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Evaluating Neutral PFAS for Potential Dermal Absorption from the Gas Phase

Per- and polyfluoroalkyl substances (PFAS) in consumer products: Current knowledge and research gaps

Synthesis Report on Understanding Side-Chain Fluorinated Polymers and Their Life Cycle

A global atmospheric chemistry model for the fate and transport of PFCAs and their precursors†

Degradation of Fluorotelomer Alcohols: A Likely Atmospheric Source of Perfluorinated Carboxylic Acids

Fate of Per- and Polyfluoroalkyl Substances from Durable Water-Repellent Clothing during Use

Quantitation of Gas-Phase Perfluoroalkyl Surfactants and Fluorotelomer Alcohols Released from Nonstick Cookware and Microwave Popcorn Bags

Release of Side-Chain Fluorinated Polymer-Containing Microplastic Fibers from Functional Textiles During Washing and First Estimates of Perfluoroalkyl Acid Emissions

Semivolatile Fluorinated Organic Compounds in Asian and Western U.S. Air Masses

Fluorotelomer Alcohol Biodegradation Yields Poly- and Perfluorinated Acids

Wastewater Treatment Plant and Landfills as Sources of Polyfluoroalkyl Compounds to the Atmosphere‡

Detection of fluorotelomer alcohols in indoor environments and their relevance for human exposure

Degradation of Fluorotelomer-Based Polymers Contributes to the Global Occurrence of Fluorotelomer Alcohol and Perfluoroalkyl Carboxylates: A Combined Dynamic Substance Flow and Environmental Fate Modeling Analysis

Simultaneous determination of perfluoroalkyl iodides, perfluoroalkane sulfonamides, fluorotelomer alcohols, fluorotelomer iodides and fluorotelomer acrylates and methacrylates in water and sediments using solid-phase microextraction-gas chromatography/mass spectrometry

Hydrolysis of FTOH provides a simple method to account for some of the unknown PFAS

A global atmospheric chemistry model for the fate and transport of PFCAs and their precursors†

Per- and polyfluoroalkyl substances in the environment

Neutral polyfluoroalkyl substances in the global Atmosphere

Significant Residual Fluorinated Alcohols Present in Various Fluorinated Materials

Low temperature thermal treatment of gas-phase fluorotelomer alcohols by calcium oxide

Emissions of Per- and Polyfluoroalkyl Substances in a Textile Manufacturing Plant in China and Their Relevance for Workers' Exposure

Closing the Mass Balance on Fluorine on Papers and Textiles

Formation of PFOA from 8:2 FTOH in closed-bottle experiments with brackish water

Measurement of fluorotelomer alcohols based on solid phase microextraction followed by gas chromatography-mass spectrometry and its application in solid waste study

Modeling the environmental fate of perfluoroalkyl alcohols and their precursors from global fluorotelomer acrylate polymer use

Prevalence and Implications of Per- and Polyfluoroalkyl Substances (PFAS) in Settled Dust

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PERSPECTIVE

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Chemical transformation, exposure assessment, and policy implications of fluorotelomer alcohol partitioning from consumer products to the indoor and outdoor environment—from production to end-of-life



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Chemical transformation, exposure assessment, and policy implications of fluorotelomer alcohol partitioning from consumer products to the indoor and outdoor environment—from production to end-of-life

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Fluorotelomer (FT) alcohols (FTOHs) belong to the subclass of per- and polyfluoroalkyl substances (PFAS) and are used as building blocks of FT-based side chain fluorinated polymers (SCFPs), which are applied to consumer products to provide hydro- and oleophobic characteristics. FTOHs are consistently detected in consumer products, indicating FTOHs as major degradation products of FT-based SCFPs. Literature on FTOHs indicates that much is known about the release of FTOHs during the production, throughout the lifetime, and at the end-of-life of consumer products. This Perspective combines information from FTOHs in consumer products with sufficient knowledge on FTOH volatility, partitioning to the gas phase, and transformation to perfluorocarboxylates (PFCAs) to understand the extent of FTOH release to the environment. In the indoor environment, FTOHs are released in textile factories to the air during the production of consumer products, indicating a potential inhalation risk for the workers. Meanwhile, indoor air FTOH levels at residential sites are estimated to pose low inhalation risk to humans based on studies of 8:2 FTOH, which is known to undergo human metabolism to perfluorooctanoate (PFOA). Release of FTOHs from FT-based SCFP-applied consumer products to the indoor environment throughout the lifetime of the products is known, as well as release to the outdoor environment through washing, weathering, or drying. At the end-of-life of consumer products, FTOHs are released to air from landfills and can be detected in biosolids. Future policies need to not only account for FTOH presence in consumer products, but also the known FTOH volatility, partitioning to the gas phase, and transformation to PFCAs.

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Environmental significance

Fluorotelomer (FT) alcohols (FTOHs) are per- and polyfluoroalkyl substances (PFAS) sub-class consistently detected in consumer products. Much is known about FTOHs, indicating their volatility, partitioning to the gas-phase, and transformation to perfluoroalkyl carboxylates (PFCAs). Based on the literature from 2000 to 2024, a Perspective on FTOHs in consumer products and FTOH release from consumer products to the indoor and outdoor environment is presented. Release of FTOHs from consumer products to indoor air is known during the production and throughout the lifetime of consumer products, indicating potential inhalation risk to humans. Release of FTOHs from consumer products to outdoor air occurs at landfills, indicating sources of FTOHs to the atmosphere. Future policies on FTOHs can be tied to their known transformation to PFCAs.

1. Introduction

Per- and polyfluoroalkyl substances (PFAS) are a group of compounds known to be present in consumer products.¹ Fluorotelomer (FT) alcohols (FTOHs) belong to the PFAS sub-class and are consistently detected in consumer products,^{1–42} with 8:2 or higher chain FTOHs as the predominant compounds found

in studies published from 2000s–2010s and 6:2 FTOH as the predominant compound found in recent years.¹ The presence of FTOHs in consumer products can originate from the degradation products of the unreacted raw materials and reaction intermediates of FT-based side-chain fluorinated polymers (SCFPs),^{43,44} and from the degradation of FT-based SCFPs once applied to consumer products.⁴⁴ Unlike fluoropolymers, where the backbone is fluorinated (*i.e.*, containing the $-\text{CF}_2-$ fragment),^{45–48} FT-based SCFPs can be composed of a fluorinated or non-fluorinated backbone as long as the side-chain is fluorinated (Fig. 1).^{44,49,50} Some SCFP-containing products are

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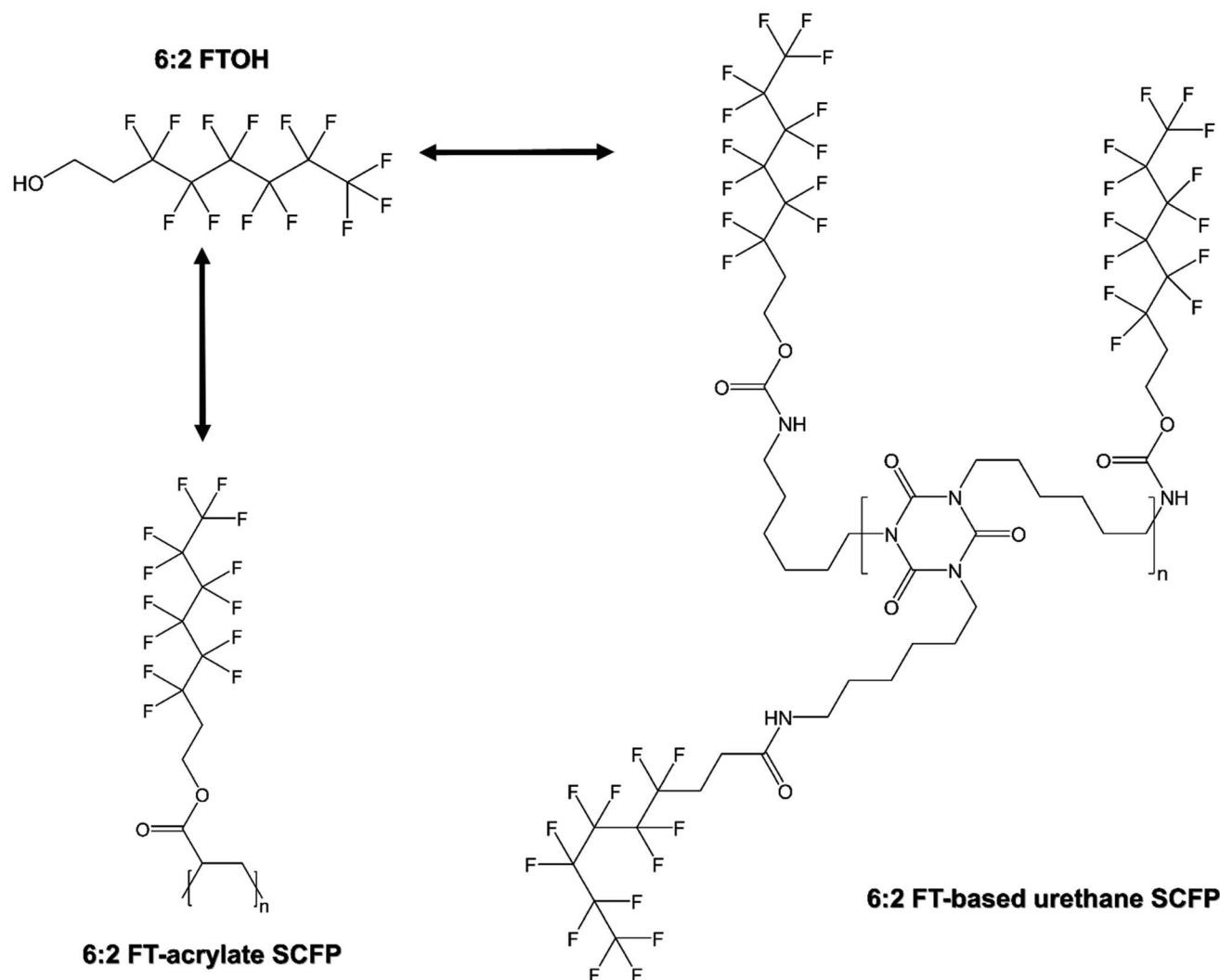


Fig. 1 Example of two FT-based SCFP structures that can degrade to FTOHs because FTOHs are the building blocks of SCFPs, with SCFP structures adapted from ref. 44. Bidirectional arrows indicate that FTOHs can be degradation products of FT-based SCFPs.

sold directly to the public, including those for carpet treatment,^{2,49,51,52} and application of SCFPs in some food contact materials is approved.^{11,53} The FTOHs found in PFAS-containing textiles are known to originate from FT-based SCFPs.^{19,25,36,38,41,44,54–61} While there are multiple types of SCFPs,⁴⁴ only FT-based SCFPs, such as FT-acrylate and -urethane SCFPs,⁴⁴ will degrade to FTOHs (Fig. 1).

A strong body of work exists on FTOH physicochemical properties, namely FTOH volatility and partitioning to the gas phase.⁶² Studies by Endo and colleagues,^{63–65} and by Dreyer *et al.*,⁶⁶ using a combination of experimental (*e.g.*, hexane-water, octanol-water partitioning, and gas and liquid chromatography) and computational (*e.g.*, COSMOtherm) approaches, indicate the volatile nature of FTOHs. FTOHs are volatile because at environmentally-relevant pH, FTOHs are neutral (*i.e.*, $pK_a > 14$);^{67–71} in contrast, perfluoroalkyl carboxylates (PFCAs), such as perfluorooctanoate (PFOA), are charged (*i.e.*, $pK_a < 0-4$).^{68–70,72–74} In air samples, FTOHs are known to partition to the gas-phase relative to the particle-phase.^{35,39,62,68,70,72,75–104}

When FTOH levels in the gas-phase are compared to sum FTOH levels in the gas- and particle phases, FTOHs in the gas-phase associated fraction represent 90% of the sum,^{72,75,86,105} whereas FTOHs in the particle-phase associated fraction represent 3–40% of the sum.^{72,85,86,105}

There is sufficient knowledge to indicate that any $n:2$ FTOH ($n = 6, 8, 10, \dots$) consistently degrades to C_n and $C[n-2]$ PFCAs, and $[n-1]:3$ FTCA, with $[n-1]:3$ FT-unsaturated-carboxylate (FTUCA) and $[n-1]:2$ secondary FTOH (sFTOH) as some of the observed intermediate products (Fig. 2).⁶² The transformation from FTOHs to PFCAs can occur in environmental and biological systems.¹⁰⁶ FTOHs are not only known to undergo atmospheric transformation to PFCAs,^{76,98,107–122} but also long range atmospheric transport, thus partially explaining the presence of PFCAs in remote areas.^{79,91,100,113,121,123–128} However, volatility, wet deposition, and scavenging can impact the amount of PFCAs formed from atmospheric transformation of FTOHs.¹²² Biotransformation of FTOHs in soil,^{129–150} sludge,^{151–159} and sediment^{160–162} also results in PFCAs. However,



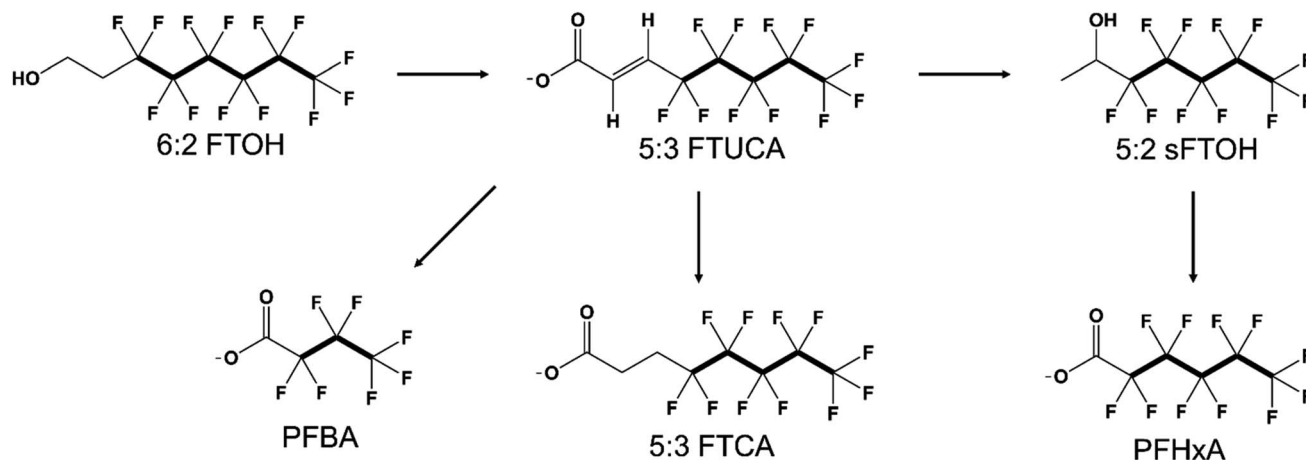


Fig. 2 A degradation pathway of 6:2 FTOH leading to the formation of PFCAs, namely perfluorohexanoate (PFHxA) and perfluorobutanoate (PFBA), and 5:3 FTCA with 5:3 FTUCA and 5:2 sFTOH as intermediate products. Carbon–fluorine bonds are highlighted in bold. Detailed degradation pathways are outlined in ref. 62.

FTOHs in soil can be taken up by plants before biotransforming to PFCAs.^{163–169} Aerobic conditions promote faster degradation (less than 1 to 14 days half-life) than anaerobic conditions (less than 1 to more than 365 days half-life) of FTOHs,¹⁷⁰ and nutrients and redox conditions are known to impact biotransformations.¹⁴³ Meanwhile, FTOHs in water samples are known to undergo photolysis to PFCAs,^{118,171,172} but microbial biodegradation of 8:2 FTOH to perfluorooctanoate (PFOA) in brackish water is known as well.¹⁷³ Nitrate and hydroxyl radicals promote photolysis, but dissolved organic carbon inhibits photolysis.¹⁷¹ In biological systems, mammalian,^{174–193} avian,¹⁹⁴ and fish^{195,196} metabolisms biotransform FTOHs to PFCAs.

The knowledge on the presence of FTOHs in consumer products and on the volatility, partitioning, and transformation of FTOHs in environmental and biological systems indicates that much is known about FTOHs. Therefore, in this personal review (Perspective), studies concerning the release of FTOHs from production to end-of-life of consumer products and on FTOHs are combined to provide further understanding in the field of PFAS. Release of FTOHs in the context of consumer products is important to examine not only due to the potential exposure of FTOHs to humans (*i.e.*, release to the indoor environment),¹⁹⁷ but also due to the eventual degradation of FTOHs to PFCAs in the outdoor environment.¹⁰⁷ Policy implications from the presence of FTOHs in consumer products and from transformation of FTOHs to PFCAs in the environment are briefly discussed.

2. Methods

This Perspective is based on publications concerning FTOHs from 2000 to 2024, collated by searching for publications in Google Scholar and Web of Science using the term “fluorotelomer alcohol”. In each of the papers, both the cited and citing references are consulted and this manual iterative process finishes once there is no newer, relevant citing reference. Publications prior to 2000 relevant to the Perspective are

included to account for knowledge that has existed for more than two decades. Relevant, newer (*e.g.*, 2024) publications are collated through daily search using the keyword “PFAS” on the search function of the American Chemical Society, the Royal Society of Chemistry, and Elsevier publication websites from mid-2023 till May 2024.

