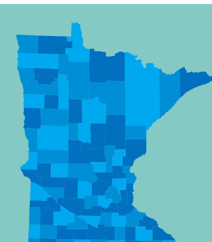
PFAS inventory analysis

May 2023

PFAS in the textile and leather industries

An inventory of information about PFAS use, environmental release pathways, and source reduction strategies.

MINNESOTA POLLUTION CONTROL AGENCY



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Acronyms

5:3 FTCA	5:3 Fluorotelomer carboxylic acid
6:2 FTAcr	(Perfluorohexyl)ethyl acrylate
C6	PFAS based on a 6-carbon chain
C8	PFAS based on an 8-carbon chain
Cr(III)	Trivalent chromium
Cr(VI)	Hexavalent chromium
DTSC	California Department of Toxic Substances Control
DWR	Durable water repellent
ELG	Effluent limit guideline
EPA	Environmental Protection Agency
ePTFE	Expanded polytetrafluoroethylene
EtFOSE	N-Ethyl Perfluorooctane Sulfonamido Ethanol
FEP	Fluorinated ethylene propylene
FTOH	Fluorotelomer alcohol
MeFBSAC	N-Methyl perfluorobutanesulfonamidoethyl acrylate
MeFBSE	N-Methyl perfluorobutanesulfonamidoethanol
MeFOSE	Perfluorooctanesulfonamidoethanol
MI EGLE	Michigan Department of Environment, Great Lakes, and Energy
MN DEED	Minnesota Department of Employment and Economic Development
NAICS	North American Industrial Classification System
PFA	Perfluoroalkoxy alkane
PFAA	Perfluoroalkyl acid
PFAS	Per- and polyfluoroalkyl substances
PFBS	Perfluorobutanesulfonate
PFCA	Perfluoroalkyl carboxylic acid
PFHxA	Perfluorohexanoic acid
PFHxS	Perfluorohexane sulfonate

PFNA	Perfluorononanoic acid
PFOA	Perfluorooctanoic acid
PFOS	Perfluorooctane sulfonic acid
PFSA	Perfluoroalkyl sulfonic acid
ppb	Parts per billion
ppm	Parts per million
ppt	Parts per trillion
PTFE	Polytetrafluoroethylene
PVDF	Polyvinylidene fluoride
WWTP	Wastewater treatment plant

Overview

Per- and polyfluoroalkyl substances (PFAS) are widely used in the textile and leather industries as waterproof membranes and surface finishes to impart water-, oil-, and stain-resistance. They have also been used as processing agents to aid in the deposition of dyes and bleaches, and to reduce foaming in textile treatment baths. The manufacturing process of a leather or textile article is complex, often involving several production steps that may occur across various facilities. Raw materials are converted into threads, fabrics, and membranes, which are woven or assembled to produce articles such as apparel, outdoor gear, carpets, furniture upholstery, bedding, and other household goods. These products can then undergo surface treatment, either as part of the manufacturing process or during after-market application.

There are applications for PFAS during each of these stages, providing pathways for environmental release at many points in the manufacturing process. Baths used to perform dyeing and bleaching and to apply water- and stain-resistance treatments can contain PFAS. When excess or spent liquids are disposed of, PFAS can be released to wastewater treatment plants and eventually conveyed to receiving waters. Volatile PFAS can be released to indoor air and outdoor air during textile and leather production, representing a pathway for textile and leather worker exposure and for deposition onto soil and surface waters. Leaks and spills from the facilities can release PFAS to soil and groundwater. Retail and consumer application of PFAS-based, after-market surface treatments can release PFAS to indoor and ambient air, soil, groundwater, and provide direct human exposure via inhalation. Once textile and leather consumer articles are disposed of, they present a source of PFAS to landfills and incinerators. Thus, there are pathways for release to groundwater via landfill leachate and ambient air via the incineration process.

Moreover, textile and leather articles containing PFAS have been found to continually emit PFAS over the course of their lifetimes. Weathering due to precipitation, sun exposure, and laundering accelerates this process and transforms PFAS used in the manufacture of the articles into various degradation products that may not have been used in the original article. These include toxic, long-chain PFAS like perfluorooctanoic acid (PFOA) that have been otherwise phased out in the US. People may be exposed to these compounds via dust and indoor air as well as direct contact with PFAS-treated products. Further, laundering and dry-cleaning PFAS-containing articles provides an additional release pathway to wastewater treatment plants, surface waters, and groundwater.

Primary textile and leather manufacturing represents a relatively small, yet not insignificant portion of Minnesota's industrial economy. The largest component of this industry sector appears to be manufacturers of textile and leather products, who convert purchased fabrics and leather into consumer goods such as carpets and shoes. In Minnesota, textile and leather manufacturing present the opportunity for PFAS release during several of the production stages as well as via the final products. PFAS in textile and leather products, regardless of manufacture origin, may be released to indoor air and more significantly, landfills, in addition to presenting an exposure pathway to people using the items.

There are PFAS alternatives available and in use in textile and leather manufacturing. Eliminating the use of PFAS by the industry and restricting imports of PFAS-containing textile and leather products would reduce PFAS loading to the environment. Chemical substitutions for PFAS pose varying levels of human and environmental risk. Risk should be evaluated when choosing alternative technologies.

The remainder of this report provides detailed information on the textile and leather manufacturing processes that use PFAS and discusses the specific applications of PFAS, pathways for environmental release, and opportunities to reduce PFAS emissions from these industries. This information is intended to be useful to regulators, environmental professionals, and industry workers in conducting mitigation, cleanup, and programmatic efforts around PFAS. Supplementary information tables are included as part of this report which detail information about specific chemistries and known names of PFAS-containing products used in manufacturing and post-market treatments for textiles and leather. These lists draw on sources including the scientific literature, chemical industry, and government reports, but they are not exhaustive. A definitive list of products is outside the scope of this report; however, the information provided here may be used as a basis for further investigation.

Textile and leather manufacturing in Minnesota

Industry classification

Textile and leather manufacturing businesses in Minnesota that may perform processes associated with PFAS were identified based on North American Industrial Classification System (NAICS) codes. NAICS is the standard system used by the federal government in classifying businesses for the purpose of statistical data collection, analysis, and publication related to the U.S. business economy. It was implemented to replace the Standard Industrial Classification (SIC) system and was most recently updated in 2022 (United States Census Bureau, 2022). NAICS codes describing industries that are known to use PFAS have been utilized by government agencies, research groups, and other organizations to identify potential industrial PFAS sources (e.g., Andrews et al., 2021; MPCA, 2022; Salvatore et al., 2022).

State and federal agencies have identified several NAICS codes capturing the textile and leather industry functions that may use PFAS (Table 1). Minnesota businesses that may perform these operations were identified by using these NAICS codes in a search of the *U.S. Businesses* module of Data Axle's Reference Solutions database, an annually updated repository of detailed business information in the United States available for government use (Data Axle, 2023). The search yielded 135 unique facilities with one of these listed as the primary NAICS code as of January 2023 (Figure 1). Duplicate facilities appearing in the dataset were removed based on geographic information. The search was limited to businesses classified as active; business records designated "closed/out of business" were excluded. Note, however, that historical business operations captured by the NAICS entries may have presented a source of PFAS to the environment in the past.

