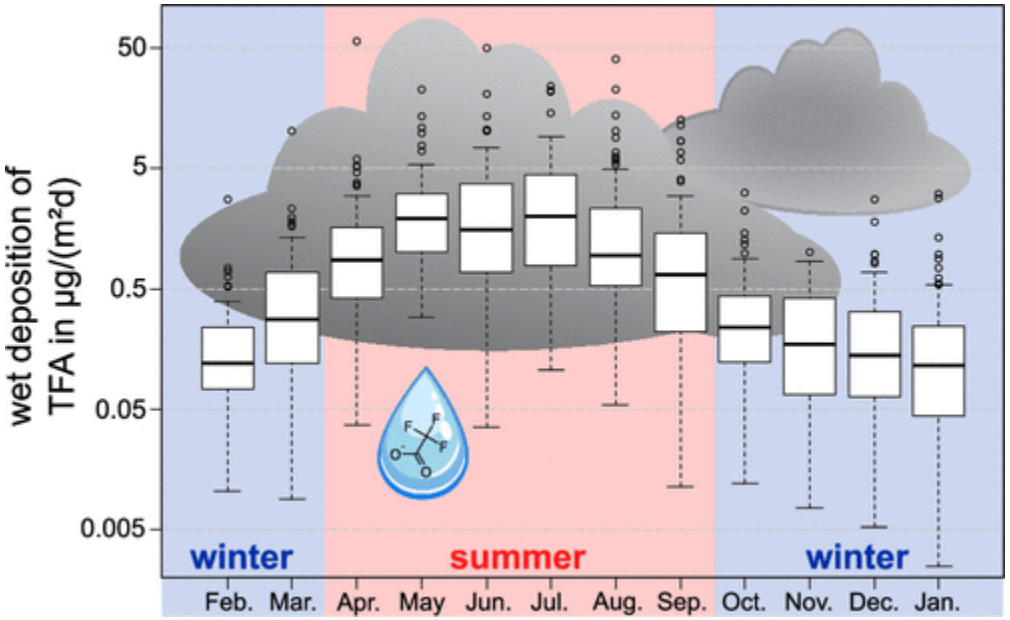
F-gases used as refrigerants and blowing agents

EU-28



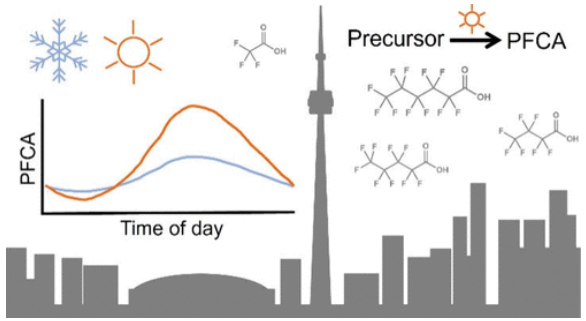
Substance	2000	2010	2020	2030	2040	2050	Total TFA sum (2000-2050)	Share of total sum
HFC-134a	3,895	7,595	6,351	1,756	1,084	836	202,781	14.7 %
u-HFC-1234yf	0	0	6,902	37,432	45,469	47,650	1,125,699	81.3 %

Behringer et al. UBA Texte | 73/2021



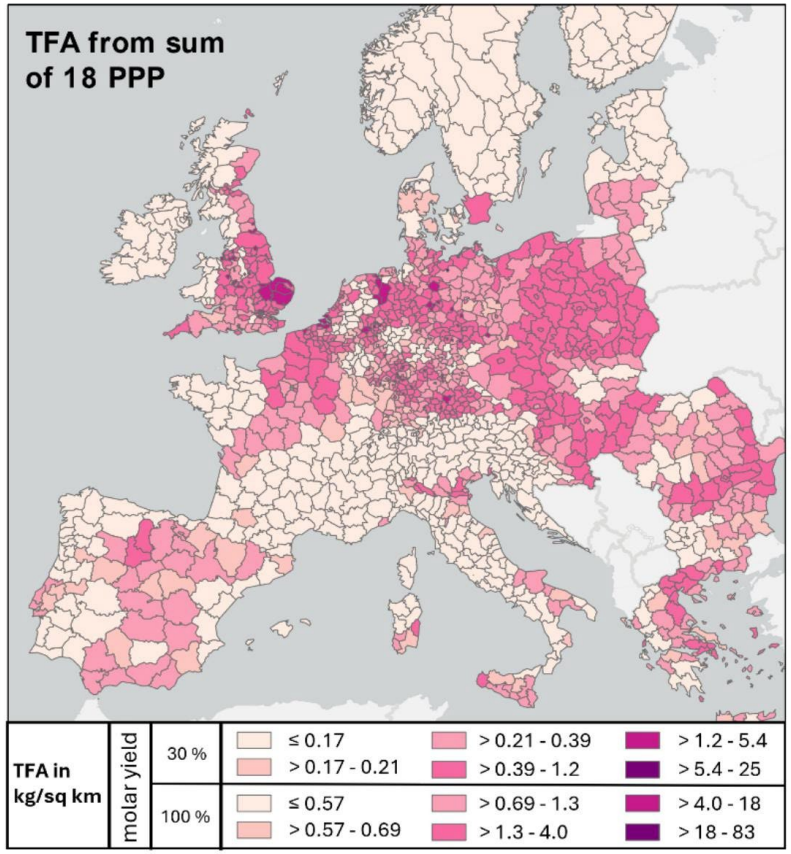
Freeling et al. *Environmental Science & Technology* **2020** *54* (18), 11210-11219

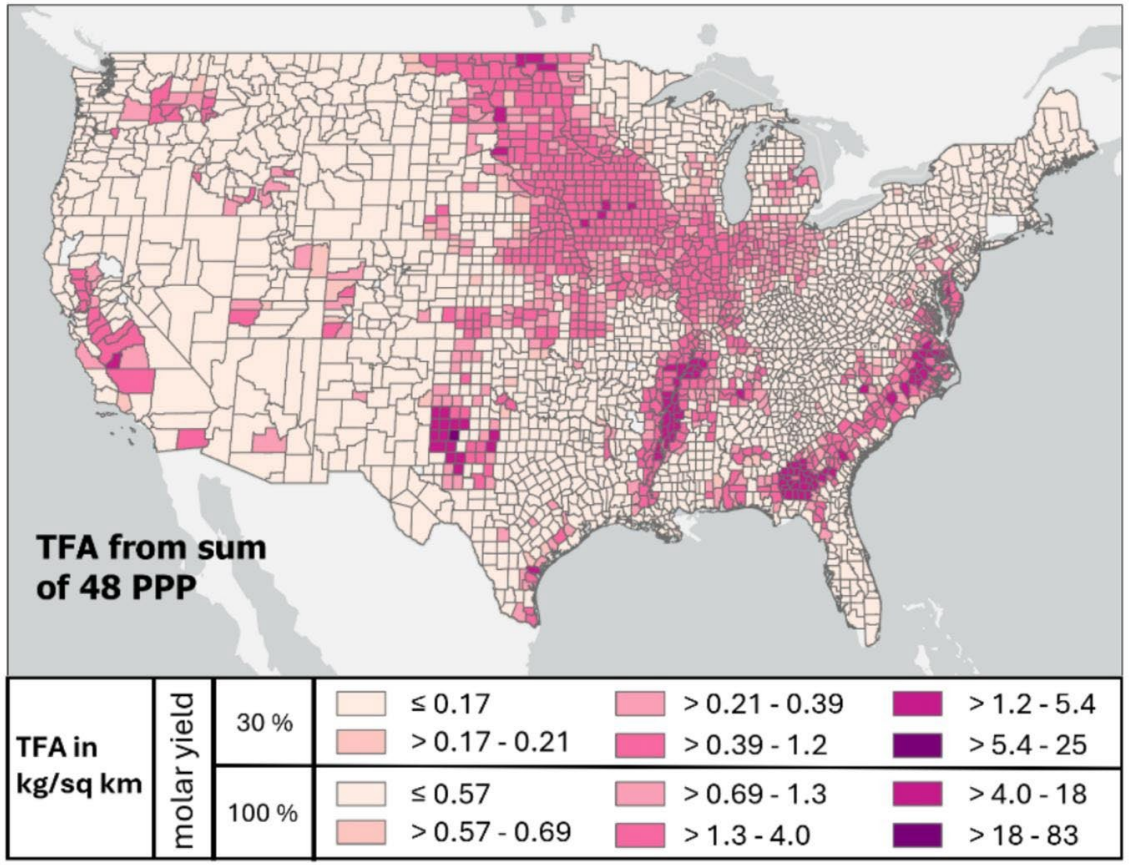
- 2020 rain concentrations in increase by a factor 5 by 2040
- This accumulates in the environment
- atmospheric TFA is formed from volatile precursors ((F-gases and others)



Young et al. *Environmental Science & Technology Letters* **2024** *11* (12), 1348-1354

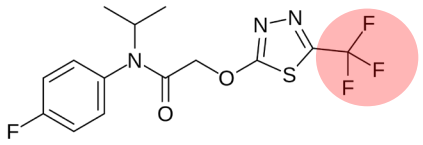
Pesticide/Herbicide precursors lead to TFA hotspots in agricultural areas



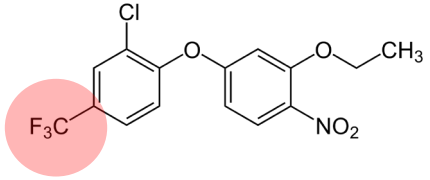


Major precursors:

flufenacet

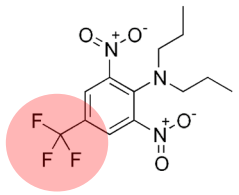


oxyfluorfen

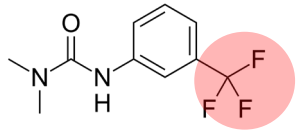


Major precursors

trifluralin

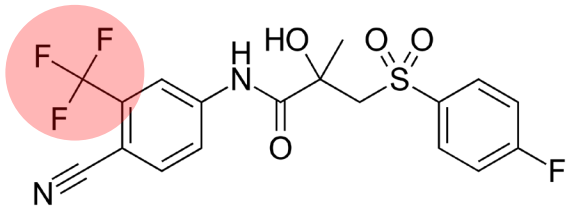


fluometuron

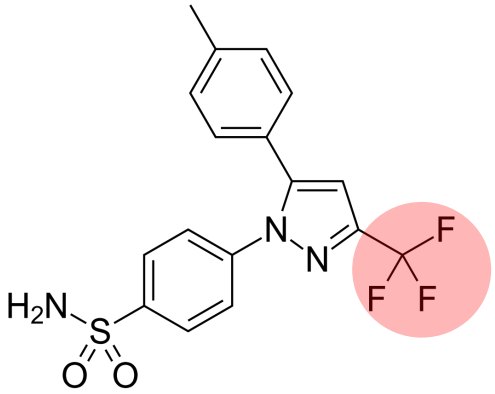


Joerss et al. (2024) *Environment International*, *193*, 109061.

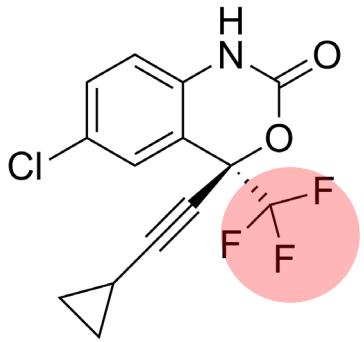
Pharmaceuticals



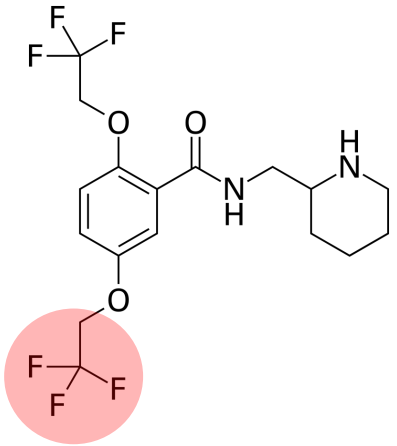
Bicalutamide – since 1995
(prostate cancer treatment)



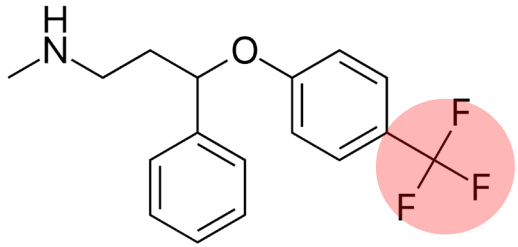
Celecoxib – since 1999
(Non-steroidal anti-inflammatory)



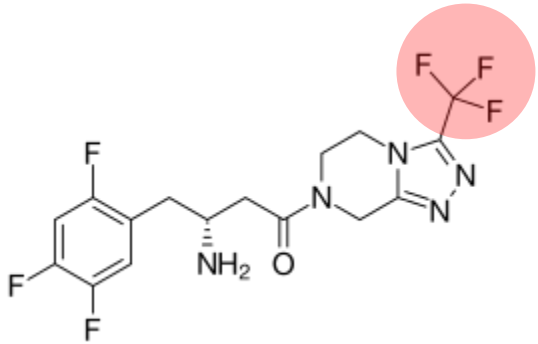
Efavirenz – since 1998
(HIV/AIDS treatment)



Flecainide – since 1985
(fast heart-rate treatment)



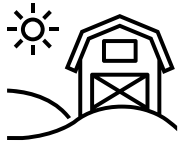
Fluoxetine (Prozac) - since1986
(Anti-depressant)



Sitagliptin – since 2006
(Anti-diabetic)

Sludge/biosolid

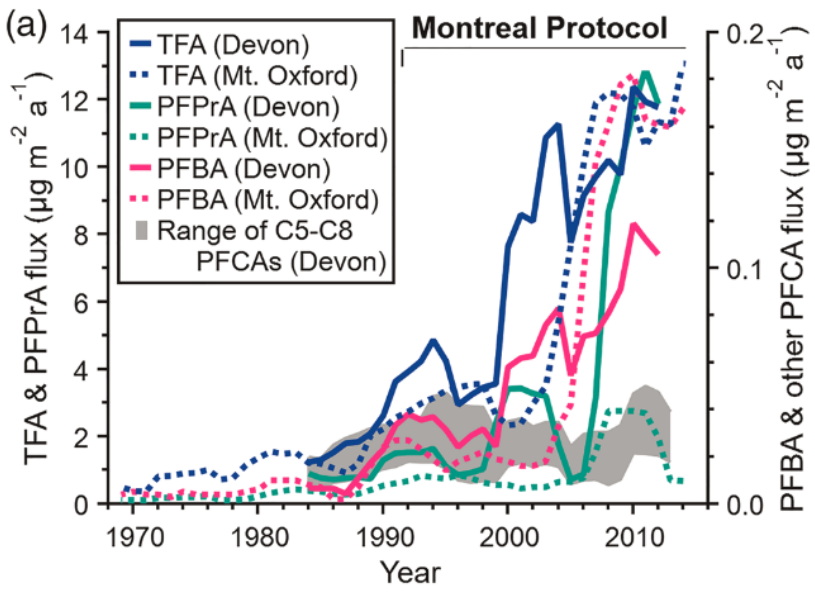




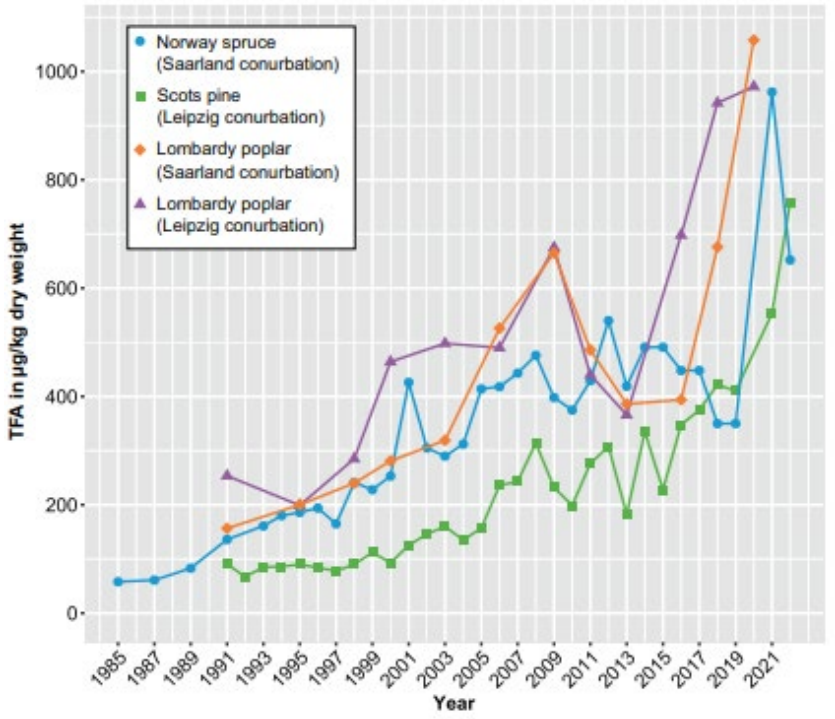
Agricultural chemicals

TFA is accumulating everywhere, largely coinciding with F-gas use following the Montreal Protocol

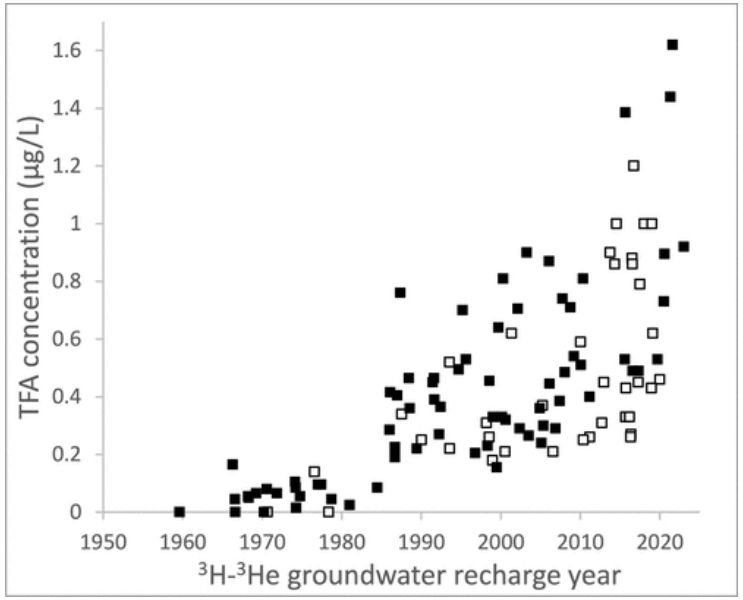
TFA accumulating in arctic ice cores



and in tree leafs



and in groundwater



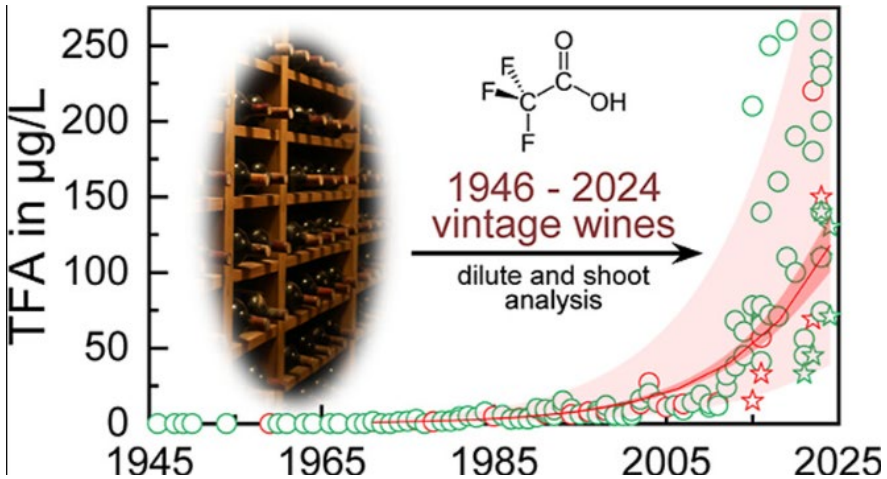
Pickard et al. Geophysical Research Letters (2020),47, e2020GL087535

