For the European Environment Agency

An assessment on PFAS in textiles in Europe's circular economy

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Report for

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Key messages

PFAS in textiles

- Per-and polyfluoroalkyl substances (PFAS) are produced and used in both polymeric and non-polymeric forms[1]. Both forms of PFAS are intentionally used in finished textile products to provide properties such as water repellence, oil repellence, protection against stain-resistance and thermal stability.
- Textiles account for approximately 35% of the total global fluoropolymer demand. In line with that, it has been reported that a third of all PFAS in the EU - between 41,000 to 143,000 tonnes - are used in the textile sector. The textile sector is therefore estimated to be the biggest contributing use sector to PFAS pollution in Europe.
- Europe is a major importer of new textiles and exporter of mainly after use textiles. Most imported textiles come from countries in Asia which commonly apply less stringent chemicals legislation than EU manufacturers.

Human health and environmental risks

- Current knowledge on non-polymeric PFAS is limited to a small number of PFAS (<1%) which are known to harm the environment and human health, but the impacts of many other PFAS compounds (including polymeric PFAS) are even less well understood. The release of PFAS into the environment can occur at each of the different stages of the lifecycle of textile products, including production, use, and disposal, which can contaminate water, soil, and air, posing potential risks to both humans and the environment.
- PFAS, both non-polymeric and polymeric, persist in the environment and some non-polymeric PFAS accumulate in food chains. Less is known about polymeric PFAS and their long-term behaviour in the environment. Nevertheless, the degradation of both polymeric and non-polymeric PFAS into smaller persistent compounds are an environmental and human health concern.
- PFAS release during the lifecycle of textile products can contaminate water, soil, and air, endangering both humans and the environment. Human exposure to PFAS occurs through inhalation, ingestion of drinking water and contaminated food, and through dermal contact. This affects workers, consumers, waste handlers and the general population at various stages of the lifecycle.
- Certain non-polymeric PFAS are associated with various health effects including carcinogenicity, mutagenicity, reproductive toxicity, immunotoxicity and specific target organ toxicity. Limited data exist on polymeric PFAS, although potential respiratory problems from inhalation exposure are reported.

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[1] Non-polymeric PFAS are small fluorinated compounds which have relatively short carbon chains. Polymeric PFAS differ in that they exist in repeating units.

Regulation

- The REACH registration obligation does not apply to PFAS in imported articles (including textiles). Some PFAS compounds are covered by harmonised Classification, Labelling and Packaging (CLP), are on the Substances of Very High Concern (SVHC) list, are restricted under the Persistent Organic Pollutant (POP) Regulation, or are covered by specific REACH restrictions (e.g. in firefighting foams). Other regulations such as for cosmetics and electronic equipment also limit the compounds that can be used in certain applications.
- Until recently, regulatory restriction in Europe has been is based on individual PFAS. However, the recently proposed universal PFAS restriction brought forward by Denmark, Germany, the Netherlands, Norway, and Sweden covers all PFAS which could have huge impacts on textiles throughout the value chain.
- The EU Strategy on Circular and Sustainable Textiles, proposed in 2022, aims to make textiles more sustainable, but does not include specific focus on PFAS.

Implications in a circular economy

- The EU is mandating separate collection of textile waste by 2025 to promote reuse and recycling.
- Various take-back and collection systems for reuse exist, with charities and professional collectors selling high-quality textiles, while others are sold to wholesalers for global distribution.
- Exporting clothing for reuse outside Europe presents environmental and social challenges, including harm to the local environment and health impacts. Whilst, creating local jobs and economic added value in sorting and reuse, it can also contribute to the decline of local textile industries in some recipient countries.
- The presence of PFAS in textiles, especially long-life items, raises concerns when textiles are reused and recycled, potentially extending PFAS exposure to humans and the environment. Recycling textiles containing PFAS introduces risks of contamination and release across a wide variety of secondary products. It is also challenging to trace the presence of PFAS in recycled textiles.
- Regulations on restricted/banned substances, like PFAS, can decrease benefits and cause new risks to recycling, and proper handling of PFAS-containing waste is hindered by a lack of information and transparency in the supply chain.
- Some European textile waste is disposed of in regulated incineration or landfill facilities within the EU. Despite regulation, incineration may release PFAS combustion products to air and landfill can create hot spots for environmental releases to soils, surface water and groundwater. However, much of Europe’s textile waste is exported mainly to Africa and Asia where after use treatment in less strictly regulated. As a result, after use textiles may end up in open dumps or open burning resulting in unmitigated release to the environment.
- To address these issues, it is important to phase out PFAS in textiles by substituting to safer alternatives, utilising design frameworks like Safe and Sustainable by Design (SSbD) and the Eco-design for Sustainable Products Regulation (ESPR). Better sorting, separation and destruction of legacy PFAS is crucial to prevent their indefinite circulation in material loops.

Executive summary

Introduction

The textile sector represents around one-third of PFAS usage in the EU and total global fluoropolymer demand. This sector is therefore a major source of PFAS pollution. The environmental and health concerns associated with PFAS have prompted growing calls for their phase-out. Regulatory responses have historically focused on individual PFAS, initially the longer-chain PFAS such as PFOS and PFOA. However, this has led to regrettable substitution with short-chain PFAS. A proposal is now in place for a universal restriction covering around 10,000 PFAS. At the same time, the EU is pushing towards a circular economy, including increased reuse and recycling of textiles. The presence of harmful chemicals, like PFAS, poses challenges to circularity efforts and may escalate costs for waste handlers. This report investigates the current state of PFAS use in EU textiles, reviewing the existing literature concerning their environmental and health impacts and implications for the circular economy transition.

PFAS in textiles

The main properties that PFAS provide in textiles are water repellence, oil repellence, stain-resistance and thermal stability. They are used in numerous consumer and professional clothing, home textiles, leather and technical applications. They exist in both polymeric and non-polymeric forms, each with unique applications. Within these broad categories there are numerous variations that exhibit different properties and behaviours. Polymeric PFAS, intentionally used in finished articles, constitutes over 75% of PFAS in textile products with the aim to provide the desired functional properties. Non-polymeric PFAS, used during manufacture as a processing aid, persist in finished articles and can be released during the product lifespan, particularly during washing.

PFAS impacts on human health and the environment

Research on a relatively small number of non-polymeric PFAS has established that they exhibit persistent, bio-accumulative and mobile properties within the environment. These PFAS can have negative effects on natural ecosystems as well as on human health. Effects induced by these compounds include endocrine disruption, reproductive toxicity, carcinogenicity and specific target organ toxicity. As a result, regulatory activity has until recently focused on these specific PFAS.

Whilst polymeric PFAS are persistent in the environment, research on their toxicological properties have been limited. This may be explained by their molecular sizes which are often considered to be too large to be taken up by living organisms and they have therefore been deemed to be less of a risk compared to non-polymeric PFAS. However, the identity and effects of polymeric PFAS degradation products are not well understood and it is thought that some of them may exhibit similar behaviour to non-polymeric PFAS. Assessing PFAS toxicity is complex due to their diversity, the lack of data, and the need to evaluate them as groups which has prevented adequate investigation. This has been a key driver for introducing the proposed universal REACH restriction brought forward by Denmark, Germany, the Netherlands, Norway, and Sweden.

Challenges at end of life

When textiles reach the after-use phase including end of life, they are either resold, incinerated, landfilled, recycled or exported. Depending on which after-use or end of life route is taken, PFAS can be released to the environment via numerous mechanisms. Most textiles waste in the EU are incinerated despite uncertainty as to whether this adequately eliminates PFAS. Thermal destruction of PFAS is a proven scaled technology, but the suitability of municipal incinerators for complete destruction is uncertain and high-temperature incineration has limited capacity for waste streams like textiles. Further investigation of emerging techniques with lower environmental impacts is required to better understand these methods and develop capacity to suitably destroy PFAS at scale.