Table 1. Textile and leather industry classes encompassing business operations associated with the use, storage, and/or release of PFAS.

NAICS code[a]	NAICS title[a]	Monitoring Plan[b]	ECHO[c]	Facilities in MN (Data Axle)[d]
313110	Fiber, yarn, and thread mills	Y	Y	1
313210	Broadwoven fabric mills	Y	Y	4
313220	Narrow fabric mills and schiffli machine embroidery	Y	N	0
313230	Nonwoven fabric mills	Y	Y	1
313310	Textile and fabric finishing mills	Y	Y	11
313320	Fabric coating mills	Y	Y	1

NAICS code[a]	NAICS title[a]	Monitoring Plan[b]	ECHO[c]	Facilities in MN (Data Axle)[d]
314110	Carpet and rug mills	Y	Y	6
314910	Textile bag and canvas mills	N	Y	14
314999	All other miscellaneous textile product mills	Y	Y	82
316110	Leather and hide tanning and finishing	Y	Y	7
316990	Other leather and allied product manufacturing	Y	Y	8

Additional NAICS codes may capture some of the consumer or commercial products included in this report. For example, hospital gowns and firefighting uniforms are captured by 315250 (*Cut and Sew Apparel Manufacturing (except Contractors)*), surgical masks are captured by 339113 (*Surgical Appliance and Supplies Manufacturing*), and post-market water repellency sprays may be captured by 325998 (*All Other Miscellaneous Chemical Product and Preparation Manufacturing*). These codes have not been included in this analysis either because they were not included on EPA or MPCA's lists of industries of concern for PFAS (315250), their industry category is not specific to textile or leather products (339113), or the manufacture of the product is outside the scope of this report (325998).

Data insights

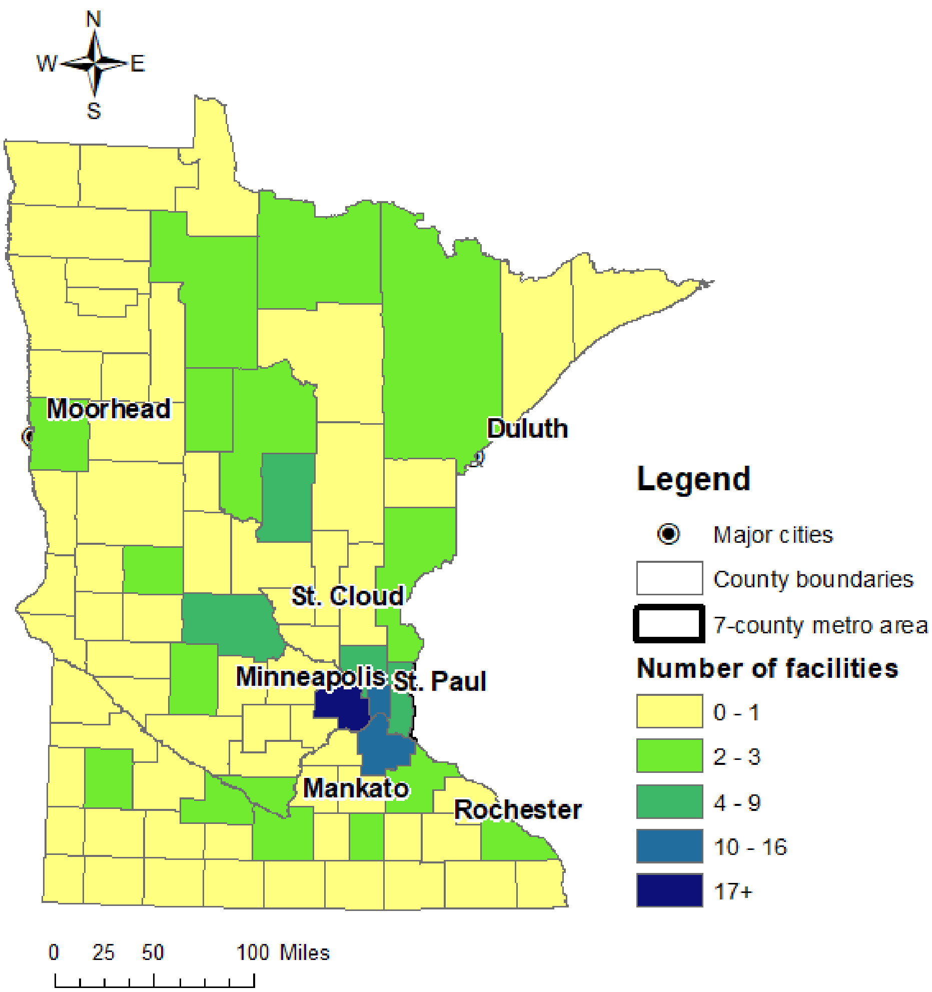
Importantly, the Reference Solutions dataset contains information about known businesses in Minnesota performing activities ascribed to the selected NAICS codes. These codes are not self-reported, but rather assigned by Data Axle. The dataset may include facilities that are not currently operating under any environmental permits. It may also include businesses performing one or more operations captured by the NAICS codes beyond the textile or leather manufacturing processes known to use PFAS that are discussed in this report. Further, the dataset may capture businesses that perform one of the textile or leather manufacturing operations as a minor portion of business. Relatedly, corporate offices for companies involved in textile or leather manufacturing may be captured, even if no manufacturing is performed onsite.

To verify Minnesota textile and leather industry data obtained from Data Axle, the facility count was cross-referenced with data from the Minnesota Department of Employment and Economic Development (MN DEED, 2022). MN DEED maintains quarterly records on businesses operating in Minnesota, classified by NAICS code. Complete data is not available for each 6-digit NAICS code, so broader industry categories were evaluated: 313 (Textile Mills), 314 (Textile Product Mills), and 316 (Leather and Allied Product Manufacturing). MN DEED's dataset indicates that as of Q2 2022, there are 175 businesses in Minnesota falling under one of these three industry categories. Data Axle lists 145 businesses falling under one of these three categories as of January 2023, pointing to general agreement with MN DEED's data.

Using MN DEED's dataset for reference, Minnesota's largest presence in the textile industry is the manufacture of textile products. These include some facilities that manufacture textile furnishings like carpets and rugs, although the majority manufacture miscellaneous other textile products like bags, canvas products, and sporting and outdoor equipment. Within the leather industry, there are a few businesses that perform leather tanning and finishing, while most use purchased leather to manufacture footwear or other consumer leather products (MN DEED, 2022).

The limitations in the datasets used for this analysis likely apply to other datasets relying on industrial classification systems to determine the potential for PFAS use. The maps and facility data included here should not be interpreted as a definitive list of PFAS users, but rather a visualization of the geographic spread of potential PFAS sources within the textile and leather industrial categories.

Figure 1. Potential textile and leather manufacturing facilities in Minnesota.



Timeline

- **1946:** Polytetrafluoroethylene (PTFE; best known by the brand name Teflon™) was introduced to the market. Applications included products to impart soil- and stain-repellence on fabric and textiles (Chemours, 2023).
- **1951:** PFAS-based dispersion products were introduced (Prevedouros et al., 2006).

