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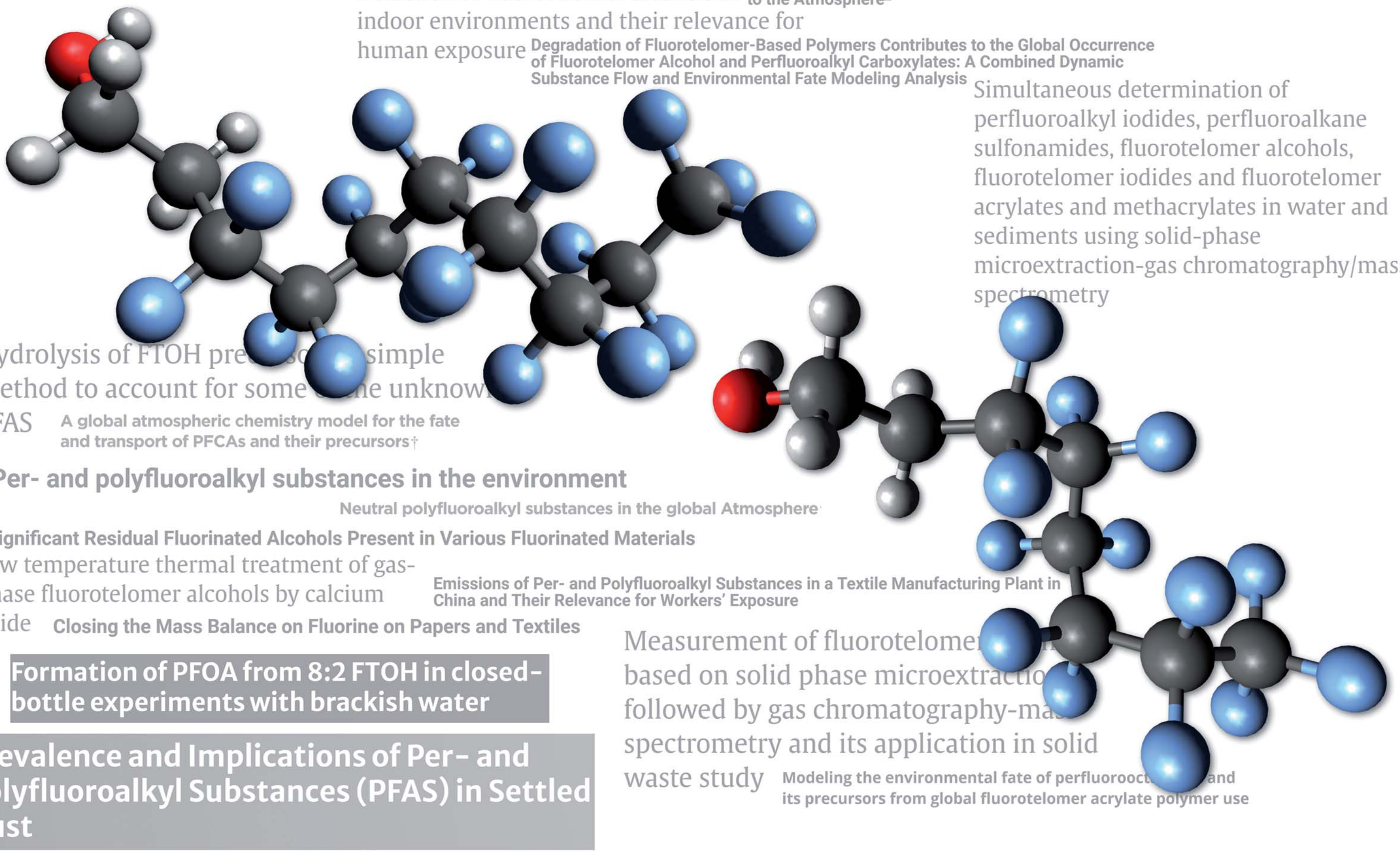

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PERSPECTIVE

Ivan A. Titaley

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.