Landfilling textiles with fluorinated polymers can result in the long-term degradation of larger PFAS compounds into smaller forms, with potential leachate release. While studies suggest this is not currently a major PFAS source in the EU, the risk increases in regions with uncontrolled landfill and open burning, common in countries receiving exports of used textiles. Wastewater treatment plants receiving PFAS-contaminated wastewater from washing processes and landfill leachate cannot handle PFAS. Instead, it is partitioned and affected sludge is spread on land which contaminates of food sources, endangering wildlife, livestock, and humans.

Challenges with reuse and recycling

Reusing and recycling textiles amplifies the risk of exposure by extending the duration of PFAS in circulation, thereby prolonging potential environmental and health risks. Reusing textiles typically exposes individuals and the environment to PFAS via similar pathways as their initial use, but repurposing them for different uses may pose increased environmental and health risks, especially for vulnerable users (e.g., use for children’s toys poses a greater hazard than use for a specific professional or technical application).

Recycling heightens the risk of contaminating a broader range of secondary products, potentially exposing humans and the environment to greater risks than the primary product would have posed, and to a greater population. This can result in uncontrolled exposure without means of tracking their presence as the link to their original supply chain is severed. Recycling processes can release PFAS into the environment, impacting worker and public health through direct and indirect emissions as evidenced by reports of recycling plant workers exhibiting elevated levels of PFAS compared to control groups.

Industrial and commercial waste handling facilities have specific criteria for accepting waste, particularly if it contains SVHCs (e.g., PFOS and PFOA), which require specialised treatment for irreversible destruction, making handling difficult and incurring substantial costs. Where the contents of a material are not known, a lack of information may lead recyclers to reject materials over concerns about potential contamination. Therefore, there is a critical need for improved identification, sorting, and removal of contaminants to prevent material loss whilst maintaining its safe handling. However, technical and financial barriers impede adequate monitoring of material flows during recycling, leading to either the disposal of valuable material and a loss of value or the continued circulation of hazardous substances in material loops.

Impacts beyond the EU

PFAS contamination is a global issue. Beyond the EU, transparency diminishes regarding the fate of textiles. The export of used textiles from Europe, whole contributing to jobs and economic added value in other regions of the world, could negatively impact local environments and also sometimes economies in recipient countries, leading to the decline of existing local textile industries and the disposal of large quantities of poor-quality textiles in open dumps or through open burning. Less stringent safety and waste management regulations outside Europe exacerbate challenges in the recycling process seen within the EU. While the EU has strict rules for its own internal market, influencing production and handling of used textiles practices and addressing environmental and social impacts beyond its borders is difficult despite relying heavily on imported textiles and exports of used textiles. Better transparency is needed to ensure that supply chains comply with EU regulations, particularly if PFAS were to be restricted in the EU.

Tracing PFAS in supply chains

PFAS are difficult to trace because REACH does not extend to polymers or finished textile products so there is often no legal requirement to provide data through the supply chain. There may also be a lack of technical understanding among suppliers and manufacturers regarding PFAS, difficulties in controlling and communicating requirements up the supply chain, and hesitation among suppliers to disclose proprietary formulation ingredients (i.e. confidential information about their products). Regional disparities in the importance placed on PFAS transparency, both within the EU and globally, hinder a unified drive for openness. Small and medium-sized enterprises (SMEs) often lack resources to trace (and address) PFAS in their supply chain, with competing regulatory demands taking precedence. Action tends to be taken only when legally required, as there is little incentive to invest resources in non-mandatory activity.

Enhancing communication within the supply chain can be accomplished through voluntary initiatives, such as updating supplier policies and building stronger relationships with suppliers and buyers. Retailers and manufacturers can use existing guidance documents and tools to improve their understanding of their supply chain and relay this information downstream. Additionally, the incorporation of information on PFAS into ecolabeling and the use of technology, such as Radio-frequency identification (RFID) tags, could be adapted to provide greater transparency and visibility downstream (e.g. to waste handlers).

Identifying, separating, and sorting PFAS at end of life

The two main options for removing PFAS from textile waste include i) destroying the entire product or ii) sorting and removing PFAS components from the product for separate destruction. The latter, whilst technically challenging, maximises textile recovery.

PFAS-containing textiles can be identified and sorted after-use or at end of life, but opportunities for this are currently limited. When identification or separation is challenging, suspected PFAS-containing textiles should be directed towards suitable end uses, rather than applications with greater exposure to vulnerable users or the environment.

Better tracing systems (e.g., labelling and sharing of information throughout the supply chain, including in product passports) and sorting technology (e.g., automatic sorting) can help identify PFAS-contaminated products at end of life and direct them to suitable treatment to prevent them from entering recycling streams, whilst maximising the amount of safe textiles for recycling.

Contents

1. Introduction

This section introduces the project background and context. It provides a definition of per- and polyfluoroalkyl substances (PFAS) specific to this project, which is aligned with the definition used within the REACH restriction proposal. It also defines the project objectives, report structure and the methodology for conducting this study.

1.1. Background and context

Per- and polyfluoroalkyl substances (PFAS) are a large cluster of over 10,000 synthetically made substances, which provide desirable attributes and properties to a wide variety of products. The substances have been in circulation since the late 1940s after 3M and Dupont first started the manufacture of these substances (Glüge et al., 2020; EEA, 2023; Pemberton, 2021). PFAS, under the European Chemicals Agency (ECHA) and Organisation for Economic Co-operation and Development (OECD) definition, can occur in polymeric and non-polymeric forms (ECHA, 2023b; OECD, 2022a). They have been used within a variety of products due to their range of useful properties such as water, oil and stain repellence, corrosion resistance, weather resistance, thermal stability, ability to lower the surface tension of water, and as a bulking agent (amongst other uses) (Glüge et al., 2020; OECD, 2022a). Their efficacy, even at low concentrations, has meant they have been used across a wide array of applications in both industrial and consumer applications such as water-repellent fabrics, technical textiles, firefighting foams, food packaging, electronics and non-stick cookware among many others.

However, the same physical properties that make them so useful and therefore widely used have contributed to a multitude of environmental and human health concerns. For example, PFAS in all forms are highly stable and are therefore persistent in the environment. Furthermore, numerous studies have indicated that some PFAS (primarily non-polymeric PFAS) can cause negative reproductive and developmental effects, can increase the risk of some cancers, and can reduce the ability of the body's immune system to fight infections (ECHA, 2023b). Combined with concerns such as bioaccumulation of PFAS in the human body, their extreme environmental persistence, their long-range transport potential in the environment, the high mobility in soils for some PFAS and their presence in drinking water, PFAS are considered a threat to both human health and the environment (NIEHS, 2019; Cousins et al, 2020; Sörengård, 2022). Toxicity of polymeric PFAS have been investigated in less detail and therefore the long term impacts are less well known.

It has been widely recognised that more research is needed to fully understand the various routes of PFAS exposure, and to fully understand their health implications (ATSDR, 2022). Although there is some general knowledge, only a relatively small number have been thoroughly assessed for health impacts. For example, ECHA (2022) highlighted that 357 PFAS have human health classification endpoints, of which 41 have harmonised classifications.