- **1956:** 3M's Scotchgard—based on fluoropolymer chemistry—was first introduced as a stain- and soil-repellent for wool (LaZerte, 1989).
- **1966:** Perfluoroalkyl carboxylic acids (PFCAs) were reportedly in wide use by manufacturers as treatments for textiles and leather (Prevedouros et al., 2006)
- **1976:** Expanded PTFE (ePTFE) was introduced to the market as GORE-TEX fabrics. These fabrics were first used in jackets and related products and have been marketed as breathable, waterproof, and windproof (W.L. Gore & Associates, 2023).
- **1986:** The first stain-resistant carpet, based on Teflon (PTFE) treatment, was introduced to the market under the Stainmaster label (Blumenthal, 1990)
- **2000:** 3M announced a voluntary phase out of PFOS, including in textile and leather treatments, to be completed by the end of December 2002 (U.S. EPA, 2000; Perfluoroalkyl Sulfonates, 2002)
- **2002:** EPA promulgated a significant new use rule requiring the notification of manufacture or import of perfluoroalkyl sulfonates (PFOS and related compounds)
- **2003:** 3M introduced repellent treatments for fabrics and leather based on perfluorobutane sulfonate (PFBS) to replace PFOS-based treatments (Lassen et al., 2017)
- **2006:** The 2010/2015 PFOA Stewardship Program was launched by the US Environmental Protection Agency (EPA) in conjunction with 8 major PFAS manufacturers. Participating companies committed to achieve a 95% reduction of PFOA emissions by 2010 and to work towards elimination of PFOA from emissions and products by 2015 (U.S. EPA, 2022a)
- **2006:** PFOS was not reported as manufactured or imported into the United States in EPA's Chemical Data Reporting effort, apart from limited ongoing uses for metal finishing (EPA, 2022a)
- **2013:** EPA promulgated a significant new use rule requiring notification of the manufacture or import of long chain perfluorocarboxylates (PFOA and related compounds) used in carpets, carpet treatments, and carpet aftercare products (Perfluoroalkyl Sulfonates and Long-Chain Perfluoroalkyl Carboxylate Chemical Substances, 2013)
- **2015:** Deadline for completion of PFOA phase out in the United States under the 2020/2015 PFOA Stewardship Program. EPA promulgated a significant new use rule designating manufacturing and importing of PFOA and related chemicals as a significant new use (Long-Chain Perfluoroalkyl Carboxylate and Perfluoroalkyl Sulfonate Chemical Substances, 2015; EPA, 2022a)
- **2020:** 3M phased out PFAS in Scotchgard, its consumer textile and leather treatment line, although PFAS may continue to be used in industrial repellency formulations (Bergen, 2021; 3M, 2023)
- **2000s – present:** Fluorotelomer manufacturing is the dominant PFAS production process (ITRC, 2020)
- **2000s – present:** Side-chain fluorinated polymers based on fluorotelomer side chains are commonly used in textile and leather treatments (Glüge et al., 2020)

PFAS in textiles and leather

The manufacture of both textiles and leather is complex, involving many processes that may occur across several facilities with a wide geographic range (e.g., G-Star, 2013; United States Census Bureau, 2022; Chemsec, 2023, Leather-Dictionary, 2023). PFAS may be used and/or released at various points across a textile or leather product's life cycle, and the long supply chains for these products can create challenges in identifying and reducing sources (e.g., Svedlund & Skedung, 2022). To address this, the following sections break down PFAS use across manufacturing steps. PFAS release pathways from consumer use and disposal, the second portion of the product life cycle, are detailed in “Environmental release pathways.”

Table 2. Summary of key PFAS used in textiles and leather. For a more detailed list, see Supplementary Tables S1-4.

PFAS compound	Processes	Products	Time period of use
Polytetrafluoroethylene (PTFE)	Woven and nonwoven textiles manufacturing; production of waterproof membranes	Dyes; waterproof membranes; medical gowns and other PPE; performance uniforms; carpet and carpet treatments	1940s – present
Perfluorooctane sulfonic acid (PFOS)*	Textile and leather manufacturing; textile and leather repellency treatment; production of consumer fabric and leather protectors	Surfactants and industrial products for textile and leather repellency; consumer fabric and leather protectors (3M’s Scotchgard); consumer textile and leather products	1950s – 2002
Perfluorooctanoic acid (PFOA)	Textile and leather manufacturing; textiles and leather repellency treatment	Industrial textile and leather treatments; consumer textile and leather products	1950s – 2015
Perfluorobutanesulfonate (PFBS)*	Textile and leather manufacturing, textiles and leather repellency treatment	Industrial textile and leather repellency products made by 3M (e.g., 3M’s Protective Materials and Repellent Polymer Melt Additives); consumer fabric and leather protectors made by 3M (3M’s Scotchgard)	2003 –?**
Fluorotelomer alcohols (FTOHs)*	Industrial waterproofing, oil- and stain-proofing, and other textile and leather treatment processes	Industrial textile and leather treatment additives; consumer-end durable water repellent (DWR) and other textile and leather protection sprays; consumer textile and leather products (especially water- and stain-resistant products); medical PPE and other high-performance uniforms	Early 2000s – present

*In textile treatments, applied as side-chain fluorinated polymers

**Discontinued for use in consumer Scotchgard products in 2020; it is unclear how long it may have been used in commercial and industrial products

Textile manufacturing

Overview

PFAS have been used for decades in the manufacture of textile apparel and garments. These include outdoor gear, waterproof apparel, school uniforms, medical garments, and high-performance uniforms such as those used in firefighting (Gaines, 2022). PFAS are also used in the manufacture of a wide range of textile products beyond wearable garments, like home furnishings and utility products. Such products include—but are not limited to—carpets, rugs, upholstery, curtains, tablecloths, bedding, canvas, rope, and sails. PFAS are typically used in textiles to impart water repellence, oil repellence, soil protection, stain-resistance, and in some cases flame retardance (Whiting et al., 2020). However, there are several identified uses for PFAS in textile manufacturing beyond surface treatment and waterproof membranes, including dye deposition and bleaching (Glüge et al., 2020).

There are key properties of PFAS that make them useful in textile production: hydrophobicity (the ability to repel water), oleophobicity (the ability to repel oil), wettability (the ability of a liquid to spread), and stability (Buck et al., 2011). Accordingly, PFAS may be involved at all stages in the life cycle of a textile product, from fabric production and surface finishing to consumer use and wear. Prior to the early 2000s, long-chain PFAS including PFOS and PFOA were used in textile manufacturing. Since the phase-out of both compounds in the United States and Europe, side-chain fluorinated polymers based on fluorotelomer alcohols (FTOHs) and short-chain PFAS like perfluorobutanesulfonate (PFBS) are most commonly used (Glüge et al., 2020). Today, the textile industry uses the majority of FTOH chemicals manufactured worldwide (Yiliqi et al., 2021). Importantly, as textile products weather, PFAS contained in them can transform to other chemicals that may not have been used in manufacture. Namely, *n*:2 FTOHs oxidize to PFCAs based on *n*-carbon chains, creating the potential for exposure to and release of PFAS chemicals that have been otherwise phased out, such as PFOA (e.g., Li et al., 2017; van der Veen et al., 2020, 2022; Schellenberger et al., 2022) (see “Product use” under “Environmental release pathways”).