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 $-CF_2-$ 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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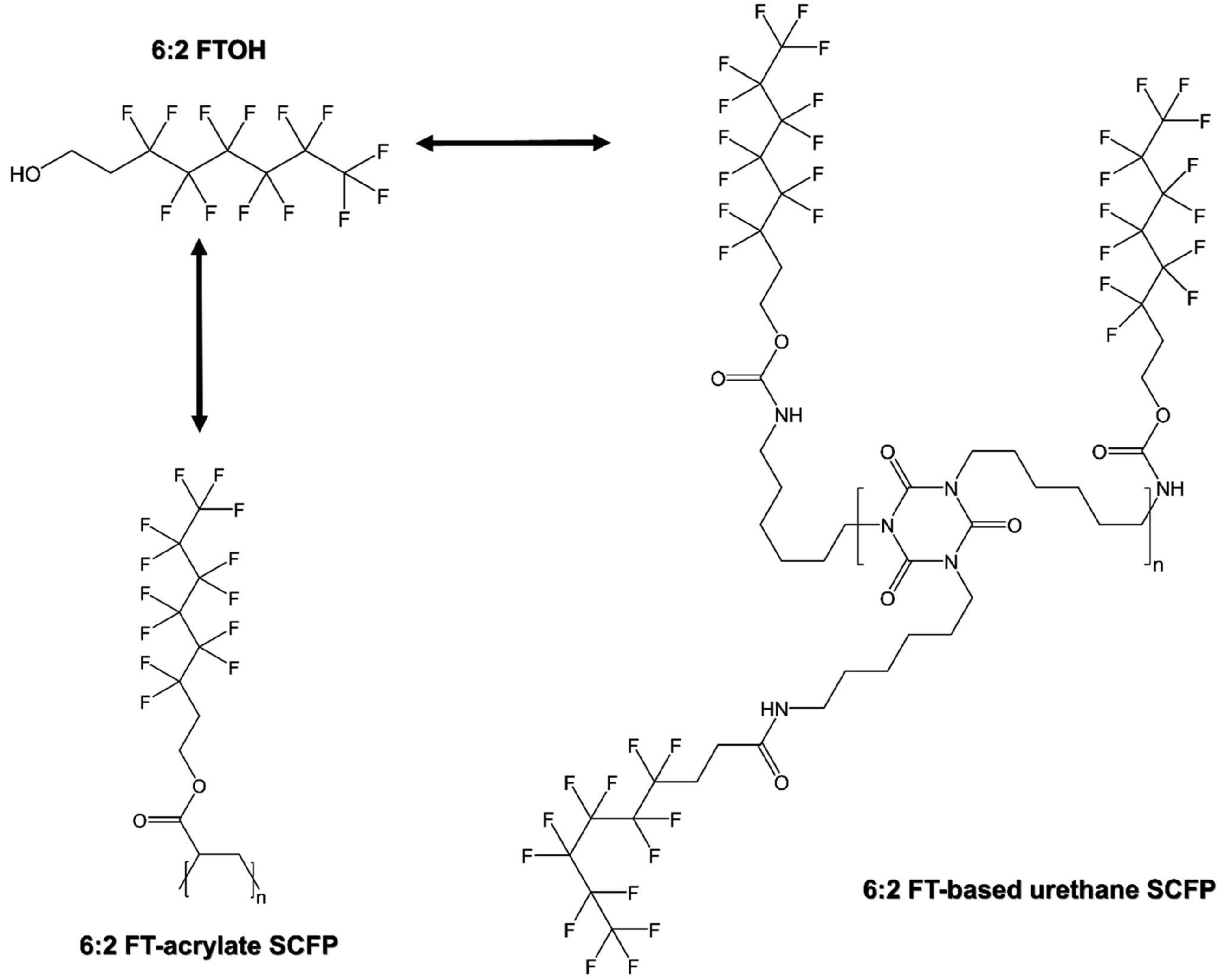

Fig. 1 Example of two FT-based SCFP structures that can degrade to FTOHs because FTOHs are the building blocks of SCFPs, with SCFP structures adapted from ref. 44. Bidirectional arrows indicate that FTOHs can be degradation products of FT-based SCFPs.