To this end, the European Commission (EC) included persistent and mobile chemicals under the EU Green Deal call for research and innovation projects[2] (WP2020 – projects to be selected for funding in 2021) with objectives including the “development of best practices for the management of waste containing persistent and mobile substances; detection and identification of specific pollution problems” (EC, 2023). The Chemicals Strategy for Sustainability Towards a Toxic-Free Environment specifically outlines the need for “phasing out the use of PFAS in the EU, unless their use is essential” (EC, 2020). This supplements the substitution strategy implemented by ECHA in 2018 (ECHA, 2018) that advocates the substitution of chemicals of concern in the EU and boosting the availability and adoption of safer alternative substances and technologies.

The regulatory approach to addressing the risks posed by PFAS at EU and international levels, has historically been on a substance-by-substance basis, and has focussed to a large degree on specific long-chain PFAS such as perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA). At international level, PFOS and PFOA are listed under Annex A of the Stockholm Convention on persistent organic pollutants (POPs), requiring parties to the Convention to ‘eliminate the production and use’ of the chemicals. At EU level, PFAS are regulated by a number of pieces of legislation and cross-regulation activities. These regulations cover the general production, sale, import and export of chemical products, the use of PFAS in specific products or applications, occupational exposure, presence in waste streams, and the acceptable levels in the environment (ECHA, 2023g).

On the 13th of January 2023, Denmark, Germany, the Netherlands, Norway, and Sweden submitted a proposal (Annex XV Restriction Dossier) to the ECHA to restrict around 10,000 PFAS (ECHA, 2023b). According to the Annex XV Restriction report, the PFAS in the scope of the restriction are all persistent in the environment and if they are not restricted this could have negative consequences on people and the environment (ECHA, 2023b). The public consultation on the proposal closed in September 2023 with 5,600 responses at least ten times the number of responses received from any previous ECHA consultation (ECHA, 2023c). It is expected that a draft RAC/SEAC opinion would be published in Spring 2024, but it could take longer due to the complexity of the dossier.

The textiles market is one of the largest consumers of PFAS and releases a large amount of PFAS into the environment. In March 2022, the EC published its strategy for sustainable and circular textiles (EC, 2022b), which noted that whilst only 1% of textiles is currently being recycled within the EU, that number is expected to increase as a result of the strategy. This is due to imposed EU regulations such as the obligation for all EU Member States to separately collect textiles waste by 2025 under the circular economy package and the revised Waste Framework Directive which also requires the EC to consider, by the end of 2024, whether targets for textile waste re-use and recycling should also be introduced (European Parliament (EP), 2018a, 2018b, 2019). However, harmful restricted chemicals in textiles are likely to impact the circularity of any reuse and recycling strategies, as well as potentially increasing costs for those tasked with the recycling activities.

There remains uncertainty over the effects that PFAS in textiles might have on the EU circular economy. For example, if more PFAS are restricted in the EU, this could result in legacy textiles containing PFAS being used and reused for longer periods, resulting in

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[2] https://www.h2020.md/en/green-deal-call-research-and-innovation-projects-now-open

greater exposure to humans and releases to the environment. The presence of PFAS may also limit recycling opportunities due to safety concerns and/or technical limits on their secondary applications which would limit the recovery of material and hinder the objectives of the strategy for sustainable and circular textiles.

Therefore, the aim of this analysis is to cover the current state of the knowledge on the use of PFAS in textiles on the EU market, the key impacts of PFAS in textiles on human health and the environment and provide an assessment of the implications of PFAS within the EU's transition to a circular economy.

1.2. Objectives

The aim of this report is to prepare an assessment on PFAS in textiles in Europe's circular economy and to set the scene on existing knowledge by compiling what is known about the types of PFAS used within textiles as well as the environmental and health effects of PFAS in textiles.

The focus is on drawing information from existing literature with a focus on identifying any knowledge gaps which will be supplemented through engagement with Eionet and experts. Specifically, this study reports on the existing and most recent information on the following aspects:

- The content and types of PFAS in textiles placed on the European market. This includes a review of the role of PFAS within the textiles categories (defined later in this report), concentrations of PFAS within textile categories and the durability and life expectancy of textiles.
- The environmental and human health impacts of PFAS in textiles on the European market.
- The implications of PFAS in textiles during the transition to a more circular economy. This includes the impacts and possibilities of substitution to non-PFAS-alternatives, the possibilities of tracing PFAS in textile waste, the role of PFAS in recycling textiles, identifying existing and innovative waste tracking and abatement technologies as well as identifying technologies that can improve the traceability of PFAS throughout the textiles supply chain.

This knowledge base will increase our understanding of challenges, opportunities and knowledge gaps and allow the relevant authorities to make better informed decisions on how to minimise the negative health and environmental impacts of PFAS in textiles in the future.

1.3. This report

This document comprises the following key chapters:

- **Chapter 1: Introduction (this chapter).**
- **Chapter 2: Knowledge on the content and types of PFAS in textiles on the European market.**
  - This chapter describes the existing knowledge on the types of PFAS used in textiles and the key product categories they are used in, based on the findings in key literature.

- **Chapter 3: Environmental and human health impacts of PFAS in textiles.**
    - This chapter sets the scene on existing impact knowledge by compiling and describing what is known about the environmental and health impacts associated with PFAS in textiles and identify key knowledge gaps. This covers aspects on release to the environment and exposure to humans. Note that this section is a brief overview of the environmental and human health impacts of PFAS in textiles and does not constitute a detailed or comprehensive assessment.
- **Chapter 4: Implications of PFAS in textiles for the transition to a circular economy.**
    - This chapter describes and identifies the key implications of textiles within a circular economy, giving insights into the recovery options and the ability/technologies to trace PFAS within the textiles supply chain. The chapter will also look at the current and developing abatement technologies alongside PFAS alternatives.
- **Chapter 5: Conclusion.**
    - This chapter reflects on the lessons learned and future pathways on PFAS in textiles in Europe's circular economy.

1.4. Methodology

This report provides an assessment of PFAS in textiles within Europe's circular economy. It covers the historical context and various types of PFAS in textiles, their environmental and human health impacts, and their implications for transitioning to a circular economy. The report relies on existing literature, such as studies by Wood et al. (2022), Glüge et al. (2020), OECD (2022), ECHA (2021), EEA (2021), and EEA (2022), to inform Section 2 and Section 3.

Section 4 has been developed from a more detailed systematic literature search based on predefined keywords and themes. This search identified key themes, gaps in information, and was supplemented with additional targeted searches. While the focus was on Europe, the geographic scope was expanded when necessary and to address certain themes such as extra-EU impacts, from imports and exports. The primary focus was on evidence from the past 10 years due to the rapidly changing nature of PFAS-related developments.

The findings from the literature have been reported on. The evidence has been compiled into an Excel-based log shared with the EEA. The literature review was supplemented by information gathered during an Eionet workshop and expert webinar with participation of EEA member country experts in the fields of chemicals and circular economy.