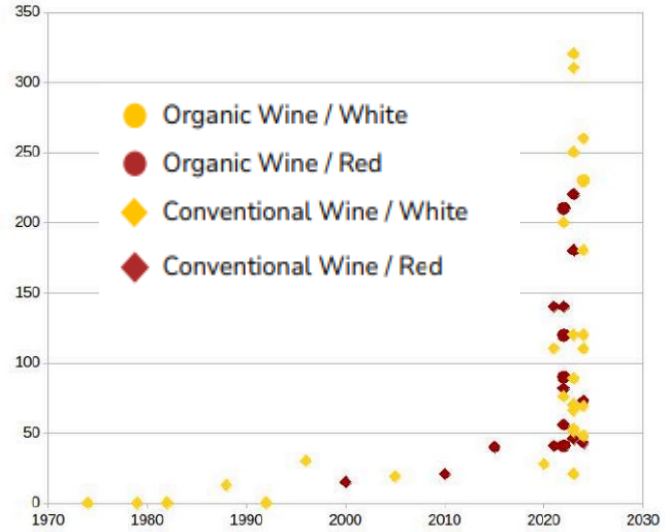
Freeling and Björnsdotter, Current Opinion in Green and Sustainable Chemistry 2023, 41:100807

Albers and Sültenfuss, Environmental Science & Technology Letters 2024 11 (10), 1090-1095

TFA is increasing in all that we drink

…Wine



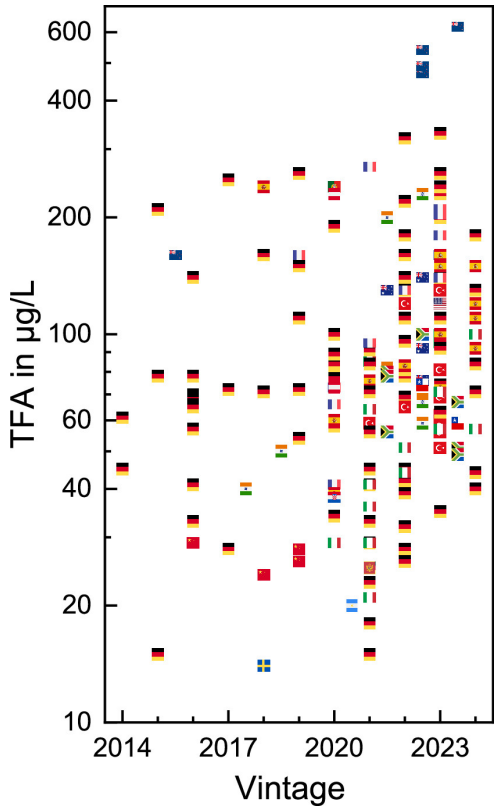


Freeling et al. *Environ. Sci. Technol.* 2025, 59, 49, 26762-26769)

Wine image: Sai Balaji Varma Gadhiraju

Up to 600 µg/L





Drinking water (median)[1,2]

- Germany: 1.5 µg/L
- 19 Countries: 0.23 µg/L

Tee (median): 2.4 µg/L[2]

Beer (median) 6.1 µg/L[2]

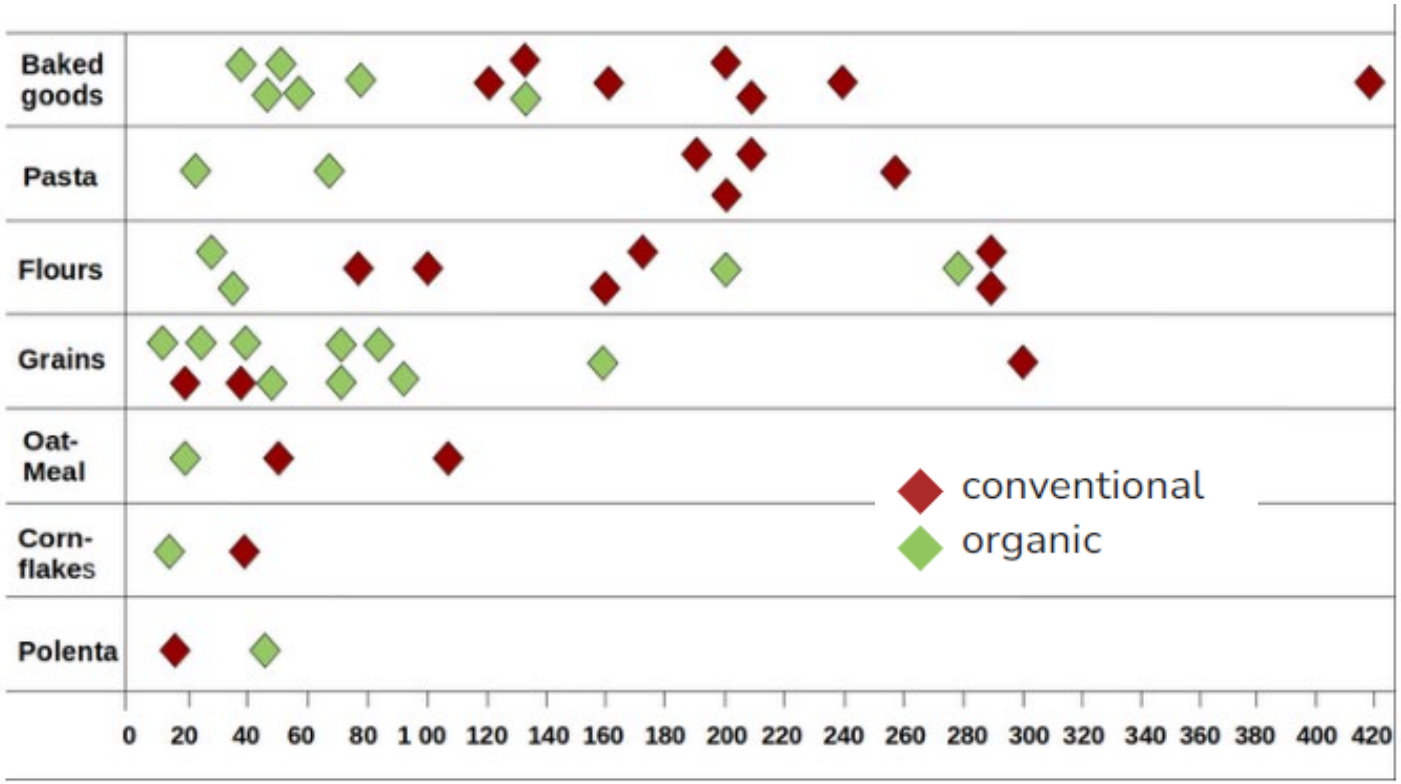
Orange juice (mean 34 µg/L)[3]

Apple juice (mean 6.2 µg/L)[3]

1. Neuwald et al. *Environmental Science & Technology* **2022** *56* (10), 6380-6390
2. Scheurer & Nödler. *Food Chemistry*, *351*, 129304.
3. Van Hees et al. https://cdnmedia.eurofins.com/european-east/media/uxcnaa2c/eurofins_tfa_tfms_juice_24_final.pdf

PAN Europe: Message from the Bottle – The Rapid Rise of TFA Contamination Across the EU

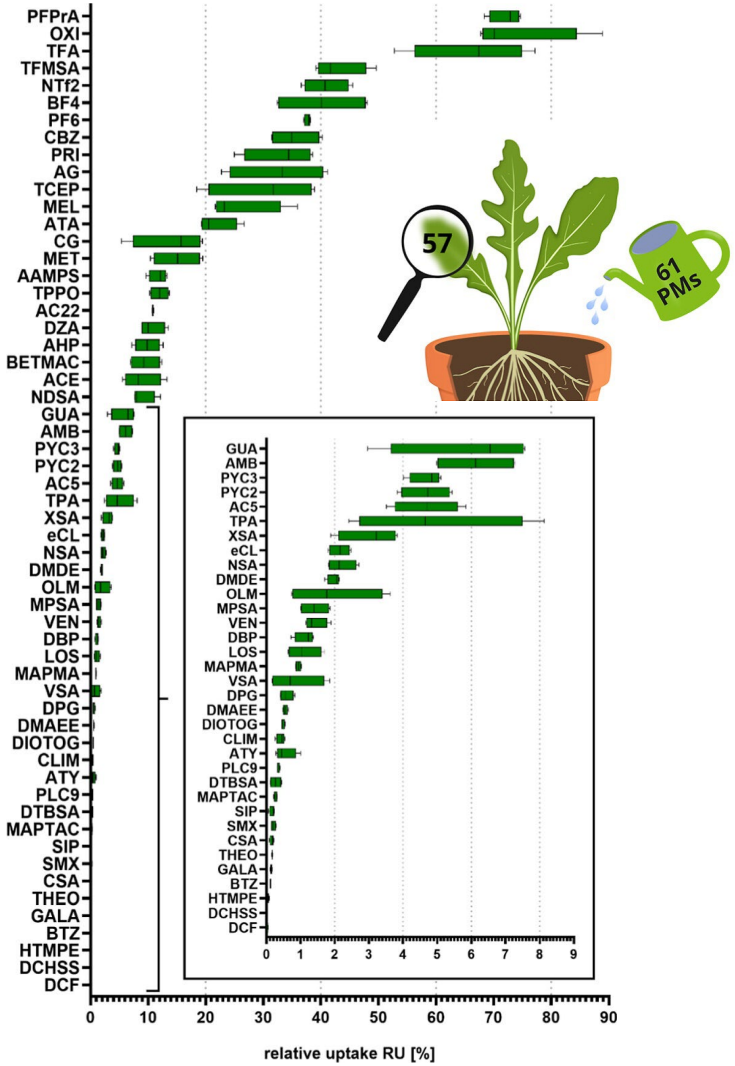




µg/kg dw

https://www.pan-europe.info/resources/reports/2025/06/forever-chemical-TFA-our-daily-bread

Many PMT/vPvMs can exhibit plant uptake



Seelig et al. *Environ. Sci. Technol.* 2025, 59, 18, 9265-9274

The increasing impacts



Toxicity to Mammals

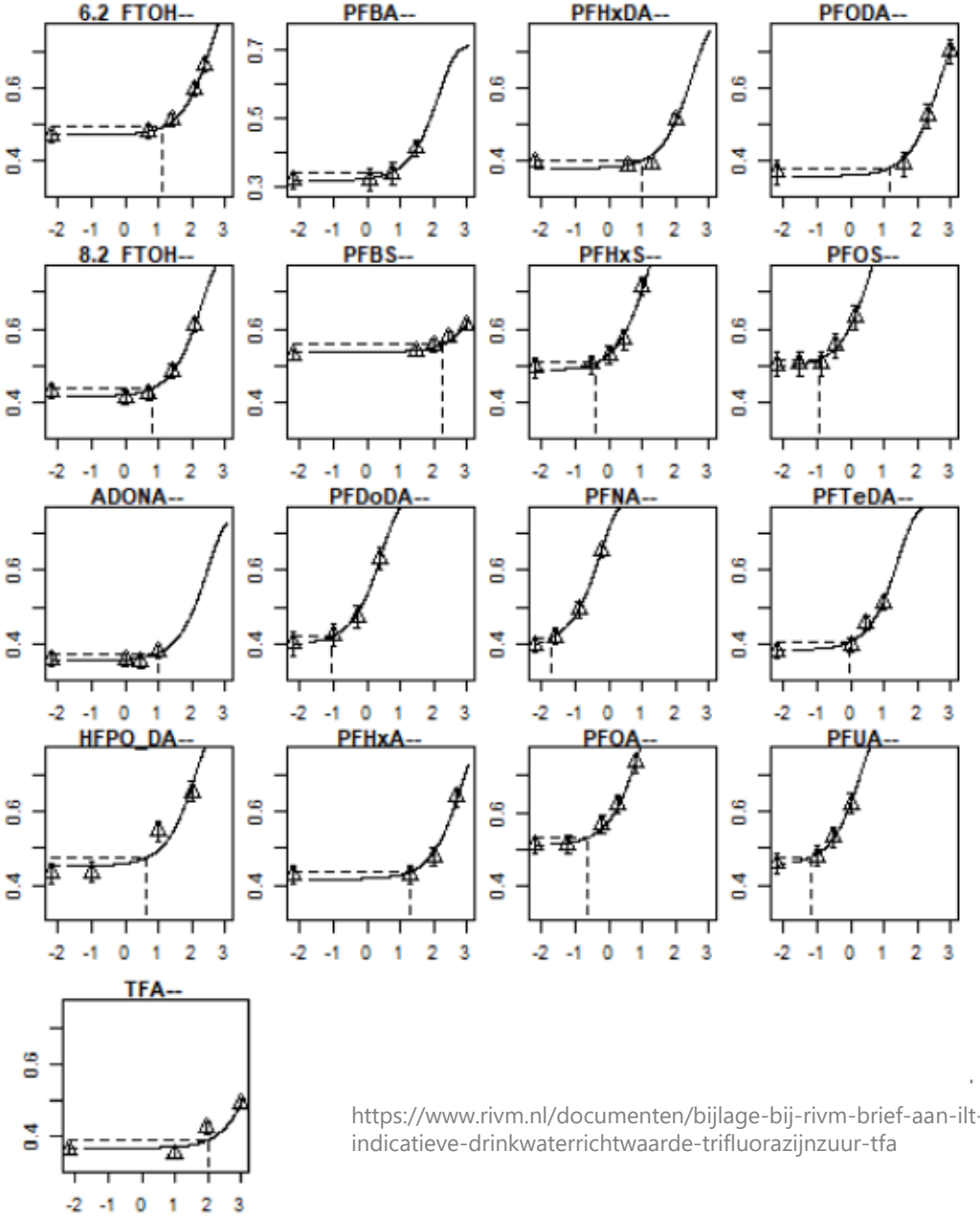
RIVM (2022)
Chronic rat toxicity (feeding)
Dose response: Male liver weight vs dose
Relevant potency factor (RPF): TFA is 0.002 x toxic as PFOA

*Corresponds to a **water threshold value of 2.2 µg/L***
Exceeded in an increasing number of areas

ECHA REACH Dossier (2024)
Han Wistar Rabbits
embryo-fetal developmental toxicity <180 mg/kg/day

multiple folded retina and absent aqueous/vitreous humor were above the … historical control data range

Category 1B: Presumed human reproductive toxicant



https://www.rivm.nl/documenten/bijlage-bij-rivm-brief-aan-ilt-indicatieve-drinkwaterrichtwaarde-trifluorazijnzuur-tfa

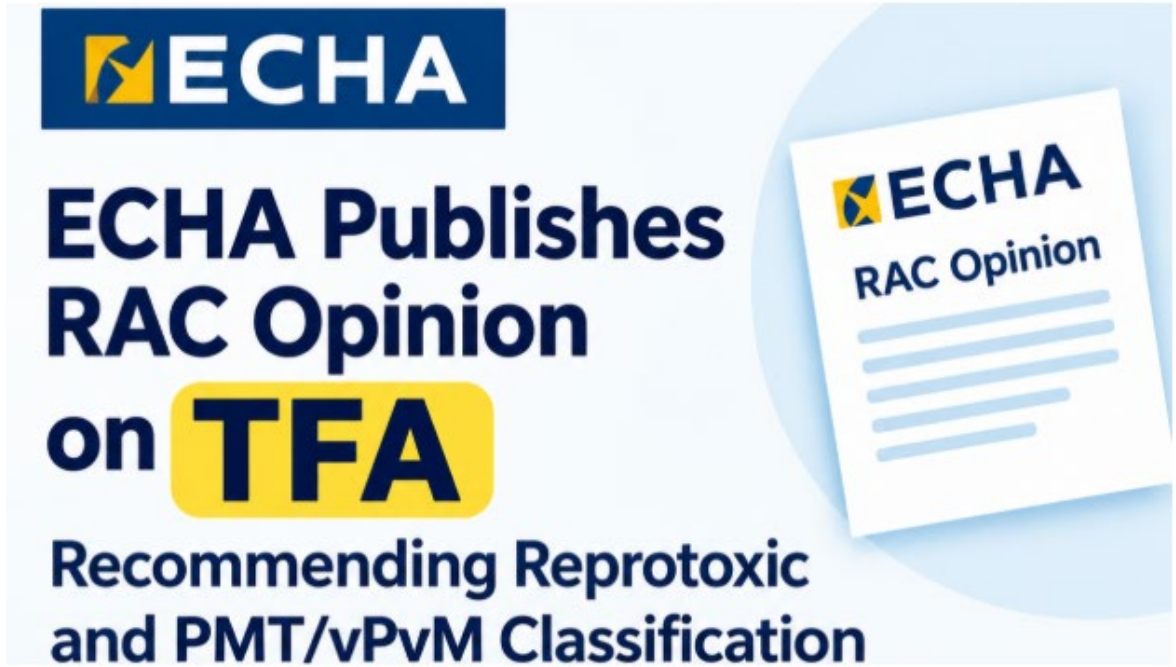
ECHA publishes opinion that TFA is Rep 1b and PMT/vPvM

8.2.2.1. Trifluoroacetic acid .... % (EC 200-929-3, CAS 76-05-1)

The Chair welcomed the Dossier Submitter representatives and experts accompanying the CEFIC and CropLife Europe Regular Stakeholder Observer as well as Occasional Stakeholder Observers from EACL, EFPIA, PAN Europe, Animal Health Europe, EUROPUR and respective experts. The Chair welcomed also EFSA observers.
He then provided some general information on the uses of **Trifluoroacetic acid .... %,** proposed classification by the Dossier Submitter (DE) and legal deadline.
Acute toxicity via all routes, reproductive toxicity, STOT RE and PMT/vPvM were open for comments during the Consultation.

consensus the opinion with a proposal for the harmonised classification and labelling as indicated in Table 1.

[Acute Tox. 3; H331 (ATE = 3 mg/L (vapours)), Acute Tox. 4; H302 (ATE = 500 mg/kg bw), Repr. 1B; H360Df, PMT; EUH450, vPvM; EUH451, EUH071]



TFA: ECHA Publishes RAC Opinion Recommending Reprotoxic and PMT/vPvM Classification



Neeta Verma
Environmental Compliance & Product Regulatory Strategy Leader | Technical Author & Industry Thought Leader

EFSA lowers safe level for exposure to TFA



EFSA's experts lowered the acceptable daily intake (ADI) to 0.014 milligrams per kilogram of bodyweight per day

3.5 times lower than the previous.

The European Food Safety Authority (EFSA) has reduced the safe level of trifluoroacetic acid (TFA) in the diet based on new scientific evidence. TFA is a breakdown product of some pesticides.

https://www.efsa.europa.eu/en/news/efsa-lowers-safe-level-exposure-tfa

EU Surface water directive update for PFAS

TFA in the PFAS 25 EQS for **surface water**

- total 4.4 ng/L PFOA equivalents = **2.2 µg/L** for JUST TFA (if no other PFAS present)
- Take effect **22 December 2027**
- deadline for achieving good status – **22 December 2039**
- Commission review May 2032) if separate EQS should be established for TFA
- ECHA will be prepare a scientific report by 11 May 2030.