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.*, $\mathrm{p}K_\mathrm{a} > 14$);[67–71] in contrast, perfluoroalkyl carboxylates (PFCAs), such as perfluorooctanoate (PFOA), are charged (*i.e.*, $\mathrm{p}K_\mathrm{a} < 0$–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 ($n = 6, 8, 10, \ldots$) consistently degrades to Cn 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,

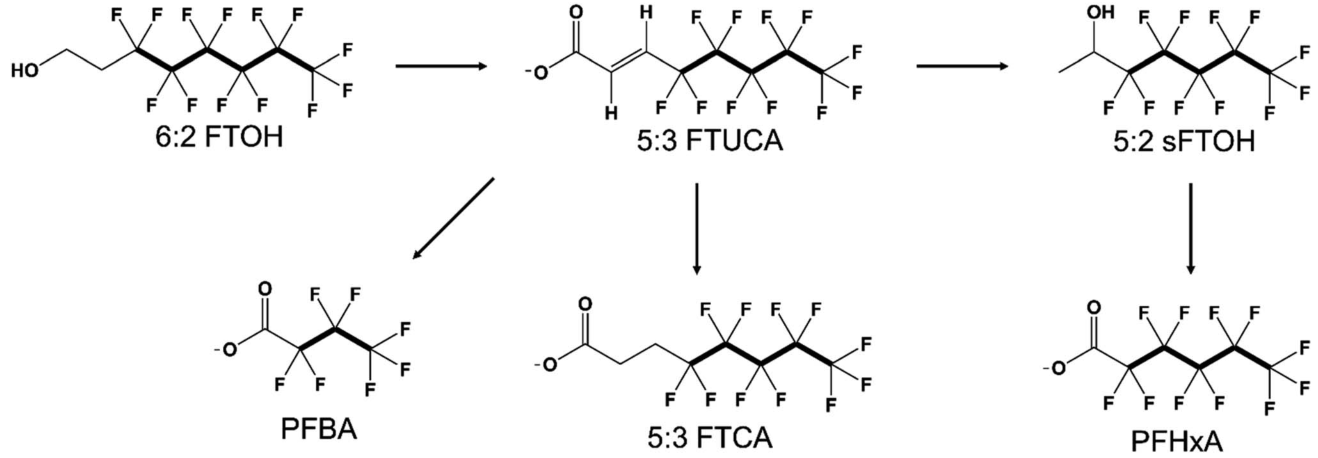

Fig. 2 A degradation pathway of 6:2 FTOH leading to the formation of PFCAs, namely perfluorohexanoate (PFHxA) and perfluorobutanoate (PFBA), and 5:3 FTCA with 5:3 FTUCA and 5:2 sFTOH as intermediate products. Carbon–fluorine bonds are highlighted in bold. Detailed degradation pathways are outlined in 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 factory[201] where FTOHs ($9.5–90 \times 10^6$ 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 25–630 pg cm^{-2} and 220–260 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). Poothong *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 offsprings[238] 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]

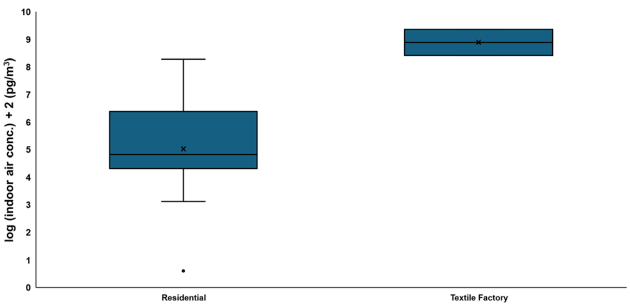

Fig. 3 Box and whisker plot comparison between min and max of reported FTOH indoor air concentration at residential sites and at a textile factory. The indoor air residential data are obtained from ref. 70.