Processes associated with PFAS

Yarn and fabric production

Primary textile production involves transforming a basic fiber (either natural, such as wool, or synthetic, such as polyester) into a yarn or fabric. The initial fibers are spun into threads or yarns and are then woven, knit, or otherwise bound into fabrics (US Census, 2022; Chemsec, 2023). PFAS can be used to lubricate yarns, making them easier to weave (Kissa, 2001).

Yarns and fabrics are subject to treatments such as washing, scouring, bleaching, and dyeing (Chemsec, 2023). These treatments are applied in industrial-scale baths in which a yarn, fabric, or garment is submerged (wet processing, e.g., Yaseen & Scholz, 2018). PFAS can be used as agents to improve the efficiency of many of these processes. Due to their utility as surfactants, which lower the surface tension of water, they can enhance the absorption of dyes and aid in penetration of bleaches (Kissa, 2001; Poulsen et al., 2005). PFAS also widely function as emulsifiers (substances which enable oil and water to mix) and to reduce friction (Buck et al., 2011). Accordingly, they have been used to reduce foaming during sulfur dyeing and other textile treatments (POPRC, 2016) and as emulsifying agents for fiber finishing treatments (Poulsen et al., 2005). Finally, PTFE and polyvinylidene fluoride (PVDF) appear to have been used as ingredients in dyes in the past (Glüge et al., 2020).

In their guide to PFAS in textiles, the Research Institutes of Sweden (RISE) note that manufacturers involved in later stages of production, like waterproofing, may not be aware of PFAS uses during these earlier textile processing stages (Svedlund & Skedung, 2022).

Membrane production

Water repellence in textiles can be accomplished through use of porous, water-resistant membranes. Fluoropolymers, notably PTFE, have been used to produce such membranes since the 1970s (W.L. Gore & Associates, 2023). PTFE-based membranes are produced by heating solid blocks of PTFE and rapidly stretching them, producing a fabric that is porous yet hydrophobic. The resulting membrane is then laminated to another textile fabric (Sewport, 2023).

Similar membranes have also been produced using the fluoropolymer PVDF (Cui et al., 2017; Anjum et al., 2019; Yi et al., 2020). PVDF-based membranes can be fabricated by electrospinning, a process by which a liquid droplet is electrified to generate a jet, followed by stretching to generate fibers (Xue et al., 2019). The current commercial availability of PVDF-based membranes is unclear; literature suggests that this is technology is being developed as an alternative to PTFE-based membranes (Cui et al., 2017).

Waterproofing and finishing processes

After a fabric is washed and dyed, further treatments can be applied by manufacturers to provide specialized technical properties (Chemsec, 2023). PFAS are commonly used in treatments to provide water-, oil-, and stain-repellence due to their hydrophobic and oleophobic properties (Kissa, 2001; van der Veen et al., 2022; Schellenberger et al., 2022; Schreder & Goldberg, 2022). Textile mills often apply these treatments by immersing fabrics into industrial-scale baths containing the PFAS treatment in an aqueous solution. Rollers are then used to remove excess liquid, and the finished fabric is cured with heat (Svedlund & Skedung, 2022). During the manufacture of carpet, high-performance uniforms like firefighters', and other specialized textile products, PFAS can be included either as an additive in individual fibers or sprayed as a coating onto finished fabrics (U.S. EPA, 2021; Gaines, 2022). Oil-, stain-, and water-repellent treatments can be applied to primary textile fabrics alone or in conjunction with membranes described in the previous section to provide further durability (Svedlund & Skedung, 2022; Schreder & Goldberg, 2022).
PFCAs have been widely used as additives in textile and leather treatments since at least the 1960s (Prevedouros et al., 2006). PFCA concentrations in industrial formulations typically contained 100-5000 ppm. Today, where PFAS are used in textile treatments, they are typically applied at concentrations of 0.05-0.5% of the textile weight to deliver repellency (Gaines, 2022).

Finishing treatment processes represent the final step before fabrics are assembled into finished garments via methods like cutting and sewing.

PFAS in products

Industrial products

PFAS may be currently or historically used in textile manufacturing as:

- Lubricants for weaving
- Wetting agents for dye deposition
- Dye ingredients
- Penetration aids for bleaches

- Antifoaming agents
- Emulsifying agents
- Breathable and waterproof membranes
- Water repellent treatments
- Oil- and stain-repellent treatments

A 1979 patent indicates that a compound based on a C6-C8 PFCA improved the surface lubricity and weavability of yarns (Kissa, 2001). A 1972 patent lists sodium 3-[3-perfluoromethylphenoxyl]-1-propanesulfonate as a surfactant to increase the exhaustion of dyes into acetate fibers (Kissa, 2001). A 1987 patent lists poly(oxy-1,2-ethanediyl), α-[[ethyl[(heptadecafluorooctyl)sulfonyl] amino]acetyl]-ω-hydroxy- and poly[oxy(methyl-1,2-ethanediyl)oxy-1,2-ethanediyl], α-[[[(heptadecafluorooctyl)sulfonyl]methylamino]acetyl]-ω-hydroxy- as release agents for dye-transfer material (Glüge et al., 2020). Other PFAS designed for industrial performance—including PFOS—have been used as wetting agents to perform several functions: enhancing dyeing, bleaching, reducing foaming in treatment baths, and emulsifying fiber finishes (RPA, 2004; Poulsen et al., 2005).

PTFE and PVDF have been used as dye ingredients in the past, according to the database Substances in Preparations in Nordic Countries (SPIN) (Glüge et al., 2020). PTFE, particularly in its expanded form (ePTFE), has also been used since the 1970s to manufacture porous, waterproof membranes for apparel and outdoor gear (W.L. Gore & Associates, 2023). There may be membranes made of PVDF, but it appears that any commercial availability is limited (Cui et al., 2017). ePTFE membranes are widely used in outdoor wear and camping accessories and are generally advertised as “breathable” and “waterproof” (Gaines, 2022; W.L. Gore & Associates, 2023).

PFAS-based treatments applied by textile manufacturers to impart water-, oil-, and stain-resistance have been commonly used since at least the 1960s, although PFAS dispersion products generally have been available since 1951 (Prevedouros et al., 2006). These treatments are typically based on side-chain fluorinated polymers consisting of a non-fluorinated acrylate, methacrylate, urethane, polyurethane, or adipate backbone bound to a fluorinated alkyl functional group (3M, 1999; Kissa, 2001; Schellenberger et al., 2022). PFOS and associated compounds were typically used prior to 3M’s PFOS phase-out in 2000 (3M, 1999; Glüge et al., 2020). Following the phase-out, 8:2 and longer fluorotelomer-based side chains were used (Glüge et al., 2020). A 2001 review of fluorinated surfactant uses suggests the need for chains of 10 perfluorinated carbon atoms (C10) to deliver maximum repellency on a textile fabric (Kissa, 2001). Since the mid-2000s, however, a shift away from longer-chain PFAS has led to the adoption of surface repellent treatments based on shorter fluorotelomers (6:2 and shorter) and shorter-chain PFSAs: chiefly PFBS (C4), which has been used in 3M’s fabric and leather protection treatments and has been increasingly detected in treated apparel since the 2006 inception of the PFOA Stewardship Program (Liu et al., 2014; Lassen et al., 2017; Schellenberger et al., 2022). Note that while 3M stopped using PFAS in its consumer-end fabric and leather protectors (Scotchgard brand) as of 2020, they may still be used in the company’s commercial and industrial textile repellent treatment lines (Bergen, 2021; 3M, 2023).