3. Release of FTOHs to the indoor environment

3.1 Release to the indoor environment during the production of consumer products

The padding process, a technique where chemicals are applied to fibers by way of immersion in a bath, followed by a curing step in an oven^{55,198,199} (*i.e.*, heating, which leads to volatilization) is a method to deposit FT-based SCFPs onto textiles.^{60,200} When U.S. EPA scientists replicated the textile padding process to apply C6 FT-based SCFPs in a laboratory setting,²⁰⁰ 6:2 FTOH was released to the indoor air, but 6:2 FTOH concentration was not provided in the study. The result from the U.S. EPA study corroborated the results from a 2016 study performed at a Chinese textile factory²⁰¹ where FTOHs ($9.5\text{--}90 \times 10^6 \text{ pg m}^{-3}$) were present in indoor air collected from the workshop area where the padding processes to apply FT-based SCFPs occur. The FTOHs can be detected in dusts in industrial sites and a thorough review and perspective was provided by Paris-Davila *et al.*²⁰²

3.2 Release to the indoor environment throughout the lifetime of consumer products

Partitioning of FTOHs from consumer products known to contain FT-based SCFPs to indoor air occurred in the orders of hours-to-months depending on the materials and factors, including temperature and light.^{4,7,33,35,104,203–205} Sinclair *et al.*⁴ measured losses of $25\text{--}630 \text{ pg cm}^{-2}$ and $220\text{--}260 \text{ ng}$ of FTOHs following heating of nonstick frying pans between 180 and 230 °



C, 20 min and microwaving of popcorn bags for 3 min, respectively. The experiment by Davern *et al.*¹⁰⁴ on microwaved popcorn bags (less than 2 min) corroborated the results from Sinclair *et al.* through the detection of 480 000 pg m⁻³ of 6:2 FTOH released to the air.

Fast food packaging was also known to emit FTOHs as indicated by Schwartz-Narbonne *et al.*³³ when an average of 85% decrease in FTOH levels (130–2400 ng) was measured following storage of ~2 years at room temperature. Textiles were also known to emit FTOHs to the air, including children rain trousers and rain jackets (750–490 000 pg m⁻³ after 3 h, 25 °C),²⁰³ and cotton clothes (210–53 000 pg m⁻³ after 9 months, 25 °C).³⁵ Emissions of FTOHs from mattress pads and membrane apparel (200–800 ng g⁻¹ loss after 2 h, 40–100 °C),⁷ from mattress pads and a cleaner product (230 and 12 400 ng g⁻¹ loss after 125 and 28 h, respectively, 25 °C),²⁰⁵ and from firefighter turnout gears (8:2 FTOH detected after 30 min, 200 °C)²⁰⁴ were also known. Products containing FT-based SCFPs were known sources of FTOHs in indoor air.

Levels of FTOHs above the limit of quantitation were reported in the range of 0.04–1 900 000 pg m⁻³ in indoor air,^{39,70,87,181,203,206–220} which were two-to-three orders of magnitude lower than the recorded indoor air levels at a Chinese textile factory (Fig. 3). While the partitioning of FTOHs from consumer products to the air was already assessed, the half-lives of FTOHs in indoor air were not studied. Once FTOHs were off-gassed from the material indoors, FTOHs were known to sorb dust in addition to air particles.^{221,222} Comprehensive reviews and perspectives on FTOHs in house dusts were provided previously by Shoeib *et al.*,¹⁴ Savvaides *et al.*,²⁰ and Zhu *et al.*²²³

3.3 Assessments of human exposures to FTOHs in the indoor environment and the associated potential human health implications

Inhalation is determined to be the major exposure route of FTOHs for humans, therefore, occupational settings where FTOHs are used, such as fluorochemical manufacturing and textile industries,^{16,182,184,200–202,224,225} are likely to encounter FTOH inhalation exposure.^{181,202,226–229} However, a significant gap exists with regard to exposure studies on FTOHs at occupational sites, therefore, comparisons with exposure to FTOHs

at residential sites still need to be performed. Meanwhile, studies of human exposure from inhalation of 8:2 FTOH in residential indoor air indicate that risk of human exposure to PFOA from inhalation of 8:2 FTOH in air or dust is low.^{14,87,203,208,211,216,217,230,231} A recent review on human exposure pathways to PFAS exclude FTOH inhalation, indicating the low potency for human health impacts from inhalation of FTOHs.²³² Langer *et al.* and Kim *et al.* estimate that 5 and 2.5% of 8:2 FTOH are transformed to PFOA through human metabolism, respectively, indicating low 8:2 FTOH contribution toward overall PFOA exposure.^{87,208} Corroborating results from Shoeib *et al.*,¹⁴ Schlummer *et al.*,²⁰³ Winkens *et al.*,²¹⁶ Padilla-Sánchez *et al.*,²¹⁷ Xu *et al.*,²³⁰ and Tian *et al.*²³¹ indicate that the risk of exposure to PFOA following inhalation of 8:2 FTOH in air or dust does not exceed the tolerable daily intake of PFOA (1500 ng per kg bw per day). Poonthong *et al.* further indicate that only 3% of PFOA exposure originates from indirect exposure, including house dust ingestion and indoor air inhalation.²³³ Shoeib *et al.* indicate that inhalation of 8:2 FTOH in air is more relevant than ingestion of 8:2 FTOH in house dusts, but the overall exposure is still less than the estimated Canadian adult dietary intake limit of PFOA (70 ng per day).²¹¹ Dermal absorption of FTOHs from air is not predicted to be a major route of exposure of FTOHs to humans.^{234,235}

Ingestion of FTOHs can be another route of exposure for humans,¹³ as the 6:2, 8:2, 10:2, and 12:2 FTOHs can be transferred to real food samples.^{32,236} The 6:2 FTOH is also predicted to be as toxic as 8:2 FTOH through ingestion.²³⁷ However, ingestion is a route of exposure that does not result from partitioning of FTOHs to the indoor environment (*e.g.*, inhalation or dermal absorption from air). Therefore, the partitioning of FTOHs to food samples (*i.e.*, ingestion) is beyond the scope of this study.

Similarly, while 6:2 FTOH can lead to reproductive dysfunction in mice male offsprings²³⁸ or abnormal adult anxiety behaviors in Zebrafish (*Danio rerio*) trans-generationally,²³⁹ the route of exposure in these studies is not through partitioning of FTOHs to the indoor or outdoor environment (*i.e.*, directly to embryos and through ingestion, respectively). However, it is noted that in a 6:2 FTOH inhalation study involving rats, the elimination half-lives of 6:2 range from 1 to 15 h and the FTOH metabolites yield is 2% mol.¹⁸³

4. Release of FTOHs to the outdoor environment

4.1 Release to air during the production of consumer products

Levels of FTOHs released to air collected near industrial sites, namely near textile and carpet manufacturing and treatment,^{77,102,201,240} and fluorochemical manufacturing facilities,^{241,242} are two-to-three orders of magnitude and one order of magnitude higher than the levels of FTOHs collected near non-industrial sites,^{70,75,79–83,86–88,91,93,96,113,114,117,121,207,211,212,243–266} respectively (Fig. 4). Of note, FTOH release from textile and carpet manufacturing and treatment facilities can be one-to-two

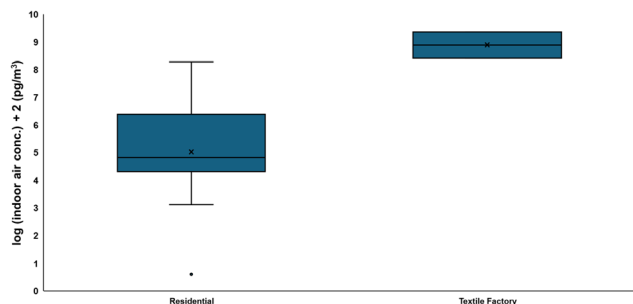


Fig. 3 Box and whisker plot comparison between min and max of reported FTOH indoor air concentration at residential sites and at a textile factory. The indoor air residential data are obtained from ref. 70.



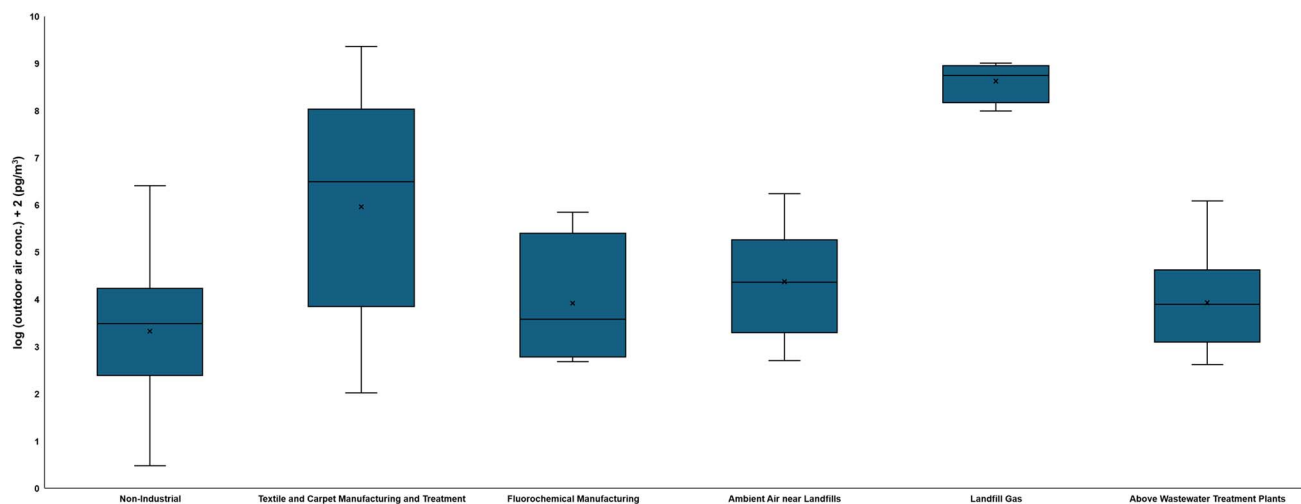


Fig. 4 Box and whisker plot comparison between min and max of reported FTOH outdoor air concentration at different sites. The non-industrial data are obtained from ref. 70.

orders of magnitude higher than the amount emitted from fluorochemical manufacturing facilities.

The composition of FTOHs at the global level is still dominated by 8:2 FTOH,^{100,117} which is attributed to the historical use of C8-based PFAS. At textile and carpet manufacturing and treatment sites, the dominant FTOH in studies before 2020 is 8:2 FTOH,^{77,201} while the dominant FTOH in studies after 2020 is 6:2 FTOH,^{102,240} likely reflecting the shift from C8- to C6-based PFAS. Similarly, at fluorochemical manufacturing sites, 8:2 FTOH is the dominant FTOH in the study performed before 2020,²⁴¹ while 6:2 FTOH is the dominant FTOH in the study performed after 2020.²⁴²

Once released, FTOHs undergo atmospheric transformation to PFCAs and there have been efforts to model the contribution of FTOHs to the PFCA level globally. Modeling studies by Wallington *et al.*¹⁰⁸ and Yarwood *et al.*¹¹⁰ estimated that 1–10% contribution of global PFOA levels are due to atmospheric degradation of 8:2 FTOH based on reported outdoor air concentrations of 8:2 FTOH. Thackray and Selin also performed modeling work based on the presence and subsequent transformation of FTOHs to PFCAs, but their modeling effort predicted 25% contribution of the global level of PFCAs from FTOH atmospheric degradation.^{120,122}

4.2 Release to air at the end-of-life of consumer products

Once used, FT-based SCFP-applied consumer products are disposed to the landfills,^{267–270} where hydrolysis can occur and degrade FT-based SCFPs to FTOHs,^{19,27,33,34,36,41,58} followed by the partitioning of FTOHs to the gas-phase.^{271–273} Release of 8:2 FTOH and its transformation product is documented in a laboratory-scale landfill leachate-sediment microcosm study,¹⁶² while Goukeh *et al.* demonstrate the degradations of FT-based SCFP-applied materials and subsequent volatilization of FTOHs in laboratory-scale landfill-simulated settings.³⁴ Landfill gas (LFG) is known to contain FTOHs ($1\text{--}10 \times 10^6$ pg m⁻³).^{34,274} Landfills are thus known to emit FTOHs based on

ambient air samples collected near landfills ($5\text{--}17\,000$ pg m⁻³).^{97,275–277} Levels of FTOHs in ambient air near landfills are comparable to the levels of FTOHs in the air collected outside fluorochemical manufacturing facilities (Fig. 4). The FTOHs found in ambient air near landfills are dominated by 8:2 and 10:2 FTOHs from studies in the 2010s,^{275,276} but 6:2 FTOH starts to dominate in recent years,^{97,274,277} which is reflective of the 6:2 FTOH detected in consumer products in recent years.¹

The release of FTOHs from landfills indicates that while landfills are a sink of FT-based SCFP-applied consumer products, landfills are a source of FTOHs to the atmosphere as well. Studies by Li *et al.*,²⁷⁸ Washington *et al.*²⁷⁹ and van Zelm *et al.*²⁸⁰ foresee the emission of FTOHs from landfills as a major contributor of PFCAs in the environment through the continual degradation of FT-based SCFPs and the subsequent release of FTOHs, followed by transformation to PFCAs. However, the existing global inventory of PFCAs based on outdoor air concentrations and atmospheric transformation models^{115,122,281,282} are yet to account for FTOHs released from landfills, which represents a research gap.

4.3 Release of FTOHs to the outdoor environment throughout the lifetime of consumer products

In the case of textiles, myriad processes degrade FT-based SCFPs applied in consumer products, as described by Schellenberger, van der Veen, and colleagues: loss of fibers, increased and/or rough surface area, disruption of non-/covalent bonding between and among monomers (*e.g.*, loss due to laundering and rain, volatilization), and UV-degradation.^{19,25,55,56,59,283} Schellenberger and van der Veen *et al.* also assess the release of FTOHs to the outdoor environment throughout the lifetime of consumer products through comparisons of FTOH concentrations pre- and post-washing, weathering (*e.g.*, temperature, humidity, and light), and drying.^{19,25,56,59} The FTOHs are detected in wastewater treatment plants (WWTPs) not known to be impacted by textile factories,^{284–291} indicating washing of FT-



based SCFP-applied consumer products as a potential source of FTOHs to WWTPs. However, estimate of FTOH release to WWTPs in Europe following washing of FTOH-containing consumer products was minimal (~ 0.7 t per year).⁵⁶

4.4 Release to water during the production of consumer products

While FTOHs are volatile and partition to the gas-phase, FTOHs can be detected in water samples, including those sampled from WWTPs near textile factories and fluorochemical manufacturing facilities.^{102,240,292–295} Levels of FTOHs in water samples recorded near fluorochemical manufacturing facilities are three-to-six orders of magnitude higher than levels recorded near textile factories (Fig. 5). However, the range of FTOHs in water samples collected from near textile factories ($2.1–43$ ng L^{−1})^{240,294,295} is comparable to the range of FTOHs in water samples collected from rivers and WWTPs not known to be impacted by textile factories ($0.003–78$ ng L^{−1}) (Fig. 5).^{284–291} In studies concerning WWTPs impacted by textile factories, FTOHs in the influents are higher than in the effluents, indicating transformation of FTOHs to PFCAs in WWTPs.^{294,295} In the only published study of its kind, FTOHs are below the limit of detection ($< \text{LOD}$) in groundwater samples collected from an active fluorochemical manufacturing facility.²⁹⁶ More data on FTOHs in any water samples can be useful, but prior data, supported by known partitioning preference of FTOHs to the gas phase and transformation of FTOHs to PFCAs, need to be acknowledged in terms of the potential results of $< \text{LODs}$ in future studies.

4.5 Release to water at the end-of-life of consumer products

Due to disposal of FT-based SCFP-applied consumer products to municipal solid waste,^{267–270} as well as the volatilization of FTOHs (Fig. 4) and the transformation of FTOHs to PFCAs, release of FTOHs to water at the end-of-life of consumer products is estimated to be insignificant.^{289,293} In landfills, FTOHs in

LFG are known to transform to FTOH degradation products through studies on LFG condensate and landfill leachates.^{297,298} Of note, 5:3 FTCA is an intermediate transformation product between 6:2 FTOH and PFHxA⁶² (Fig. 2), and is a major PFAS consistently measured in landfill leachates.^{299–301}

4.6 Release to soil during the production of consumer products

Comparable amount of FTOHs were measured in soil samples collected near fluorochemical manufacturing in the U.S. ($60–36\,000$ and $100–243\,000$ pg g^{−1}),^{296,302} China ($70–7200$ and $2600–50\,000$ pg g^{−1}),^{169,241} and Japan ($100–12\,000$ pg g^{−1}).²⁴² The levels of FTOHs in soil near fluorochemical manufacturing facilities were two-to-three orders of magnitude higher than levels of FTOHs collected from roadside in the U.S. ($0.51–10$ pg g^{−1}).³⁹ No publication on FTOHs in soil samples collected near textile and carpet manufacturing and treatment facilities was located by the author.

4.7 Release to soil at the end-of-life of consumer products

The pathway for FTOHs to be released to soil at the end-of-life of consumer products involves biosolids,^{303,304} which are collected from WWTPs. Studies by Ellington *et al.*,¹³³ Yoo *et al.*,¹⁵³ and Zhang *et al.*¹⁶³ indicate FTOH concentration in the range of $13\,000–57\,000$, $4000–820\,000$, and $1000–170\,000$ pg g^{−1}, respectively. The levels of FTOHs in biosolid-amended soil are two-to-five orders of magnitude higher than FTOHs in roadside soil samples ($0.5–10$ pg g^{−1}).³⁹ A potential source of FTOHs in biosolids is FT-based SCFPs as the estimated degradation half-lives of FT-based SCFPs can vary between 10 and 110 years^{305–308} or up to a thousand years.^{309–311} Any FTOHs remaining in the biosolids can breakdown to PFCAs and further transformation products, indicating a potential pathway of PFOA exposure to humans when biosolids are applied to soils for farming.