(26) 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), Perfluoroh (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 0 206-196-6) (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- (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 (PFDo 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, 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 33 (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 a 2,3,3,3-tetrafluoro-2-(heptafluoropropoxy)propionic acid (HFPO-DA) (CAS 13252-13-6) (RPF 0,06), 2,2,3-trifluoro-3-(1,1,2,2,3,3-hexafluoro-3-(trifluoromethoxy)p (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 (trifluoromethoxy)-1,3-dioxolan-4-yl)oxy) acetic acid (C6O4) (CAS 1190931-41-9) (RPF 0,06), Trifluoroacetic acid (TFA) (CAS 76-05-1, EU 200-929-3) (RPF 0,002)

Link: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32026L0805

More of Europe already has TFA in Surface/Groundwater > 2.2 µg/L



Forever chemical linked to fertility issues found in rivers in England

Data shared exclusively with The i Paper reveals trifluoroacetic acid has been detected in areas that supply drinking water

October 07, 2026 10:00 am (Updated 2:04 pm) · 3 min read

The highest concentration of forever chemical trifluoroacetic acid in surface water was found in the River Ancholme in Lincolnshire (Photo: James Martin)

https://inews.co.uk/news/forever-chemical-linked-to-fertility-issues-found-in-rivers-in-england-4809901

UK Environment Agency data:

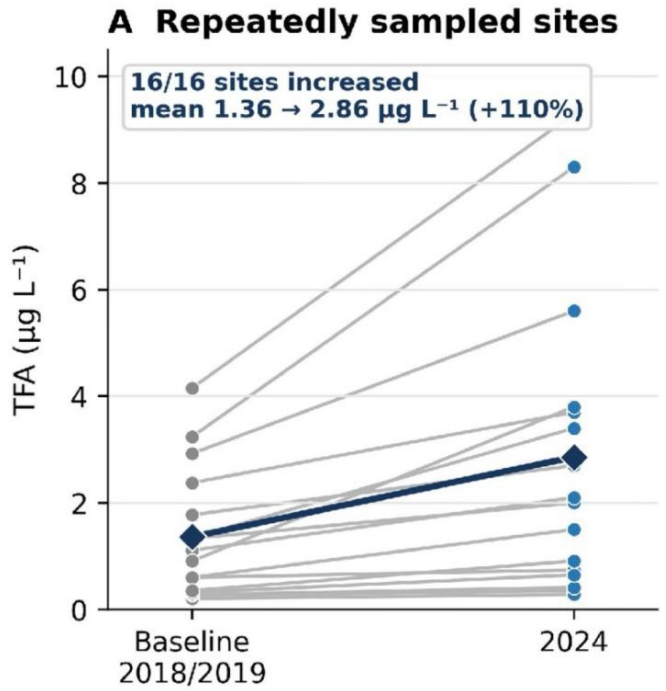
- TFA average 2.6 µg/L in SW (> 2.2 µg/L in 42% of samples);
- TFA average 2.8 µg/L in groundwater (>2.2 µg/L in 45% of samples).

Official Austrian groundwater data

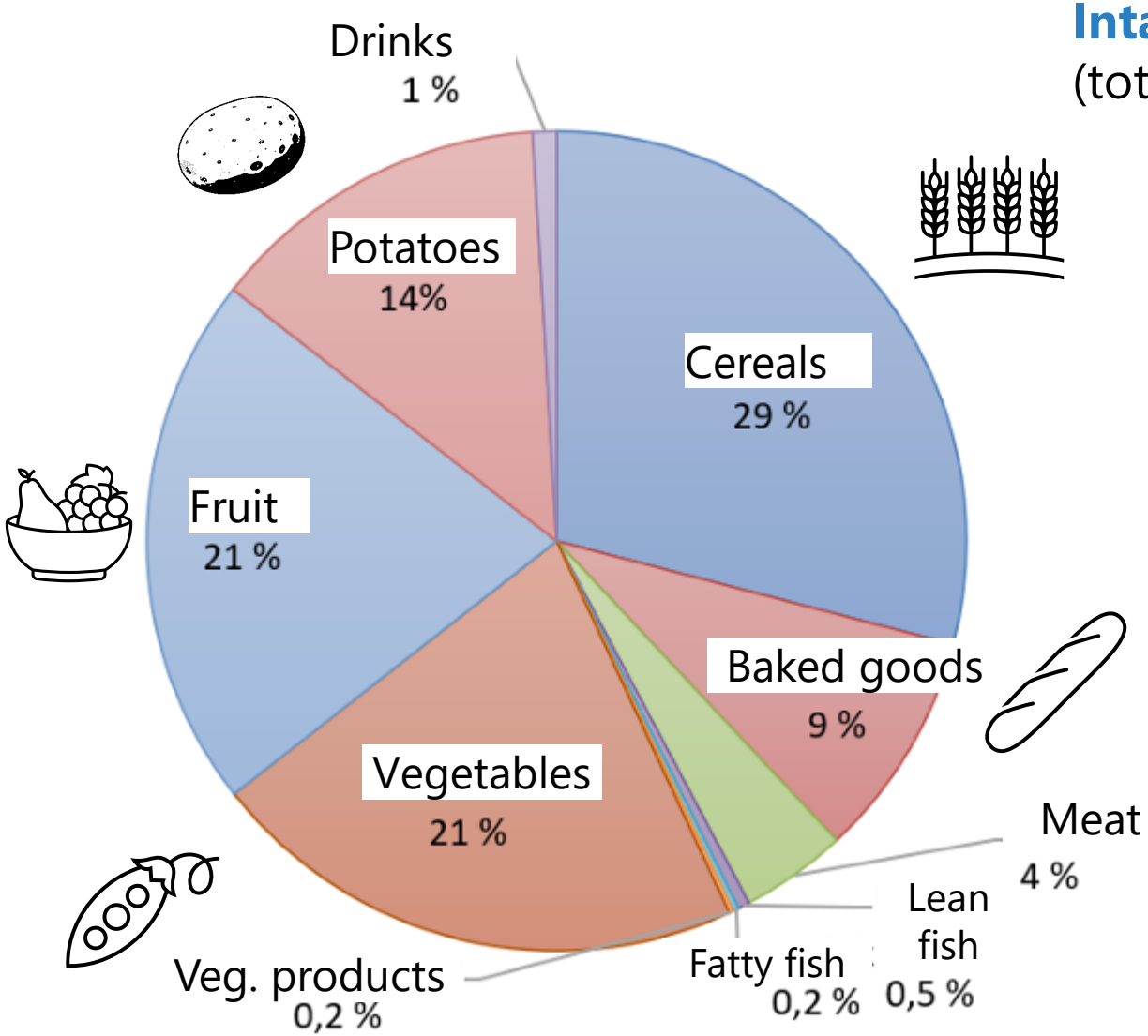
TFA increased at all paired sites from 2018/2019 -> 2024

TFA average rose from 1.36 to 2.86 µg/L (+110%)

.



Diet is the main exposure route for TFA



Intake of TFA from a typical Swedish Diet

(total 24.1 µg TFA/person/day in 2022)*

Simple risk assessment:

0.344 µg/kg /day (70 kg/person)

= 2.5 % EFSA draft Acceptable Daily Intake for TFA of 14 µg/kg/day (expressed as TFA)

= 110% of the EFSA TWI of 0.0044 µg/kg/week $PFOA_{equivalents}$ based on immunotoxicity (using an RPF of 0.002) of 0.314 µg/kg/day

*Source: Gyllenhammar et al. (2026) «Halter av Trifluorättiksyra (TFA) och andra ultrakorta PFAS i Livsmedelsverkets Matkorgsstudie från 2022 ”

PFAS in blood is increasing

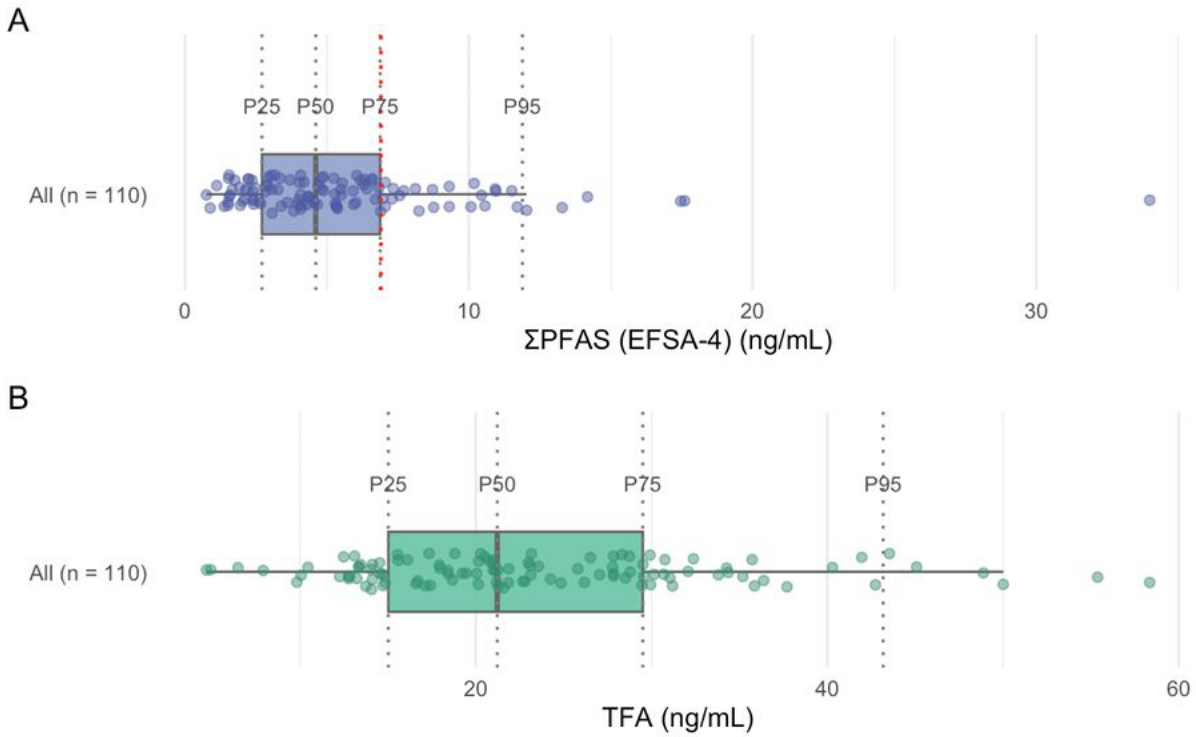


Figure 3. Sum of serum levels of long-chain EFSA-4 PFAS (ΣEFSA-4 = PFOS + PFOA + PFHxS + PFNA, in ng/mL; A) and TFA (B) in all study participants (n=110). The ΣEFSA-4 or TFA levels were divided into quartiles (P25, P50, P75), where P50 represents the median levels, meaning that half of the measured PFAS levels are lower and half are higher. P95 represents the 95th percentile, which is often used in human studies to indicate extreme values, highly exposed subgroups, or worst-case scenarios. Each dot represents one participant in this study. The red dotted line represents the EFSA threshold value for serum (6.9 ng ΣEFSA-4 /mL; see 1.2.3). Please note the difference in scale of the X-axis: for ΣEFSA-4 levels (A) the maximum level was 34 ng/mL and for TFA the maximum measured level was 58 ng/mL.

🩸 The Greens/EFA Group in the European Parliament organized a blood sampling campaign with 110 volunteers.[1]

⬆️ TFA concentration higher than EFSA PFAS

⬆️ MedianTFA concentrations were highest reported (21 µg/L)

- Higher than Indiana, USA (7 µg/L)[2]
- Similar to Wilmington USA (17 µg/L)[3] near fluorochemical plant

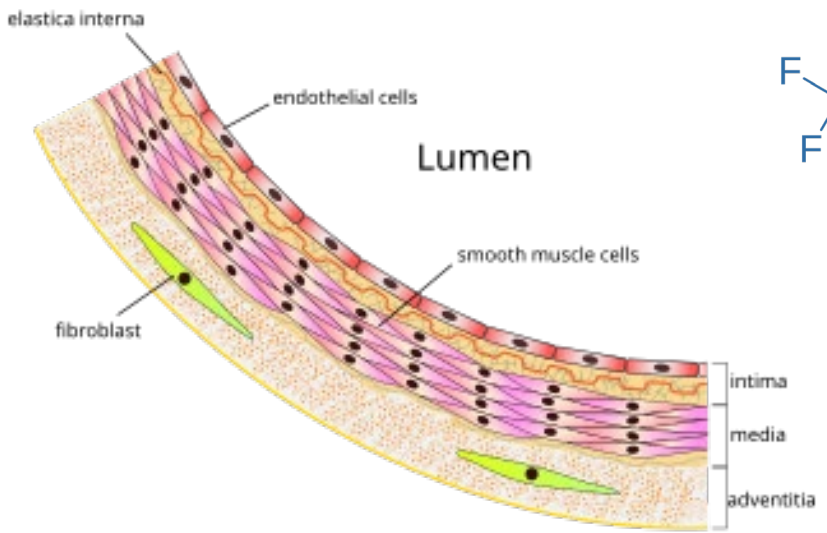
Simple exposure modelling indicates this median level is near EFSA

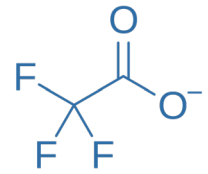
1. https://www.greens-efa.eu/en/article/study/pfas-levels-in-europeans
2. Zheng et al. *Environ. Sci. Technol.* (2023) 57 (42): 15782–15793
3- Cheng et al *Environ. Sci. Technol.* (2025) 59 (43): 23125–23135.

TFA could impair blood vessel developent

New research in human endothelial cells

- TFA interferes with how endothelial cells produce energy,
- Impacts growth new blood vessels.
- TFA can bind to the lactate dehydrogenase enzyme, preventing the enzyme from binding pyruvate and converting it to lactate.



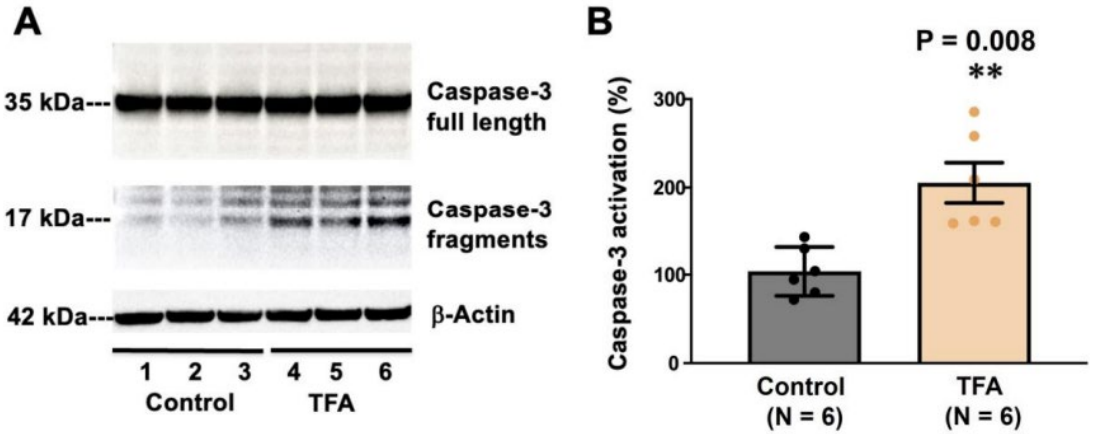


Lumen By Stijn Ghesquiere, Drsrisenthil -CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=58257331

Cao *et al. Environ. Sci. Technol.* (2026) 60 (38): 27001–27011

XioZhi Lim C&EN . *Small, abundant PFAS could impair blood vessel development (2026)*

Link to neurotoxicity with TFA-binding to proteins (differently than acetic acid)

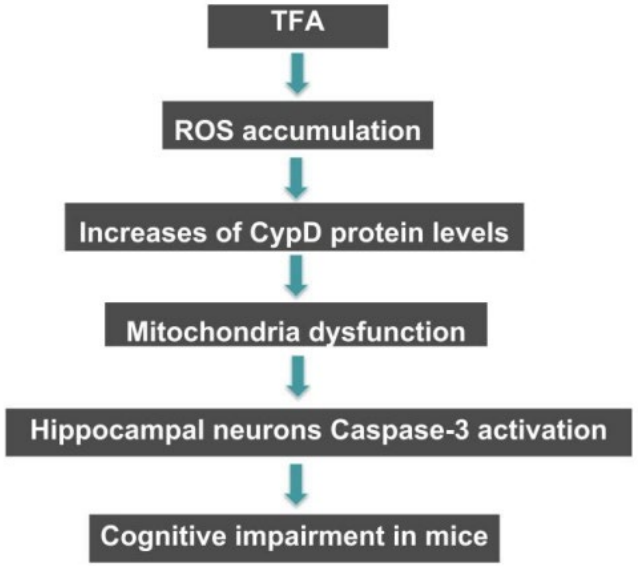


Aging and Disease
www.aginganddisease.org
Early access date: February 26, 2025
http://dx.doi.org/10.14336/AD.2024.1430

Original Article

Trifluoroacetic Acid Induced a Cyclophilin D-Dependent Cognitive Impairment in Mice

Yun Li[1,2#], Yichi Xu[1,3], Yuanlin Dong[1], Christa J. Nehs[4], Zhongcong Xie[1], Yiying Zhang[1*]

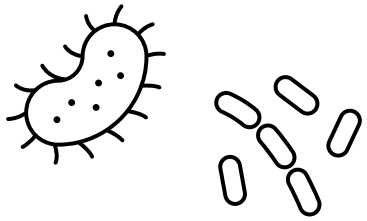


EFFECTS OF TRIFLUOROACETIC ACID, A HALOTHANE METABOLITE, ON C6 GLIOMA CELLS

T. G. Ma, Y. H. Ling, G. D. McClure, M. T. Tseng

Department of Anatomical Sciences and Neurobiology, University of Louisville, Louisville, Kentucky

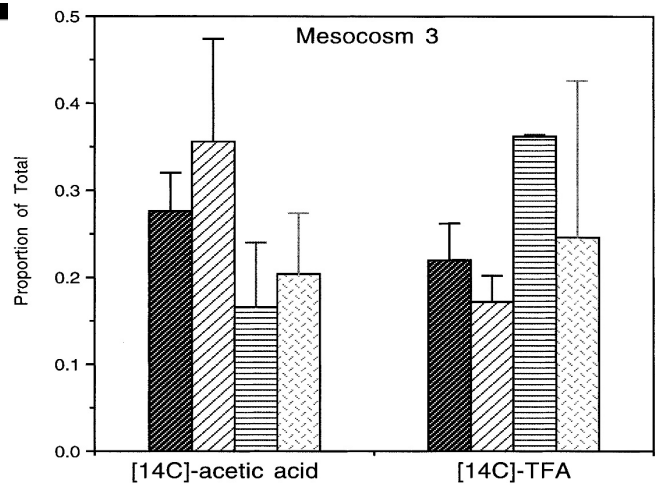
TFA able to become part of the lipids and biomolecules inside microbes …. no follow-up since 1999