Several trade names for PFAS-containing commercial and industrial textile treatment products are listed in Table 3. While detailed chemistries are not available for most of these, a list of PFAS compounds used and/or patented for use in textile manufacturing is included as Supplementary Table S1.

Consumer products

PFAS-containing consumer products include both textile products and home water, oil-, and stain-proofing products. Side-chain fluorinated polymers based on FTOHs are most commonly used in consumer repellent treatments today (see "After-market sprays"), but numerous studies have detected PFCAs and perfluoroalkyl sulfonic acids (PFSAs) in addition to FTOHs in a range of consumer-end products across this category. These include not only apparel and outdoor wear but also home furnishings—carpets, rugs, upholstered furniture, bedding, tablecloths, linens, and napkins—and utility products like canvas, rope, and sails (e.g., Guo et al., 2009; Liu et al., 2014; Whiting et al., 2020; Schellenberger et al., 2022; Schreder & Goldberg, 2022). PFAS, particularly FTOHs, have also been found in products designed for use by children such as school uniforms (Xia et al., 2022). ePTFE-based waterproofing membranes can be found in outdoor gear, including apparel and camping equipment (Gaines, 2022).

Table 3. Commercial and industrial textile treatment products containing PFAS. For discussion of consumer fabric and leather protection products, see "After-market sprays."

Manufacturer	Product line	Description of PFAS	Citation
Big Sky Technologies	Greenshield	Manufacturer indicates that the textile finishing product line switched from C8 to C6 technology after 2012	Greenshield, 2023
BASF	Lurotex	C6 fluorocarbon-based textile finishing	Textile World, 2009
Pulcra Chemicals	Repellan, Pellan, Pulcra	Fluorocarbon chemistry for medical PPE textiles	Pulcra Chemicals, 2021
Huntsman* (agent of Chemours, formerly Dupont)	Phobol, Zonyl, Capstone, Foraperle	Fluorochemical fabric finishing/repellent agent based on C6 chemistry (Capstone, Phobol); PTFE, PFA, and FEP repellents for nonwoven textiles (Zonyl)	DuPont, 2010; Chemours, 2020; Industry Search, 2023;
Rudolf Group	Ruco-Guard, Rucostar, Ruco-coat, Rucotec	C6 fluorocarbon chemistry for water, oil, and soil repellent fabric finishing; fluorocarbon impregnating agents	Rudolf GmbH, 2023a; 2023b; 2023c
Daikin	Unidyne TG	C6 fluorochemical barrier coatings for textiles, surgical wear, and carpets	Daikin Industries, 2023; Daikin America, 2023
Nanotex	Resist	Advertised as "PFAS free" on website, but FAQs page indicates use of C6 PFAS chemistry (PFOA-free)	Nanotex, 2023a; Nanotex, 2023b
Nicca	NK Guard	Advertised as fluorinated, but not containing PFOA or PFOS	Nicca USA, 2023
3M	Scotchgard Protective Material, 3M Protective	N-Methyl perfluorobutanesulfonamidoethyl	Lassen et al., 2017

Manufacturer	Product line	Description of PFAS	Citation
	Material, 3M Protective Chemical, 3M Repellent Polymer Melt Additive	acrylate (MeFBSAC); N-Methyl perfluorobutanesulfonamidoethanol (MeFBSE); N-Methyl perfluorobutanesulfonamide (MeFBSA); fluorochemical acrylate polymer; fluorochemical polyurethane; perfluorobutanesulfonamide and polyoxyalkylene containing polyurethane (see Table S1).	

***Huntsman recently announced the sale of its textile chemicals business to Archroma (Huntsman Corporation, 2023).**

A list of PFAS compounds used and/or patented for use in textile manufacturing is included as Supplementary Table S1.

Leather manufacturing

Overview

Leather is a flexible and durable material made from livestock byproducts (China et al., 2020). Products such as nubuck and suede are included in this category; different types of leather utilize different parts of the hides and skins from various types of livestock (Steel Horse Leather, 2021). The production of leather uses a variety of chemicals, often including PFAS. There are four major steps in leather manufacturing:

1) pre-tanning, which prepares raw hides and skins for tanning
2) tanning, which converts raw animal hides and skins to leather
3) post-tanning, which enhances the properties of tanned leather, and
4) finishing (China et al., 2020; U.S. EPA, 2023b).

PFAS can be used to improve the efficiency of the tanning and related processes (1-3) or in finishing to provide water and oil repellence and stain resistance (Kissa, 2001; Glüge et al., 2020).

EPA promulgated effluent limit guidelines (ELGs) for leather tanning and finishing in 1982 (Textile Mills Point Source Category Effluent Limitations Guidelines, 1982)) and conducted a preliminary review starting in 2021 to assess the need to incorporate PFAS into these guidelines, in addition to evaluating other pollutants (U.S. EPA, 2023b). Data on PFAS discharge from leather manufacturing facilities is limited due to a lack of federal reporting requirements (U.S. EPA, 2023b), but a review of PFAS wastewater data from Michigan leather tanneries found that PFAS were present at detectable levels of PFAS in most of the tannery effluent, with a maximum concentration of 83 ppt PFOS. The Michigan Department of Environment, Great Lakes, and Energy (MI EGLE) determined that active leather tanneries were not high priority sources of PFAS compared to Michigan industries like chrome plating, but inactive tanneries that used PFAS historically have been sources of contamination (MI EGLE, 2020). One such site is the former Wolverine World Wide tannery in Rockford, Michigan, which is contaminated with PFOS at maximum concentrations exceeding 1 million ppt (1 ppm) in groundwater, in addition to contamination from other PFAS chemicals (MI EGLE, 2023; MPART, 2023).

Processes associated with PFAS

Leather tanning

Before hides can be tanned, they undergo a number of preparation processes including trimming, soaking, bating, and pickling (China et al., 2020). Bating refers to the application of enzymes to open up the collagen fiber network in hides and skins, to achieve cleaner and softer leather (Zhang et al., 2022). Pickling is performed to lower pH and prevent the acid swelling of skin collagen during tanning (China et al., 2020). PFAS-based surfactants are used in the hydrating, bating, pickling, and degreasing processes to improve process efficiency, reduce processing time, and increase the quality of the final product. Acid pickling promotes the penetration of chromium ions into the pelt; use of fluorinated surfactants in pretreatment steps results in more even distribution of chromate (Kissa, 2001; Zhu et al., 2020).

Though vegetable-based leather tanning has been performed since ancient times, trivalent chromium (Cr(III)) oxide is the primary tanning agent used today, accounting for 90% of leather production worldwide (China et al., 2020; Zhu et al., 2020). Chrome tanning serves to strengthen the bonds between the collagen fibers in a hide, although the tanning process is not fully efficient with regards to chromium uptake. PFAS-based surfactants are used in tanning at weight concentrations of 0.025-0.05% to increase the exhaustion of the chrome tanning agent. As with textiles, PFAS can aid in the deposition of dyes onto tanned leather at similar concentrations. They can also improve the leveling of acrylic brightener emulsions on leather products, including shoes (Kissa, 2001; Glüge et al., 2020).