1.5. PFAS Definition and regulation

Definition

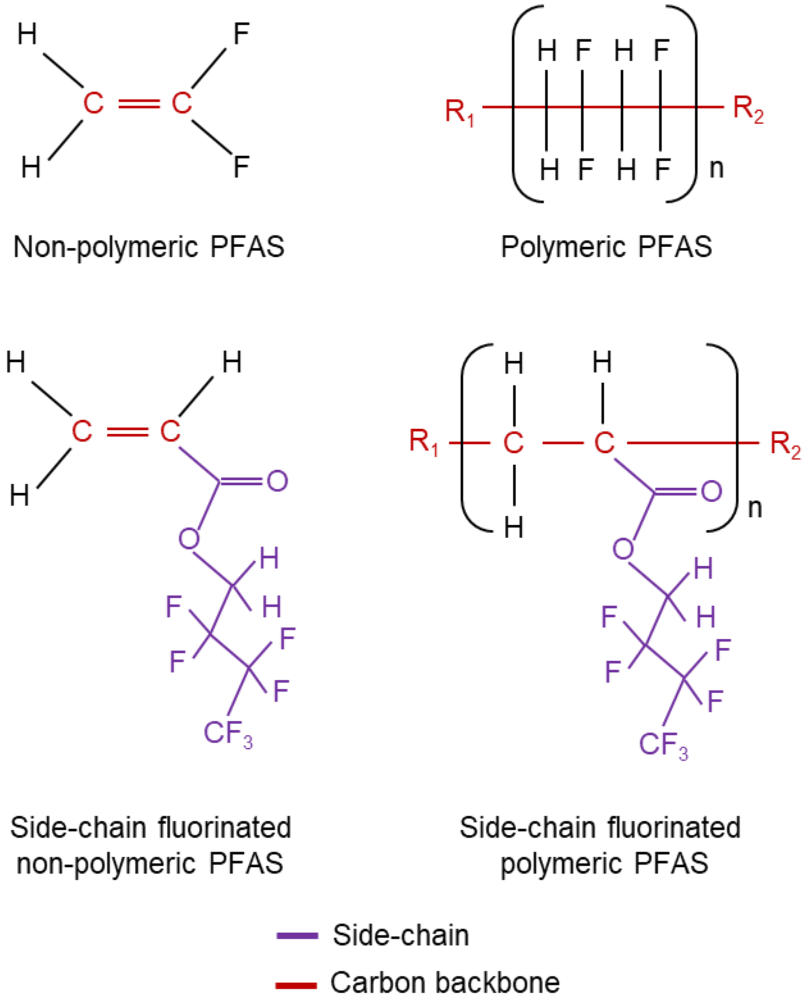
PFAS are defined by ECHA and the OECD as "fluorinated substances that contain at least one fully fluorinated methyl or methylene carbon (without any H/Cl/Br/I atom attached to it)" (Wang, 2021; ECHA, 2023a). They are a group of synthetic chemicals that are characterised by their strong carbon-fluorine bonds and are known for their water- and grease-resistant properties, making them useful in a wide range of products.

PFAS can generally be separated into two main categories:

- Non-polymeric PFAS; and
- Polymeric PFAS.

The distinction between these two types of PFAS is typically based on their chain length, which corresponds to the number of carbon atoms in the longest consecutive carbon 'backbone' (shown in red) of the molecule. A side chain is a group of atoms attached to the main carbon backbone of a molecule, influencing its properties and reactivity. A branched structure is a molecule that has side chain(s) (shown in purple).

Figure 1.1 Examples of polymeric vs non-polymeric PFAS



Non-polymeric PFAS

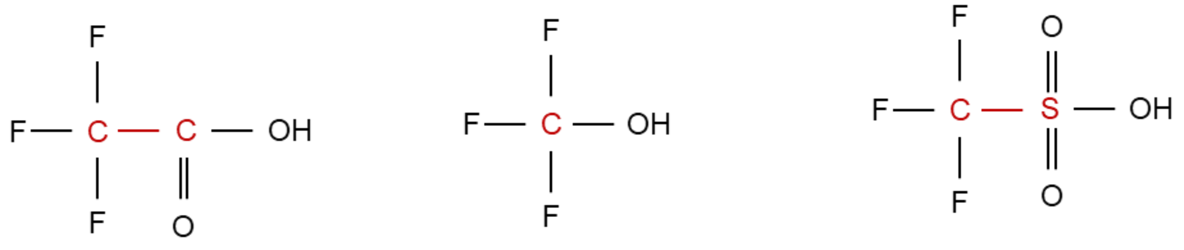
Polymeric PFAS

Side-chain fluorinated non-polymeric PFAS

Side-chain fluorinated polymeric PFAS

Non-polymeric PFAS are a subgroup of PFAS that consist of individual molecules, typically with a linear or branched structure. These non-polymeric PFAS do not have repeating units in their structure, unlike polymeric PFAS. Examples of non-polymeric PFAS include PFOA and PFOS, which have been widely studied.

Figure 1.2 Examples of non-polymeric PFAS.



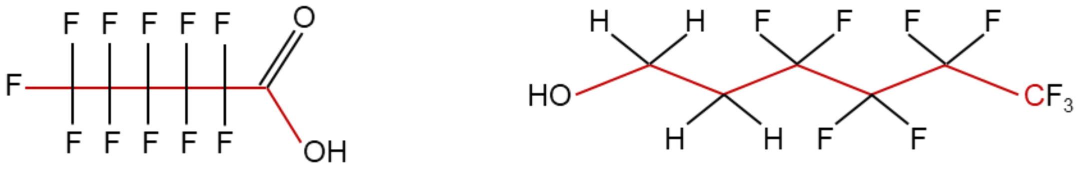
Perfluoroalkyl carboxylic acid

Perfluoroalkyl acid

Perfluoroalkyl sulfonic acid

They can be used, for example, as processing aids, fillers, and the building block (monomers) for polymeric PFAS (Interstate Technology and Regulatory Council (ITRC), 2020). Non-polymeric PFAS can generally be split into *polyfluorinated alkyl* substances, where not every carbon is fully fluorinated, and *perfluorinated alkyl* substances, where every carbon is fully fluorinated. Longer chains of PFAS with an alcohol at one end, called fluorotelomers, are also included in the category of non-polymeric PFAS.

Figure 1.3 Example of per- vs polyfluorinated substances.



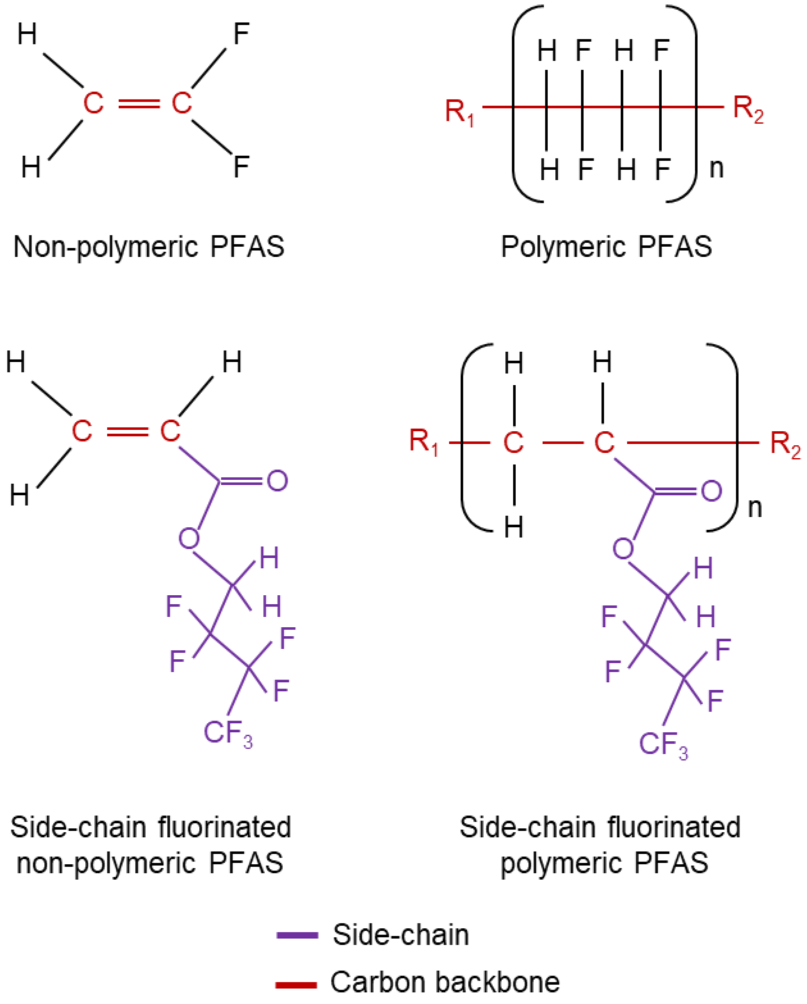
Per-fluorinated

Poly-fluorinated

Polymeric PFAS have a repeating unit or chain in their molecular structure. These repeating units consist of carbon and fluorine atoms and create a long chain, giving the polymer its unique properties. The chain can vary in length, and these compounds are often used for their non-stick, water- and oil-resistant properties.