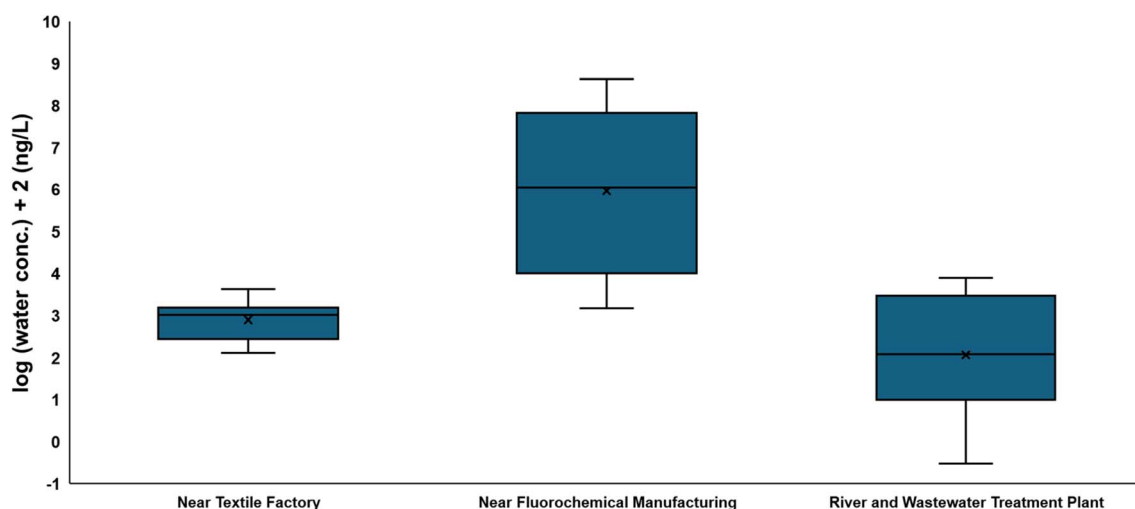


Fig. 5 Box and whisker plot comparison between min and max of reported FTOH water concentration at different sites.



5. Policy implications of release of FTOHs associated with consumer products

Within the U.S., aside from states' initiatives on consumer products^{312,313} and the U.S. Food and Drug Administration (FDA)'s announcement of 6:2 FTOH voluntary phase-out from the food contact material (FCM) market,³¹⁴ there are no regulations on the release of FTOHs to the environment. The phase-out of FTOH-containing FCMs indicates that less FTOH-containing FCMs will end up in landfills, which will also lead to the reduction of FTOHs and PFCAs released to the environment. The phase-out of FTOH-containing textile³¹⁵ likely also leads to less FTOHs and PFCAs in the environment, but regulations on active and closed textile mills are still needed due to the potential formation of PFCAs downstream.³¹⁶

The lack of existing regulations on FTOHs may be indicative of legislative and general public understanding and approaches toward PFAS that are still limited to ionic PFAS including, PFOA, perfluorooctane sulfonate, and their PFAS-replacements, such as hexafluoropropylene oxide-dimer acid.^{317–320} Lawmakers can thus consider tying the transformation of FTOHs released from FT-based SCFPs in landfills to the presence of PFCAs in the atmosphere within existing regulations as the foundation for any policies regarding FTOH use in consumer products.

An approach where entities that emit FTOHs are capped at certain levels can be considered. This approach can be relevant for landfill operators because FTOHs are estimated to continue to be emitted from landfills to the atmosphere due to past and current FT-based SCFP use.^{56,278,279,321,322} However, the proportion of FTOHs released to the gas-phase due to hydrolysis of FT-based SCFP-applied products in landfills is yet to be studied. Therefore, there are likely to be pushbacks from landfill operators on any proposed regulations of FTOHs. For comparison, hydrolysis experiments performed in laboratory settings indicate an increase in FTOH concentrations in FT-based SCFP-applied consumer products up to 1500× pre- and post-hydrolysis.^{19,27,33,36,58}

Policies discouraging the use of FTOHs can also be considered as alternatives to FTOHs are available, such as silicone-based polymers, wax, hyperbranched polymers, silicone-based PFAS, and melamin.^{323–326} However, the environmental impacts of alternatives to FTOHs are unclear, though the presence of silicone-based PFAS monomers in soil and earthworms is known.^{326,327}

Future policies can also promote treatment efforts known to mitigate the release of FTOHs to the environment. Researchers from the U.S. EPA indicate that thermal treatments containing calcium oxide and alumina-based catalysts can be useful to treat FTOHs through mineralization.^{328,329} Calcium oxides are distributed in a flameless tube furnace operated between 400 and 800 °C as gas-phase FTOHs are flowing, and degradation efficiency of FTOHs following experiments achieves 85–99% removal of FTOHs.³²⁸ Comparable degradation efficiency can also be achieved with the use of alumina catalysts at a lower temperature range of 200–500 °C.³²⁹ If these techniques can be

recreated and applied on a large scale, such as in landfills where gas-phase FTOHs are detected, then the potential for FTOHs to transform into PFCAs in the environment can be inhibited.

Data availability

No new data were generated as part of this Perspective.

Conflicts of interest

The author declares no competing interest. No artificial intelligence³³⁰ was used in this work. The Table of Contents (TOC) art was created with <https://www.BioRender.com>.

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References

- 1 P. Dewapriya, L. Chadwick, S. G. Gorji, B. Schulze, S. Valsecchi, S. Samanipour, K. V. Thomas and S. L. Kaserzon, Per- and polyfluoroalkyl substances (PFAS) in consumer products: current knowledge and research gaps, *J. Hazard. Mater. Lett.*, 2023, **4**, 100086.
- 2 M. J. A. Dinglasan-Panlilio and S. A. Mabury, Significant Residual Fluorinated Alcohols Present in Various Fluorinated Materials, *Environ. Sci. Technol.*, 2006, **40**, 1447–1453.
- 3 B. S. Larsen, P. Stchur, B. Szostek, S. F. Bachmura, R. C. Rowand, K. B. Prickett, S. H. Korzeniowski and R. C. Buck, Method development for the determination of residual fluorotelomer raw materials and perfluorooctanoate in fluorotelomer-based products by gas chromatography and liquid chromatography mass spectrometry, *J. Chromatogr. A*, 2006, **1110**, 117–124.
- 4 E. Sinclair, S. K. Kim, H. B. Akinleye and K. Kannan, Quantitation of Gas-Phase Perfluoroalkyl Surfactants and Fluorotelomer Alcohols Released from Nonstick Cookware and Microwave Popcorn Bags, *Environ. Sci. Technol.*, 2007, **41**, 1180–1185.
- 5 S. Fiedler, G. Pfister and K.-W. Schramm, Poly- and perfluorinated compounds in household consumer products, *Toxicol. Environ. Chem.*, 2010, **92**, 1801–1811.



- 6 D. Herzke, E. Olsson and S. Posner, Perfluoroalkyl and polyfluoroalkyl substances (PFASs) in consumer products in Norway – A pilot study, *Chemosphere*, 2012, **88**, 980–987.
- 7 X. Liu, Z. Guo, E. E. Folk and N. F. Roache, Determination of fluorotelomer alcohols in selected consumer products and preliminary investigation of their fate in the indoor environment, *Chemosphere*, 2015, **129**, 81–86.
- 8 F. Ye, Y. Zushi and S. Masunaga, Survey of perfluoroalkyl acids (PFAAs) and their precursors present in Japanese consumer products, *Chemosphere*, 2015, **127**, 262–268.
- 9 R. Vestergren, D. Herzke, T. Wang and I. T. Cousins, Are imported consumer products an important diffuse source of PFASs to the Norwegian environment?, *Environ. Pollut.*, 2015, **198**, 223–230.
- 10 M. Kothhoff, J. Müller, H. Jürling, M. Schlummer and D. Fiedler, Perfluoroalkyl and polyfluoroalkyl substances in consumer products, *Environ. Sci. Pollut. Res.*, 2015, **22**, 14546–14559.
- 11 P. A. Rice, C6-Perfluorinated Compounds: The New Greaseproofing Agents in Food Packaging, *Curr. Environ. Health Rep.*, 2015, **2**, 33–40.
- 12 C. Gremmel, T. Frömel and T. P. Knepper, Systematic determination of perfluoroalkyl and polyfluoroalkyl substances (PFASs) in outdoor jackets, *Chemosphere*, 2016, **160**, 173–180.
- 13 G. Yuan, H. Peng, C. Huang and J. Hu, Ubiquitous Occurrence of Fluorotelomer Alcohols in Eco-Friendly Paper-Made Food-Contact Materials and Their Implication for Human Exposure, *Environ. Sci. Technol.*, 2016, **50**, 942–950.
- 14 T. Shoeib, Y. Hassan, C. Rauert and T. Harner, Poly- and perfluoroalkyl substances (PFASs) in indoor dust and food packaging materials in Egypt: Trends in developed and developing countries, *Chemosphere*, 2016, **144**, 1573–1581.
- 15 A. E. Robel, K. Marshall, M. Dickinson, D. Lunderberg, C. Butt, G. Peaslee, H. M. Stapleton and J. A. Field, Closing the Mass Balance on Fluorine on Papers and Textiles, *Environ. Sci. Technol.*, 2017, **51**, 9022–9032.
- 16 P. T. J. Scheepers, L. Masen-Poos, F. G. B. G. J. van Rooy, A. Oerlemans, E. van Daalen, R. Cremers, H. Lichtenbeld, B. Biesma, J. B. Sørli, I. K. Koponen, S. T. Larsen, P. Wolkoff and A. W. Nørgaard, Pulmonary injury associated with spray of a water-based nano-sized waterproofing product: a case study, *J. Occup. Med. Toxicol.*, 2017, **12**, 1–15.
- 17 J. N. Rewerts, J. T. Morré, S. L. Massey Simonich and J. A. Field, In-Vial Extraction Large Volume Gas Chromatography Mass Spectrometry for Analysis of Volatile PFASs on Papers and Textiles, *Environ. Sci. Technol.*, 2018, **52**, 10609–10616.
- 18 Y. Wu, G. Z. Miller, J. Gearhart, G. Peaslee and M. Venier, Side-chain Fluorotelomer based Polymers in Children Car Seats, *Environ. Pollut.*, 2020, **268**(Part B), 115477.
- 19 I. van der Veen, A.-C. Hanning, A. Stare, P. E. G. Leonards, J. de Boer and J. M. Weiss, The effect of weathering on per- and polyfluoroalkyl substances (PFASs) from durable water repellent (DWR) clothing, *Chemosphere*, 2020, **249**, 126100.
- 20 T. Savvaides, J. P. Koelmel, Y. Zhou, E. Z. Lin, P. Stelben, J. J. Aristizabal-Henao, J. A. Bowden and K. J. Godri Pollitt, Prevalence and Implications of Per- and Polyfluoroalkyl Substances (PFAS) in Settled Dust, *Curr. Environ. Health Rep.*, 2021, **8**, 323–335.
- 21 H. D. Whitehead, M. Venier, Y. Wu, E. Eastman, S. Urbanik, M. L. Diamond, A. Shalin, H. Schwartz-Narbonne, T. A. Bruton, A. Blum, Z. Wang, M. Green, M. Tighe, J. T. Wilkinson, S. McGuinness and G. F. Peaslee, Fluorinated Compounds in North American Cosmetics, *Environ. Sci. Technol. Lett.*, 2021, **8**, 538–544.
- 22 R. C. Buck, S. H. Korzeniowski, E. Laganis and F. Adamsky, Identification and classification of commercially relevant per- and poly-fluoroalkyl substances (PFAS), *Integr. Environ. Assess. Manage.*, 2021, **17**, 1045–1055.
- 23 C. Wang, H. Zhang, L. Zhu, W. Hu and Z. Lin, Simultaneous determination of 11 volatile perfluorinated compound precursors in textiles using gas chromatography-triple quadrupole mass spectrometry, *SePu Chin. J. Chromatogr.*, 2021, **39**, 1239–1246.
- 24 D. J. Muensterman, I. A. Titaley, G. F. Peaslee, L. D. Minc, L. Cahuas, A. E. Rodowa, Y. Horiuchi, S. Yamane, T. N. J. Fouquet, J. C. Kissel, C. C. Carignan and J. A. Field, Disposition of Fluorine on New Firefighter Turnout Gear, *Environ. Sci. Technol.*, 2022, **56**, 974–983.
- 25 I. van der Veen, S. Schellenberger, A.-C. Hanning, A. Stare, J. de Boer, J. M. Weiss and P. E. G. Leonards, Fate of Per- and Polyfluoroalkyl Substances from Durable Water-Repellent Clothing during Use, *Environ. Sci. Technol.*, 2022, **56**, 5886–5897.
- 26 L. Cahuas, D. J. Muensterman, M. L. Kim-Fu, P. N. Reardon, I. A. Titaley and J. A. Field, Paints: A Source of Volatile PFAS in Air–Potential Implications for Inhalation Exposure, *Environ. Sci. Technol.*, 2022, **56**, 17070–17079.
- 27 C. Xia, M. L. Diamond, G. F. Peaslee, H. Peng, A. Blum, Z. Wang, A. Shalin, H. D. Whitehead, M. Green, H. Schwartz-Narbonne, D. Yang and M. Venier, Per- and Polyfluoroalkyl Substances in North American School Uniforms, *Environ. Sci. Technol.*, 2022, **56**, 13845–13857.
- 28 N. J. Herkert, C. D. Kassotis, S. Zhang, Y. Han, V. F. Pulikkal, M. Sun, P. L. Ferguson and H. M. Stapleton, Characterization of Per- and Polyfluorinated Alkyl Substances Present in Commercial Anti-fog Products and Their *In Vitro* Adipogenic Activity, *Environ. Sci. Technol.*, 2022, **56**, 1162–1173.
- 29 P. Siao, S.-H. Tseng and C.-Y. Chen, Determination of perfluoroalkyl substances in food packaging in Taiwan using ultrasonic extraction and ultra-performance liquid chromatography/tandem mass spectrometry, *J. Food Drug Anal.*, 2022, **30**, 11–25.
- 30 L. Minet, Z. Wang, A. Shalin, T. A. Bruton, A. Blum, G. F. Peaslee, H. Schwartz-Narbonne, M. Venier, H. Whitehead, Y. Wu and M. L. Diamond, Use and release of per- and polyfluoroalkyl substances (PFASs) in consumer food packaging in U.S. and Canada, *Environ. Sci.: Processes Impacts*, 2022, **24**, 2032–2042.