Leather finishing

PFAS are used in leather treatment processes to impart water and oil repellence, stain resistance, and soil release capabilities. These are facilitated by the hydrophobic, oleophobic, and surface tension-lowering properties of PFAS (Glüge et al., 2020). In the repellency process, PFAS are applied to tanned leather by spraying, cast coating, or tumbling in a drum, in which the leather sorbs the PFAS from an emulsion, suspension, or solution (Lassen et al., 2017). At this stage, PFAS-treated leather may be complexed with chromium and zirconium to optimize oil and water repellency (Kissa, 2001).

In addition to genuine leather, PFAS can be used to manufacture synthetic leather with water and oil repellence. Synthetic leather is generally made by impregnating non-woven textiles with polyurethane or other non-fluorinated polymers using a wet or dry coagulation process, which bonds the material and provides the feel of genuine leather (Mobley et al., 2003; Liberty Leather Goods, 2023). In synthetic leather production, PFAS can serve as ingredients in polymer melt additives, which are processing aids added to the host polymer to alleviate defects and improve efficiency of the production process (Briers et al., 2005; Glüge et al., 2020; 3M, 2023).

PFAS in products

PFAS are used in industrial products for manufacturing and finishing leather and have been detected in numerous consumer-end leather products. They are used in impregnation products for water and oil resistance, similar to products used for textiles. Hydrocarbon- and silicone-based repellents were used in the past, but these only repel water. Since their commercial inception in the 1950s-1960s (Prevedouros et al., 2006), PFAS have been added to repellency mixtures to repel oil. Since PFAS are expensive compared to hydrocarbons, in the past they have been used at relatively low concentrations and extended with the traditional hydrocarbon and silicone repellents. The first PFAS repellents used commercially were PFCAs like PFOA, but these have been superseded by fluoropolymers and side-chain fluorinated polymers based on a variety of PFAS, particularly fluorotelomers (Kissa, 2001; Prevedouros et al., 2006; Schellenberger et al., 2022).

In addition to repellency products, PFAS have been traced to industrial products used in the primary manufacture of leather. In a case study following their leather supply chain, the apparel company G-star attributed PFOS detected in their leather products to wet blue, which refers to the solution used to preserve chrome-tanned leather as it is traded—potentially worldwide—before it is dried, re-tanned, bleached, and dyed (G-star, 2013; Leather-dictionary, 2023). The company determined that the PFOS concentrations of 5-6 ppb measured in the wet blue could explain the 1.1-2 ppb concentrations present in the finished leather products (G-star, 2013).

PFAS have also been detected in a number of consumer products made of leather. A study of consumer products available in Norway found that leather samples had the highest concentrations of PFAS amongst the goods studied, exceeding Europe's regulatory standards for PFOS greater than twentyfold. Leather shoes and office furniture also had detectable perfluorohexane sulfonate (PFHxS) and PFBS. The shoes had high concentrations of 8:2 and 10:2 FTOH, indicating the use of fluorotelomer alcohols in stain and waterproofing (Herzke et al., 2012). In another European study, leather samples showed levels of PFAS up to 200 ppt perfluorobutanoic acid (PFBA) and 120 ppt PFBS as well as detectable levels of PFOS, PFOA, and other PFCAs and PFSAs (Kotthoff et al., 2015). A recent study of leather shoes sold by manufacturer Wolverine Worldwide detected PFBA, PFOS, 6:2, 8:2, and 10:2 FTOH at concentrations ranging from 33-4200 ppb. These shoes were manufactured in China but sold in the US, indicating that PFAS phased out by US manufacturers may still be present in leather products that are imported (Ecology Center, 2019).

A list of PFAS compounds used and/or patented for use in leather manufacturing is included as Supplementary Tables S2-3.

After-market treatments

Overview

While PFAS-based water and stain repellents can be applied by textile and leather manufacturers, they are also available as consumer products for apparel, outdoor gear, furniture, carpet, and leather protection (U.S. EPA, 2021). These products are often sold as aerosol sprays that can be directly applied by users at home or by retailers. Common types of products are durable water repellent sprays (DWR) and stain-resistance sprays for carpet care (Kotthoff et al., 2015; Glüge et al., 2020; ITRC, 2021). These products tend to be highly concentrated in PFAS—on the order of 10^1 ppm—and pose potential inhalation risk to users during application (Herzke et al., 2012). Furthermore, depending on the settings in which these products are used, application may pose PFAS release pathways to indoor air, soil, and water.

PFAS in products

Prior to its phase-out in the early 2000s, PFOS was an active ingredient in household fabric and leather protection products, notably 3M's Scotchgard line. After 2003, 3M largely switched to PFBS-based formulas, although they have been the only company known to manufacture PFBS-based textile and leather protection products (Lassen et al., 2017). It should be noted that 3M has reportedly discontinued use of PFAS in the consumer Scotchgard line as of 2020 (Bergen, 2021), although earlier PFAS-based products could still be in use in households.

FTOHs are otherwise commonly detected in after-market spray coatings today. Prior to phase-out of long-chain PFAS, samples of impregnating agents found that 8:2 and 10:2 FTOH tended to be the dominant PFAS present, with chemical signatures of ~0.01-0.02 6:2/8:2 FTOH and ~0.4-0.6 10:2/8:2 FTOH (Fiedler et al., 2010; Herzke et al., 2012). PFOA has been detected at lower levels, and its presence is thought to result from degradation of the FTOHs originally used (Herzke et al., 2012). For comparison, Herzke et al. found a distinct 6:2/8:2 FTOH ratio in carpet samples (0.68), indicating a difference in the composition between manufacture-applied and consumer treatments (Herzke et al., 2012). A later study indicated the presence of a number of PFCAs in addition to FTOHs in post-market repellency products sold in Europe (Kotthoff et al., 2015).

More recently, 6:2 FTOH and (perfluorohexyl)ethyl acrylate (6:2 FTAcr) were detected in a shoe protector spray marketed as made in the United States (Ecology Center, 2019).

A list of PFAS compounds used and/or detected in after-market textile and leather treatment products is included as Supplementary Table S4.

Environmental release pathways

PFAS can be released from textiles and leather during all stages of their lifetime: manufacture, use, and disposal. Manufacturing processes using PFAS can result in release via industrial wastewater, air emissions, and incidental release to soil and groundwater. During consumer use, PFAS bound in treated articles or present in post-market treatment sprays can be released to indoor air or directly expose users. Residential or commercial washing and drycleaning can also release PFAS to domestic wastewater and septage. Disposal of textile and leather products can release PFAS to landfills and incinerators, in turn impacting groundwater and air.

Note that while PFAS used during manufacture are generally released locally—with the exception of potential long-range atmospheric transport and deposition (Lassen et al., 2017)—PFAS release from product use and disposal can occur regardless of origin of manufacture.