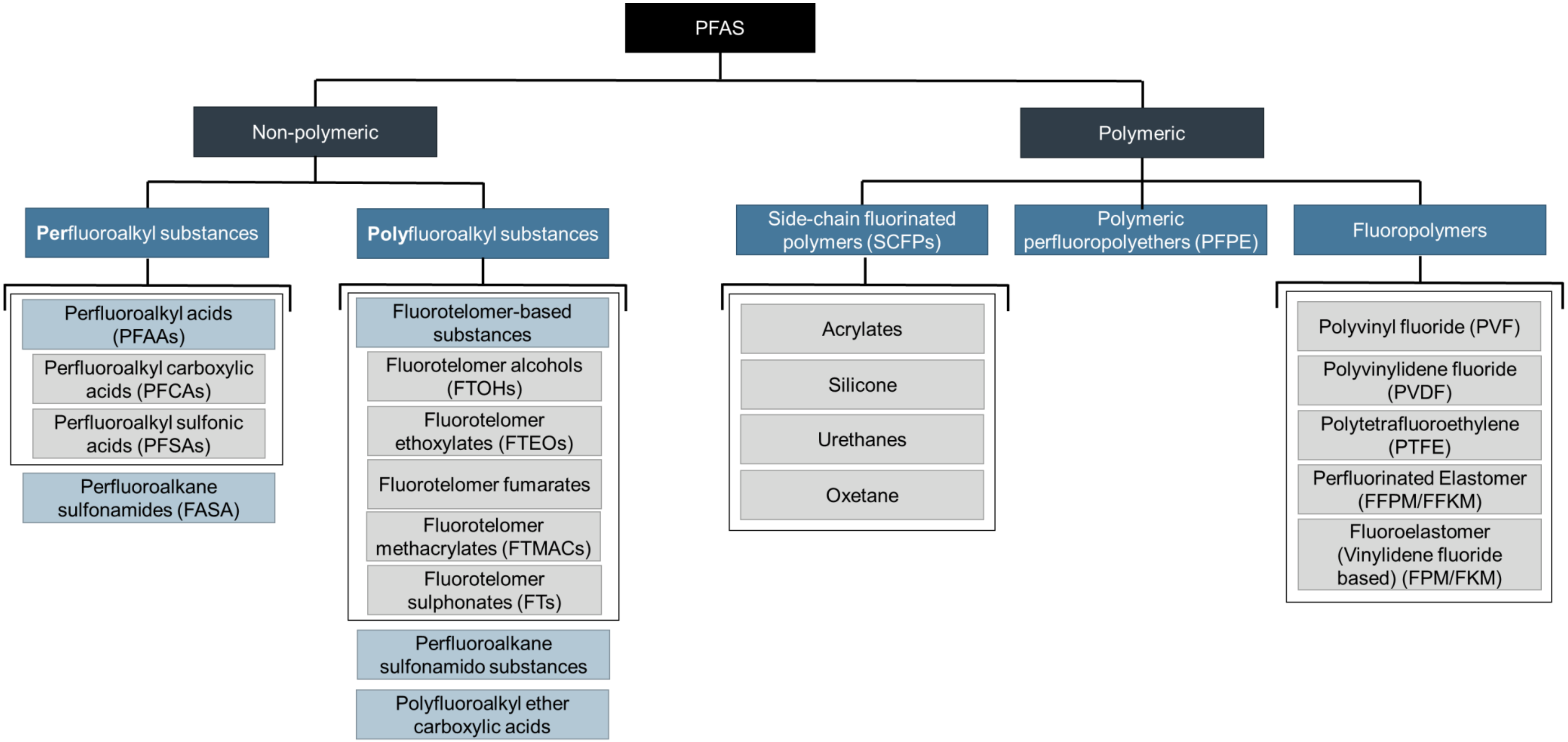
The number of carbons in the chain to go from non-polymeric to polymeric PFAS differs based on the specific substance. Fluoropolymers (FPs), side-chain fluorinated polymers (SCFPs), and polymeric perfluoropolyether (PFPE) are all included under polymeric PFAS (Figure 1.3) (ITRC, 2020).

Figure 1.4 Examples of polymeric PFAS (fluoropolymers, perfluoropolyethers, and side-chain fluorinated polymers).



A more in-depth view of non-polymeric and polymeric PFAS is shown in Figure 1.5. It is important to note that PFAS comprise a wide variety of molecules with differing structures and properties therefore exhibiting different specific properties and behaviours depending on their application and environment.

Figure 1.5 Overview of PFAS categories.



Adapted from ICRC, 2020.

Regulation

Currently, REACH requires substances to be registered if manufactured or imported in more than 1 tonne per company per year and applies to both chemical substances and chemical mixtures ((EC) No 1907/2006). However, the use of PFAS in an imported article (such as a waterproof coat) does not need to be registered, or notified unless the substance is on the list of Substances of Very High Concern (SVHCs) (ECHA, 2023e).

REACH registration requirements currently do not extend to polymers, and therefore polymeric PFAS is beyond the scope of REACH, unless the substance is one that is globally regulated under the Stockholm Convention (such as polymeric PFAS that is known to degrade to PFOA or PFOS). This lack of mandatory reporting for polymeric PFAS results in the known use, hazard and environmental fate data being primarily available for non-polymeric PFAS.

Both polymeric and non-polymeric PFAS are extremely persistent. The information available for non-polymeric PFAS indicates that many display the potential for bioaccumulation, long range transport potential, high mobility, ecotoxicity, and can lead to serious health hazards (ECHA, 2023a). This information is not available for polymeric PFAS, so there is limited information regarding the, bioaccumulation, and toxicity of these substances. While in use, polymeric PFAS may have less environmental and health hazards than non-polymeric PFAS. In general, there is little information available regarding how polymeric PFAS will degrade over time. However, polymeric PFAS can degrade into non-polymeric PFAS, although the conditions and time it takes to degrade polymeric PFAS to potentially bioaccumulative, and toxic non-polymeric PFAS is unknown.

2. Knowledge on content and types of PFAS in EU textiles

This chapter sets the scene on existing knowledge by compiling what is known about the types of PFAS and the types of textiles that they are found within. This chapter has been primarily informed by the key literature identified within Section 1.4 and summarises the work undertaken on PFAS in textiles in Europe to date with commentary on the knowledge bases and highlighting knowledge gaps. An overview of the textiles market in Europe, including a description of the value chain including sources and end of life pathways, is also presented here with discussion on the origin of textile products and the implications this might have on PFAS composition.

2.1. Overview

The REACH Annex XV Restriction Dossier[3] for a universal PFAS restriction identifies textiles as a priority sector due to the high levels of PFAS used within certain textiles and the potential release and exposure to PFAS during their use. The European Environmental Bureau (EEB) reports that a third of all PFAS in the EU are used within the textile sector (EEB, 2023). This is supported by estimates from ECHA (2023a) that put the use of PFAS in the textiles sector to be between 41,000 to 143,000 tonnes annually in Europe.