- 31 R. Seró, J. F. Ayala-Cabrera, F. J. Santos and E. Moyano, Paper spray-atmospheric pressure photoionization-high resolution mass spectrometry for the direct analysis of neutral fluorinated compounds in waterproof impregnation sprays, *Anal. Chim. Acta*, 2022, **1204**, 339720.
- 32 M. Lerch, K. H. Nguyen and K. Granby, Is the use of paper food contact materials treated with per- and polyfluorinated alkyl substances safe for high-temperature applications? – Migration study in real food and food simulants, *Food Chem.*, 2022, **393**, 133375.
- 33 H. Schwartz-Narbonne, C. Xia, A. Shalin, H. D. Whitehead, D. Yang, G. F. Peaslee, Z. Wang, Y. Wu, H. Peng, A. Blum, M. Venier and M. L. Diamond, Per- and Polyfluoroalkyl Substances in Canadian Fast Food Packaging, *Environ. Sci. Technol. Lett.*, 2023, **10**, 343–349.
- 34 M. N. Goukeh, T. Abichou and Y. Tang, Measurement of fluorotelomer alcohols based on solid phase microextraction followed by gas chromatography-mass spectrometry and its application in solid waste study, *Chemosphere*, 2023, **345**, 140460.
- 35 C. M. A. Eichler, N. Y. Chang, E. A. Cohen Hubal, D. E. Amparo, J. Zhou, J. D. Surratt, G. C. Morrison and B. J. Turpin, Cloth–Air Partitioning of Neutral Per- and Polyfluoroalkyl Substances (PFAS) in North Carolina Homes during the Indoor PFAS Assessment (IPA) Campaign, *Environ. Sci. Technol.*, 2023, **57**, 15173–15183.
- 36 J. Zweigle, C. Capitain, F. M. Simon, P. Roesch, B. Bugsel and C. Zwiener, Non-extractable PFAS in functional textiles – Characterization by complementary methods: oxidation, hydrolysis, and fluorine sum parameters, *Environ. Sci.: Processes Impacts*, 2023, **25**, 1298–1310.
- 37 P. Zuccaro, J. Licato, E. A. Davidson, D. C. Thompson and V. Vasiliou, Assessing extraction-analysis methodology to detect fluorotelomer alcohols (FTOH), a class of perfluoroalkyl and polyfluoroalkyl substances (PFAS), in artificial turf fibers and crumb rubber infill, *Case Stud. Chem. Environ. Eng.*, 2023, **7**, 100280.
- 38 P. Roesch, A. Schinnen, M. Riedel, T. Sommerfeld, G. Sawal, N. Bandow, C. Vogel, U. Kalbe and F.-G. Simon, Investigation of pH-dependent extraction methods for PFAS in (fluoropolymer-based) consumer products: A comparative study between targeted and sum parameter analysis, *Chemosphere*, 2024, **351**, 141200.
- 39 W. Li and K. Kannan, A Simple and Sensitive Method for Simultaneous Analysis of 58 Neutral and Ionic PFAS Using UPLC-MS/MS, *Environ. Sci. Technol. Lett.*, 2024, **11**, 308–314.
- 40 P. Vázquez Loureiro, K.-H. Nguyen, A. Rodríguez Bernaldo de Quirós, R. Sendón, K. Granby and A. A. Niklas, Identification and quantification of per- and polyfluorinated alkyl substances (PFAS) migrating from food contact materials (FCM), *Chemosphere*, 2024, **360**, 142360.
- 41 H. Matsukami, J. Saito, Q. Wang and Y. Miyake, Impact of tightening environmental regulations against long-chain perfluoroalkyl acids on composition of durable water repellents containing side-chain fluorinated polymers, *Sci. Total Environ.*, 2024, 173708.
- 42 K. Bouma, D. Kalsbeek-van Wijk, L. Steendam, D. T. H. M. Sijm, T. de Rijk, R. Kause, R. Hoogenboom and S. van Leeuwen, Plant-based food contact materials: presence of hazardous substances, *Food Addit. Contam.: Part A*, 2024, 1–10.
- 43 E. Kissa, *Fluorinated Surfactants and Repellents*, CRC Press, 2nd edn, 2001.
- 44 OECD, *Synthesis Report on Understanding Side-Chain Fluorinated Polymers and Their Life Cycle*, Organisation for Economic Co-operation and Development (OECD), Paris, 2022.
- 45 H. W. Fox and W. A. Zisman, The spreading of liquids on low energy surfaces. I. Polytetrafluoroethylene, *J. Colloid Sci.*, 1950, **5**, 514–531.
- 46 M. Yamauchi, T. Hirono, S. Kodama and M. Mastuo, The evaluation of new fluoropolymer emulsion for exterior paint use, *Surf. Coat. Int. JOCCA J. Oil Colour Chem. Assoc.*, 1996, **79**, 312–318.
- 47 J. Gardiner, Fluoropolymers: Origin, Production, and Industrial and Commercial Applications, *Aust. J. Chem.*, 2014, **68**, 13–22.
- 48 A. R. Bock and B. E. Laird, in *Perfluoroalkyl Substances Synthesis, Applications, Challenges and Regulations*, ed. B. Améduri, Royal Society of Chemistry, 2022, pp. 1–21.
- 49 F. Audenaert, H. Lens, D. Rolly and P. Vander Elst, Fluorochemical Textile Repellents—Synthesis and Applications: A 3M Perspective, *J. Text. Inst.*, 1999, **90**, 76–94.
- 50 V. Castelvetro, M. Aglietto, F. Ciardelli, O. Chiantore, M. Lazzari and L. Toniolo, Structure control, coating properties, and durability of fluorinated acrylic-based polymers, *J. Coat. Technol.*, 2002, **74**, 57–66.
- 51 3M Company, *Fluorochemical Use, Distribution and Release Overview*, 1999.
- 52 S. Chu and R. J. Letcher, Side-chain fluorinated polymer surfactants in aquatic sediment and biosolid-augmented agricultural soil from the Great Lakes basin of North America, *Sci. Total Environ.*, 2017, **607–608**, 262–270.
- 53 B. Bokkers, B. van de Ven, P. Janssen, W. Bil, F. van Broekhuizen, M. Zeilmaker and A. G. Oomen, *Per- and Polyfluoroalkyl Substances (PFASs) in Food Contact Materials*, Rijksinstituut voor Volksgezondheid en Milieu RIVM, 2019.
- 54 K. Rankin and S. A. Mabury, Matrix Normalized MALDI-TOF Quantification of a Fluorotelomer-Based Acrylate Polymer, *Environ. Sci. Technol.*, 2015, **49**, 6093–6101.
- 55 H. Holmquist, S. Schellenberger, I. van der Veen, G. M. Peters, P. E. G. Leonards and I. T. Cousins, Properties, performance and associated hazards of state-of-the-art durable water repellent (DWR) chemistry for textile finishing, *Environ. Int.*, 2016, **91**, 251–264.
- 56 S. Schellenberger, C. Jönsson, P. Mellin, O. A. Levenstam, I. Liagkouridis, A. Ribbenstedt, A.-C. Hanning, L. Schultes, M. M. Plassmann, C. Persson, I. T. Cousins and J. P. Benskin, Release of Side-Chain Fluorinated



- Polymer-Containing Microplastic Fibers from Functional Textiles During Washing and First Estimates of Perfluoroalkyl Acid Emissions, *Environ. Sci. Technol.*, 2019, **53**, 14329–14338.
- 57 I. Liagkouridis, R. Awad, S. Schellenberger, M. M. Plassmann, I. T. Cousins and J. P. Benskin, Combined Use of Total Fluorine and Oxidative Fingerprinting for Quantitative Determination of Side-Chain Fluorinated Polymers in Textiles, *Environ. Sci. Technol. Lett.*, 2021, **9**, 30–36.
- 58 V. A. Nikiforov, Hydrolysis of FTOH precursors, a simple method to account for some of the unknown PFAS, *Chemosphere*, 2021, **276**, 130044.
- 59 S. Schellenberger, I. Liagkouridis, R. Awad, S. Khan, M. Plassmann, G. Peters, J. P. Benskin and I. T. Cousins, An Outdoor Aging Study to Investigate the Release of Per-And Polyfluoroalkyl Substances (PFAS) from Functional Textiles, *Environ. Sci. Technol.*, 2022, **56**, 3471–3479.
- 60 P. Roesch, C. Vogel, P. Wittwer, T. Huthwelker, C. Borca, T. Sommerfeld, S. Kluge, C. Piechotta, U. Kalbe and F.-G. Simon, Taking a Look at the Surface: μ -XRF Mapping and Fluorine K-edge μ -XANES Spectroscopy of Organofluorinated Compounds in Environmental Samples and Consumer Products, *Environ. Sci.: Processes Impacts*, 2023, **25**, 1213–1223.
- 61 R. Lohmann and R. J. Letcher, The universe of fluorinated polymers and polymeric substances and potential environmental impacts and concerns, *Curr. Opin. Green Sustainable Chem.*, 2023, **41**, 100795.
- 62 M. G. Evich, M. J. B. Davis, J. P. McCord, B. Acrey, J. A. Awkerman, D. R. U. Knappe, A. B. Lindstrom, T. F. Speth, C. Tebes-Stevens, M. J. Strynar, Z. Wang, E. J. Weber, W. M. Henderson and J. W. Washington, Per- and polyfluoroalkyl substances in the environment, *Science*, 2022, **375**, eabg9065.
- 63 J. Hammer and S. Endo, Volatility and Nonspecific van der Waals Interaction Properties of Per- and Polyfluoroalkyl Substances (PFAS): Evaluation Using Hexadecane/Air Partition Coefficients, *Environ. Sci. Technol.*, 2022, **56**, 15737–15745.
- 64 S. Endo, J. Hammer and S. Matsuzawa, Experimental Determination of Air/Water Partition Coefficients for 21 Per- and Polyfluoroalkyl Substances Reveals Variable Performance of Property Prediction Models, *Environ. Sci. Technol.*, 2023, **57**, 8406–8413.
- 65 S. Endo, Intermolecular Interactions, Solute Descriptors, and Partition Properties of Neutral Per- and Polyfluoroalkyl Substances (PFAS), *Environ. Sci. Technol.*, 2023, **57**, 17534–17541.
- 66 A. Dreyer, V. Langer and R. Ebinghaus, Determination of Octanol–Air Partition Coefficients (KOA) of Fluorotelomer Acrylates, Perfluoroalkyl Sulfonamides, and Perfluoroalkylsulfonamido Ethanols, *J. Chem. Eng. Data*, 2009, **54**, 3022–3025.
- 67 Y. D. Lei, F. Wania, D. Mathers and S. A. Mabury, Determination of Vapor Pressures, Octanol–Air, and Water–Air Partition Coefficients for Polyfluorinated Sulfonamide, Sulfonamidoethanols, and Telomer Alcohols, *J. Chem. Eng. Data*, 2004, **49**, 1013–1022.
- 68 I. Abusallout, C. Holton, J. Wang and D. Hanigan, Henry's Law Constants of 15 Per- and Polyfluoroalkyl Substances Determined by Static Headspace Analysis, *J. Hazard. Mater. Lett.*, 2022, **3**, 100070.
- 69 J. Murillo-Gelvez, O. Dmitrenko, T. L. Torralba-Sanchez, P. G. Tratnyek and D. M. D. Toro, pK_a prediction of per- and polyfluoroalkyl acids in water using *in silico* gas phase stretching vibrational frequencies and infrared intensities, *Phys. Chem. Chem. Phys.*, 2023, **25**, 24745–24760.
- 70 M. A. G. Wallace, M. G. Smeltz, J. M. Mattila, H. K. Liberatore, S. R. Jackson, E. P. Shields, X. Khani, E. Y. Li and J. H. Johansson, A Review of Sample Collection and Analytical Methods for Detecting Per- and Polyfluoroalkyl Substances in Indoor and Outdoor Air, *Chemosphere*, 2024, **358**, 142129.
- 71 W. Qin, B. I. Escher, J. Huchthausen, Q. Fu and L. Henneberger, Species Difference? Bovine, Trout, and Human Plasma Protein Binding of Per- and Polyfluoroalkyl Substances, *Environ. Sci. Technol.*, 2024, **58**, 9954–9966.
- 72 L. Ahrens, T. Harner, M. Shoeib, D. A. Lane and J. G. Murphy, Improved Characterization of Gas–Particle Partitioning for Per- and Polyfluoroalkyl Substances in the Atmosphere Using Annular Diffusion Denuder Samplers, *Environ. Sci. Technol.*, 2012, **46**, 7199–7206.
- 73 L. J. Musegades, O. P. Curtin and J. D. Cyran, Determining the Surface pK_a of Perfluorooctanoic Acid, *J. Phys. Chem. C*, 2024, **128**, 1946–1951.
- 74 R. Patel, L. E. Saab, P. J. Brahana, K. T. Valsaraj and B. Bharti, Interfacial Activity and Surface pK_a of Perfluoroalkyl Carboxylic Acids (PFCAs), *Langmuir*, 2024, **40**, 3651–3658.
- 75 A. Dreyer and R. Ebinghaus, Polyfluorinated compounds in ambient air from ship- and land-based measurements in northern Germany, *Atmos. Environ.*, 2009, **43**, 1527–1535.
- 76 D. A. Ellis, J. W. Martin, S. A. Mabury, M. D. Hurley, M. P. Sulbaek Andersen and T. J. Wallington, Atmospheric Lifetime of Fluorotelomer Alcohols, *Environ. Sci. Technol.*, 2003, **37**, 3816–3820.
- 77 N. L. Stock, F. K. Lau, D. A. Ellis, J. W. Martin, D. C. G. Muir and S. A. Mabury, Polyfluorinated Telomer Alcohols and Sulfonamides in the North American Troposphere, *Environ. Sci. Technol.*, 2004, **38**, 991–996.
- 78 D. P. Cobranchi, M. Botelho, L. W. Buxton, R. C. Buck and M. A. Kaiser, Vapor pressure determinations of 8-2 fluorotelomer alcohol and 1-H perfluorooctane by capillary gas chromatography: Relative retention time versus headspace methods, *J. Chromatogr. A*, 2006, **1108**, 248–251.
- 79 M. Shoeib, T. Harner and P. Vlahos, Perfluorinated Chemicals in the Arctic Atmosphere, *Environ. Sci. Technol.*, 2006, **40**, 7577–7583.
- 80 N. L. Stock, V. I. Furdui, D. C. G. Muir and S. A. Mabury, Perfluoroalkyl Contaminants in the Canadian Arctic:



- Evidence of Atmospheric Transport and Local Contamination, *Environ. Sci. Technol.*, 2007, **41**, 3529–3536.
- 81 S. Oono, K. H. Harada, M. A. M. Mahmoud, K. Inoue and A. Koizumi, Current levels of airborne polyfluorinated telomers in Japan, *Chemosphere*, 2008, **73**, 932–937.
 - 82 S. Oono, E. Matsubara, K. H. Harada, S. Takagi, S. Hamada, A. Asakawa, K. Inoue, I. Watanabe and A. Koizumi, Survey of Airborne Polyfluorinated Telomers in Keihan Area, Japan, *Bull. Environ. Contam. Toxicol.*, 2008, **80**, 102–106.
 - 83 A. Dreyer, I. Weinberg, C. Temme and R. Ebinghaus, Polyfluorinated Compounds in the Atmosphere of the Atlantic and Southern Oceans: Evidence for a Global Distribution, *Environ. Sci. Technol.*, 2009, **43**, 6507–6514.
 - 84 A. Dreyer, M. Shoeib, S. Fiedler, J. Barber, T. Harner, K.-W. Schramm, K. C. Jones and R. Ebinghaus, Field intercomparison on the determination of volatile and semivolatile polyfluorinated compounds in air, *Environ. Chem.*, 2010, **7**, 350–358.
 - 85 L. Vierke, L. Ahrens, M. Shoeib, E. J. Reiner, R. Guo, W.-U. Palm, R. Ebinghaus and T. Harner, Air concentrations and particle–gas partitioning of polyfluoroalkyl compounds at a wastewater treatment plant, *Environ. Chem.*, 2011, **8**, 363–371.
 - 86 M. Cai, Z. Xie, A. Möller, Z. Yin, P. Huang, M. Cai, H. Yang, R. Sturm, J. He and R. Ebinghaus, Polyfluorinated compounds in the atmosphere along a cruise pathway from the Japan Sea to the Arctic Ocean, *Chemosphere*, 2012, **87**, 989–997.
 - 87 S.-K. Kim, M. Shoeib, K.-S. Kim and J.-E. Park, Indoor and outdoor poly- and perfluoroalkyl substances (PFASs) in Korea determined by passive air sampler, *Environ. Pollut.*, 2012, **162**, 144–150.
 - 88 Z. Xie, Z. Zhao, A. Möller, H. Wolschke, L. Ahrens, R. Sturm and R. Ebinghaus, Neutral poly- and perfluoroalkyl substances in air and seawater of the North Sea, *Environ. Sci. Pollut. Res.*, 2013, **20**, 7988–8000.
 - 89 Z. Xie, Z. Wang, W. Mi, A. Möller, H. Wolschke and R. Ebinghaus, Neutral Poly-/perfluoroalkyl Substances in Air and Snow from the Arctic, *Sci. Rep.*, 2015, **5**, 8912.
 - 90 Z. Wang, Z. Xie, A. Möller, W. Mi, H. Wolschke and R. Ebinghaus, Estimating dry deposition and gas/particle partition coefficients of neutral poly-/perfluoroalkyl substances in northern German coast, *Environ. Pollut.*, 2015, **202**, 120–125.
 - 91 Z. Wang, Z. Xie, W. Mi, A. Möller, H. Wolschke and R. Ebinghaus, Neutral Poly/Per-Fluoroalkyl Substances in Air from the Atlantic to the Southern Ocean and in Antarctic Snow, *Environ. Sci. Technol.*, 2015, **49**, 7770–7775.
 - 92 Z. Zhao, J. Tang, L. Mi, C. Tian, G. Zhong, G. Zhang, S. Wang, Q. Li, R. Ebinghaus, Z. Xie and H. Sun, Perfluoroalkyl and polyfluoroalkyl substances in the lower atmosphere and surface waters of the Chinese Bohai Sea, Yellow Sea, and Yangtze River estuary, *Sci. Total Environ.*, 2017, **599–600**, 114–123.
 - 93 X. Fang, Q. Wang, Z. Zhao, J. Tang, C. Tian, Y. Yao, J. Yu and H. Sun, Distribution and dry deposition of alternative and legacy perfluoroalkyl and polyfluoroalkyl substances in the air above the Bohai and Yellow Seas, China, *Atmos. Environ.*, 2018, **192**, 128–135.
 - 94 T. P. Riedel, J. R. Lang, M. J. Strynar, A. B. Lindstrom and J. H. Offenberg, Gas-Phase Detection of Fluorotelomer Alcohols and Other Oxygenated Per- and Polyfluoroalkyl Substances by Chemical Ionization Mass Spectrometry, *Environ. Sci. Technol. Lett.*, 2019, **6**, 289–293.
 - 95 Q. Wang, Z. Zhao, Y. Ruan, X. Hua, H. Chen, Y. Wang, L. Jin, M. M. P. Tsui, Y. Yao, P. K. S. Lam and H. Sun, Occurrence and seasonal distribution of legacy and emerging per- and polyfluoroalkyl substances (PFASs) in different environmental compartments from areas around ski resorts in northern China, *J. Hazard. Mater.*, 2021, **407**, 124400.
 - 96 E. Yamazaki, S. Taniyasu, X. Wang and N. Yamashita, Per- and polyfluoroalkyl substances in surface water, gas and particle in open ocean and coastal environment, *Chemosphere*, 2021, **272**, 129869.
 - 97 H. Lin, J.-Y. Lao, Q. Wang, Y. Ruan, Y. He, P. K. H. Lee, K. M. Y. Leung and P. K. S. Lam, Per- and polyfluoroalkyl substances in the atmosphere of waste management infrastructures: Uncovering secondary fluorotelomer alcohols, particle size distribution, and human inhalation exposure, *Environ. Int.*, 2022, **167**, 107434.
 - 98 S. Wang, X. Lin, Q. Li, C. Liu, Y. Li and X. Wang, Neutral and ionizable per- and polyfluoroalkyl substances in the urban atmosphere: Occurrence, sources and transport, *Sci. Total Environ.*, 2022, **823**, 153794.
 - 99 P. Shen, X. Song, N. Li and C. Zhao, Concentrations and distributions of fluorotelomer alcohols and perfluoroalkane sulfonamido substances in the atmosphere in the Pearl River Delta, China, *J. Environ. Sci. Health, Part A: Toxic/Hazard. Subst. Environ. Eng.*, 2023, **58**, 183–190.
 - 100 A. Saini, S. Chinnadurai, J. K. Schuster, A. Eng and T. Harner, Per- and polyfluoroalkyl substances and volatile methyl siloxanes in global air: Spatial and temporal trends, *Environ. Pollut.*, 2023, **323**, 121291.
 - 101 B. Qiao, D. Song, B. Fang, H. Yu, X. Li, L. Zhao, Y. Yao, L. Zhu, H. Chen and H. Sun, Nontarget Screening and Fate of Emerging Per- and Polyfluoroalkyl Substances in Wastewater Treatment Plants in Tianjin, China, *Environ. Sci. Technol.*, 2023, **57**, 20127–20137.
 - 102 S. Mok, S. Lee, Y. Choi, J. Jeon, Y. Hee Kim and H.-B. Moon, Target and non-target analyses of neutral per- and polyfluoroalkyl substances from fluorochemical industries using GC-MS/MS and GC-TOF: Insights on their environmental fate, *Environ. Int.*, 2023, **182**, 108311.
 - 103 J. Liu, L. Dong, L. Zhou, W. Yang, S. Shi, S. Dong, H. Zhang, X. Zhang, J. Guo and L. Zhang, Tree barks for retrospective measurement and source appointment of airborne perfluoroalkyl and polyfluoroalkyl substances, *Environ. Pollut.*, 2024, **344**, 123346.
 - 104 M. J. Davern, G. V. West, C. M. A. Eichler, B. J. Turpin, Y. Zhang and J. D. Surratt, External Liquid Calibration Method for Iodide Chemical Ionization Mass Spectrometry Enables Quantification of Gas-Phase Per-