Industrial wastewater

Industrial wastewater is likely the dominant path for PFAS release from textile and leather manufacturing facilities. PFAS are applied to industrial baths to perform dyeing, bleaching, waterproofing, coating with surface treatments, and for leather, tanning and related steps. When these baths are emptied, PFAS contained in the effluent process water are discharged to wastewater treatment plants (WWTPs), which may result in further contamination of sludge, soils, aquatic biota, groundwater, drinking water, and surface water bodies (Heydebreck et al., 2016; Svedlund & Skedung, 2022).

Air

Volatile PFAS used in textile and leather process and treatment baths can escape, releasing to indoor air at manufacturing facilities and outdoor air via stacks and fugitive emissions (Heydebreck et al., 2016; Svedlund & Skedung, 2022). Many PFAS, including PFOS, PFOA, and the other PFSAs and PFCAs have low enough vapor pressures that atmospheric release is generally considered to be a relatively minor pathway compared to wastewater. However, other PFAS compounds—especially FTOHs, N-Ethyl perfluorooctanesulfonamidoethanol (EtFOSE), and N-methyl perfluorooctanesulfonamidoethanol (MeFOSE)—have higher vapor pressures, and their release is considered a major environmental release pathway (Lassen et al., 2015). These compounds are all commonly used in textile manufacturing and in impregnation treatments for textiles and leather (Table S1), indicating the potential for long-range transport of PFAS originating from textile and leather manufacturing facility air emissions. Notably, PFBS is also known to travel long distances in the atmosphere and has been detected in the Arctic (Lassen et al., 2017). PFBS has been the primary replacement for PFOS in 3M's Scotchgard (consumer line, 2003-2020) and Protective Material for Fabrics (commercial/industrial line)—which are designed for water, oil, and stain repellency—and appears to have been increasingly used in textile products since the mid-2000s (Liu et al., 2014; Lassen et al., 2017).

Solid waste

In the United States, textile and leather products may be recycled, disposed of in landfills, or incinerated at the end of their lives. In 2018, textiles contributed nearly 6% of total municipal solid waste produced, while leather and rubber [tires] contributed over 3%. Between these two waste categories, the majority was landfilled, while minor portions were recycled or combusted for energy (approximately 20% each) (U.S. EPA, 2022).

Studies have shown that accordingly, textiles are a potentially significant source of PFAS to landfills. An investigation of a Vermont landfill found that textiles were the second largest source of PFAS in waste streams to the landfill and that carpeting was the third largest source (Sanborn, Head, & Associates, Inc., 2019). A study of model landfill reactors found that carpets and clothing are likely sources of PFAS in landfill leachate, with release from carpets primarily contributing 5:3 FTCA and perfluorohexanoic acid (PFHxA), and release from clothing primarily contributing PFOA (Lang et al., 2016). Notably, a study of several landfills around the US found that 5:3 FTCA was the dominant PFAS compound in most untreated leachate samples (Lang et al., 2017), while a survey of PFAS in Florida landfills found that PFHxA, PFHxS, PFOA, PFBS, and 5:3 FTCA were the most abundant PFAS compounds in all leachate (Solo-Gabriele et al., 2020).

PFAS in landfill leachate resulting from textile or leather disposal may ultimately represent a source to groundwater, in the case of unlined landfills, or wastewater treatment plants, in the cased of lined landfills.

Incineration of textiles and leather may represent a source of PFAS to air. In Denmark, treated clothing has been determined to make up the largest source of PFAS to incinerators, specifically contributing fluorotelomers (Lassen et al., 2015). Incineration of PFAS-containing waste like disposed textile and leather products can result in the release of incompletely combusted PFAS to ambient air, which may then be deposited onto soil and surface waters (Stoiber et al., 2020).

Product use

PFAS-treated textile and leather products continually "shed" PFAS over the course of their lifetimes, presenting indoor air release pathways and direct human exposure pathways during product storage and use (Svedlund & Skedung, 2022). Importantly, PFAS used in the original treatments can degrade over time to intermediate and terminal breakdown products which are then emitted from the articles. Studies have demonstrated that side-chain fluorinated polymers—the most common PFAS used in textile and leather treatments today—can degrade to perfluoroalkyl acids (PFAAs), which are some of the most environmentally persistent PFAS (Schellenberger et al., 2022). These include PFCAs like PFOA, PFHxA, PFBA, and perfluorononanoic acid (PFNA). One study of the effects of outdoor weathering found that after PFAS-treated outdoor apparel was exposed to rain and ultraviolet radiation, PFAA concentrations in the clothing increased significantly. This was explained by the transformation of fluorotelomers in DWR ranging from 4-10 carbon chain lengths over the study period. Notably, even when clothing originally met regulatory standards for PFOA in Europe—where the study was conducted—weathering caused PFOA concentrations to increase to the point of exceedance within months (Schellenberger et al., 2022). Another study performing laboratory-controlled weathering of outdoor apparel found similar effects of weathering on increased PFOA content, in addition to an increase in volatile PFAS (van der Veen et al., 2020). These studies highlight implications for release of otherwise restricted PFAS compounds.

Indoor air and dust

Emissions from the surfaces of treated carpets, upholstery, and other textile and leather products can lead to elevated PFAS concentrations in indoor air and dust in spaces spanning homes, childcare centers, schools, and retail shops (Schlummer et al., 2013; Liu et al., 2014; Fromme et al., 2015; Winkens et al., 2017; Wu et al., 2020; Morales-McDevitt et al., 2021). One study showed that replacing PFAS-containing carpet and furniture reduced dust concentrations by 78%, indicating the significance of home textile products as a PFAS source to dust and indoor air (Young et al., 2021). Levels of fluorotelomer alcohols were of particular note from the results of these studies, although elevated levels of PFCAs were observed as well. Some studies have concluded that levels of exposure from consumer product emissions to indoor air do not pose a risk to human health on their own (e.g., Schlummer et al., 2013; Fromme et al., 2015). However, a recent synthesis study suggested that exposure to PFAS from contaminated house dust could explain a median of 13%, 3%, 7%, and 25% of participants' blood serum concentrations of PFOA, PFOS, PFNA, and PFHxS, respectively (DeLuca et al., 2022).

Human contact

There is emerging evidence that PFAS can be absorbed by sweat and saliva, indicating the potential for PFAS exposure through dermal absorption and ingestion of PFAS in treated textile products. A study of PFAS in children's car seats found that all car seats sampled had been treated with side-chain fluorotelomer-based polymers. The study furthered showed that synthetic sweat was able to extract shorter-chain PFAS from the car seats, suggesting a pathway for dermal exposure (Wu et al., 2021). The Danish EPA found that PFAS could be transferred from children's textile products to artificial saliva. Notably, the artificial saliva ended up more concentrated in PFCAs and PFSAs than the original textile products, which were dominated by FTOHs (Lassen et al., 2015). The potential for PFAS migration through saliva and subsequent ingestion has particular implications for children and infants, who often put objects in their mouths (WA Department of Ecology, 2022).

Domestic wastewater

PFAS on the surface of treated textile and leather products can be released to domestic wastewater from laundering and drycleaning. One study of the effects of laundering on children's textile products found that, on average, 1% of the total PFAS present in the original material was released to laundry water during washing. Relative concentrations of PFCAs, especially PFOA, tended to be higher in laundry water after washing than in the original articles (Lassen et al., 2015). A more recent study showed that PFAAs were washed out of DWR-treated clothing during laundering, representing a source to laundry wastewater (van der Veen et al., 2022). A study of drycleaning operations in Florida found elevated PFOS and PFOA concentrations in laundry discharge water, exceeding 200 ng/L and 100 ng/L, respectively, at the most highly contaminated site. By sampling water at different operational points as well as cleaning detergents, the study found that PFAS from the clothing being cleaned was the likely source to underlying contaminated groundwater, rather than drycleaning chemical agents themselves (Barnes et al., 2021).