As discussed in Section 3.2, the textile sector is estimated to be the sector of use contributing the highest volumes of PFAS release to the environment in Europe (based on the ECHA, 2023a estimates)[4]. Despite this, there is relatively little knowledge on the uptake of the substances from textiles to the skin and lungs as covered in Chapter 3 (EEA, 2019a).

The Annex XV Restriction Dossier indicates that the use of PFAS is expected to rise, primarily driven by the increase in use of polymeric PFAS (see Section 2.3), although the dossier does not provide a timescale for this increase. The use of these substances is estimated to have increased by 2% annually and is expected to continue at this rate at least to 2030, with predominantly more demand from home textiles over consumer apparel. Side chain fluorinated polymers have seen lower growth in use over recent years due to more awareness over the emissions of non-polymeric PFAS, therefore a steady growth rate of 2% annually is expected for side-chain polymers in other textile applications (ECHA 2023a).

PFAS has been identified in textiles or during the manufacturing of textiles from the following categories:

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[3] A comprehensive technical document that supports the restriction proposal. It contains scientific data, risk assessments, exposure scenarios, and information on potential alternative substances or technologies.

[4] It should be noted that based on the estimates in the ECHA (2023a) assessment, the volumes of release of PFAS from the textiles sector is marginally lower than those estimated for fluorinated gases. The distinction made here is that releases of PFAAs and PFAA precursors, and polymeric PFASs are the highest in the textile sector.

- Consumer and professional clothing
- Home textiles
- Technical textiles
- Leather and protection spray treatment

Appendix A contains a breakdown of the different textiles categories by PRODCOM[5] category (ECHA, 2023a).

2.2. The textiles market in Europe

Consumption

Global consumption of clothing could rise from 62 million tonnes in 2019 to an estimated 102 million tonnes by 2030 (Wood, 2020). In 2019, the EU clothing and textile sector had a turnover of EUR 162 billion and employed 1.5 million people across 160,000 companies (EEA, 2022a). Also in 2019, it was found that the average European spent EUR 600 on clothing, EUR 150 on footwear, and EUR 70 on household textiles per year (EEA, 2022a).

In 2020, the average European consumed 14.8 kg of textiles (6.0 kg of clothing, 6.1 kg of household textiles, and 2.7 kg of shoes) per year (EEA, 2022a). Textile lifespan varies by application and treatment, influenced by changing consumer habits. For instance, carpets last around 14 years, but office buildings may replace them more frequently (Canadian Environmental Law Association, 2019). Fast fashion accelerates turnover; clothing is worn roughly seven times before disposal every six months (ProjectCECE, 2022). The surge in fast fashion has led to significant PFAS entering the waste stream, with over half of disposed textiles going to landfill or incineration (European Parliament, 2022).

Technical textiles, such as those used in industrial or construction applications can have longer lifespans than consumer textiles and therefore PFAS remain in the use phase for much longer. Furthermore, for some technical applications such as certain uses within the energy sector, viable alternatives have not been developed therefore PFAS are likely to continue to remain in use until they have been developed, further prolonging the period in which they would remain in use.

Technical textiles make up a significant proportion of EU textiles, accounting for 27% of total textile industry turnover in 2019 (Euratex, 2019). The European technical textiles market is projected to experience a Compound Annual Growth Rate (CAGR) of 4.54% between 2022 to 2027 (technavio, 2023). This growth is influenced by various factors, such as a rising demand for technical textiles from an increasing need for these textiles in the healthcare sector, and a growing market for lightweight and fuel-efficient transportation vehicles (technavio, 2023).

Production

In 2017, 7.4kg of textiles per person were produced within the EU making Europe highly reliant on imports to meet consumer demand (EEA, 2019b). The EEA published the updated production data for the year 2020 (following the UK's EU exit) when 6.9 million

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[5] PRODCOM is an EU system for collecting and classifying statistics on manufactured goods production.

tonnes of finished textile products, were produced within the EU (EEA, 2022a and ETC, 2022). EU production specialises in carpets, household textiles and other textile products including non-woven textiles, technical and industrial textiles and rope products (EEA, 2019b). Between 60% and 70% of textiles produced within the EU are made from plastics, predominantly polyester or polyester blends. Italy, Germany and France are the largest European producers of technical textiles (Euratex, 2019).

The production of textiles products within the EU requires roughly 175 million tonnes of raw materials, which is roughly 391 kg per person in the EU (EEA, 2022a). Most textile fibres used today are synthetic with around 60% of all products being made from a manmade material such as polyester (EEA, 2019b). Cotton fibre products make up most of the rest of the textile market.

Imports and Exports

The textiles industry is highly globalised, and Europe plays a significant role in both importing and exporting textiles. In 2020, the EU imported 8.7 million tonnes of finished textile products valued at EUR 125 billion (EEA, 2022a). Clothing makes up 45% of these imports by volume, followed by household textiles, other textiles, and footwear. Europe predominantly imports finished textile items, clothing, footwear and accessories for clothing (EEA, 2022a). A large proportion of textiles imported into the EU originate from countries in Asia. 29% (equivalent to approx. EUR 23 billion) is imported from China, 19% (equivalent to approx. EUR 15 billion) from Bangladesh, and roughly 11% from Türkiye (equivalent to approx. EUR 9 billion) (Eurostat, 2020). In 2020, 8.7 million tonnes of textile products, with a value of roughly EUR 125 billion was imported into the EU. The EU is a net importer of textiles products, with ~50% of reported imports from the consumer apparel and technical textiles markets (EEA, 2019b). China, the United States, Türkiye, India and Switzerland and the largest suppliers of technical textiles to the EU (Euratex, 2019).

The EU exports a large proportion of the produced textiles with 11kg per person being sent abroad. It should be noted that EU exports exceed production due to re-export, where imported textiles are manufactured into new products that are subsequently exported. EU exports of textiles primarily consist of intermediate products like non-woven materials, fibres, technical textiles, and premium fabrics (EEA, 2019b). Between 2000 and 2019 the volume of used textiles exported from the EU increased from just over 550,000 tonnes to over 1.7 million tonnes. This is roughly 25% of the annual 15kg of clothing, footwear and household textiles consumed annually per person (EEA, 2022a). Exports of finished textiles are mainly to the United Kingdom, Switzerland and the United States (European Apparel and Textile Confederation (Euratex), 2020). EU exports its used textiles to Africa and Asia, where some is resold, recycled or re-exported, but large shares end in landfills, dumps and rivers. The EU is the second largest exporter of textiles after China with roughly EUR 56 billion exported annually (Euratex, 2022).

End of life

At the end of a textile product's life, it enters waste streams, including municipal or industrial channels, where it may be recycled or undergo treatment via incineration or landfill. The EC estimates that only 1% of textiles are currently being recycled within the EU. That number is expected to increase due to new EU regulations such as the obligation for all EU Member States to separately collect textiles waste by 2025 under the circular economy package and the revised Waste Framework Directive (EP 2018a, 2018b, 2019).

Some companies already promote textile recycling, like Zara and TK Maxx, providing in-store services, and H&M offers vouchers for clothing donations (Zara, 2023; H&M, 2023). Despite recycling efforts, handling PFAS-containing textiles remains a significant challenge (European Parliament, 2022).

Technical textiles are used in a variety of applications including the medical, construction and energy sectors and, since these textiles are typically commercial or industrial products, the regulations around their waste collection and treatment differ from consumer textiles.

Recycling methods and impacts are elaborated in Chapter 4. If the textile goes to incineration, there's a risk of releasing fully or partially degraded PFAS (e.g. TFE and TFA) into the air in gaseous form or through fly ash. In addition, non-thermally degraded PFAS may stay in the bottom ash. Alternatively, if the textile goes to landfill, PFAS can slowly leach out over time during degradation, potentially contaminating water sources or soils as discussed in the following chapter (EEA, 2021).