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

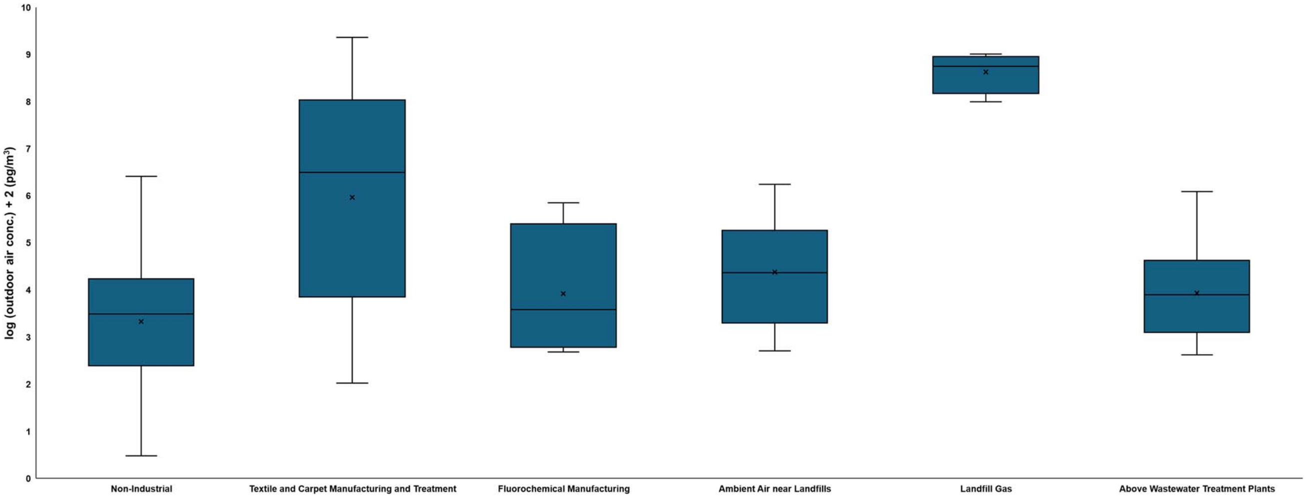

Fig. 4 Box and whisker plot comparison between min and max of reported FTOH outdoor air concentration at different sites. The non-industrial data are obtained from ref. 70.

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 (1–10 × 10^6 pg m^{-3}).[34,274] Landfills are thus known to emit FTOHs based on ambient air samples collected near landfills (5–17 000 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 (<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 <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 PFHxA[62] (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.

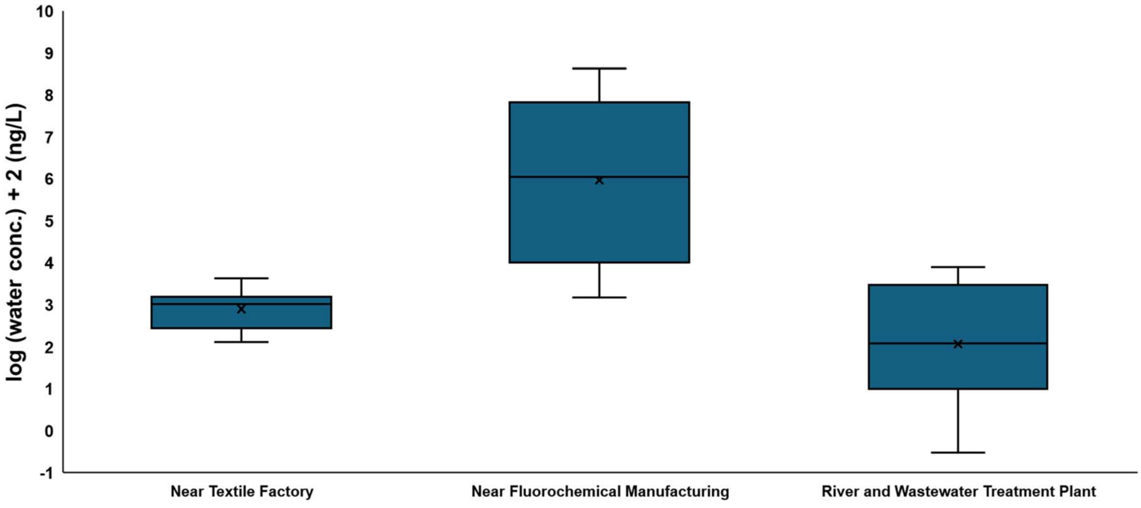

Fig. 5 Box and whisker plot comparison between min and max of reported FTOH water concentration at different sites.

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 textile[315] 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 SFCP-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 intelligence[330] was used in this work. The Table of Contents (TOC) art was created with **https://www.BioRender.com**.

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