- and Polyfluoroalkyl Substances (PFAS) Dynamics in Indoor Air, *Analyst*, 2024, **149**, 3405–3415.
- 105 L. Ahrens, M. Shoeib, T. Harner, D. A. Lane, R. Guo and E. J. Reiner, Comparison of Annular Diffusion Denuder and High Volume Air Samplers for Measuring Per- and Polyfluoroalkyl Substances in the Atmosphere, *Anal. Chem.*, 2011, **83**, 9622–9628.
 - 106 E. J. Weber, C. Tebes-Stevens, J. W. Washington and R. Gladstone, Development of a PFAS reaction library: identifying plausible transformation pathways in environmental and biological systems, *Environ. Sci.: Processes Impacts*, 2022, **24**, 689–753.
 - 107 D. A. Ellis, J. W. Martin, A. O. De Silva, S. A. Mabury, M. D. Hurley, M. P. Sulbaek Andersen and T. J. Wallington, Degradation of Fluorotelomer Alcohols: A Likely Atmospheric Source of Perfluorinated Carboxylic Acids, *Environ. Sci. Technol.*, 2004, **38**, 3316–3321.
 - 108 T. J. Wallington, M. D. Hurley, J. Xia, D. J. Wuebbles, S. Sillman, A. Ito, J. E. Penner, D. A. Ellis, J. Martin, S. A. Mabury, O. J. Nielsen and M. P. Sulbaek Andersen, Formation of C₇F₁₅COOH (PFOA) and Other Perfluorocarboxylic Acids during the Atmospheric Oxidation of 8:2 Fluorotelomer Alcohol, *Environ. Sci. Technol.*, 2006, **40**, 924–930.
 - 109 S. Kutsuna, Y. Nagaoka, K. Takeuchi and H. Hori, TiO₂-Induced Heterogeneous Photodegradation of a Fluorotelomer Alcohol in Air, *Environ. Sci. Technol.*, 2006, **40**, 6824–6829.
 - 110 G. Yarwood, S. Kembell-Cook, M. Keinath, R. L. Waterland, S. H. Korzeniowski, R. C. Buck, M. H. Russell and S. T. Washburn, High-Resolution Atmospheric Modeling of Fluorotelomer Alcohols and Perfluorocarboxylic Acids in the North American Troposphere, *Environ. Sci. Technol.*, 2007, **41**, 5756–5762.
 - 111 F. Wania, A Global Mass Balance Analysis of the Source of Perfluorocarboxylic Acids in the Arctic Ocean, *Environ. Sci. Technol.*, 2007, **41**, 4529–4535.
 - 112 C. J. Young and S. A. Mabury, in *Reviews of Environmental Contamination and Toxicology Volume 208: Perfluorinated Alkylated Substances*, ed. P. De Voogt, Springer, New York, NY, 2010, pp. 1–109.
 - 113 S. D. Vento, C. Halsall, R. Gioia, K. Jones and J. Dachs, Volatile per- and polyfluoroalkyl compounds in the remote atmosphere of the western Antarctic Peninsula: an indirect source of perfluoroalkyl acids to Antarctic waters?, *Atmos. Pollut. Res.*, 2012, **3**, 450–455.
 - 114 C. E. Müller, A. C. Gerecke, C. Bogdal, Z. Wang, M. Scheringer and K. Hungerbühler, Atmospheric fate of poly- and perfluorinated alkyl substances (PFASs): I. Day-night patterns of air concentrations in summer in Zurich, Switzerland, *Environ. Pollut.*, 2012, **169**, 196–203.
 - 115 Z. Wang, M. Scheringer, M. MacLeod, C. Bogdal, C. E. Müller, A. C. Gerecke and K. Hungerbühler, Atmospheric fate of poly- and perfluorinated alkyl substances (PFASs): II. Emission source strength in summer in Zurich, Switzerland, *Environ. Pollut.*, 2012, **169**, 204–209.
 - 116 S. A. Styler, A. L. Myers and D. J. Donaldson, Heterogeneous Photooxidation of Fluorotelomer Alcohols: A New Source of Aerosol-Phase Perfluorinated Carboxylic Acids, *Environ. Sci. Technol.*, 2013, **47**, 6358–6367.
 - 117 A. Gawor, C. Shunthirasingham, S. J. Hayward, Y. D. Lei, T. Gouin, B. T. Mmereki, W. Masamba, C. Ruepert, L. E. Castillo, M. Shoeib, S. C. Lee, T. Harner and F. Wania, Neutral polyfluoroalkyl substances in the global Atmosphere, *Environ. Sci.: Processes Impacts*, 2014, **16**, 404–413.
 - 118 J. Kongpran, S. Tanaka, S. Fujii, Y. Suzuki, N. Sakui and N. Saito, Wet Deposition and Photodegradation of Perfluoroalkyl Carboxylates and Fluorotelomer Alcohols: Distribution Pathways from Air to Water Environment, *J. Water Environ. Technol.*, 2014, **12**, 481–499.
 - 119 Z. Wang, J. M. Boucher, M. Scheringer, I. T. Cousins and K. Hungerbühler, Toward a Comprehensive Global Emission Inventory of C₄–C₁₀ Perfluoroalkanesulfonic Acids (PFASs) and Related Precursors: Focus on the Life Cycle of C₈-Based Products and Ongoing Industrial Transition, *Environ. Sci. Technol.*, 2017, **51**, 4482–4493.
 - 120 C. P. Thackray and N. E. Selin, Uncertainty and variability in atmospheric formation of PFCAs from fluorotelomer precursors, *Atmos. Chem. Phys.*, 2017, **17**, 4585–4597.
 - 121 Q. Wang, Y. Ruan, H. Lin and P. K. S. Lam, Review on perfluoroalkyl and polyfluoroalkyl substances (PFASs) in the Chinese atmospheric environment, *Sci. Total Environ.*, 2020, **737**, 139804.
 - 122 C. P. Thackray, N. E. Selin and C. J. Young, A global atmospheric chemistry model for the fate and transport of PFCAs and their precursors, *Environ. Sci.: Processes Impacts*, 2020, **22**, 285–293.
 - 123 C. M. Butt, U. Berger, R. Bossi and G. T. Tomy, Levels and trends of poly- and perfluorinated compounds in the arctic environment, *Sci. Total Environ.*, 2010, **408**, 2936–2965.
 - 124 C. J. Young, V. I. Furdui, J. Franklin, R. M. Koerner, D. C. G. Muir and S. A. Mabury, Perfluorinated Acids in Arctic Snow: New Evidence for Atmospheric Formation, *Environ. Sci. Technol.*, 2007, **41**, 3455–3461.
 - 125 U. Schenker, M. Scheringer, M. MacLeod, J. W. Martin, I. T. Cousins and K. Hungerbühler, Contribution of Volatile Precursor Substances to the Flux of Perfluorooctanoate to the Arctic, *Environ. Sci. Technol.*, 2008, **42**, 3710–3716.
 - 126 M. Cai, H. Yang, Z. Xie, Z. Zhao, F. Wang, Z. Lu, R. Sturm and R. Ebinghaus, Per- and polyfluoroalkyl substances in snow, lake, surface runoff water and coastal seawater in Fildes Peninsula, King George Island, Antarctica, *J. Hazard. Mater.*, 2012, **209–210**, 335–342.
 - 127 F. Wong, H. Hung, H. Dryfhout-Clark, W. Aas, P. Bohlin-Nizzetto, K. Breivik, M. N. Mastromonaco, E. B. Lundén, K. Ólafsdóttir, Á. Sigurðsson, K. Vorkamp, R. Bossi, H. Skov, H. Hakola, E. Barresi, E. Sverko, P. Fellin, H. Li, A. Vlasenko, M. Zapevalov, D. Samsonov and S. Wilson, Time trends of persistent organic pollutants (POPs) and Chemicals of Emerging Arctic Concern (CEAC) in Arctic



- air from 25 years of monitoring, *Sci. Total Environ.*, 2021, **775**, 145109.
- 128 W. F. Hartz, M. K. Björnsdotter, L. W. Y. Yeung, A. Hodson, E. R. Thomas, J. D. Humby, C. Day, I. E. Jogsten, A. Kärrman and R. Kallenborn, Levels and distribution profiles of Per- and Polyfluoroalkyl Substances (PFAS) in a high Arctic Svalbard ice core, *Sci. Total Environ.*, 2023, **871**, 161830.
 - 129 M. J. A. Dinglasan, Y. Ye, E. A. Edwards and S. A. Mabury, Fluorotelomer Alcohol Biodegradation Yields Poly- and Perfluorinated Acids, *Environ. Sci. Technol.*, 2004, **38**, 2857–2864.
 - 130 N. Wang, B. Szostek, R. C. Buck, P. W. Folsom, L. M. Sulecki, V. Capka, W. R. Berti and J. T. Gannon, Fluorotelomer Alcohol Biodegradation Direct Evidence that Perfluorinated Carbon Chains Breakdown, *Environ. Sci. Technol.*, 2005, **39**, 7516–7528.
 - 131 J. Liu, L. S. Lee, L. F. Nies, C. H. Nakatsu and R. F. Turco, Biotransformation of 8:2 Fluorotelomer Alcohol in Soil and by Soil Bacteria Isolates, *Environ. Sci. Technol.*, 2007, **41**, 8024–8030.
 - 132 N. Wang, B. Szostek, R. C. Buck, P. W. Folsom, L. M. Sulecki and J. T. Gannon, 8-2 Fluorotelomer alcohol aerobic soil biodegradation: Pathways, metabolites, and metabolite yields, *Chemosphere*, 2009, **75**, 1089–1096.
 - 133 J. J. Ellington, J. W. Washington, J. J. Evans, T. M. Jenkins, S. C. Hafner and M. P. Neill, Analysis of fluorotelomer alcohols in soils: Optimization of extraction and chromatography, *J. Chromatogr. A*, 2009, **1216**, 5347–5354.
 - 134 J. Liu, N. Wang, R. C. Buck, B. W. Wolstenholme, P. W. Folsom, L. M. Sulecki and C. A. Bellin, Aerobic biodegradation of [¹⁴C] 6:2 fluorotelomer alcohol in a flow-through soil incubation system, *Chemosphere*, 2010, **80**, 716–723.
 - 135 J. Liu, N. Wang, B. Szostek, R. C. Buck, P. K. Panciroli, P. W. Folsom, L. M. Sulecki and C. A. Bellin, 6-2 Fluorotelomer alcohol aerobic biodegradation in soil and mixed bacterial culture, *Chemosphere*, 2010, **78**, 437–444.
 - 136 M. H. Kim, N. Wang, T. McDonald and K.-H. Chu, Biodefluorination and biotransformation of fluorotelomer alcohols by two alkane-degrading *Pseudomonas* strains, *Biotechnol. Bioeng.*, 2012, **109**, 3041–3048.
 - 137 C. M. Butt, D. C. G. Muir and S. A. Mabury, Biotransformation pathways of fluorotelomer-based polyfluoroalkyl substances: A review, *Environ. Toxicol. Chem.*, 2014, **33**, 243–267.
 - 138 N. Tseng, N. Wang, B. Szostek and S. Mahendra, Biotransformation of 6:2 fluorotelomer alcohol (6:2 FTOH) by a wood-rotting fungus, *Environ. Sci. Technol.*, 2014, **48**, 4012–4020.
 - 139 M. H. Kim, N. Wang and K. H. Chu, 6:2 Fluorotelomer alcohol (6:2 FTOH) biodegradation by multiple microbial species under different physiological conditions, *Appl. Microbiol. Biotechnol.*, 2014, **98**, 1831–1840.
 - 140 M. Lewis, M.-H. Kim, N. Wang and K.-H. Chu, Engineering artificial communities for enhanced FTOH degradation, *Sci. Total Environ.*, 2016, **572**, 935–942.
 - 141 N. Merino, M. Wang, R. Ambrocio, K. Mak, E. O'Connor, A. Gao, E. L. Hawley, R. A. Deeb, L. Y. Tseng and S. Mahendra, Fungal biotransformation of 6:2 fluorotelomer alcohol, *Remed. J.*, 2018, **28**, 59–70.
 - 142 X. Yu, F. Nishimura and T. Hidaka, Enhanced generation of perfluoroalkyl carboxylic acids (PFCAs) from fluorotelomer alcohols (FTOHs) via ammonia-oxidation process, *Chemosphere*, 2018, **198**, 311–319.
 - 143 Y. J. Choi, D. E. Helbling, J. Liu, C. I. Olivares and C. P. Higgins, Microbial biotransformation of aqueous film-forming foam derived polyfluoroalkyl substances, *Sci. Total Environ.*, 2022, **824**, 153711.
 - 144 P.-F. Yan, S. Dong, K. E. Manz, C. Liu, M. J. Woodcock, M. P. Mezzari, L. M. Abriola, K. D. Pennell and N. L. Cápiro, Biotransformation of 8:2 Fluorotelomer Alcohol in Soil from Aqueous Film-Forming Foams (AFFFs)-Impacted Sites under Nitrate-, Sulfate-, and Iron-Reducing Conditions, *Environ. Sci. Technol.*, 2022, **56**, 13728–13739.
 - 145 M. F. Khan and C. D. Murphy, Fluorotelomer alcohols are efficiently biotransformed by *Cunninghamella elegans*, *Environ. Sci. Pollut. Res.*, 2023, **30**, 23613–23623.
 - 146 S. Dong, P.-F. Yan, C. Liu, K. E. Manz, M. P. Mezzari, L. M. Abriola, K. D. Pennell and N. L. Cápiro, Assessing aerobic biotransformation of 8:2 fluorotelomer alcohol in aqueous film-forming foam (AFFF)-impacted soils: Pathways and microbial community dynamics, *J. Hazard. Mater.*, 2023, **446**, 130629.
 - 147 N. Merino, N. Wang, Y. Gao, M. Wang and S. Mahendra, Roles of various enzymes in the biotransformation of 6:2 fluorotelomer alcohol (6:2 FTOH) by a white-rot fungus, *J. Hazard. Mater.*, 2023, **450**, 131007.
 - 148 A. Berhanu, I. Mutanda, J. Taolin, M. A. Qaria, B. Yang and D. Zhu, A review of microbial degradation of per- and polyfluoroalkyl substances (PFAS): Biotransformation routes and enzymes, *Sci. Total Environ.*, 2023, **859**, 160010.
 - 149 S.-H. Yang, L. Shan and K.-H. Chu, Root exudates enhanced 6:2 FTOH defluorination, altered metabolite profiles and shifted soil microbiome dynamics, *J. Hazard. Mater.*, 2024, **466**, 133651.
 - 150 J. Popovic, C. J. Bee, K. H. Beam, K. Dovantzis, J. M. Stapleton, M. A. Barba, M. R. P. Callier and W. Yoon, Network Meta-Analysis and Systematic Review of Conditions Facilitating Microbial Biotransformation of 6:2 and 8:2 Fluorotelomer Alcohols to Perfluoroalkyl Carboxylates, *Environ. Sci. Technol. Lett.*, 2024, **11**, 292–300.
 - 151 N. Wang, B. Szostek, P. W. Folsom, L. M. Sulecki, V. Capka, R. C. Buck, W. R. Berti and J. T. Gannon, Aerobic Biotransformation of ¹⁴C-Labeled 8-2 Telomer B Alcohol by Activated Sludge from a Domestic Sewage Treatment Plant, *Environ. Sci. Technol.*, 2005, **39**, 531–538.
 - 152 M. Sáez, P. de Voogt and J. R. Parsons, Persistence of perfluoroalkylated substances in closed bottle tests with municipal sewage sludge, *Environ. Sci. Pollut. Res.*, 2008, **15**, 472–477.
 - 153 H. Yoo, J. W. Washington, J. J. Ellington, T. M. Jenkins and M. P. Neill, Concentrations, Distribution, and Persistence