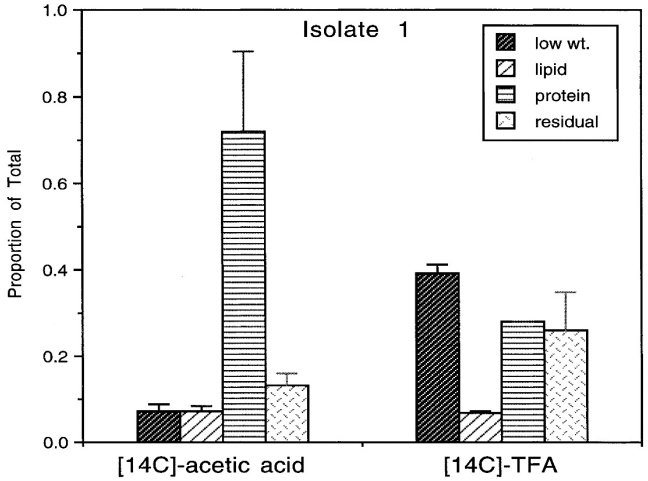


Trifluoroacetate, an Atmospheric Breakdown Product of Hydrofluorocarbon Refrigerants: Biomolecular Fate in Aquatic Organisms

LAUREL J. STANDLEY* AND
THOMAS L. BOTT

Stroud Water Research Center, Academy of Natural Sciences of Philadelphia, 970 Spencer Road, Avondale, Pennsylvania 19311





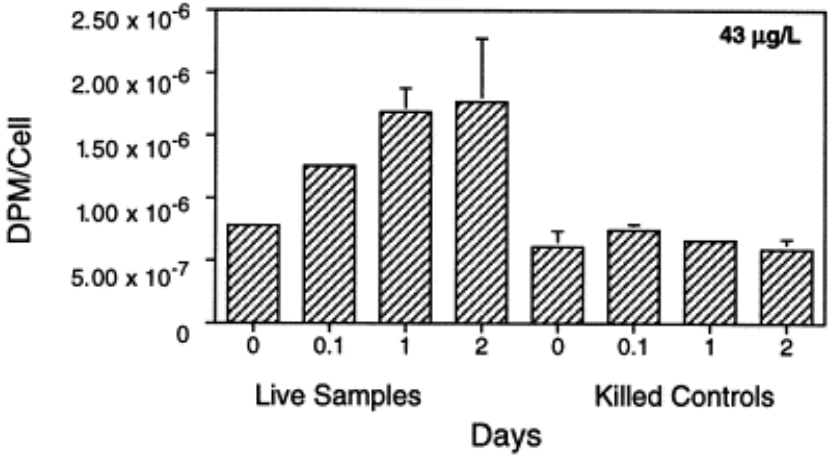
ELSEVIER

Water Research
Volume 33, Issue 6, April 1999, Pages 1538-1544

Research Note

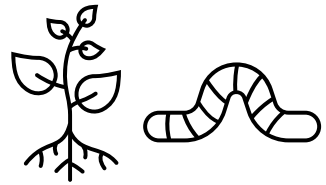
Incorporation of trifluoroacetate, a hydrofluorocarbon decomposition byproduct, by freshwater benthic microbial communities

Thomas L. Bott, Laurel J. Standley



If TFA covalently bonded with lipids, membranes, biomolecules, etc. they would ultimately be degraded to TFA… again

TFA toxicity to soil and terrestrial systems



Soils / terrestrial ecosystems

- TFA readily bioaccumulates in plants/shoots from soil
- Effects on the soil pH, microbial respiration, bacterial abundance and litter decomposition were reported at TFA concentrations in soil in hotspots **(0.0013–2.4 mg/kg_{dw})**, above this problems related to TFA acidity can occur.



- **Lack of long exposure studies on terrestrial and agricultural systems**

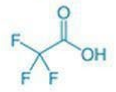
Jan Kopřiva

Xu et al. Concentration-Dependent Response of Soil Parameters and Functions to Trifluoroacetic Acid. *Eur. J. Soil Sci.* 2022, *73* (4),

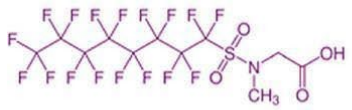
No. e13266.Chen et al. *Environ. Sci. Technol.* **2018**, *52* (15), 8263− 8271

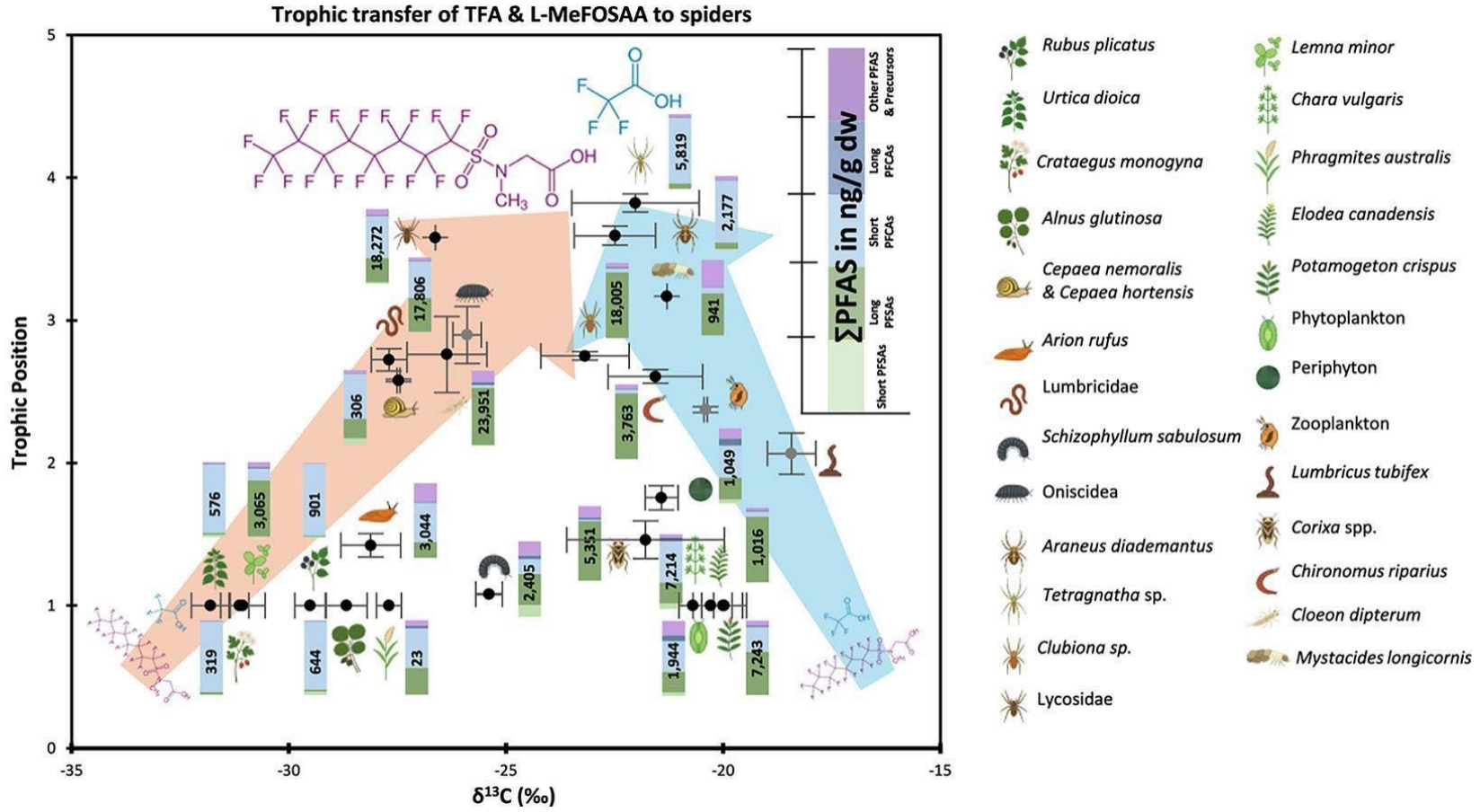
TFA biomagnifies to spiders in terrestrial food webs

TFA



L-MeFOSAA



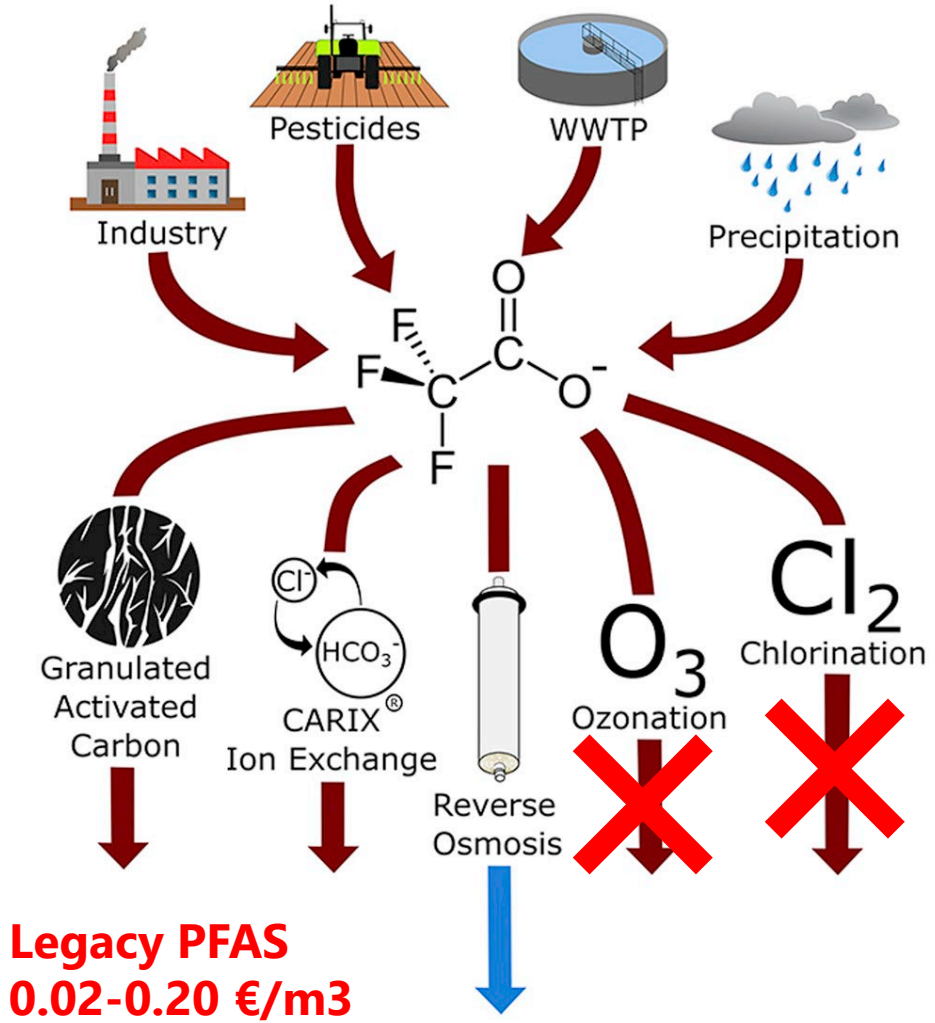


Gkika et al. Environment International 215 (2026) 110439

Technological and cost limitations

- **Enhanced degradation techniques** (ozonation, chlorination, photolysis, electrolysis, incineration, pyrolysos etc.) **can lead to TFA formation from precursors** (along with other PFAS, F-gases)
- Sorption techniques (activated carbon, ion exchange resins) -> **do not filter TFA**
- **Reverse osmosis** only technique that works for TFA, but requires an expensive destruction step for brines

- TFA removal from water is Reverse Osmosis followed by Supercriticial water oxidation (ca 8 €/m^3)



Scheurer et al. (2017). *Water research*, *126*, 460-471.

Costs of Remediation

Legacy PFAS: existing hotspots of long-chain PFAS

Emerging: Ongoing emissions of new PFAS like TFA



PFAS | THE COST OF INACTION

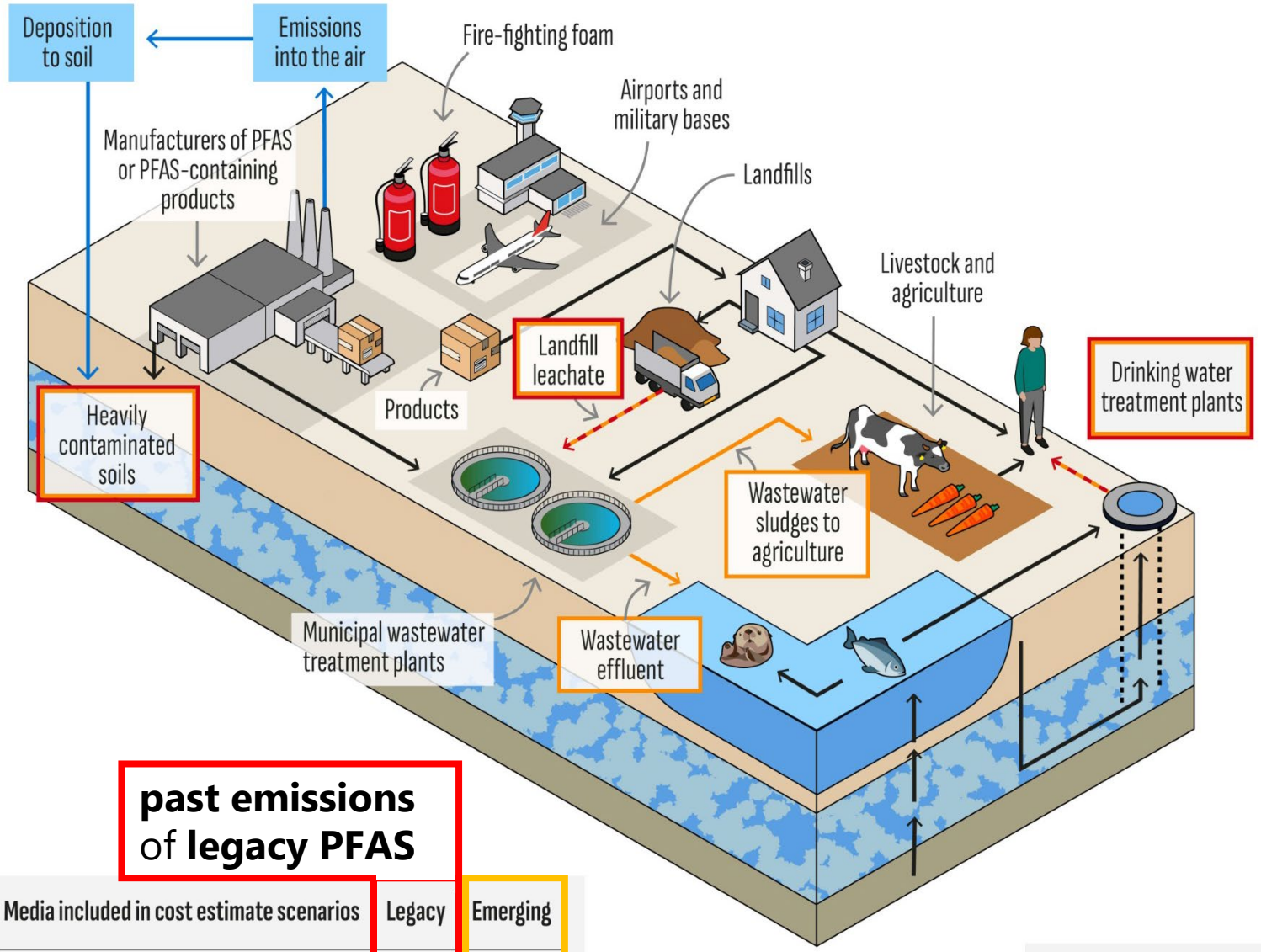
LES DÉCODEURS • PFAS

PFAS: The astronomical cost of depolluting Europe

By Raphaëlle Aubert and Stéphane Horel (with Eurydice Bersi [Reporters United])

Published on January 14, 2025, at 5:55 am (Paris), updated on January 14, 2025, at 4:21 pm

8 min read Lire en français



past emissions of **legacy PFAS**

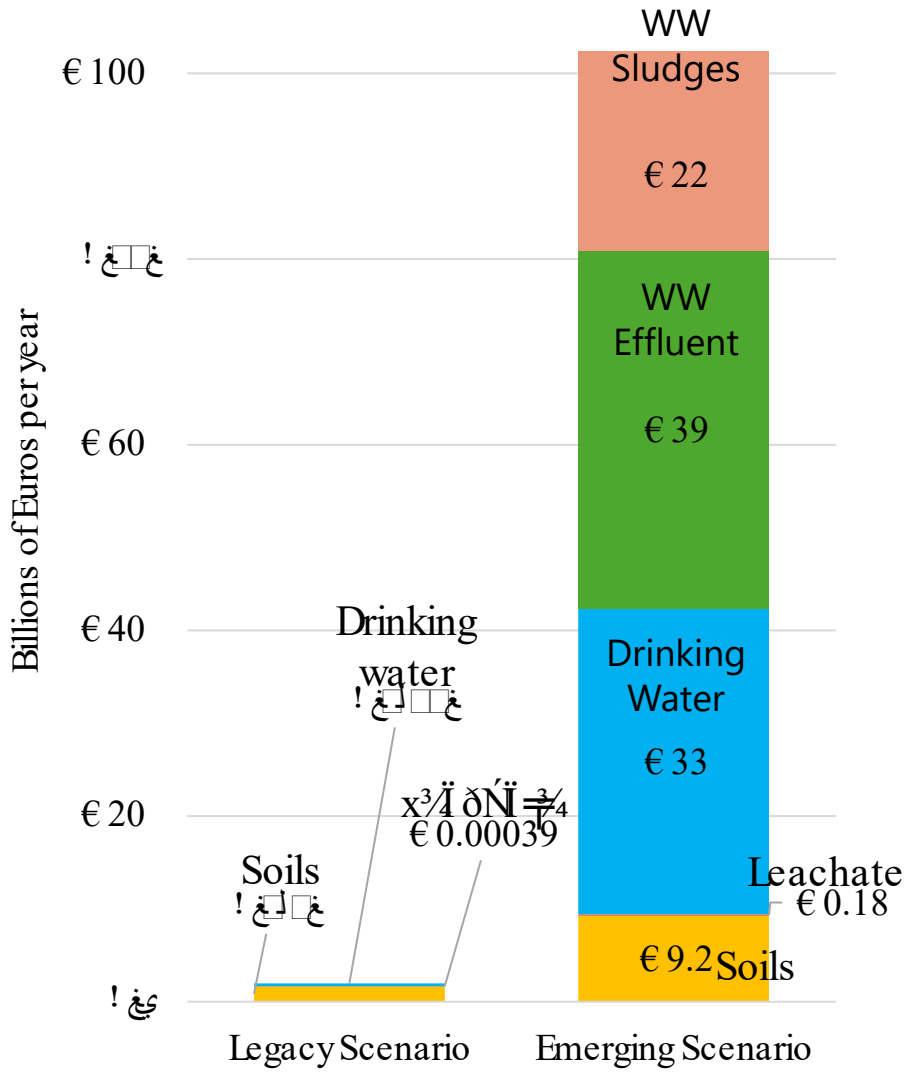
Media included in cost estimate scenarios	Legacy	Emerging
Heavily contaminated soils	X	X
Drinking water	X	X
Landfill leachate	X	X
Wastewater effluent		X
Wastewater biosolids sent to agriculture		X

ongoing emissions of **all PFAS**

Treatment applications not included in cost estimates:

– industrial wastewater
– industrial air emissions
– ambient soil and water

Emerging costs are unaffordable



About €100B/year for emerging scenario, aggressive remediation and targeting TFA removal

- Mostly from wastewater

When targeting TFA, drinking water costs increase by factor of 100:

- More utilities have TFA (20x)
- Removing TFA more expensive than long-chains (5x)

Removal can only address 0.02% - 2% current emissions

Total 3-50 tons/year addressable through aggressive remediation

REACH Annex XV Documents: 2,800-12,500 tons/yr emission

Application	PFAAs and PFAA precursors (t/y)		
	low	mid	high
Manufacture	54	86	118
TULAC[b]	2 058	6 177	10 295
Food contact materials and packaging	123	491	858
Metal plating and manufacture of metal products[c]	0.5	6	11.4
Consumer mixtures			
Cosmetics			
Ski wax			
Applications of fluorinated gases[d,e]			
Medical devices	128	239	350
Transport[d]			
Electronics and semiconductors	348	513	677
Energy sector	42	42	42
Construction products	88	152	216
Lubricants	0.11	0.6	1.1
Petroleum and mining[c]	0.3		2.3
TOTAL[f]	**2 842**	**7 707**	**12 571**
Total[g]	2 842	7 707	12 571

Annex XV Restriction Report, Table 1: https://echa.europa.eu/documents/10162/f605d4b5-7c17-7414-8823-b49b9fd43aea

Environmental Science Processes & Impacts

ROYAL SOCIETY OF CHEMISTRY

PAPER

Published on 06 July 2026
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Check for updates

Cite this: *Environ. Sci.: Processes Impacts*, 2026, **28**, 2092

PFAS remediation across Europe: costs and limited impacts

Alison L. Ling, *[a] Raphaëlle Aubert, [b] Eurydice Bersi, [c] Stéphane Horel[b] and Hans Peter H. Arp [de]

Planetary Boundary Threat of Persistent Synthetics

Disturbances to the «homeostasis» or of earth processes. Exceed this, Earth would leave the Holocene where humans evolved.