Results of these studies point to PFAS-treated textile products as a potentially significant source to domestic wastewater and therefore wastewater treatment plants and surface waters. As the Florida drycleaning study showed, PFAS may also be released to groundwater from commercial laundry operations. Literature is not readily available regarding the impacts of textile and leather products to residential wastewater specifically; this is an opportunity for further study.

Groundwater and soil

PFAS may be released to soil and groundwater from leaks and spills during textile and leather manufacturing operations. Examples of contaminated groundwater due to leather tannery operations include the former Alpena Hide and Leather and Wolverine tanneries in Michigan (MPART 2020; 2023). PFAS was released at the former Wolverine site due to tannery dumping and the use and outdoor storage of 3M's PFOS-based Scotchgard chemicals (Ellison, 2019). Maximum PFOS concentrations in groundwater exceed 1 million ppt (1 ppm) (MPART, 2023), pointing to significant PFAS use within historical operations. Notably, the presence of Cr(VI) has been shown to increase the migration potential of PFOS in soil and groundwater (Huang et al., 2022). Co-contamination from chrome tanning, therefore, may be a factor in PFOS impacts at leather tanneries.

PFAS releases from textile manufacturing have also been linked to contaminated groundwater. For example, site investigation is ongoing at textile company Saint Gobain's New Hampshire operation. The facility's manufacture of coated textiles using PFOA and other PFAS led to PFOA contamination of the public drinking water supply (NH DES, 2023).

Source reduction considerations

PFAS substitutes

PFAS are commonly detected in textile and leather products marketed as water-, oil-, and/or stain-resistant (Schreder & Goldberg, 2022). There are several PFAS-free alternatives for waterproofing available and in use today. Paraffin wax- and other hydrocarbon-based surface treatments have been in use since at least the 1930s (Snyder, 1932; Kissa, 2001), although the practice of applying other oils and waxes to canvas for water repellency dates at least as far back as the 17th century (Anthony-Langsdale, 1924). Today, wax-based treatments are being increasingly adopted again by manufacturers of outdoor apparel and gear (Schreder & Goldberg, 2022).

While wax treatments are the oldest and most economical way to impart water resistance to fabric, they are only capable of repelling water, not oil or stains (Kissa, 2001). Products marketed as "stain-resistant" have been identified that do not have detectable levels of PFAS measured, indicating that non-fluorinated alternative treatments are available and in use (Schreder & Goldberg, 2022). Non-PFAS chemical treatments for carpets and rugs as well as after-market stain- and water-resistance products have been found on the market that meet the Washington State Department of Ecology's criteria for "safer" products, although the precise chemistries have been preserved as confidential business information (WA Ecology, 2022).

Besides surface treatments (DWR), water repellency can also be achieved through use of PFAS-based membranes. Notably, microporous membranes based on tightly woven fabric have been in use since before the advent of PFAS. Today, materials such as polyurethane and polyester are in use by outdoor brands to create microporous membranes (Schreder & Goldberg, 2022). Through reviewing consumer brand and product policies, several textile and leather manufacturers have been identified that claim not to use PFAS in their products. These include products where PFAS is commonly used: rain and outdoor gear, apparel, shoes, furniture, DWR, and children's clothing (Segedie, 2021; 2022; Green Science Policy Institute, 2023).

The California Department of Toxic Substance Control (DTSC) has compiled a list of potential alternatives to PFAS in treatments for both converted textiles and leathers. These include silicones, nanoparticle technology, polyurethanes, acrylates, and paraffin wax and hydrocarbons. DTSC further identified potential alternatives to PFAS specifically during textile and leather manufacture: dendrimers and silanes. These react with fabrics to impart repellency and may also be used as surfactants and processing aids generally (DTSC, 2022).

Life cycle assessments of DWR-treated garments have indicated that PFAS-based DWRs have higher toxicity and environmental impacts than silicone, hyperbranched, and paraffin alternatives (e.g., Holmquist et al., 2021). However, it is important to consider the potential impacts of PFAS alternatives to avoid "regrettable substitution": replacing PFAS with substances that may also pose environmental and health risks. Silicone and siloxane-based treatments pose human and aquatic toxicity risks (DTSC, 2022) and have been identified as potential examples of "regrettable substitutions." Note also that surface treatments based on these chemicals face potential phase-out in Europe over the coming years (Svedlund & Skedung, 2022). Repellents based on nanomaterials are emerging as commercially available PFAS alternatives, but little is currently known about specific risks. It is suggested that nanoparticle formulations may have added risk due to the molecular scale, as they could more easily penetrate cell membranes and impact biological functioning (Svedlund & Skedung, 2022). Paraffin waxes can be made from either fossil or renewable sources (Svedlund & Skedung, 2022); choosing fully biodegradable waxes as PFAS replacements is more desirable from environmental and human health standpoints.

Process alternatives

In addition to replacing PFAS in treatments for textiles and leather, alternative processes can be used that do not require chemical treatment to achieve protection from water and stains. Choice of material may play an important role in stain resistance and cleanability of textile products. A recent study showed that PFAS-based surface treatments in upholstery played a negligible role in repelling water-based stains, and that time to cleaning and differences in fabric were more significant factors in repelling oil-based stains. Therefore, use of fabrics with properties allowing for stain removal may reduce the need for PFAS-based repellents for household textile products (LaPier et al., 2023). Fabric materials are also available that are inherently water- and/or stain-resistant, including polyolefins, wool, polyester, thermoplastic polyurethane, and nylon. PFAS-based treatments may be avoided by choosing these materials in designing textile products, particularly furnishings and carpets (WA Department of Ecology, 2022).

To minimize the use of PFAS-based treatments, products can also be designed to be easier to clean. Products like tablecloths and school uniforms can be designed to be machine washable, and larger products like furniture and rugs can be designed with removable and washable covers (Schreder & Goldberg, 2022; WA Department of Ecology, 2023). Furnishings and carpets for which machine-washable coverings may not be practical can be cleaned using specialized cleaners. There are such products available that are designated “safer” under EPA’s Safer Choice Program (EPA, 2023c). The longevity of outdoor furniture and furnishings can be further extended by storage under cover or indoors when necessary.

Gaps

During leather manufacturing, in addition to repellency treatments, PFAS may be used to prepare hides and skins for tanning and to enhance the uptake of chromium during the tanning process. Information regarding alternatives to PFAS in leather tanning was not identified in the scientific literature or internet searches at the time of this report. Notably, non-chromium tanning is an emerging field of research, including investigation into vegetable tanning, which has been done since ancient times. Other tanning methods actively being investigated are based on aldehydes, synthetic tannins, and aluminum sulfate. (China et al., 2020; Zhu et al., 2020).

Supplementary information

Supplementary information tables can be found online as report number gp3-06a, “PFAS in the textile and leather industries: Supplementary information.”

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