- of Fluorotelomer Alcohols in Sludge-Applied Soils near Decatur, Alabama, USA, *Environ. Sci. Technol.*, 2010, **44**, 8397–8402.
- 154 L. Zhao, P. K. McCausland, P. W. Folsom, B. W. Wolstenholme, H. Sun, N. Wang and R. C. Buck, 6:2 Fluorotelomer alcohol aerobic biotransformation in activated sludge from two domestic wastewater treatment plants, *Chemosphere*, 2013, **92**, 464–470.
 - 155 S. Zhang, B. Szostek, P. K. McCausland, B. W. Wolstenholme, X. Lu, N. Wang and R. C. Buck, 6:2 and 8:2 Fluorotelomer Alcohol Anaerobic Biotransformation in Digester Sludge from a WWTP under Methanogenic Conditions, *Environ. Sci. Technol.*, 2013, **47**, 4227–4235.
 - 156 X. Yu, Y. Takabe, K. Yamamoto, C. Matsumura and F. Nishimura, Biodegradation Property of 8:2 Fluorotelomer Alcohol (8:2 FTOH) under Aerobic/Anoxic/Anaerobic Conditions, *J. Water Environ. Technol.*, 2016, **14**, 177–190.
 - 157 F. Li, Q. Su, Z. Zhou, X. Liao, J. Zou, B. Yuan and W. Sun, Anaerobic biodegradation of 8:2 fluorotelomer alcohol in anaerobic activated sludge: Metabolic products and pathways, *Chemosphere*, 2018, **200**, 124–132.
 - 158 X. Yu, F. Nishimura and T. Hidaka, Effects of microbial activity on perfluorinated carboxylic acids (PFCAs) generation during aerobic biotransformation of fluorotelomer alcohols in activated sludge, *Sci. Total Environ.*, 2018, **610–611**, 776–785.
 - 159 W. Qiao, J. Miao, H. Jiang and Q. Yang, Degradation and effect of 6:2 fluorotelomer alcohol in aerobic composting of sludge, *Biodegradation*, 2021, **32**, 99–112.
 - 160 L. Zhao, P. W. Folsom, B. W. Wolstenholme, H. Sun, N. Wang and R. C. Buck, 6:2 Fluorotelomer alcohol biotransformation in an aerobic river sediment system, *Chemosphere*, 2013, **90**, 203–209.
 - 161 S. Zhang, N. Merino, N. Wang, T. Ruan and X. Lu, Impact of 6:2 fluorotelomer alcohol aerobic biotransformation on a sediment microbial community, *Sci. Total Environ.*, 2017, **575**, 1361–1368.
 - 162 H. Hamid, L. Y. Li and J. R. Grace, Aerobic biotransformation of fluorotelomer compounds in landfill leachate-sediment, *Sci. Total Environ.*, 2020, **713**, 136547.
 - 163 H. Zhang, B. Wen, X. Hu, Y. Wu, L. Luo, Z. Chen and S. Zhang, Determination of fluorotelomer alcohols and their degradation products in biosolids-amended soils and plants using ultra-high performance liquid chromatography tandem mass spectrometry, *J. Chromatogr. A*, 2015, **1404**, 72–80.
 - 164 H. Zhang, B. Wen, X. Hu, Y. Wu, Y. Pan, H. Huang, L. Liu and S. Zhang, Uptake, Translocation, and Metabolism of 8:2 Fluorotelomer Alcohol in Soybean (*Glycine max* L. Merrill), *Environ. Sci. Technol.*, 2016, **50**, 13309–13317.
 - 165 S. Zhao and L. Zhu, Uptake and metabolism of 10:2 fluorotelomer alcohol in soil-earthworm (*Eisenia fetida*) and soil-wheat (*Triticum aestivum* L.) systems, *Environ. Pollut.*, 2017, **220**, 124–131.
 - 166 M. Muschket, N. Keltsch, H. Paschke, T. Reemtsma and U. Berger, Determination of transformation products of per- and polyfluoroalkyl substances at trace levels in agricultural plants, *J. Chromatogr. A*, 2020, **1625**, 461271.
 - 167 Y. Yao, Z. Lan, H. Zhu, J. Xu and H. Sun, Foliar uptake overweighs root uptake for 8:2 fluorotelomer alcohol in ryegrass (*Lolium perenne* L.): A closed exposure chamber study, *Sci. Total Environ.*, 2022, **829**, 154660.
 - 168 H. Just, B. Göckener, R. Lämmer, L. Wiedemann-Krantz, T. Stahl, J. Breuer, M. Gassmann, E. Weidemann, M. Bücking and J. Kowalczyk, Degradation and Plant Transfer Rates of Seven Fluorotelomer Precursors to Perfluoroalkyl Acids and F-53B in a Soil-Plant System with Maize (*Zea mays* L.), *J. Agric. Food Chem.*, 2022, **70**, 8920–8930.
 - 169 Y. Zhang, S. Wu, Q.-Q. Chen, P.-F. Yu, H.-M. Zhao, N.-X. Feng, B.-L. Liu, Y.-W. Li, Q.-Y. Cai, L. Xiang, C.-H. Mo and Q. X. Li, Highly Efficient and Simultaneous Analysis of Three Common Fluorotelomer Alcohols in Vegetables and Soils, *J. Agric. Food Chem.*, 2023, **71**, 11704–11715.
 - 170 I. A. Titaley, J. Khattak, J. Dong, C. I. Olivares, B. DiGuseppi, C. C. Lutes and J. A. Field, Neutral Per- and Polyfluoroalkyl Substances, Butyl Carbitol, and Organic Corrosion Inhibitors in Aqueous Film-Forming Foams: Implications for Vapor Intrusion and the Environment, *Environ. Sci. Technol.*, 2022, **56**, 10785–10797.
 - 171 S. A. Gauthier and S. A. Mabury, Aqueous photolysis of 8:2 fluorotelomer alcohol, *Environ. Toxicol. Chem.*, 2005, **24**, 1837–1846.
 - 172 S. Taniyasu, N. Yamashita, E. Yamazaki, G. Petrick and K. Kannan, The environmental photolysis of perfluorooctanesulfonate, perfluorooctanoate, and related fluorochemicals, *Chemosphere*, 2013, **90**, 1686–1692.
 - 173 J. Keränen, H. Ahkola, J. Knuutinen, S. Herve, M. Reinikainen and J. Koistinen, Formation of PFOA from 8:2 FTOH in closed-bottle experiments with brackish water, *Environ. Sci. Pollut. Res.*, 2013, **20**, 8001–8012.
 - 174 J. W. Martin, S. A. Mabury and P. J. O'Brien, Metabolic products and pathways of fluorotelomer alcohols in isolated rat hepatocytes, *Chem.-Biol. Interact.*, 2005, **155**, 165–180.
 - 175 W. J. Fasano, S. C. Carpenter, S. A. Gannon, T. A. Snow, J. C. Stadler, G. L. Kennedy, R. C. Buck, S. H. Korzeniowski, P. M. Hinderliter and R. A. Kemper, Absorption, Distribution, Metabolism, and Elimination of 8-2 Fluorotelomer Alcohol in the Rat, *Toxicol. Sci.*, 2006, **91**, 341–355.
 - 176 D. L. Nabb, B. Szostek, M. W. Himmelstein, M. P. Mawn, M. L. Gargas, L. M. Sweeney, J. C. Stadler, R. C. Buck and W. J. Fasano, In Vitro Metabolism of 8-2 Fluorotelomer Alcohol: Interspecies Comparisons and Metabolic Pathway Refinement, *Toxicol. Sci.*, 2007, **100**, 333–344.
 - 177 W. M. Henderson, E. J. Weber, S. E. Duirk, J. W. Washington and M. A. Smith, Quantification of fluorotelomer-based chemicals in mammalian matrices



- by monitoring perfluoroalkyl chain fragments with GC/MS, *J. Chromatogr. B*, 2007, **846**, 155–161.
- 178 W. J. Fasano, L. M. Sweeney, M. P. Mawn, D. L. Nabb, B. Szostek, R. C. Buck and M. L. Gargas, Kinetics of 8:2 fluorotelomer alcohol and its metabolites, and liver glutathione status following daily oral dosing for 45 days in male and female rats, *Chem.-Biol. Interact.*, 2009, **180**, 281–295.
 - 179 H. Nilsson, A. Kärrman, A. Rotander, B. van Bavel, G. Lindström and H. Westberg, Inhalation Exposure to Fluorotelomer Alcohols Yield Perfluorocarboxylates in Human Blood?, *Environ. Sci. Technol.*, 2010, **44**, 7717–7722.
 - 180 H. Nilsson, A. Kärrman, H. Westberg, A. Rotander, B. van Bavel and G. Lindström, A Time Trend Study of Significantly Elevated Perfluorocarboxylate Levels in Humans after Using Fluorinated Ski Wax, *Environ. Sci. Technol.*, 2010, **44**, 2150–2155.
 - 181 A. J. Fraser, T. F. Webster, D. J. Watkins, J. W. Nelson, H. M. Stapleton, A. M. Calafat, K. Kato, M. Shoeib, V. M. Vieira and M. D. McClean, Polyfluorinated Compounds in Serum Linked to Indoor Air in Office Environments, *Environ. Sci. Technol.*, 2012, **46**, 1209–1215.
 - 182 H. Nilsson, A. Kärrman, A. Rotander, B. van Bavel, G. Lindström and H. Westberg, Biotransformation of fluorotelomer compound to perfluorocarboxylates in humans, *Environ. Int.*, 2013, **51**, 8–12.
 - 183 M. H. Russell, M. W. Himmelstein and R. C. Buck, Inhalation and oral toxicokinetics of 6:2 FTOH and its metabolites in mammals, *Chemosphere*, 2015, **120**, 328–335.
 - 184 M. I. Gomis, R. Vestergren, H. Nilsson and I. T. Cousins, Contribution of Direct and Indirect Exposure to Human Serum Concentrations of Perfluorooctanoic Acid in an Occupationally Exposed Group of Ski Waxers, *Environ. Sci. Technol.*, 2016, **50**, 7037–7046.
 - 185 S. Dagnino, M. J. Strynar, R. L. McMahan, C. S. Lau, C. Ball, S. Garantziotis, T. F. Webster, M. D. McClean and A. B. Lindstrom, Identification of Biomarkers of Exposure to FTOHs and PAPs in Humans Using a Targeted and Nontargeted Analysis Approach, *Environ. Sci. Technol.*, 2016, **50**, 10216–10225.
 - 186 C. M. Makey, T. F. Webster, J. W. Martin, M. Shoeib, T. Harner, L. Dix-Cooper and G. M. Webster, Airborne Precursors Predict Maternal Serum Perfluoroalkyl Acid Concentrations, *Environ. Sci. Technol.*, 2017, **51**, 7667–7675.
 - 187 M. C. Huang, V. G. Robinson, S. Waidyanatha, A. L. Dzierlenga, M. J. DeVito, M. A. Eifrid, S. T. Gibbs and C. R. Blystone, Toxicokinetics of 8:2 fluorotelomer alcohol (8:2-FTOH) in male and female Hsd:Sprague Dawley SD rats after intravenous and gavage administration, *Toxicol Rep*, 2019, **6**, 924–932.
 - 188 S. Xie, Y. Cui, Y. Yang, K. Meng, Y. Pan, Z. Liu and D. Chen, Tissue distribution and bioaccumulation of 8:2 fluorotelomer alcohol and its metabolites in pigs after oral exposure, *Chemosphere*, 2020, **249**, 126016.
 - 189 S. V. Kabadi, J. W. Fisher, D. R. Doerge, D. Mehta, J. Aungst and P. Rice, Characterizing biopersistence potential of the metabolite 5:3 fluorotelomer carboxylic acid after repeated oral exposure to the 6:2 fluorotelomer alcohol, *Toxicol. Appl. Pharmacol.*, 2020, **388**, 114878.
 - 190 O. Daramola and A. A. Rand, Emerging investigator series: human CYP2A6 catalyzes the oxidation of 6:2 fluorotelomer alcohol, *Environ. Sci.: Processes Impacts*, 2021, **23**, 1688–1695.
 - 191 N. Xu, H. Lin, J.-M. Lin, J. Cheng, P. Wang and L. Lin, Microfluidic Chip-Based Modeling of Three-Dimensional Intestine–Vessel–Liver Interactions in Fluorotelomer Alcohol Biotransformation, *Anal. Chem.*, 2023, **96**, 17064–17072.
 - 192 N. Xu, H. Lin, Q. Du, S. Dong, J. Cheng, P. Wang and J.-M. Lin, *In situ* investigation of detoxification and metabolic effects of polyfluoroalkyl substances on metal-organic frameworks combined with cell-cultured microfluidics, *Lab Chip*, 2023, **23**, 3062–3069.
 - 193 P. A. Rice, S. V. Kabadi, D. R. Doerge, M. M. Vanlandingham, M. I. Churchwell, V. P. Tryndyak, J. W. Fisher, J. Aungst and F. A. Beland, Evaluating the toxicokinetics of some metabolites of a C6 polyfluorinated compound, 6:2 fluorotelomer alcohol in pregnant and nonpregnant rats after oral exposure to the parent compound, *Food Chem. Toxicol.*, 2024, **183**, 114333.
 - 194 D. Chen, Y. Zhao, W. Xu, Y. Pan, Q. Wei and S. Xie, Biotransformation and tissue bioaccumulation of 8:2 fluorotelomer alcohol in broiler by oral exposure, *Environ. Pollut.*, 2020, **267**, 115611.
 - 195 C. M. Butt, D. C. G. Muir and S. A. Mabury, Elucidating the Pathways of Poly- and Perfluorinated Acid Formation in Rainbow Trout, *Environ. Sci. Technol.*, 2010, **44**, 4973–4980.
 - 196 S. H. Brandsma, M. Smithwick, K. Solomon, J. Small, J. de Boer and D. C. G. Muir, Dietary exposure of rainbow trout to 8:2 and 10:2 fluorotelomer alcohols and perfluorooctanesulfonamide: Uptake, transformation and elimination, *Chemosphere*, 2011, **82**, 253–258.
 - 197 A. A. Rand and S. A. Mabury, Is there a human health risk associated with indirect exposure to perfluoroalkyl carboxylates (PFCAs)?, *Toxicology*, 2017, **375**, 28–36.
 - 198 R. W. Speke, Variables in Padding Processes, *J. Soc. Dyers Colour.*, 1954, **70**, 221–226.
 - 199 U. Sayed and P. Dabhi, in *Waterproof and Water Repellent Textiles and Clothing*, ed. J. Williams, Woodhead Publishing, 2014, pp. 139–152.
 - 200 L. C. Wickersham, J. M. Mattila, J. D. Krug, S. R. Jackson, M. A. G. Wallace, E. P. Shields, H. Halliday, E. Y. Li, H. K. Liberatore, S. Farrior, W. Preston, J. V. Ryan, C.-W. Lee and W. P. Linak, Characterization of PFAS Air Emissions from Thermal Application of Fluoropolymer Dispersions on Fabrics, *J. Air Waste Manage. Assoc.*, 2023, **73**, 533–552.
 - 201 F. Heydebreck, J. Tang, Z. Xie and R. Ebinghaus, Emissions of Per- and Polyfluoroalkyl Substances in a Textile Manufacturing Plant in China and Their Relevance for Workers' Exposure, *Environ. Sci. Technol.*, 2016, **50**, 10386–10396.