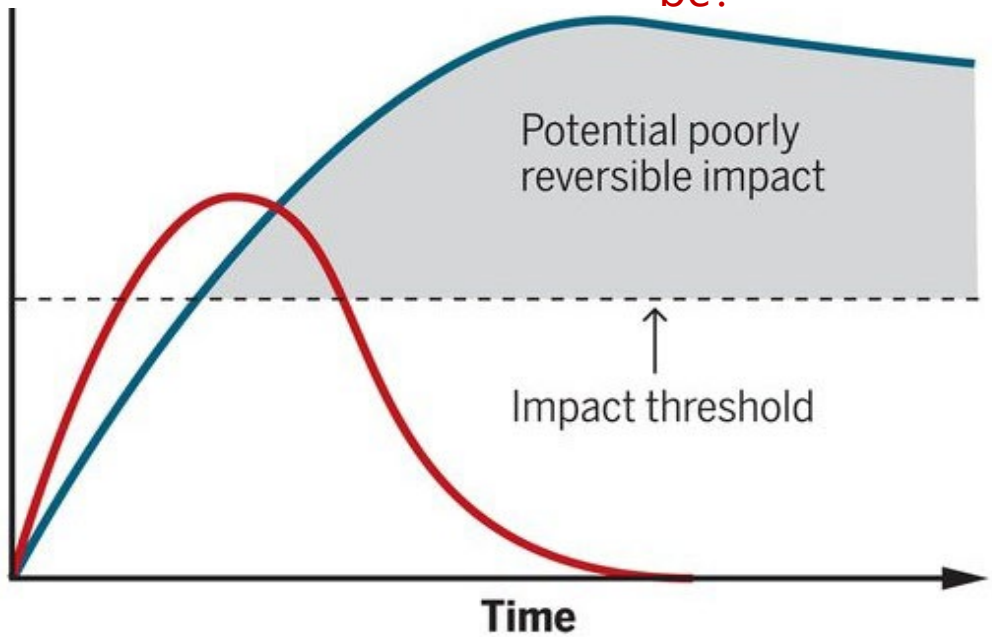
Conditions for novel entities:[1,2]

Condition 1: pollution disrupts a vital earth system process of which we are ignorant.
TRUE: impacts at hotspots occur now, ignorant of impacts from life-long intergeneration exposure (ignorant)

Condition 2: disruptive effect is not discovered until …manifested at a global scale
TRUE: Concentration increases globally

Condition 3: impacts are poorly reversible because level of global pollution cannot be readly reduced
TRUE: Stockpiles of sources exist and degrade slowly. Most PFAS and TFA and many plastics we emit will exist in water for the future of earth

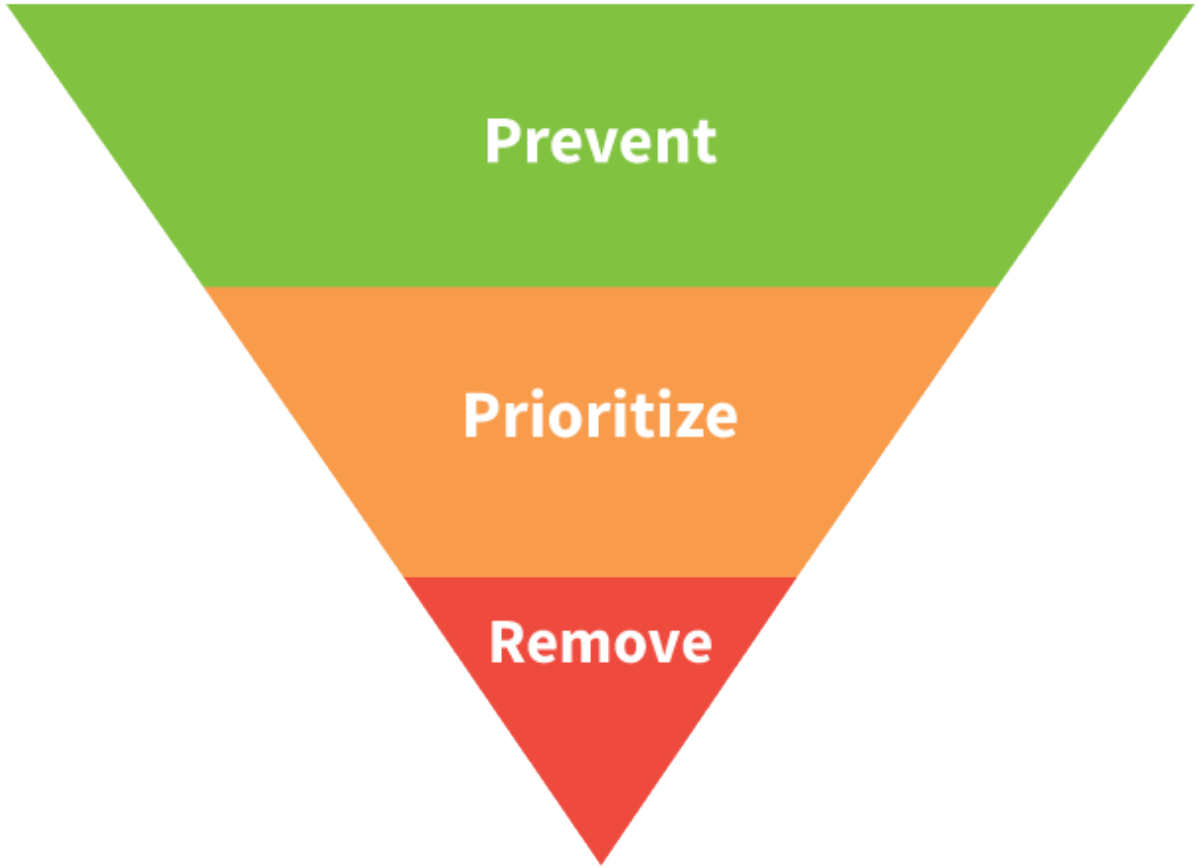
Impacts persist even after phase-out due to latency. What will the severity be?



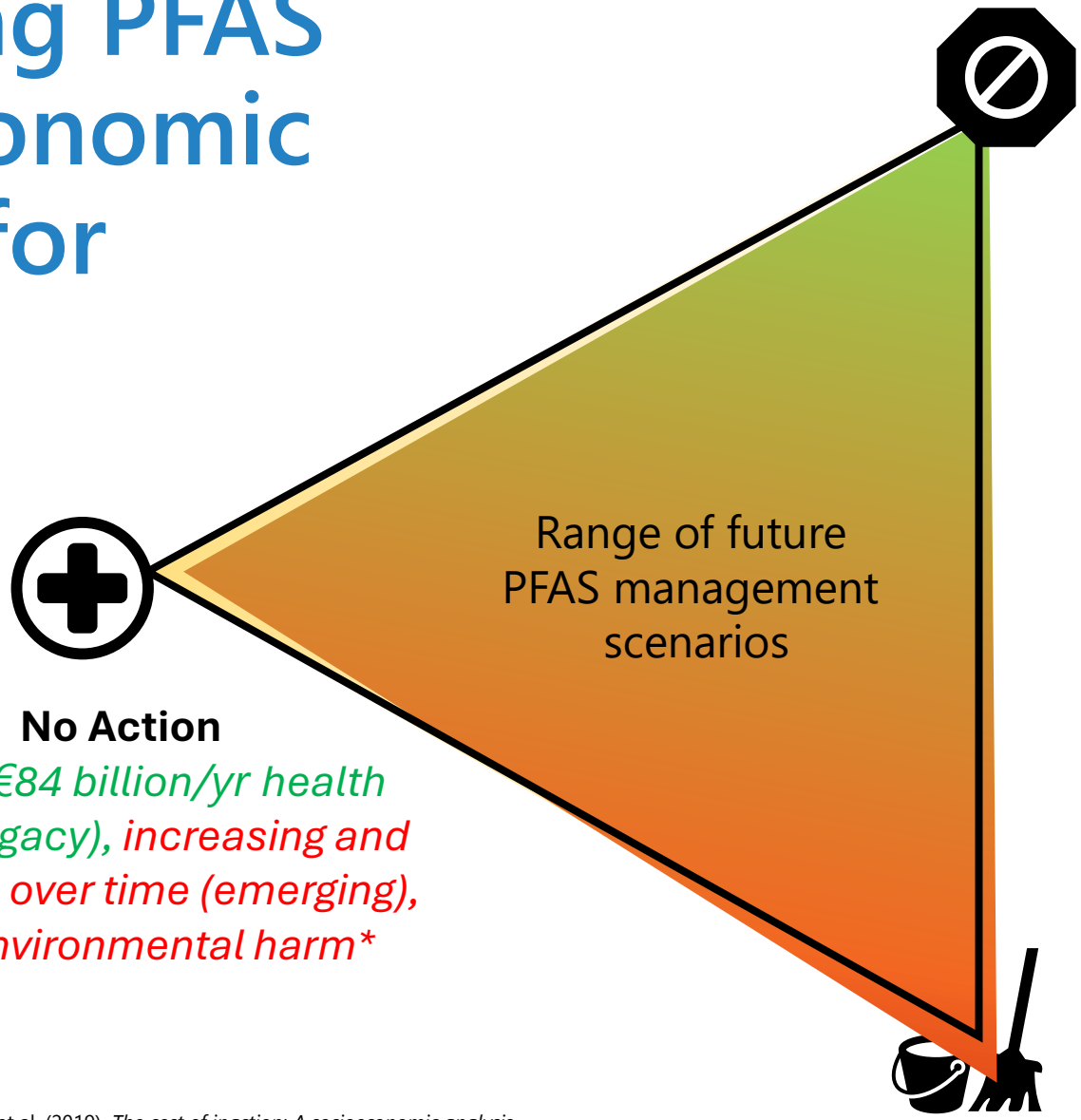
TFA, PFAS, Plastic emissions

1. Persson et al. *Environ. Sci. Technol.* **2013**, *47* (22), 12619− 12622
2. MacLeod et al. *Science* 373,61-65(2021)

The solutions



Reducing PFAS only economic opiton for society



No Action

*€52 to €84 billion/yr health costs (legacy), increasing and unknown over time (emerging), plus environmental harm**

Reduce PFAS Use and Emissions

€100 to €100,000/kg PFAS reduced.
€1 to €6 billion/yr remediation (legacy)

Remediation after Release to Environment

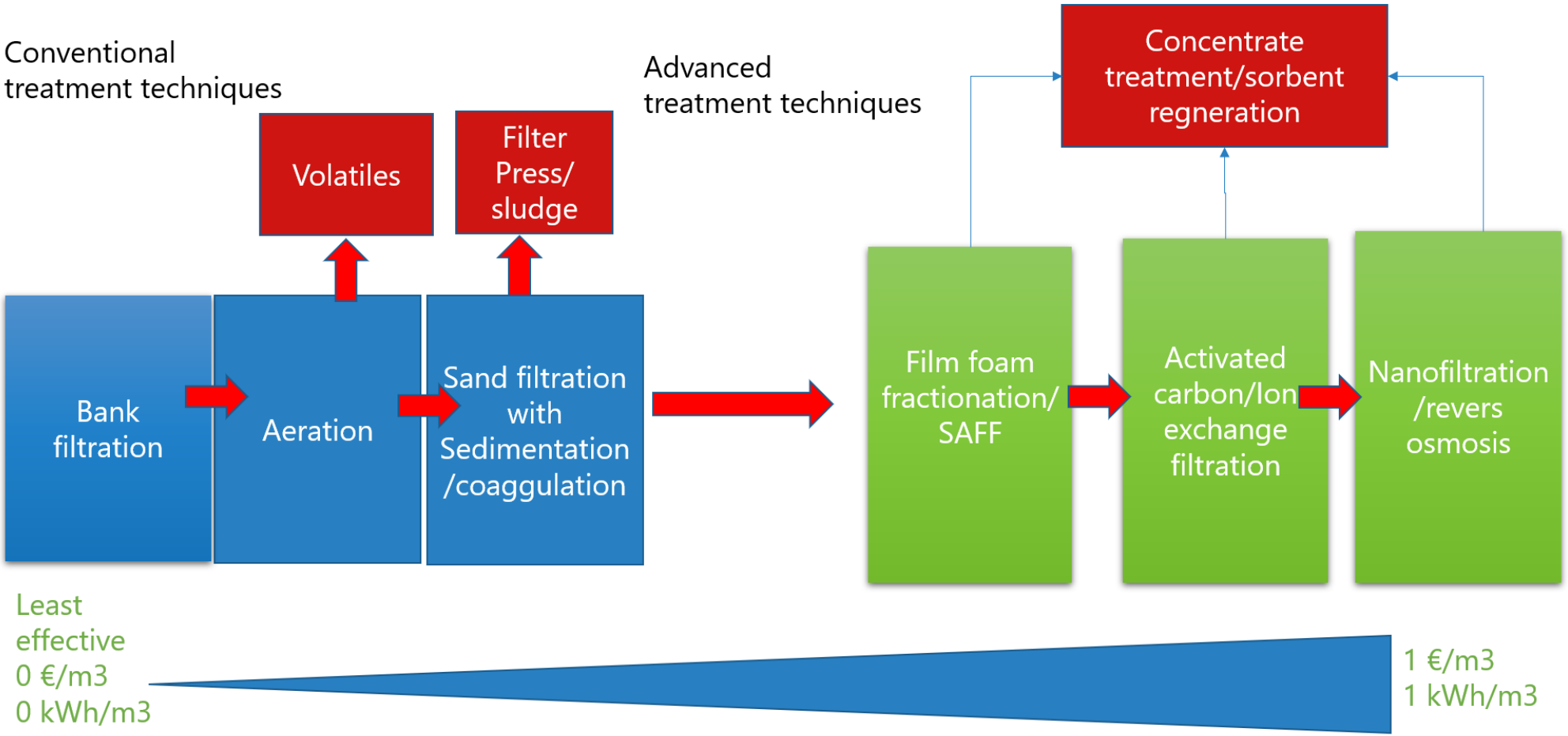
Financially unachievable.
€1 to €90 million/kg PFAS removed and destroyed.
€52 to €200 billion/yr remediation (emerging) covers <2% of use

*Goldenman et al. (2019). *The cost of inaction: A socioeconomic analysis of environmental and health impacts linked to exposure to PFAS*. Nordic Council of Ministers.