2019 saw Asian countries receive 41% of European textiles waste, with African nations receiving roughly 46%. This equates to 582 million kg received by the Asian region and 398 million kg by African countries. Globally the EU exports 1,783 million kgs of waste textiles (EEA, 2022b). The fate of these used textiles is relatively unknown, however, in African nations there is high demand for cheap imports from Europe for local re-use. The impacts of PFAS in end of life textiles is explored in Chapter 4.

2.3. PFAS in textiles

Use within textiles

PFAS are used in a variety of textile applications as previously highlighted. The textile industry accounts for an estimated 35% of the global fluoropolymer demand (ECHA, 2023a). In 2020, over 10,000 tonnes/year of PFAS were used for textile applications, with 5-25% emissions emitted during the manufacturing and in use phases (ECHA, 2023). It is expected that that the use of PFAS in textiles will continue to increase, with several PFAS groups (i.e. non-polymeric C2-C3 substances, C6 substances and other non-polymeric substances) predicted to increase at a rate of 2% per year, while the use of non-polymeric PFAS of C_9-C_{14} expected to cease due to their proposed restriction under EU 2021/1297 (ECHA, 2023).

The main properties that PFAS provide in textiles are water repellence, oil repellence, stain-resistance and thermal stability. Over 75% of the PFAS used in textile products are polymeric PFAS. The use of PFAS in textiles is often intended to increase the durability and life expectancy of the final product. For example, 3M Scotchgard fabric protector, which contains polymeric PFAS, is used to improve the durability of the textile over its use period and increase the lifespan (Canadian Environmental Law Association, 2019). PFAS has been used to increase the durability and lifespan of construction products, home upholstery, clothing, and professional equipment (such as tents and uniforms), among others, by providing UV protection, stain, oil, and water repellence (Paramo Clothing, n.d.).

Table 2.1 provides an overview of the most common uses of different types of PFAS in textiles (Wood, 2020; Research Institutes of Sweden (RI.SE), 2022).

Legacy non-polymeric PFAS such as PFOA and PFOA-related species are no longer used in the EU and by most global fluoropolymer manufacturers, however, these substances are not restricted in parts of Asia and the Middle East and could continue to be present in imported textiles (Wood, 2020).

Table 2.1 Overview of types of PFAS and their uses in textiles (Wood, 2020; RI.SE, 2022).

Type of PFAS	Example of use
Non-polymeric PFAS	
Perfluoroalky acids (PFAAs)	Used in the production of polymeric PFAS (such as polytetrafluoroethylene)
Fluorotelomers	Used to make durable water repellents and as additives in other PFAS based coatings
Perfluoroalkane sulfonyl fluoride (PASF) substances	Used in durable water repellents as the side chains of polymeric PFAS and as processing aids
Polymeric PFAS	
Side-chain fluorinated polymers	Used often as textile durable water repellents
Fluoropolymers	Used commonly to make microporous membrane textiles
Perfluoropolyethers	Used in high-performance lubricants for textile machinery

As a result of policy interventions such as the regulation on POPs, there has been a notable shift towards reducing the usage of long-chain sidechain fluorinated polymers in textile finishes in recent years (EEA, 2021). Instead, short-chain sidechain fluorinated polymers have been substituted in their place for many applications. However, concerns over regrettable substitution have arisen due to the persistence, mobility and lack of available data on the health effects associated with these short chain PFAS. This observation provides the main motivation to include all PFAS having equivalent hazard and risk in a single restriction proposal, to avoid regrettable substitution by other PFAS. Currently available hazard data for PFAS is primarily focused on non-polymeric PFAS as discussed in Chapter 3 (ECHA, 2023a). Some PFAS included in the scope of the proposed restriction may have a negligible or indeed no current use. However, such PFAS would need to be included in the scope, either because their use may increase as a result of becoming an alternative for other, restricted PFAS, or due to new uses (ECHA, 2023a).

Despite the health and environmental risks of PFAS, these substances are still regularly used as non-fluorinated alternatives do not currently exhibit comparable performance levels in certain applications as discussed further in Chapter 4 (ECHA, 2023a). In situations where certain PFAS applications are crucial for health and safety and/or societal functioning and no alternative solutions are available, these applications may be exempted under specified derogations. (Cousins et al., 2020). This is discussed further in Chapter 4.

Use within manufacturing

PFAS (both non-polymeric and polymeric), can be used in the manufacturing process of textile products and/or can be present in the final textile product (Glüge et al., 2020). Non-polymeric PFAS can be used in the manufacturing process to help colours adhere to fabrics through wetting of the product, to prevent the foaming of solutions, and to help dyes spread evenly throughout a product. PFAS can also be used to improve the dispersion and solubility of other polymers during textile production (Glüge et al., 2020).

Furthermore, non-polymeric PFAS are also used during the manufacturing of polymeric PFAS. For example, polytetrafluoroethylene (PTFE) requires non-polymeric PFAS to enable even dispersion (Glüge et al., 2020; OECD, 2022). While non-polymeric PFAS are usually only required during the manufacturing stage, they are often left on the finished article as impurities and can be released from the product during its lifespan. Similar issues arise during the manufacture of smaller PFAS molecules, resulting in mixtures of different PFAS present in finished articles (Wood, 2020; OECD, 2022).

Several PFAS are commonly used for certain textile applications; These PFAS groups are shown in Table 2.2. Fluoropolymers and SCFPs are the most used forms of PFAS within textile applications (Wood, 2020). However, PASF-based substances are an example of a non-polymeric PFAS that has been detected in textiles as an unintended contaminant from production, rather than intentional usage for its desired properties in the final use (Wood, 2020).

Table 2.2 PFAS used for textiles.

Group	Name	CAS No.	Application
Fluoropolymer	Poly(hexadecyl methacrylate/2-hydroxyethyl methacrylate/octadecyl methacrylate)/ gamma-omega-perfluoro-C10-C16-alkyl acrylate	203743-03-7	Spot and dirt repellent
	Fluorochemical urethane polymers	N/A	Protective treatment for textiles
	Fluorinated acrylate polymers	N/A	Water and oil repellent and stain release for textiles
Non-polymeric PFAAs	Perfluorohexanoic acid (PFHxA)	307-24-4	Carpets, impregnating sprays, rainwear, outdoor materials, furniture, clothing, carpets, mats, and cotton and leather cloths
	Perfluoroheptanoic acid (PFHpA)	375-85-9	
	Perfluorooctanoic acid (PFOA)	335-67-1	
	Perfluoronananoic acid (PFNA)	375-95-1	
	Perfluorodecanoic acid (PFDA)	335-76-2	

Consumer and professional clothing

The category of consumer and professional clothing includes durable water repellent jackets and coats, shoes and boots, gloves, snowsuits, etc. PFAS are used in consumer and professional clothing to improve the oil, water, and stain resistance of the textile (Cousins et al., 2020). The most commonly used PFAS in this category are SCFPs such as polytetrafluoroethylene and polyvinylidene fluoride. Polytetrafluoroethylene is used in the form of a microporous membrane that keeps rainwater out, but allows body moisture to pass through, keeping the wearer dry. The most famous polytetrafluoroethylene membrane is Gore-Tex™, which is an internal membrane that makes up a larger Gore-Tex™ fabric (Wood, 2020; EEA, 2021). Other fluoropolymers include fluorochemical urethanes and acrylates. Perfluoroalkyl carboxylic acids (a non-polymeric PFAS), both short and long chain, are also used in consumer and professional clothing. For example, the short chain perfluoroalkyl carboxylic acid, perfluoropentanoic acid (PFPeA), has been used in children's fabrics, jackets, and hats and several other non-polymeric PFAS have also been intentionally used in shoe care products (Wood, 2020). However, polymeric PFAS, and especially those with fluorinated side chains will degrade over time to smaller, more mobile polymeric PFAS, and eventually to highly mobile non-polymer PFAS, which increases the potential for negative environmental and human health impacts (Wood, 2020).