- 202 T. Paris-Davila, L. G. T. Gaines, K. Lucas and L. A. Nylander-French, Occupational exposures to airborne per- and polyfluoroalkyl substances (PFAS)—A review, *Am. J. Ind. Med.*, 2023, **66**, 393–410.
- 203 M. Schlummer, L. Gruber, D. Fiedler, M. Kizlauskas and J. Müller, Detection of fluorotelomer alcohols in indoor environments and their relevance for human exposure, *Environ. Int.*, 2013, **57–58**, 42–49.
- 204 A. Shinde and R. B. Ormond, Headspace sampling-gas chromatograph-mass spectrometer as a screening method to thermally extract fireground contaminants from retired firefighting turnout jackets, *Fire Mater.*, 2020, **45**, 415–428.
- 205 Z. G. Robbins, X. Liu, B. A. Schumacher, M. G. Smeltz and H. K. Liberatore, Method development for thermal desorption-gas chromatography-tandem mass spectrometry (TD-GC-MS/MS) analysis of trace level fluorotelomer alcohols emitted from consumer products, *J. Chromatogr. A*, 2023, **1705**, 464204.
- 206 A. Jahnke, S. Huber, C. Temme, H. Kylin and U. Berger, Development and application of a simplified sampling method for volatile polyfluorinated alkyl substances in indoor and environmental air, *J. Chromatogr. A*, 2007, **1164**, 1–9.
- 207 J. L. Barber, U. Berger, C. Chaemfa, S. Huber, A. Jahnke, C. Temme and K. C. Jones, Analysis of per- and polyfluorinated alkyl substances in air samples from Northwest Europe, *J. Environ. Monit.*, 2007, **9**, 530–541.
- 208 V. Langer, A. Dreyer and R. Ebinghaus, Polyfluorinated Compounds in Residential and Nonresidential Indoor Air, *Environ. Sci. Technol.*, 2010, **44**, 8075–8081.
- 209 L. S. Haug, S. Huber, M. Schlabach, G. Becher and C. Thomsen, Investigation on Per- and Polyfluorinated Compounds in Paired Samples of House Dust and Indoor Air from Norwegian Homes, *Environ. Sci. Technol.*, 2011, **45**, 7991–7998.
- 210 S. Huber, L. S. Haug and M. Schlabach, Per- and polyfluorinated compounds in house dust and indoor air from northern Norway – A pilot study, *Chemosphere*, 2011, **84**, 1686–1693.
- 211 M. Shoeib, T. Harner, G. M. Webster and S. C. Lee, Indoor Sources of Poly- and Perfluorinated Compounds (PFCS) in Vancouver, Canada: Implications for Human Exposure, *Environ. Sci. Technol.*, 2011, **45**, 7999–8005.
- 212 I. Ericson Jogsten, M. Nadal, B. van Bavel, G. Lindström and J. L. Domingo, Per- and polyfluorinated compounds (PFCs) in house dust and indoor air in Catalonia, Spain: Implications for human exposure, *Environ. Int.*, 2012, **39**, 172–180.
- 213 Y. Wu and V. W.-C. Chang, Development of analysis of volatile polyfluorinated alkyl substances in indoor air using thermal desorption-gas chromatography-mass spectrometry, *J. Chromatogr. A*, 2012, **1238**, 114–120.
- 214 W. Liu, S. Takahashi, Y. Sakuramachi, K. H. Harada and A. Koizumi, Polyfluorinated telomers in indoor air of Japanese houses, *Chemosphere*, 2013, **90**, 1672–1677.
- 215 H. Fromme, A. Dreyer, S. Dietrich, L. Fembacher, T. Lahrz and W. Völkel, Neutral polyfluorinated compounds in indoor air in Germany – The LUPE 4 study, *Chemosphere*, 2015, **139**, 572–578.
- 216 K. Winkens, J. Koponen, J. Schuster, M. Shoeib, R. Vestergren, U. Berger, A. M. Karvonen, J. Pekkanen, H. Kiviranta and I. T. Cousins, Perfluoroalkyl acids and their precursors in indoor air sampled in children's bedrooms, *Environ. Pollut.*, 2017, **222**, 423–432.
- 217 J. A. Padilla-Sánchez, E. Papadopoulou, S. Poothong and L. S. Haug, Investigation of the Best Approach for Assessing Human Exposure to Poly- and Perfluoroalkyl Substances through Indoor Air, *Environ. Sci. Technol.*, 2017, **51**, 12836–12843.
- 218 B. Sha, A.-K. Dahlberg, K. Wiberg and L. Ahrens, Fluorotelomer alcohols (FTOHs), brominated flame retardants (BFRs), organophosphorus flame retardants (OPFRs) and cyclic volatile methylsiloxanes (cVMSs) in indoor air from occupational and home environments, *Environ. Pollut.*, 2018, **241**, 319–330.
- 219 Y. Yao, Y. Zhao, H. Sun, S. Chang, L. Zhu, A. C. Alder and K. Kannan, Per- and Polyfluoroalkyl Substances (PFASs) in Indoor Air and Dust from Homes and Various Microenvironments in China: Implications for Human Exposure, *Environ. Sci. Technol.*, 2018, **52**, 3156–3166.
- 220 M. E. Morales-McDevitt, J. Becanova, A. Blum, T. A. Bruton, S. Vojta, M. Woodward and R. Lohmann, The Air That We Breathe: Neutral and Volatile PFAS in Indoor Air, *Environ. Sci. Technol. Lett.*, 2021, **8**, 897–902.
- 221 C. M. A. Eichler and J. C. Little, A framework to model exposure to per- and polyfluoroalkyl substances in indoor environments, *Environ. Sci.: Processes Impacts*, 2020, **22**, 500–511.
- 222 C. M. A. Eichler, C. Bi, C. Wang and J. C. Little, A modular mechanistic framework for estimating exposure to SVOCs: Next steps for modeling emission and partitioning of plasticizers and PFAS, *J. Exposure Sci. Environ. Epidemiol.*, 2022, **32**, 356–365.
- 223 L. Zhu, P. Hajeb, P. Fauser and K. Vorkamp, Endocrine disrupting chemicals in indoor dust: A review of temporal and spatial trends, and human exposure, *Sci. Total Environ.*, 2023, **874**, 162374.
- 224 H. Nilsson, A. Kärrman, A. Rotander, B. van Bavel, G. Lindström and H. Westberg, Professional ski waxers' exposure to PFAS and aerosol concentrations in gas phase and different particle size fractions, *Environ. Sci.: Processes Impacts*, 2013, **15**, 814–822.
- 225 K. A. Crawford, B. T. Doherty, D. Gilbert-Diamond, M. E. Romano and B. Claus Henn, Waxing activity as a potential source of exposure to per- and polyfluoroalkyl substances (PFAS) and other environmental contaminants among the US ski and snowboard community, *Environ. Res.*, 2022, **215**, 114335.
- 226 C. Holder, N. DeLuca, J. Luh, P. Alexander, J. M. Minucci, D. A. Vallerio, K. Thomas and E. A. Cohen Hubal, Systematic Evidence Mapping of Potential Exposure Pathways for Per- and Polyfluoroalkyl Substances Based on Measured Occurrence in Multiple Media, *Environ. Sci. Technol.*, 2023, **57**, 5107–5116.



- 227 L. G. T. Gaines and L. A. Nylander-French, Occupational exposure to PFAS: Research and protection needed, *Am. J. Ind. Med.*, 2023, **66**, 424–426.
- 228 K. A. Crawford and N. Hartmann, Respiratory Exposure to Highly Fluorinated Chemicals *via* Application of Ski Wax and Related Health Effects, *Curr. Environ. Health Rep.*, 2024, **11**, 39–45.
- 229 S. Niu, X. Zhu, R. Chen, A. Winchell, P. Gao, A. Barchowsky, J. M. Buchanich and C. Ng, Personal Wearable Sampler for Per- and Polyfluoroalkyl Substances Exposure Assessment, *Environ. Sci. Technol. Lett.*, 2024, **11**, 301–307.
- 230 Z. Xu, S. Fiedler, G. Pfister, B. Henkelmann, C. Mosch, W. Völkel, H. Fromme and K.-W. Schramm, Human exposure to fluorotelomer alcohols, perfluorooctane sulfonate and perfluorooctanoate *via* house dust in Bavaria, Germany, *Sci. Total Environ.*, 2013, **443**, 485–490.
- 231 Z. Tian, S.-K. Kim, M. Shoeib, J.-E. Oh and J.-E. Park, Human exposure to per- and polyfluoroalkyl substances (PFASs) *via* house dust in Korea: Implication to exposure pathway, *Sci. Total Environ.*, 2016, **553**, 266–275.
- 232 N. M. DeLuca, J. M. Minucci, A. Mullikin, R. Slover and E. A. Cohen Hubal, Human exposure pathways to poly- and perfluoroalkyl substances (PFAS) from indoor media: A systematic review, *Environ. Int.*, 2022, **162**, 107149.
- 233 S. Poonthong, E. Papadopoulou, J. A. Padilla-Sánchez, C. Thomsen and L. S. Haug, Multiple pathways of human exposure to poly- and perfluoroalkyl substances (PFASs): From external exposure to human blood, *Environ. Int.*, 2020, **134**, 105244.
- 234 J. C. Kissel, I. A. Titaley, D. J. Muensterman and J. A. Field, Evaluating Neutral PFAS for Potential Dermal Absorption from the Gas Phase, *Environ. Sci. Technol.*, 2023, **57**, 4951–4958.
- 235 J. C. Kissel, I. A. Titaley, D. J. Muensterman and J. A. Field, Correction to “Evaluating Neutral PFAS for Potential Dermal Absorption from the Gas Phase”, *Environ. Sci. Technol.*, 2023, **57**, 9894.
- 236 A. Ramírez Carnero, A. Lestido-Cardama, P. Vazquez Loureiro, L. Barbosa-Pereira, A. Rodríguez Bernaldo de Quirós and R. Sendón, Presence of Perfluoroalkyl and Polyfluoroalkyl Substances (PFAS) in Food Contact Materials (FCM) and Its Migration to Food, *Foods*, 2021, **10**, 1443.
- 237 P. A. Rice, J. Aungst, J. Cooper, O. Bandele and S. V. Kabadi, Comparative analysis of the toxicological databases for 6:2 fluorotelomer alcohol (6:2 FTOH) and perfluorohexanoic acid (PFHxA), *Food Chem. Toxicol.*, 2020, **138**, 111210.
- 238 Y. Xia, L. Hao, Y. Li, Y. Li, J. Chen, L. Li, X. Han, Y. Liu, X. Wang and D. Li, Embryonic 6:2 FTOH exposure causes reproductive toxicity by disrupting the formation of the blood-testis barrier in offspring mice, *Ecotoxicol. Environ. Saf.*, 2023, **250**, 114497.
- 239 Y. Rericha, L. Truong, C. Leong, D. Cao, J. A. Field and R. L. Tanguay, Dietary Perfluorohexanoic Acid (PFHxA) Exposures in Juvenile Zebrafish Produce Subtle Behavioral Effects across Generations, *Toxics*, 2022, **10**, 372.
- 240 M. E. Morales-McDevitt, M. Dunn, A. Habib, S. Vojta, J. Becanova and R. Lohmann, Poly- and Perfluorinated Alkyl Substances in Air and Water from Dhaka, Bangladesh, *Environ. Toxicol. Chem.*, 2022, **41**, 334–342.
- 241 H. Chen, Y. Yao, Z. Zhao, Y. Wang, Q. Wang, C. Ren, B. Wang, H. Sun, A. C. Alder and K. Kannan, Multimedia Distribution and Transfer of Per- and Polyfluoroalkyl Substances (PFASs) Surrounding Two Fluorochemical Manufacturing Facilities in Fuxin, China, *Environ. Sci. Technol.*, 2018, **52**, 8263–8271.
- 242 P. Thepaksorn, P. Lee, Y. Shiwaku, B. Zheng, A. Koizumi and K. H. Harada, Formation and Degradability of Per- and Polyfluoroalkyl Substances in River Soils around a Fluoropolymer-Manufacturing Plant in Osaka, Japan, *Arch. Environ. Contam. Toxicol.*, 2023, **84**, 427–435.
- 243 A. M. Piekarz, T. Primbs, J. A. Field, D. F. Barofsky and S. Simonich, Semivolatile Fluorinated Organic Compounds in Asian and Western U.S. Air Masses, *Environ. Sci. Technol.*, 2007, **41**, 8248–8255.
- 244 T. Primbs, A. Piekarz, G. Wilson, D. Schmedding, C. Higginbotham, J. Field and S. M. Simonich, Influence of Asian and Western United States Urban Areas and Fires on the Atmospheric Transport of Polycyclic Aromatic Hydrocarbons, Polychlorinated Biphenyls, and Fluorotelomer Alcohols in the Western United States, *Environ. Sci. Technol.*, 2008, **42**, 6385–6391.
- 245 J. W. Martin, D. C. G. Muir, C. A. Moody, D. A. Ellis, W. C. Kwan, K. R. Solomon and S. A. Mabury, Collection of Airborne Fluorinated Organics and Analysis by Gas Chromatography/Chemical Ionization Mass Spectrometry, *Anal. Chem.*, 2002, **74**, 584–590.
- 246 A. Jahnke, L. Ahrens, R. Ebinghaus and C. Temme, Urban versus Remote Air Concentrations of Fluorotelomer Alcohols and Other Polyfluorinated Alkyl Substances in Germany, *Environ. Sci. Technol.*, 2007, **41**, 745–752.
- 247 A. Jahnke, L. Ahrens, R. Ebinghaus, U. Berger, J. L. Barber and C. Temme, An improved method for the analysis of volatile polyfluorinated alkyl substances in environmental air samples, *Anal. Bioanal. Chem.*, 2007, **387**, 965–975.
- 248 A. Jahnke, U. Berger, R. Ebinghaus and C. Temme, Latitudinal Gradient of Airborne Polyfluorinated Alkyl Substances in the Marine Atmosphere between Germany and South Africa (53° N–33° S), *Environ. Sci. Technol.*, 2007, **41**, 3055–3061.
- 249 M. Loewen, F. Wania, F. Wang and G. Tomy, Altitudinal Transect of Atmospheric and Aqueous Fluorinated Organic Compounds in Western Canada, *Environ. Sci. Technol.*, 2008, **42**, 2374–2379.
- 250 A. Dreyer, V. Matthias, C. Temme and R. Ebinghaus, Annual Time Series of Air Concentrations of Polyfluorinated Compounds, *Environ. Sci. Technol.*, 2009, **43**, 4029–4036.
- 251 A. Jahnke, J. L. Barber, K. C. Jones and C. Temme, Quantitative trace analysis of polyfluorinated alkyl substances (PFAS) in ambient air samples from Mace Head (Ireland): A method intercomparison, *Atmos. Environ.*, 2009, **43**, 844–850.



- 252 S. Genualdi, S. C. Lee, M. Shoeib, A. Gawor, L. Ahrens and T. Harner, Global Pilot Study of Legacy and Emerging Persistent Organic Pollutants using Sorbent-Impregnated Polyurethane Foam Disk Passive Air Samplers, *Environ. Sci. Technol.*, 2010, **44**, 5534–5539.
- 253 L. Ahrens, M. Shoeib, S. D. Vento, G. Codling and C. Halsall, Polyfluoroalkyl compounds in the Canadian Arctic atmosphere, *Environ. Chem.*, 2011, **8**, 399–406.
- 254 L. Ahrens, T. Harner, M. Shoeib, M. Koblikova and E. J. Reiner, Characterization of Two Passive Air Samplers for Per- and Polyfluoroalkyl Substances, *Environ. Sci. Technol.*, 2013, **47**, 14024–14033.
- 255 Y. Wu and V. W.-C. Chang, Comparison of solvent extraction and thermal desorption methods for determination of volatile polyfluorinated alkyl substances in the urban atmosphere, *Anal. Methods*, 2013, **5**, 3410–3417.
- 256 Y. Yao, S. Chang, H. Sun, Z. Gan, H. Hu, Y. Zhao and Y. Zhang, Neutral and ionic per- and polyfluoroalkyl substances (PFASs) in atmospheric and dry deposition samples over a source region (Tianjin, China), *Environ. Pollut.*, 2016, **212**, 449–456.
- 257 S. Lai, J. Song, T. Song, Z. Huang, Y. Zhang, Y. Zhao, G. Liu, J. Zheng, W. Mi, J. Tang, S. Zou, R. Ebinghaus and Z. Xie, Neutral polyfluoroalkyl substances in the atmosphere over the northern South China Sea, *Environ. Pollut.*, 2016, **214**, 449–455.
- 258 Z. Xu, L. Li, B. Henkelmann and K.-W. Schramm, Occurrence of fluorotelomer alcohols at two Alpine summits: sources, transport and temporal trends, *Environ. Chem.*, 2017, **14**, 215–223.
- 259 C. Rauert, M. Shoeib, J. K. Schuster, A. Eng and T. Harner, Atmospheric concentrations and trends of poly- and perfluoroalkyl substances (PFAS) and volatile methyl siloxanes (VMS) over 7 years of sampling in the Global Atmospheric Passive Sampling (GAPS) network, *Environ. Pollut.*, 2018, **238**, 94–102.
- 260 C. Rauert, T. Harner, J. K. Schuster, A. Eng, G. Fillmann, L. E. Castillo, O. Fentanes, M. Villa Ibarra, K. S. B. Miglioranza, I. Moreno Rivadeneira, K. Pozo and B. H. Aristizábal Zuluaga, Atmospheric Concentrations of New Persistent Organic Pollutants and Emerging Chemicals of Concern in the Group of Latin America and Caribbean (GRULAC) Region, *Environ. Sci. Technol.*, 2018, **52**, 7240–7249.
- 261 X. Wang, J. Schuster, K. C. Jones and P. Gong, Occurrence and spatial distribution of neutral perfluoroalkyl substances and cyclic volatile methylsiloxanes in the atmosphere of the Tibetan Plateau, *Atmos. Chem. Phys.*, 2018, **18**, 8745–8755.
- 262 E. Dixon-Anderson and R. Lohmann, Field-testing polyethylene passive samplers for the detection of neutral polyfluorinated alkyl substances in air and water, *Environ. Toxicol. Chem.*, 2018, **37**, 3002–3010.
- 263 Z. Lu, R. Lu, H. Zheng, J. Yan, L. Song, J. Wang, H. Yang and M. Cai, Risk exposure assessment of per- and polyfluoroalkyl substances (PFASs) in drinking water and atmosphere in central eastern China, *Environ. Sci. Pollut. Res.*, 2018, **25**, 9311–9320.
- 264 R. Wu, H. Lin, E. Yamazaki, S. Taniyasu, M. Söregård, L. Ahrens, P. K. S. Lam, H. Eun and N. Yamashita, Simultaneous analysis of neutral and ionizable per- and polyfluoroalkyl substances in air, *Chemosphere*, 2021, **280**, 130607.
- 265 H. Lin, S. Taniyasu, E. Yamazaki, R. Wu, P. K. S. Lam, H. Eun and N. Yamashita, Fluorine mass balance analysis and per- and polyfluoroalkyl substances in the atmosphere, *J. Hazard. Mater.*, 2022, **435**, 129025.
- 266 C. Xia, S. L. Capozzi, K. A. Romanak, D. C. Lehman, A. Dove, V. Richardson, T. Greenberg, D. McGoldrick and M. Venier, The Ins and Outs of Per- and Polyfluoroalkyl Substances in the Great Lakes: The Role of Atmospheric Deposition, *Environ. Sci. Technol.*, 2024, **58**, 9303–9313.
- 267 T. Stoiber, S. Evans and O. V. Naidenko, Disposal of products and materials containing per- and polyfluoroalkyl substances (PFAS): A cyclical problem, *Chemosphere*, 2020, **260**, 127659.
- 268 H. Hamid, L. Y. Li and J. R. Grace, Review of the fate and transformation of per- and polyfluoroalkyl substances (PFASs) in landfills, *Environ. Pollut.*, 2018, **235**, 74–84.
- 269 D. R. Reinhart, S. C. Bolyard and J. Chen, Fate of Per- and Polyfluoroalkyl Substances in Postconsumer Products during Waste Management, *J. Environ. Eng.*, 2023, **149**, 03123002.
- 270 T. Tolaymat, N. Robey, M. Krause, J. Larson, K. Weitz, S. Parvathikar, L. Phelps, W. Linak, S. Burden, T. Speth and J. Krug, A critical review of perfluoroalkyl and polyfluoroalkyl substances (PFAS) landfill disposal in the United States, *Sci. Total Environ.*, 2023, **905**, 167185.
- 271 E. S. Coffin, D. M. Reeves and D. P. Cassidy, PFAS in Municipal Solid Waste Landfills: Sources, Leachate Composition, Chemical Transformations, and Future Challenges, *Curr. Opin. Environ. Sci. Health*, 2022, **31**, 100418.
- 272 Q. Wang, X. Gu, S. Tang, A. Mohammad, D. N. Singh, H. Xie, Y. Chen, X. Zuo and Z. Sun, Gas transport in landfill cover system: A critical appraisal, *J. Environ. Manage.*, 2022, **321**, 116020.
- 273 L. Tang, X. Yu, W. Zhao, D. Barceló, S. Lyu and Q. Sui, Occurrence, behaviors, and fate of per- and polyfluoroalkyl substances (PFASs) in typical municipal solid waste disposal sites, *Water Res.*, 2024, **252**, 121215.
- 274 I. A. Titaley, F. B. De la Cruz, M. A. Barlaz and J. A. Field, Neutral Per- and Polyfluoroalkyl Substances in *In Situ* Landfill Gas by Thermal Desorption–Gas Chromatography–Mass Spectrometry, *Environ. Sci. Technol. Lett.*, 2023, **10**, 214–221.
- 275 L. Ahrens, M. Shoeib, T. Harner, S. C. Lee, R. Guo and E. J. Reiner, Wastewater Treatment Plant and Landfills as Sources of Polyfluoroalkyl Compounds to the Atmosphere, *Environ. Sci. Technol.*, 2011, **45**, 8098–8105.
- 276 I. Weinberg, A. Dreyer and R. Ebinghaus, Landfills as sources of polyfluorinated compounds, polybrominated