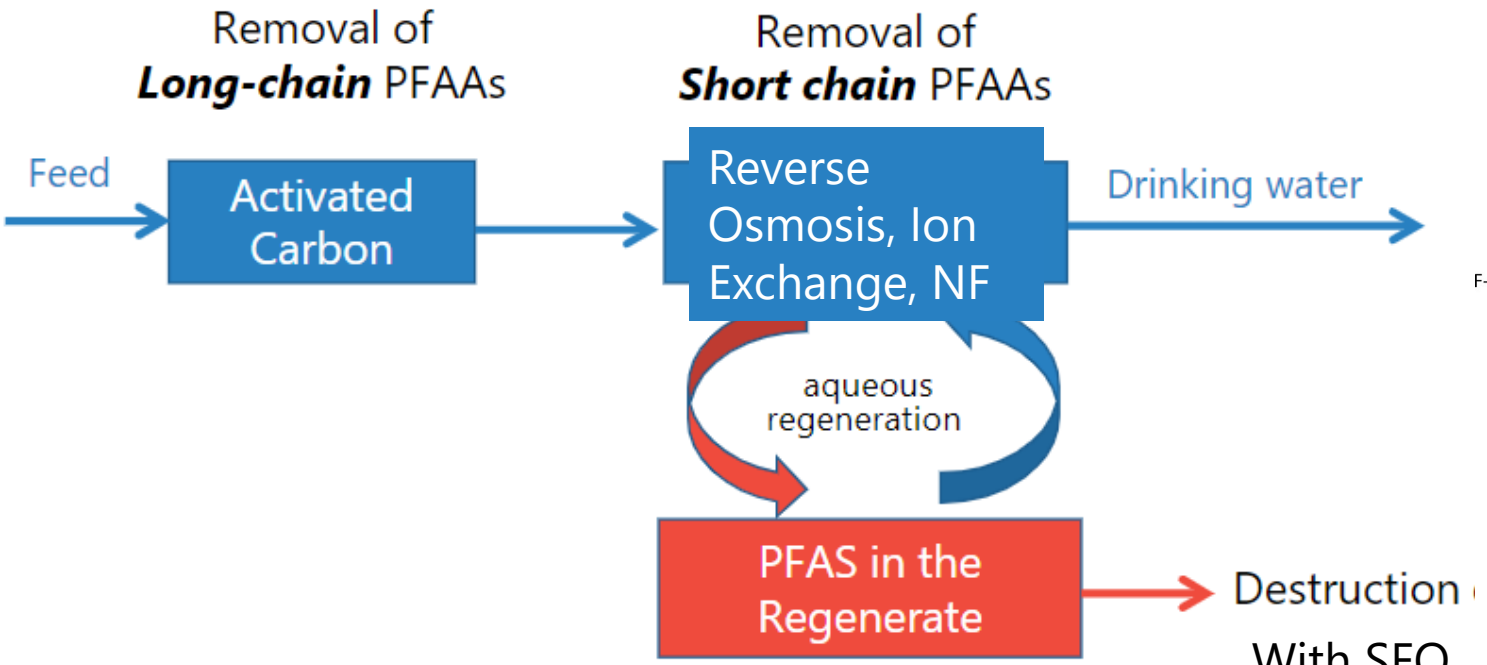
Toxic-Free Heirarchy

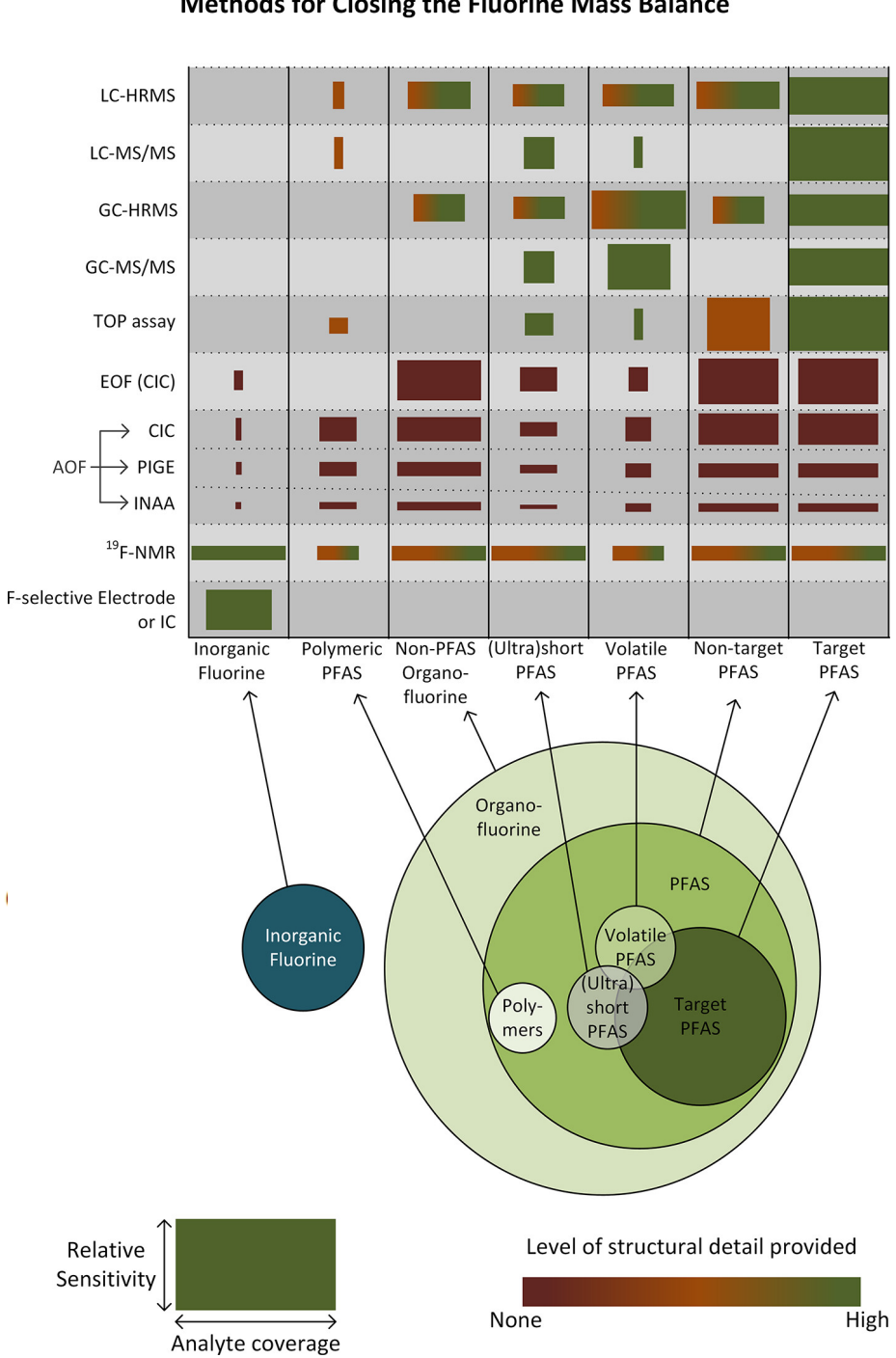


Improve removal technology through treatment train opitimization



Optimize separation and destruction; though ensure mass balance of PFAS

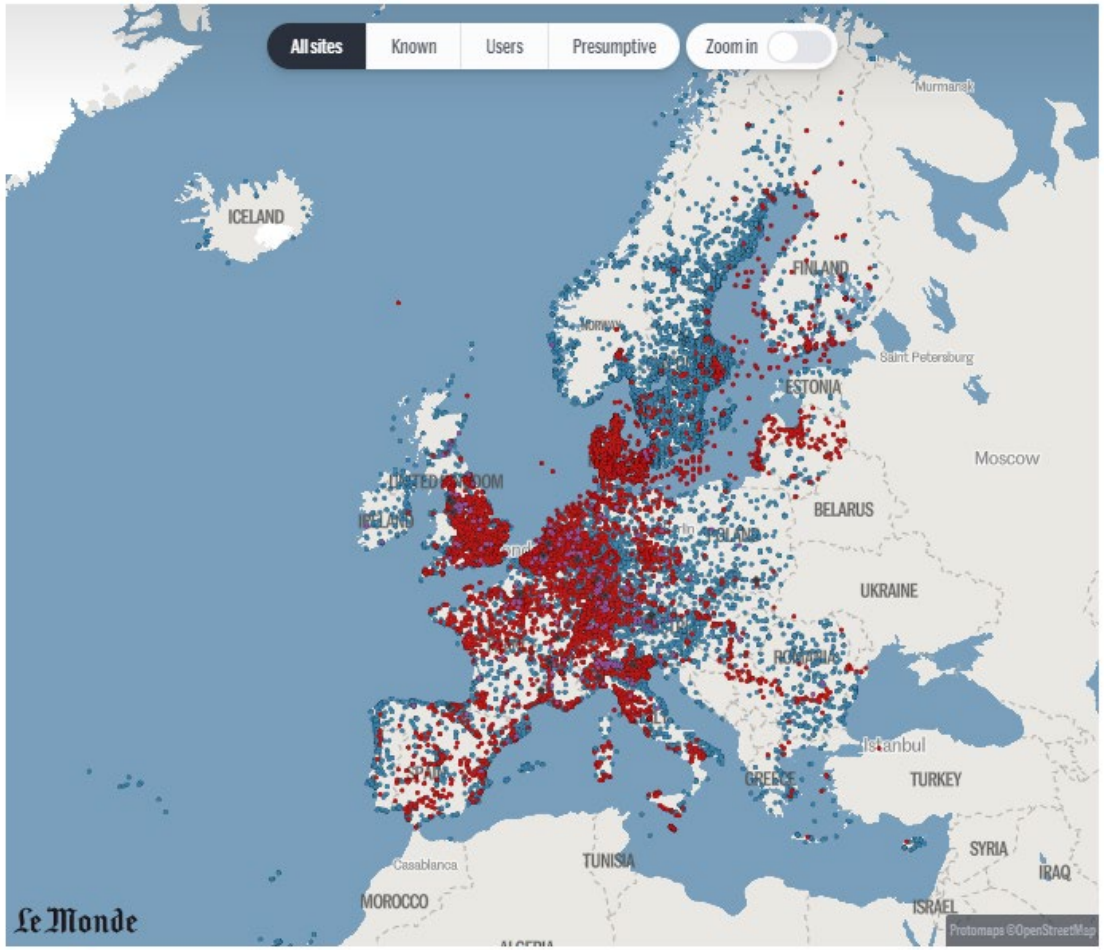




Lukas Lesmeister, ZeroPM pieces #18 - Using ion exchange resins to clean PFAS contaminated water - https://zenodo.org/records/10642824

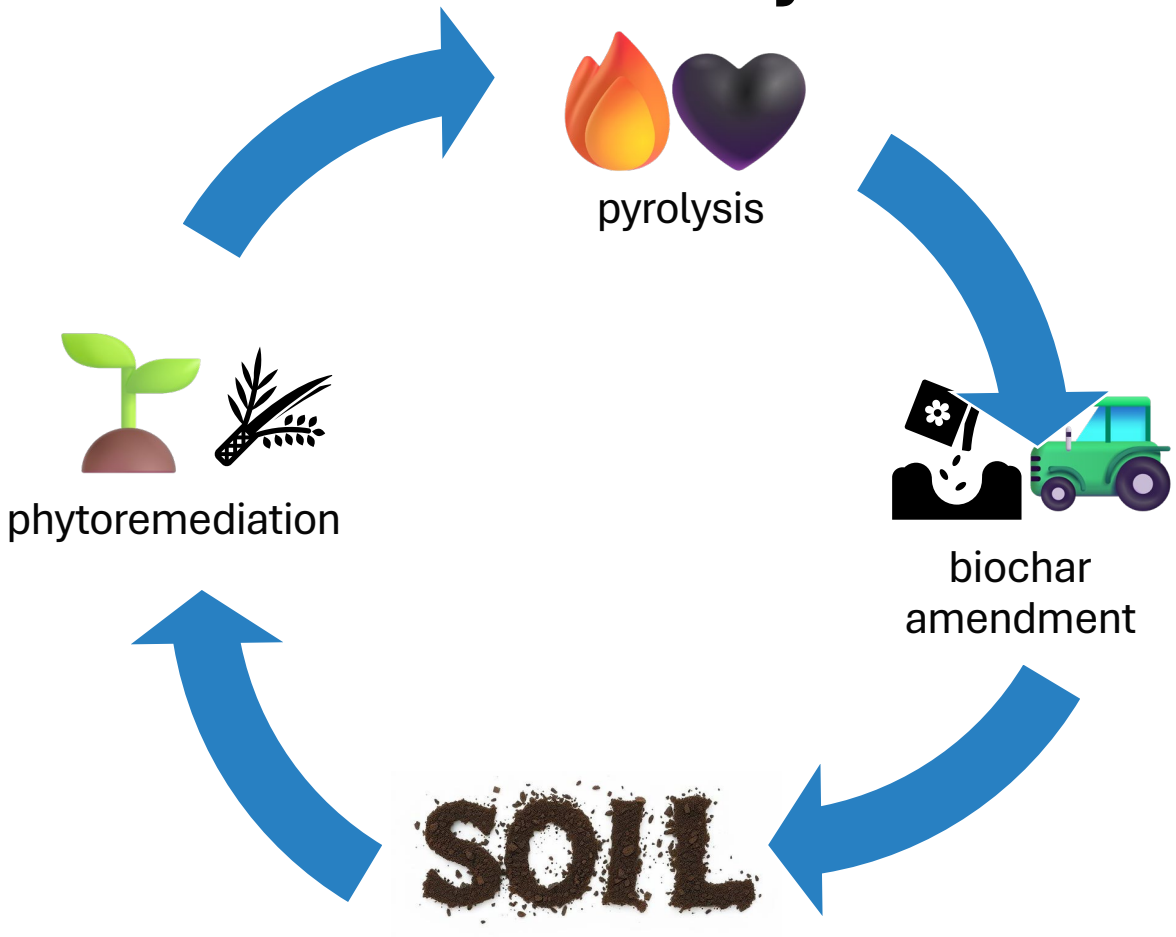
Smith et al. ES&T 2024
https://pubs.acs.org/doi/10.1021/acs.est.3c10617

Pyrolysis and soil pollution



Large number PFAS contaminated soils, including agricultural areas

The virtuous cycle



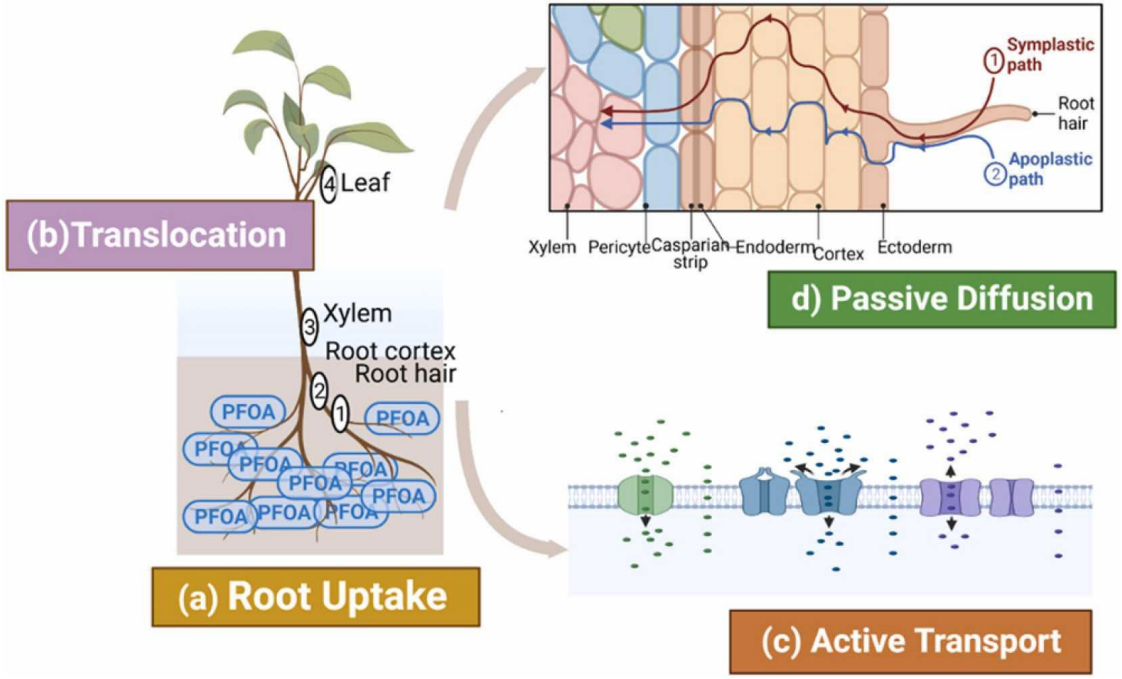
JOURNAL OF AGRICULTURAL AND FOOD CHEMISTRY
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pubs.acs.org/JAFC
Viewpoint

A Virtuous Cycle of Phytoremediation, Pyrolysis, and Biochar Applications toward Safe PFAS Levels in Soil, Feed, and Food

Gerard Cornelissen,* Nathalie Briels, Thomas D. Bucheli, Nicolas Estoppey, Andrea Gredelj, Nikolas Hagemann, Sylvain Lerch, Simon Lotz, Daniel Rasse, Hans-Peter Schmidt, Erlend Sørmo, and Hans Peter H. Arp

Cite This: *J. Agric. Food Chem.* 2025, 73, 3283–3285
Read Online

Step 1: Plant Uptake of PFAS (Phytoremediation)



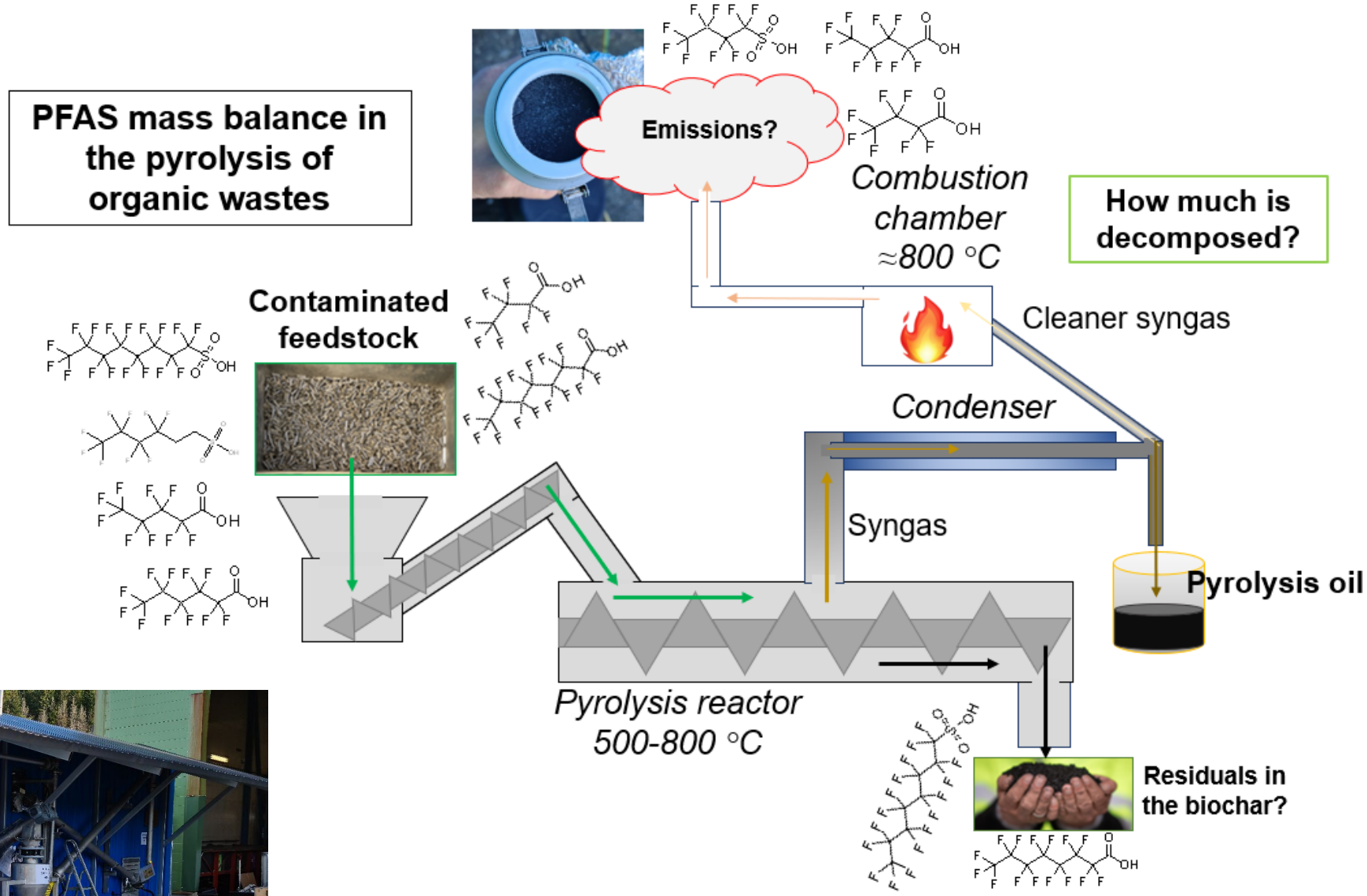




NGI field trial at a PFAS factory site in Belgium

Adu et al. (2023) J. Haz. Mat.130805 https://doi.org/10.1016/j.jhazmat.2023.130805
Mei et al. (2021) Env. International. 106642
https://doi.org/10.1016/j.envint.2021.106642

Pyrolysis to mineralize > 96% of PFAS





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

Boiling points deciding factor → volatilized or decomposed[2]