- diphenyl ethers and musk fragrances to ambient air, *Atmos. Environ.*, 2011, **45**, 935–941.
- 277 Y. Tian, Y. Yao, S. Chang, Z. Zhao, Y. Zhao, X. Yuan, F. Wu and H. Sun, Occurrence and Phase Distribution of Neutral and Ionizable Per- and Polyfluoroalkyl Substances (PFASs) in the Atmosphere and Plant Leaves around Landfills: A Case Study in Tianjin, China, *Environ. Sci. Technol.*, 2018, **52**, 1301–1310.
- 278 L. Li, J. Liu, J. Hu and F. Wania, Degradation of Fluorotelomer-Based Polymers Contributes to the Global Occurrence of Fluorotelomer Alcohol and Perfluoroalkyl Carboxylates: A Combined Dynamic Substance Flow and Environmental Fate Modeling Analysis, *Environ. Sci. Technol.*, 2017, **51**, 4461–4470.
- 279 J. W. Washington and T. M. Jenkins, Abiotic Hydrolysis of Fluorotelomer-Based Polymers as a Source of Perfluorocarboxylates at the Global Scale, *Environ. Sci. Technol.*, 2015, **49**, 14129–14135.
- 280 R. van Zelm, M. A. J. Huijbregts, M. H. Russell, T. Jager and D. van de Meent, Modeling the environmental fate of perfluorooctanoate and its precursors from global fluorotelomer acrylate polymer use, *Environ. Toxicol. Chem.*, 2008, **27**, 2216–2223.
- 281 R. Holland, M. A. H. Khan, R. Chhantyal-Pun, A. J. Orr-Ewing, C. J. Percival, C. A. Taatjes and D. E. Shallcross, Investigating the Atmospheric Sources and Sinks of Perfluorooctanoic Acid Using a Global Chemistry Transport Model, *Atmosphere*, 2020, **11**, 407.
- 282 A. L. Ling, Estimated scale of costs to remove PFAS from the environment at current emission rates, *Sci. Total Environ.*, 2024, **918**, 170647.
- 283 L.-P. Sung, S. Vicini, D. L. Ho, L. Hedhli, C. Olmstead and K. A. Wood, Effect of microstructure of fluorinated acrylic coatings on UV degradation testing, *Polymer*, 2004, **45**, 6639–6646.
- 284 M. A. M. Mahmoud, A. Kärrman, S. Oono, K. H. Harada and A. Koizumi, Polyfluorinated telomers in precipitation and surface water in an urban area of Japan, *Chemosphere*, 2009, **74**, 467–472.
- 285 T. Portolés, L. E. Rosales, J. V. Sancho, F. J. Santos and E. Moyano, Gas chromatography–tandem mass spectrometry with atmospheric pressure chemical ionization for fluorotelomer alcohols and perfluorinated sulfonamides determination, *J. Chromatogr. A*, 2015, **1413**, 107–116.
- 286 J. F. Ayala-Cabrera, F. Javier Santos and E. Moyano, Negative-ion atmospheric pressure ionisation of semi-volatile fluorinated compounds for ultra-high-performance liquid chromatography tandem mass spectrometry analysis, *Anal. Bioanal. Chem.*, 2018, **410**, 4913–4924.
- 287 X. Hua, J. Luo, Z. Zhao, Q. Wang and H. Sun, Neutral polyfluoroalkyl and perfluoroalkyl substances in surface water and sediment from the Haihe River and Dagu Drainage Canal deserve more attention, *Environ. Sci. Pollut. Res.*, 2019, **26**, 32911–32918.
- 288 J. F. Ayala-Cabrera, E. Moyano and F. J. Santos, Gas chromatography and liquid chromatography coupled to mass spectrometry for the determination of fluorotelomer olefins, fluorotelomer alcohols, perfluoroalkyl sulfonamides and sulfonamido-ethanols in water, *J. Chromatogr. A*, 2020, **1609**, 460463.
- 289 C. Chen, J. Wang, L. Li, W. Xu and J. Liu, Comparison of fluorotelomer alcohol emissions from wastewater treatment plants into atmospheric and aquatic environments, *Environ. Int.*, 2020, **139**, 105718.
- 290 S. Taniyasu, L. W. Y. Yeung, H. Lin, E. Yamazaki, H. Eun, P. K. S. Lam and N. Yamashita, Quality assurance and quality control of solid phase extraction for PFAS in water and novel analytical techniques for PFAS analysis, *Chemosphere*, 2022, **288**, 132440.
- 291 A. Habib, E. N. Landa, K. L. Holbrook, W. S. Walker and W.-Y. Lee, Rapid, efficient, and green analytical technique for determination of fluorotelomer alcohol in water by stir bar sorptive extraction, *Chemosphere*, 2023, **338**, 139439.
- 292 C. Bach, V. Boiteux, J. Hemard, A. Colin, C. Rosin, J.-F. Munoz and X. Dauchy, Simultaneous determination of perfluoroalkyl iodides, perfluoroalkane sulfonamides, fluorotelomer alcohols, fluorotelomer iodides and fluorotelomer acrylates and methacrylates in water and sediments using solid-phase microextraction-gas chromatography/mass spectrometry, *J. Chromatogr. A*, 2016, **1448**, 98–106.
- 293 X. Dauchy, V. Boiteux, C. Bach, A. Colin, J. Hemard, C. Rosin and J.-F. Munoz, Mass flows and fate of per- and polyfluoroalkyl substances (PFASs) in the wastewater treatment plant of a fluorochemical manufacturing facility, *Sci. Total Environ.*, 2017, **576**, 549–558.
- 294 H. Chen, H. Peng, M. Yang, J. Hu and Y. Zhang, Detection, Occurrence, and Fate of Fluorotelomer Alcohols in Municipal Wastewater Treatment Plants, *Environ. Sci. Technol.*, 2017, **51**, 8953–8961.
- 295 C. Ma, H. Peng, H. Chen, W. Shang, X. Zheng, M. Yang and Y. Zhang, Long-term trends of fluorotelomer alcohols in a wastewater treatment plant impacted by textile manufacturing industry, *Chemosphere*, 2022, **299**, 134442.
- 296 B. A. Schumacher, J. H. Zimmerman, A. C. Williams, C. C. Lutes, C. W. Holton, E. Escobar, H. Hayes and R. Warriar, Distribution of Select Per- and Polyfluoroalkyl Substances at a Chemical Manufacturing Plant, *J. Hazard. Mater.*, 2023, **464**, 133025.
- 297 T. J. Smallwood, N. M. Robey, Y. Liu, J. A. Bowden, T. M. Tolaymat, H. M. Solo-Gabriele and T. G. Townsend, Per- and polyfluoroalkyl substances (PFAS) distribution in landfill gas collection systems: leachate and gas condensate partitioning, *J. Hazard. Mater.*, 2023, **448**, 130926.
- 298 Y. Chen, H. Zhang, Y. Liu, J. A. Bowden, T. M. Tolaymat, T. G. Townsend and H. M. Solo-Gabriele, Evaluation of per- and polyfluoroalkyl substances (PFAS) in leachate, gas condensate, stormwater and groundwater at landfills, *Chemosphere*, 2023, **318**, 137903.



- 299 B. M. Allred, J. R. Lang, M. A. Barlaz and J. A. Field, Physical and Biological Release of Poly- and Perfluoroalkyl Substances (PFASs) from Municipal Solid Waste in Anaerobic Model Landfill Reactors, *Environ. Sci. Technol.*, 2015, **49**, 7648–7656.
- 300 J. R. Lang, B. M. Allred, J. A. Field, J. W. Levis and M. A. Barlaz, National Estimate of Per- and Polyfluoroalkyl Substance (PFAS) Release to U.S. Municipal Landfill Leachate, *Environ. Sci. Technol.*, 2017, **51**, 2197–2205.
- 301 N. T. Joseph, T. Schwichtenberg, D. Cao, G. D. Jones, A. E. Rodowa, M. A. Barlaz, J. A. Charbonnet, C. P. Higgins, J. A. Field and D. E. Helbling, Target and Suspect Screening Integrated with Machine Learning to Discover Per- and Polyfluoroalkyl Substance Source Fingerprints, *Environ. Sci. Technol.*, 2023, **57**, 14351–14362.
- 302 W. M. Henderson, M. G. Evich, J. W. Washington, T. T. Ward, B. A. Schumacher, J. H. Zimmerman, Y. D. Kim, E. J. Weber, A. C. Williams, M. G. Smeltz and D. A. Glinski, Analysis of Legacy and Novel Neutral Per- and Polyfluoroalkyl Substances in Soils from an Industrial Manufacturing Facility, *Environ. Sci. Technol.*, 2024, **58**, 10729–10739.
- 303 C. P. Goossen, R. E. Schattman and J. D. MacRae, Evidence of compost contamination with per- and polyfluoroalkyl substances (PFAS) from “compostable” food serviceware, *Biointerphases*, 2023, **18**, 030501.
- 304 G. W. Link, D. M. Reeves, D. P. Cassidy and E. S. Coffin, Per- and Polyfluoroalkyl Substances (PFAS) in Final Treated Solids (Biosolids) from 190 Michigan Wastewater Treatment Plants, *J. Hazard. Mater.*, 2023, **463**, 132734.
- 305 K. Rankin, H. Lee, P. J. Tseng and S. A. Mabury, Investigating the Biodegradability of a Fluorotelomer-Based Acrylate Polymer in a Soil-Plant Microcosm by Indirect and Direct Analysis, *Environ. Sci. Technol.*, 2014, **48**, 12783–12790.
- 306 J. W. Washington, J. E. Naile, T. M. Jenkins and D. G. Lynch, Characterizing Fluorotelomer and Polyfluoroalkyl Substances in New and Aged Fluorotelomer-Based Polymers for Degradation Studies with GC/MS and LC/MS/MS, *Environ. Sci. Technol.*, 2014, **48**, 5762–5769.
- 307 J. W. Washington, T. M. Jenkins, K. Rankin and J. E. Naile, Decades-Scale Degradation of Commercial, Side-Chain, Fluorotelomer-Based Polymers in Soils and Water, *Environ. Sci. Technol.*, 2015, **49**, 915–923.
- 308 J. W. Washington, K. Rankin, E. L. Libelo, D. G. Lynch and M. Cyterski, Determining global background soil PFAS loads and the fluorotelomer-based polymer degradation rates that can account for these loads, *Sci. Total Environ.*, 2019, **651**, 2444–2449.
- 309 M. H. Russell, W. R. Berti, B. Szostek and R. C. Buck, Investigation of the Biodegradation Potential of a Fluoroacrylate Polymer Product in Aerobic Soils, *Environ. Sci. Technol.*, 2008, **42**, 800–807.
- 310 J. W. Washington, J. J. Ellington, T. M. Jenkins, J. J. Evans, H. Yoo and S. C. Hafner, Degradability of an Acrylate-Linked, Fluorotelomer Polymer in Soil, *Environ. Sci. Technol.*, 2009, **43**, 6617–6623.
- 311 M. H. Russell, W. R. Berti, B. Szostek, N. Wang and R. C. Buck, Evaluation of PFO formation from the biodegradation of a fluorotelomer-based urethane polymer product in aerobic soils, *Polym. Degrad. Stab.*, 2010, **95**, 79–85.
- 312 J. Chen, L. Tang, W.-Q. Chen, G. F. Peaslee and D. Jiang, Flows, Stock, and Emissions of Poly- and Perfluoroalkyl Substances in California Carpet in 2000–2030 under Different Scenarios, *Environ. Sci. Technol.*, 2020, **54**, 6908–6918.
- 313 D. Jiang and T. Zhang, State-level material flow analysis suggests the need to reconsider current monitoring practice and mitigation policies for poly- and perfluoroalkyl substances in carpet, *J. Ind. Ecol.*, 2022, **26**, 815–823.
- 314 J. B. Pollack, I. Q. Carey and V. Y. Xu, Regulation of Products with PFAS, *Environ. Law Rep.*, 2024, **54**, 10148.
- 315 C. Hogue, *California bans cosmetics and apparel with PFAS*, <https://cendigitalmagazine.acs.org/2022/10/09/california-bans-cosmetics-and-apparel-with-pfas-3/content.html>, accessed 10 October 2022.
- 316 M. Dunn, N. Noons, S. Vojta, J. Becanova, H. Pickard, E. M. Sunderland and R. Lohmann, Unregulated Active and Closed Textile Mills Represent a Significant Vector of PFAS Contamination into Coastal Rivers, *ACS ES&T Water*, 2024, **4**, 114–124.
- 317 R. Bakhshoodeh and R. M. Santos, Comparative bibliometric trends of microplastics and perfluoroalkyl and polyfluoroalkyl substances: how these hot environmental remediation research topics developed over time, *RSC Adv.*, 2022, **12**, 4973–4987.
- 318 H. Tian, C. Gaines, L. Launi, A. Pomales, G. Vazquez, A. Goharian, B. Goodnight, E. Haney, C. M. Reh and R. D. Rogers, Understanding Public Perceptions of Per- and Polyfluoroalkyl Substances: Infodemiology Study of Social Media, *J. Med. Internet Res.*, 2022, **24**, e25614.
- 319 T. A. Berthold, A. McCrary, S. deVilleneuve and M. Schramm, Let's talk about PFAS: Inconsistent public awareness about PFAS and its sources in the United States, *PLoS One*, 2023, **18**, e0294134.
- 320 C. Moody, EPA Finalizes Standards for Six PFAS, *J. AWWA*, 2024, **116**, 8.
- 321 Z. Wang, I. T. Cousins, M. Scheringer, R. C. Buck and K. Hungerbühler, Global emission inventories for C4–C14 perfluoroalkyl carboxylic acid (PFCA) homologues from 1951 to 2030, Part I: production and emissions from quantifiable sources, *Environ. Int.*, 2014, **70**, 62–75.
- 322 Z. Wang, I. T. Cousins, M. Scheringer, R. C. Buck and K. Hungerbühler, Global emission inventories for C4–C14 perfluoroalkyl carboxylic acid (PFCA) homologues from 1951 to 2030, part II: The remaining pieces of the puzzle, *Environ. Int.*, 2014, **69**, 166–176.
- 323 H. Holmquist, S. Roos, S. Schellenberger, C. Jönsson and G. Peters, What difference can drop-in substitution



- actually make? A life cycle assessment of alternative water repellent chemicals, *J. Cleaner Prod.*, 2021, **329**, 129661.
- 324 Y. Cheng, S. Wang, Z. Xu, L. Jiang and Y. Zhao, Non-fluorine oil repellency: To what extent can it substitute perfluoroalkyl substances?, *Prog. Org. Coat.*, 2023, **183**, 107726.
- 325 G. Zheng and A. Salamova, Are Melamine and Its Derivatives the Alternatives for Per- and Polyfluoroalkyl Substance (PFAS) Fabric Treatments in Infant Clothes?, *Environ. Sci. Technol.*, 2020, **54**, 10207–10216.
- 326 L. Zhi, H. Sun, L. Xu and Y. Cai, Distribution and Elimination of Trifluoropropylmethylsiloxane Oligomers in Both Biosolid-Amended Soils and Earthworms, *Environ. Sci. Technol.*, 2021, **55**, 985–993.
- 327 M. S. McLachlan, A. Kierkegaard, M. Radke, A. Sobek, A. Malmvärn, T. Alsberg, J. A. Arnot, T. N. Brown, F. Wania, K. Breivik and S. Xu, Using Model-Based Screening to Help Discover Unknown Environmental Contaminants, *Environ. Sci. Technol.*, 2014, **48**, 7264–7271.
- 328 T. P. Riedel, M. A. G. Wallace, E. P. Shields, J. V. Ryan, C. W. Lee and W. P. Linak, Low temperature thermal treatment of gas-phase fluorotelomer alcohols by calcium oxide, *Chemosphere*, 2021, **272**, 129859.
- 329 E. P. Shields and M. A. G. Wallace, Low temperature destruction of gas-phase per- and polyfluoroalkyl substances using an alumina-based catalyst, *J. Air Waste Manage. Assoc.*, 2023, **763**, 525–532.
- 330 J. M. Parrilla, ChatGPT use shows that the grant-application system is broken, *Nature*, 2023, **623**, 443.