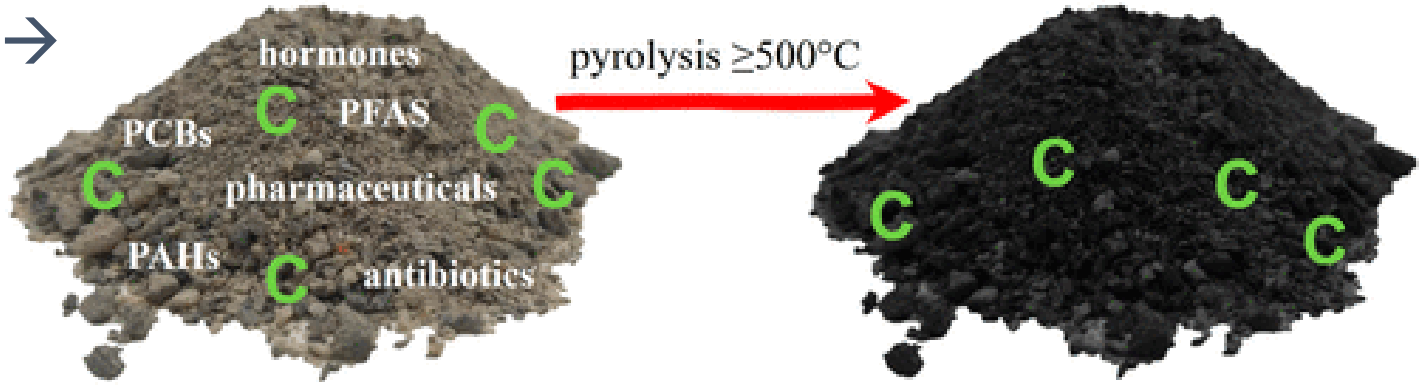


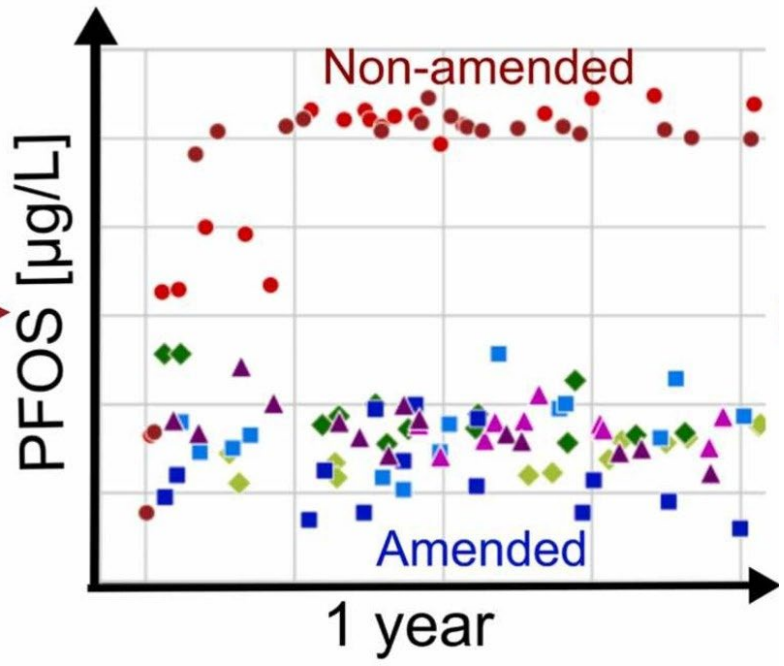
Figure: Buss (2021) ACS Sust Chem. Eng. https://doi.org/10.1021/acssuschemeng.1c03651

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

Step 3: Field testing of biochar



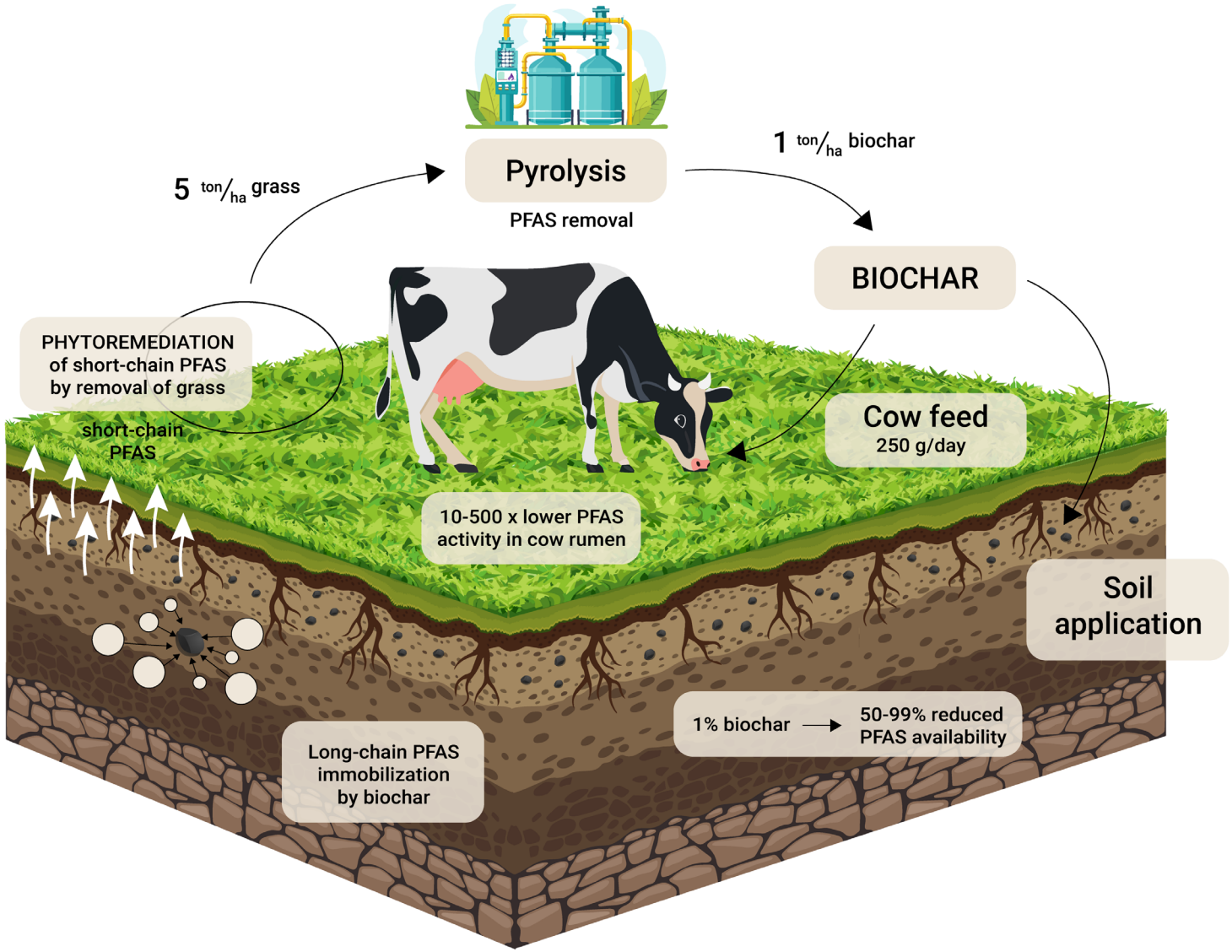


No biochar
PFOS leached in less than 1 year

With Biochar
PFOS immobile in soil for > 100 years

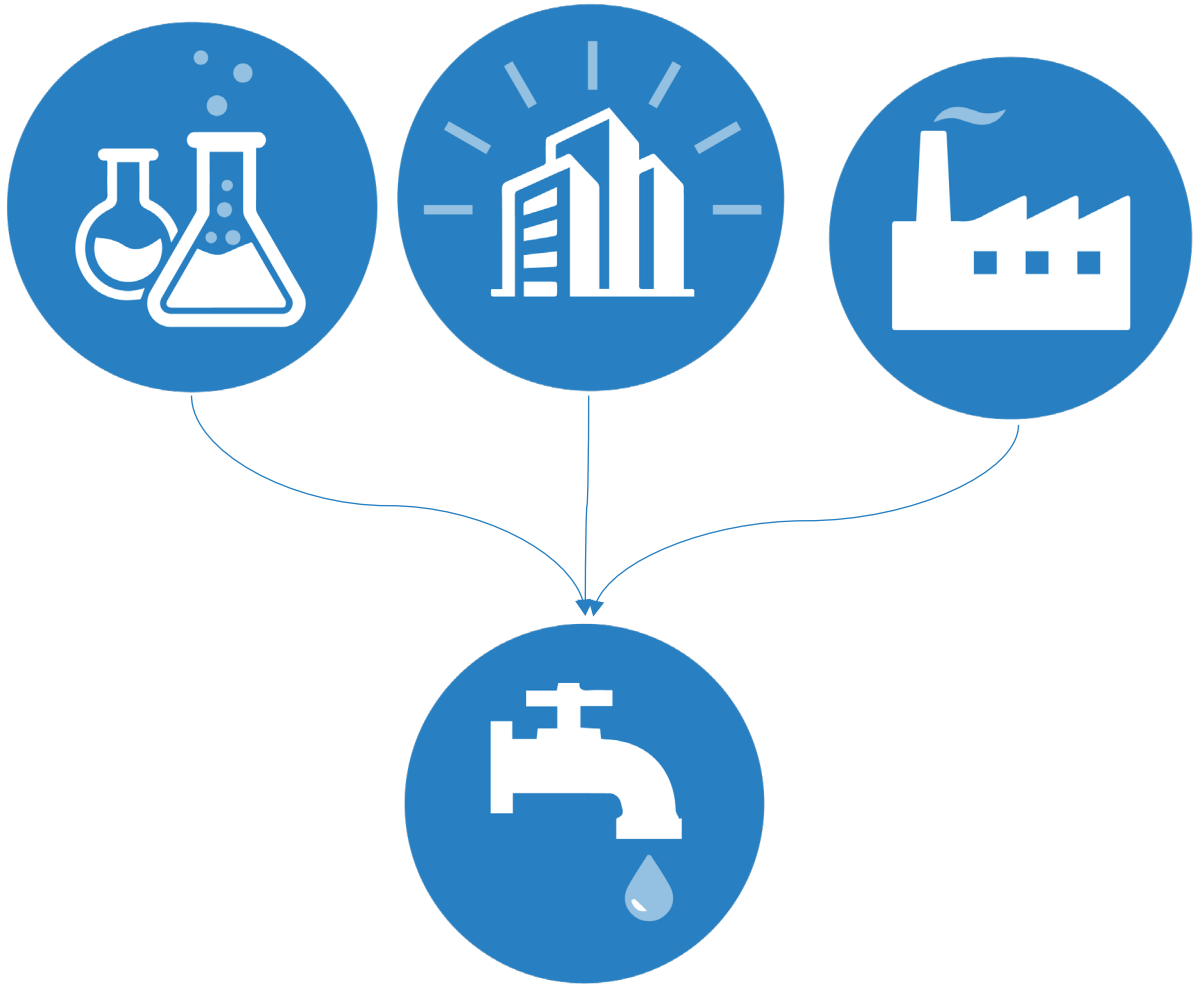
Hubert et al, J Haz Mat 2025

Repeating the cycle to turn contaminated land to arable land



Prioritize

Remove at source, rather than downstream





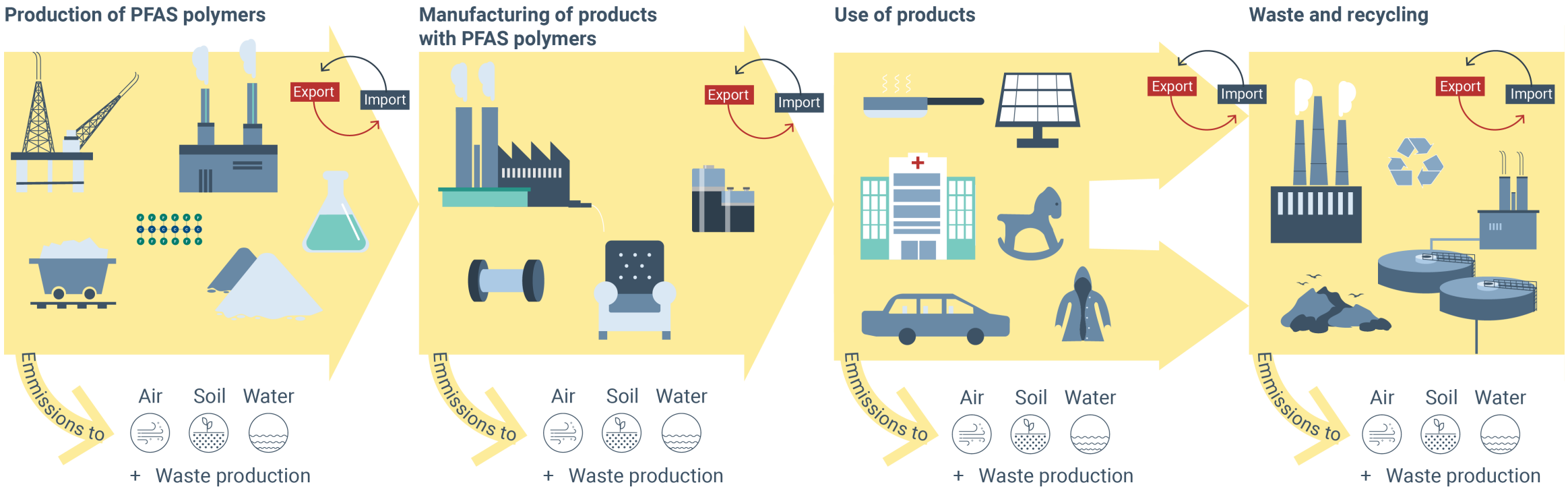
Lo stabilimento Miteni di Trissino, in provincia di Vicenza (Foto Federico Bevilacqua)

https://lavialibera.it/it-schede-2139-pfas_in_europa_40_anni_di_inquinamento_ma_il_profitto_vince_su_tutto

- More downstream is more inefficient

- Strong leadership
- Clear policy
- Citizen participation
- Socioeconomics
- Environmental sociologists

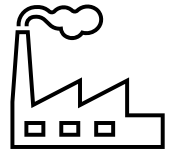
The rising problem of pollutants in the supply chain



Identify, prevent and remove PFAS from supply chains to enable a circular economy, including fluoropolymers

EEA, 2025 - https://www.eea.europa.eu/en/analysis/publications/pfas-polymers-in-focus

Effective labelling what products use TFA



PFAS production

and products

How do PFAS labels affect consumer intentions?

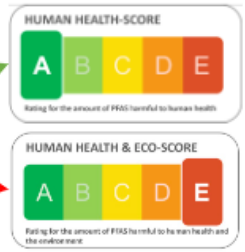
N = 450

- Prelim data (subject to updates!)
- No effect of framing on WTB (eco, health or eco-health).
- Big effects of rating (Control vs. A; Control vs. E).

Contrasts and Estimates (H_{1a})

Rating Label	β	*SE*	*z*	*p*
Control vs A Rating	-0.558	0.057	-9.845	< .001***
Control vs E Rating	1.832	0.059	30.830	< .001***
A Rating vs E Rating	2.390	0.083	28.845	< .001***

Note: The table provides estimate pairwise comparisons for all contrasts (β), along with the





29% of Europeans **have previously heard of the term PFAS**, also known as 'forever chemicals'

When given the definition of PFAS, also known as 'forever chemicals'...



81% of citizens are concerned about the potential **health effects when exposed to PFAS**

16% Disagree

While **84%** of citizens are concerned about **the effects of PFAS on the environment**



13% Disagree

Source: Special Eurobarometer 550 – "Attitudes of Europeans to the environment" Fieldwork: March-April 2024
* The figures show the top-3 most frequently cited items out of 8 options
** The figures show the top-3 most frequently cited items out of 5 options

Ellise Suffill, ZeroPM pieces #17 - Expert & non-expert perceptions on PFAS & essentiality in everyday products. https://zenodo.org/records/10628255

Updated Prioritized PFAS monitoring lists and recommended thresholds

- TFA included in surface water regulation (max 2.2 µg/L)
- 43 PFAS included for monitoring in EU Soil Monitoring and Resilience Directive
- Suggest guidelines for water/sludge reuse



ARAGORN coordinates expert recommendation on Monitoring of PFAS in Europe's soils

News

New expert recommendations coordinated by ARAGORN and ZeroPM support the EU's Soil Monitoring Directive with practical, cost-effective methods to detect and prevent toxic chemical pollution.

Environmental Science & Technology Letters

pubs.acs.org/journal/estlcu

Highlight

Urgency to Propose Normative Soil Limits for Per- and Polyfluoroalkyl Substances Targeting PFOA and PFOS

Sébastien Sauvé* and Hans Peter H. Arp*

Environ. Sci. Technol. Lett. 2026, 13, 862−864

Link: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32026L0805

Prevent

ECHA PFAS Restriction Proposal

	No derogation (for certain identified sub-use(s))	Derogation proposed or for consideration (for certain identified sub-use(s))	Length of proposed / considered derogation	
			5-year	12-year
TULAC (textile, upholstery, leather, apparel and carpets)	✓	✓	✓	✓
Food contact materials and packaging	✓	✓	✓	
Metal plating and manufacture of metal products	✓	✓	✓	
Consumer mixtures	✓			
Cosmetics	✓			
Ski wax	✓			
Applications of fluorinated gases	✓	✓	✓	✓
Medical devices	✓	✓		✓
Transport		✓	✓	✓
Electronics and semiconductors	✓	✓		✓
Energy sector		✓	✓	
Construction products	✓			
Lubricants		✓		✓
Petroleum and mining	✓	✓		✓

Note – graphic form 2023 used for illustrative purposes
Source: ERM
https://www.erm.com/insights/eu-reach-restrictions-how-to-prepare-for-the-proposed-pfas-restriction/

To address to the changing world we must adapt through innovation without PFAS

BBC

Air conditioning creates political divide after France records hottest day

1 hour ago

Hugh Schofield
Paris correspondent



Only about 25% of homes in France have an air-con unit

With temperatures soaring, France is being forced to re-think its longstanding reservations about one possible answer to climate change: air-con.

US environmental groups urge EPA to reject new Pfas to cool datacenters



The Chemours Company's PPA facility at the Fayetteville Works plant near Fayetteville, North Carolina, in 2018. Photograph: Gerry Broome/AP

Tom Perkins
https://www.theguardian.com/us-news/2026/jul/27/pfas-datacenter-cooling-epa

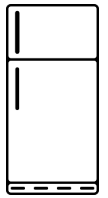
Progress: *Ban on PFAS foams to put out fires*



https://en.wikipedia.org/wiki/Firefighting_foam#/media/File:Firefighters_spray_foam.jpg

Solution to F-gases used as refrigerants

Fifth generation of F-gases in the Montreal Protocol can be free of TFA precursors



Refrigerants and blowing agents

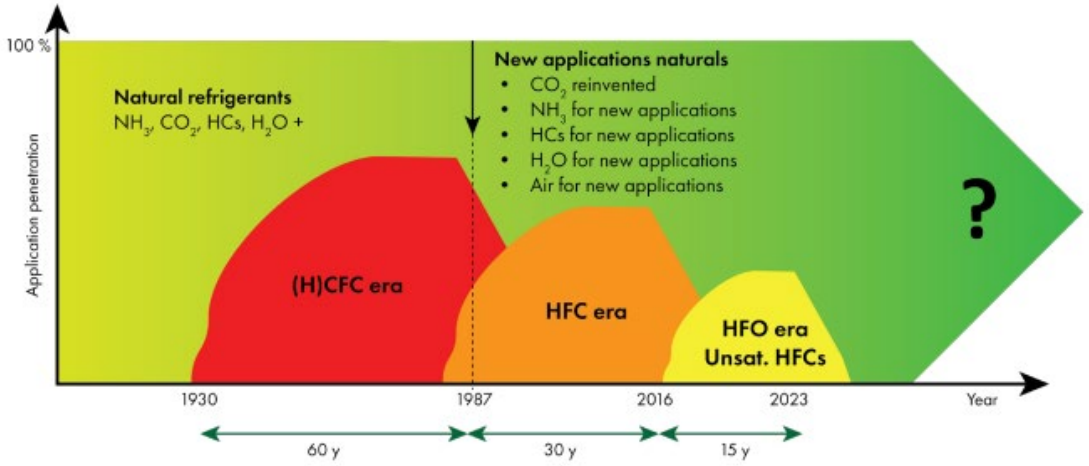
Refrigeration | Indoor Climate | Miscellaneous








	CO_2	Ammonia	Propane	Isobutane	Others
Domestic refrigeration				X	
Stand-alone refrigeration systems in commercial stores	x	x	X	x	x
Multipack centralized refrigeration systems in commercial stores	X	x	x		
Industrial refrigeration	x	X			
Transport refrigeration of goods	x		x		x
Ultra-low and low temperature freezers		x	x		x



Environmental Science Processes & Impacts

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CRITICAL REVIEW

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Cite this: *Environ. Sci.: Processes Impacts*, 2024, **26**, 1955

Finding non-fluorinated alternatives to fluorinated gases used as refrigerants†

Juliane Glüge, ‡*[a] Katharina Breuer, ‡[b] Armin Hafner,[c] Christian Vering,[b] Dirk Müller,[b] Ian T. Cousins,[d] Rainer Lohmann,[e] Gretta Goldenman[f] and Martin Scheringer[a]

Petter NEKSÅ
DOI: 10.18462/iir.gl2024.1295

Full conversion to natural refrigerants - Feasible and likely to happen?

Solution to TFA from Pesticides and Pharmaceuticals



The Danish Environmental Protection Agency has withdrawn the approval of 8 more pesticides that contain PFAS active substances. They can form and leach TFA into the groundwater. Pesticides approved for use in Denmark must not pose a risk to groundwater. In June, they already banned 25 other products. PFAS pesticides that have not yet been directly linked to TFA are still allowed in Denmark. The Danish Nature Conservation Organisation applauds the decision but calls for a swift ban of the other PFAS pesticides, especially the very harmful insecticide lambda-cyhalothrin.



PERSISTENT POLLUTANTS

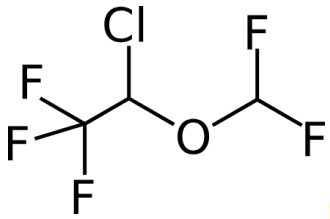
Are fluorinated drugs PFAS?

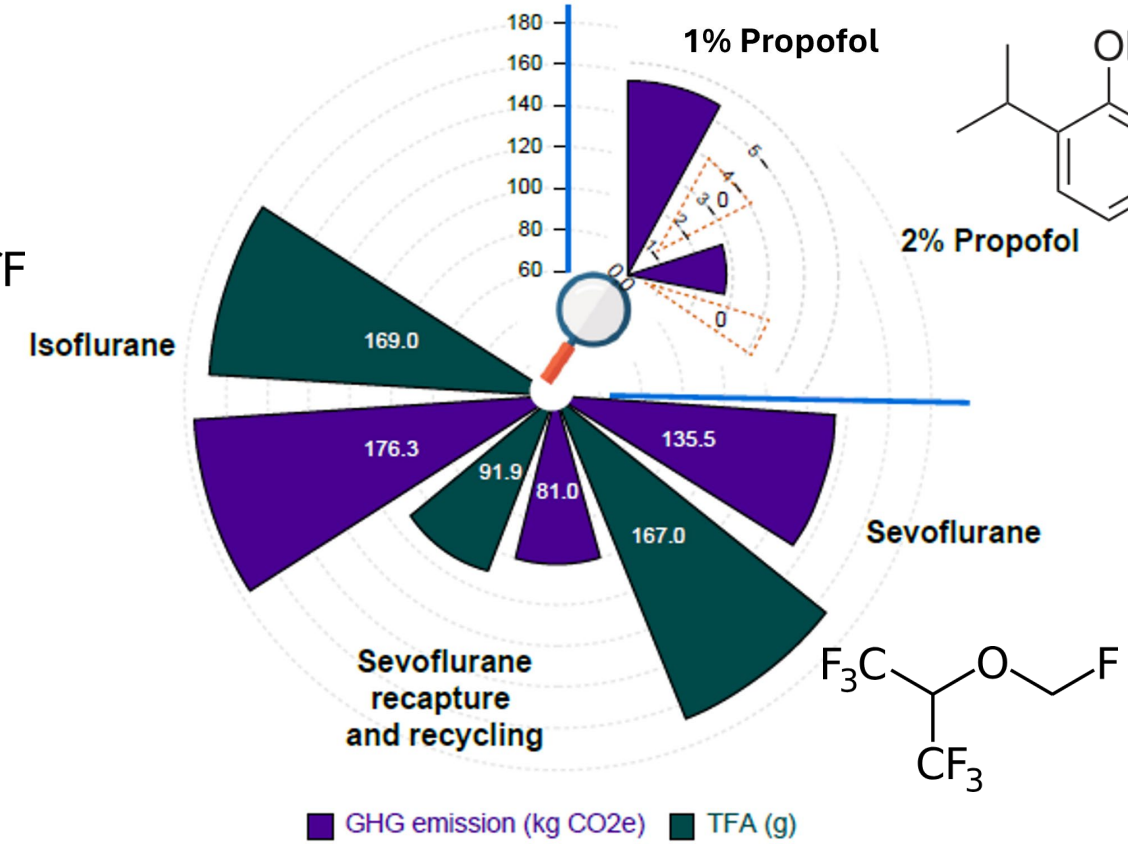
Proposed regulations in the European Union present an uncertain future for pharmaceuticals and agrochemicals—and motivation to design greener ones

BRIANNA BARBU, C&EN STAFF

- Biodegradable, non-fluorinated drugs an active area of «green pharmacy» innovation
- Evaluate switching to PFAS free alternatives when recommending medications

When two treatments give the same patient outcomes, choose the most enviornmentally friendly one





Propofol anasthesia has minimal GHG impacts and no PFAS pollution compared to isoflurane and sevoflurane

BJA

British Journal of Anaesthesia, 137 (3): 902–904 (2026)

CORRESPONDENCE

Inhaled sedation in intensive care units: a modelling study of the environmental impact

Nicolas Massart[1,*], Florence Boissier[2,3], Matthieu Bernat[4], David Grimaldi[5], Marie Lecronier[6], Julien Poissy[7], Erwan D'Aranda[8], Marc Leone[4], Hans P. Arp[9,10], Alain Kalmar[11] and Laurent Zieleskiewicz[4]

Provide tools for industry to find where and in what it is using TFA and other PFAS



The rap battle against PFAS
https://www.youtube.com/watch?v=1q06fUMT_U4

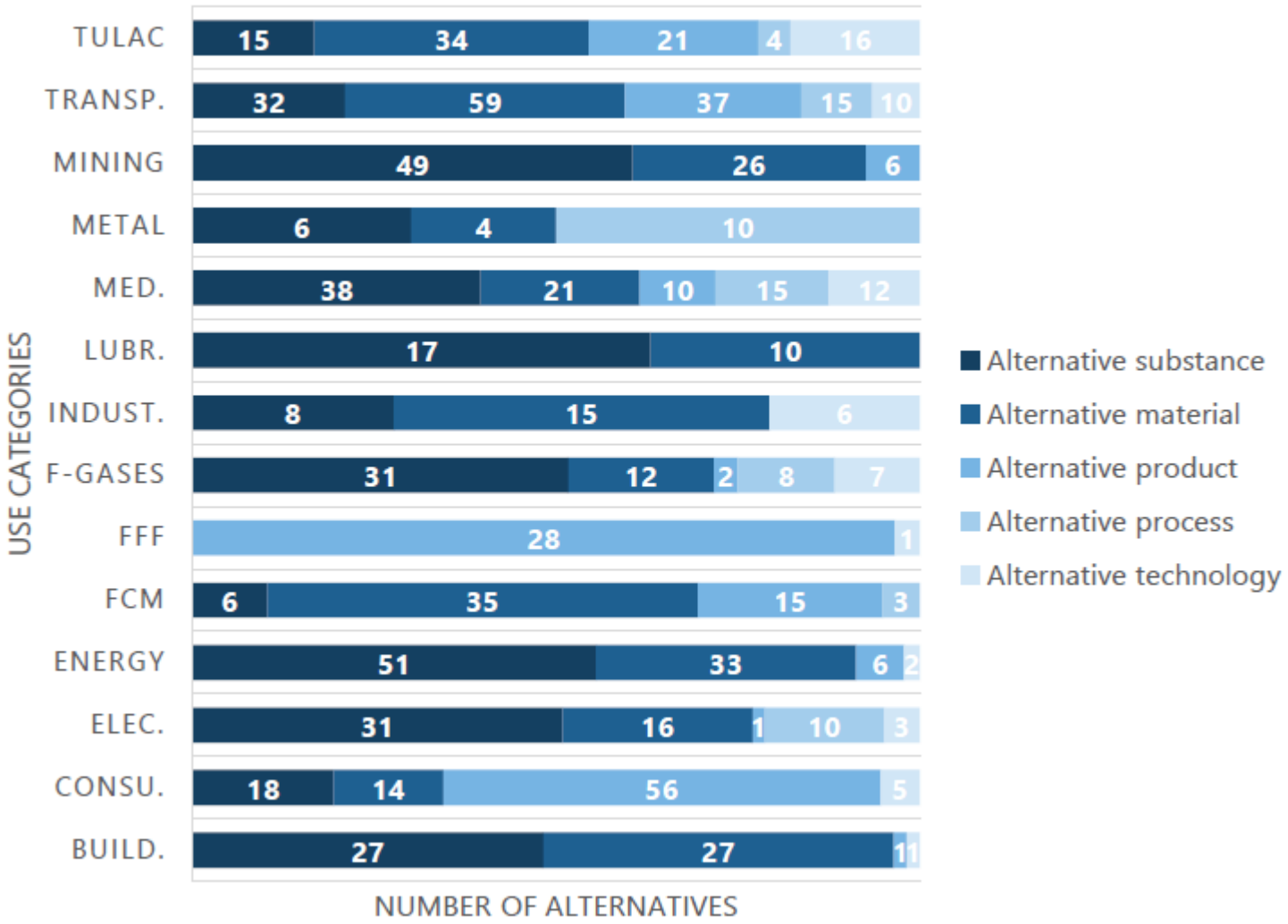


https://pfas.chemsec.org/



ZeroPM alternative assessment database

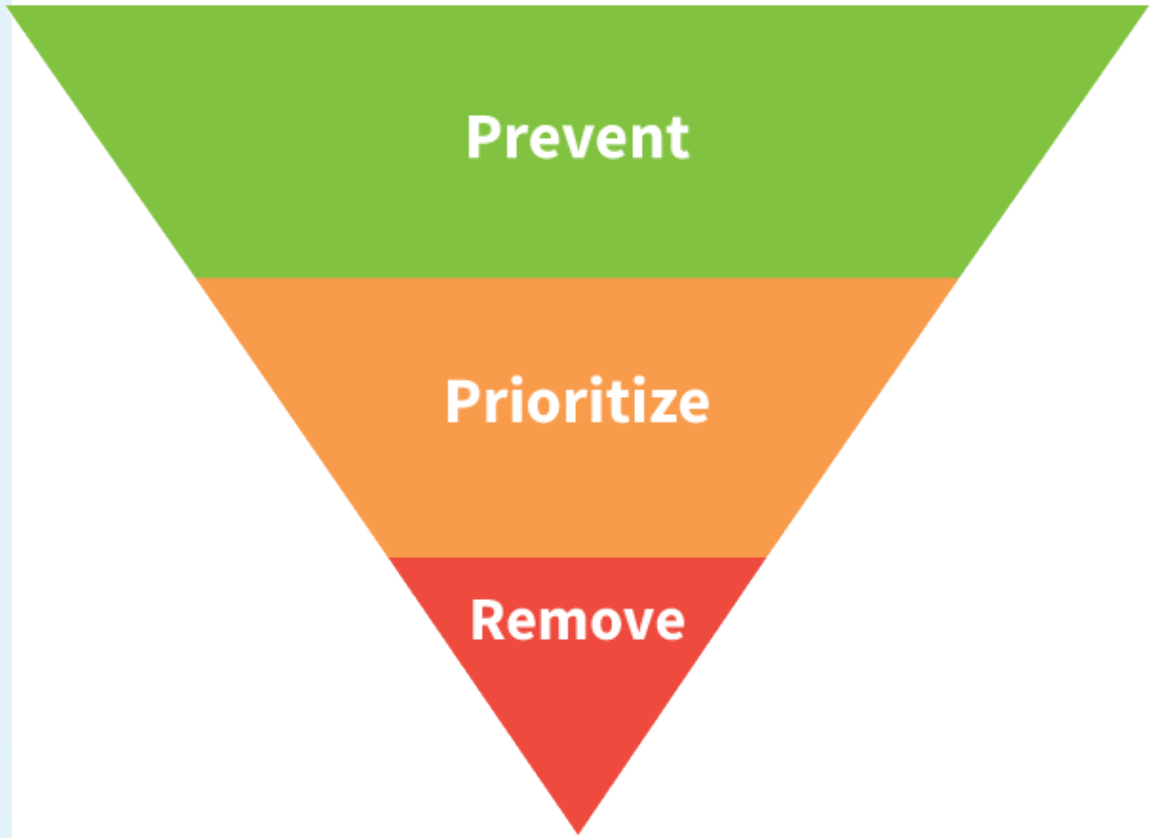
Find alternative for PFAS based on chemical function, end-use function, and function as a service





https://zeropm.eu/alternative-assessment-database/

How to confront the threat of persistent synthetic substances

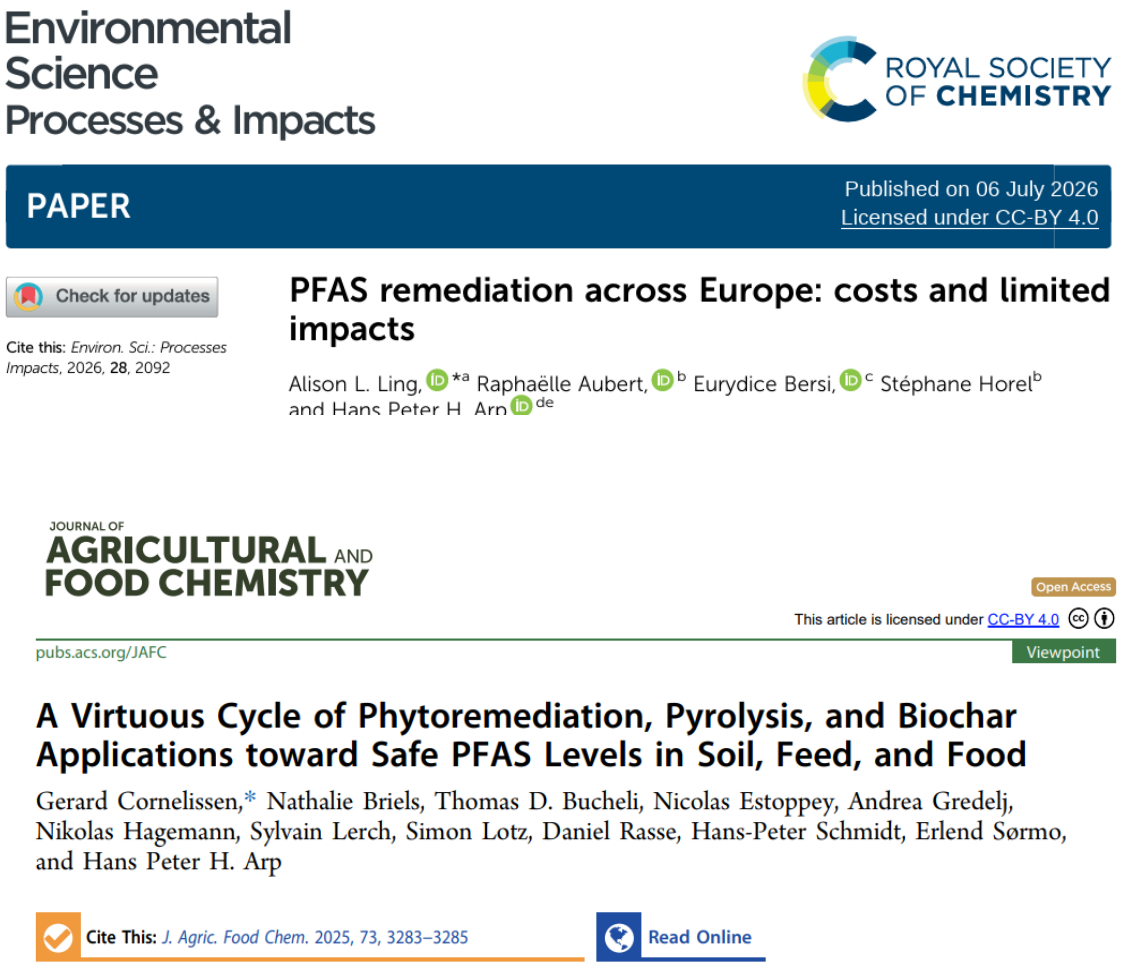


All you need is love and regulatory clarity to:

- Focus preventing uses and phasing out PFAS
- Identify largest PFAS emission sources to prevention and removal
- Remediate at the point of emissions and hot spots first with better techniques



Thank you!



Environmental Science Processes & Impacts

ROYAL SOCIETY OF CHEMISTRY

PAPER

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Cite this: *Environ. Sci.: Processes Impacts*, 2026, **28**, 2092

PFAS remediation across Europe: costs and limited impacts

Alison L. Ling, *[a] Raphaëlle Aubert, [b] Eurydice Bersi, [c] Stéphane Horel[b] and Hans Peter H. Arp [de]

JOURNAL OF AGRICULTURAL AND FOOD CHEMISTRY

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Viewpoint

A Virtuous Cycle of Phytoremediation, Pyrolysis, and Biochar Applications toward Safe PFAS Levels in Soil, Feed, and Food

Gerard Cornelissen,* Nathalie Briels, Thomas D. Bucheli, Nicolas Estoppey, Andrea Gredelj, Nikolas Hagemann, Sylvain Lerch, Simon Lotz, Daniel Rasse, Hans-Peter Schmidt, Erlend Sørmo, and Hans Peter H. Arp

Cite This: *J. Agric. Food Chem.* 2025, 73, 3283−3285

Read Online

Acknowledgments

ZerOPM — Prevent, Prioritize, Remove

aragorn

Thanks to funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101036756 and Horizon Europe Program under grant agreement 101112723

Thanks to the Research Council of Norway, through the joint-industry sustainability (BIA-X) project "Valorization of Organic Waste" (VOW) (NFR 299070) and the Miljøforsk project SLUDGEFFECT (NFR 302371);

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or REA. Neither the European Union nor the granting authority can be held responsible for them

Published in January 2025 in European News Outlets



Raphaëlle Aubert
Le Monde



Stéphane Horel
Le Monde



Eurydice Bersi
Reporters United



Ali Ling
St Thomas University



Me..
S

PFAS | THE COST OF INACTION

LES DÉCODEURS • PFAS

PFAS: The astronomical cost of depolluting Europe

By Raphaëlle Aubert and Stéphane Horel (with Eurydice Bersi [Reporters United])

Published on January 14, 2025, at 5:55 am (Paris), updated on January 14, 2025, at 4:21 pm

8 min read Lire en français

Cost to clean up toxic PFAS pollution could top £1.6tn in UK and Europe

Exclusive: Costs of UK cleanup will reach £9.9bn a year in UK if emissions of 'forever chemicals' remain uncontrolled

Industry using 'tobacco playbook' to fend off 'forever chemicals' regulation



The Guardian

US