Home textiles

PFAS are found in several home textiles, including tablecloths, placemats, tents and garden furniture. The compounds used are primarily fluoroalkyl acrylates and (meth)acrylates (EEA, 2021). Urethane side chain fluorinated polymers (polymeric-PFAS), such as 3M Scotchgard™ Fabric Protector, are used in home textile applications to enhance the water, oil, and stain resistance of the textile (OECD, 2022). Other mixtures of acrylate and urethane polymeric PFAS, such as Teflon Advance Carpet Protector, are used to treat home textiles, and are often combined with various nonfluorinated compounds to enhance durability or modify the texture of the treated fabric (OECD, 2022). Several PFCAs are also used in home textiles such as outdoor furniture and office upholstery (Wood, 2020). Non-polymeric PFAS, such as perfluoropentanesulfonic acids (PFPeS) and perfluorononanesulfonic acids (PFNS), have been found in the workshops of a textile company that produces outdoor materials (Wood, 2020). Longer chain non-polymeric PFAS have historically been found in upholstery, however it is not clear if the substances are used intentionally or if it is a by-product of a different PFAS breaking down over time (Wood, 2020).

Table 2.3 PFAS used for home textiles.

Group	Substance	CAS No.	Application
Fluoropolymer	Hexane, 1,6-diisocyanato-, homopolymer, .gamma.-omega.-perfluoro-C6-20-alc.-blocked Fluorochemical urethane polymers Fluorinated acrylate polymers	135228-60-3 N/A N/A	Carpet and upholstery shampoo Rugs and carpets Carpet protector
Non-polymeric PFAAs	PFPeA Perfluorobutanoic acid (PFBA)	2706-90-3 375-22-44	Pillowcases, office upholstery Carpets and mats

Leather and spray for protection

Like consumer and professional clothing and home textiles, PFAS are used for leathers to provide water repellent and stain resistant properties. PFAS are used in the manufacturing process of both natural and synthetic leathers; For natural leather, PFAS improves the efficiency of hydrating, pickling, degreasing and tanning, while in synthetic leathers the PFAS is used to impart oil and water repellence to the final textile (Cousins et al., 2020). PFAS are also used as impregnation sprays for water and oil repellence and protection applications (Cousins et al., 2020). A number of PFCAs have been used in spray protectants, as the small molecules are able to well disperse in a sprayable medium. Impregnation agents use formulations containing non-polymeric PFAS which can degrade into smaller non-polymeric PFAS (Wood, 2020). Fluoroalkyl silane compounds have been reported in some sprays which exist in non-polymeric form in the spray can but polymerises upon being sprayed on to the textile (ECHA, 2017).

Table 2.4 PFAS used for leather and spray protection.

Group	Substance	CAS No.	Application
Fluoropolymer	α-fluoro-ω-[2-[(1-oxooctadecly)oxy]ethyl]-poly(difluoromethylene)	65530-65-6	Leathers
Non-polymeric PFAA	Perfluorotridecanoic acid (PFTrA)	N/A	Leather (nanosprays and impregnation sprays)
	Fluoroalkyl silane compounds	N/A	Sprays (polymerizes upon application)

Technical textiles

PFAS are also used in a variety of technical applications including in outdoor technical textiles, medical applications and high performance membranes (Wood, 2020). For example, PFAS have been used in low carbon energy production (e.g. for membranes for hydrogen production) and in the field of environmental protection for exhaust air filters, technologies which are deemed necessary for the transition to a net zero carbon emission and circular economy (Glüge et al., 2021). Medical utensils, where polymer-based textiles have been used in wound care products such as in surgical drapes and gowns to improve the blood, water, oil, and dirt resistance (EEA, 2021; Cousins et al., 2020). Similarly, several professional uniforms are treated with PFAS to improve blood, water, oil, and dirt resistance (Wood, 2020). Some dental floss also contains PFAS, as the PFAS improves the ability of the fibres to slip easily between close teeth (Cousins et al., 2020). PFAS are also used in the automotive industry for textiles, including as a brake pad additive or in the interior as a water and stain repellent, and in other mechanical textiles such those used in engines (Cousins et al., 2020; Wood, 2020). Other technical textiles that contain PFAS include parachutes, sails, tents and sacks/bags where PFAS is used improve the water repellence (Wood, 2020). The selection of PFAS for technical application varies depending on the specific application. Many of the technical applications have long lifespans and there are currently no suitable alternatives for some of them, therefore they are likely to be present in the production chain a longer period compared to clothing and household textiles (Wood, 2020).

2.4. Knowledge gaps and uncertainties

There is uncertainty regarding whether the presence of non-polymeric PFAS in textiles is the result of intentional use or not, as the concentrations non-polymeric PFAS is found in can vary drastically between different manufacturing formulations, even if used for the same application. For some textiles, it is clear that PFAS is incorporated into the textile as an internal membrane (such as GoreTex™), however in others it is not clear if it is incorporated into the textile during production in some manner, or if it is applied after production. Polytetrafluoroethylene appears to be the most widely used PFAS within the textile industry, finding application from consumer goods to specialised applications. However, further than this, it is often unclear whether other PFAS types found are due to their use in manufacturing process, their intentional addition to a textile product, or as the result of degradation of other PFAS.

There is also limited information regarding the concentration of PFAS used in textiles. This may be due to the inherent impurities as a result of the production process, or it may be due to the low concentration of PFAS typically incorporated into textiles. Many of the applications of PFAS in textiles are in patent-protected formulations, such as GoreTex™ and Scotchgard™, so the true concentration may not be reported.

In accordance with REACH and CLP Regulations, information on the presence and concentration of PFAS within a mixture would only need to be included in safety data sheets if they are known to display hazardous properties, i.e. listed as SVHCs under REACH or that is classified as hazardous according to CLP classifications[6]. However, only a relatively small proportion of the 10,000 PFAS covered have been fully assessed for these hazardous properties. Furthermore, safety data sheets only apply for chemical mixtures (e.g. Scotchgard™ treatment formulations) and not for the treated textile (e.g. GoreTex™ fabric).

There are data gaps on the overall volumes of use for a number of applications. (Wood, 2020). There is no reported data in PRODCOM[5] for professional sports wear, medical applications, high performance membranes, home textile treatments for fabrics and leathers, and many types of footwear (Wood, 2020).

While the addition of PFAS can improve the longevity and durability of a textile, there is no information regarding the life expectancy of the application of PFAS. It is known that over time, PFAS used for waterproofing will degrade and lose its water repellent properties, but this depends on several factors. Sunlight, body oils and fluids, contact with other chemicals and substances, and improper use or storage can alter the life expectancy of PFAS within a textile. In addition, users may report a decline in expected properties before the end of the expected product life, which can skew laboratory testing results.

Beyond textile production, there is limited information regarding end of life specific to textiles with PFAS within the reviewed literature. Currently, used textiles are primarily exported or sent to landfill or incineration, however, textiles are defined as articles and hence the presence of classified substances will not have an impact on the end of life handling requirements.

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[6] E.g., carcinogenic category 2 or toxic to reproduction category 1A, 1B and 2, skin sensitiser category 1, respiratory sensitiser category 1, or has effects on or via lactation or is persistent, bioaccumulative and toxic (PBT) in accordance with the criteria set out in REACH Annex XIII or very persistent and very bioaccumulative (vPvB) in accordance with the criteria set out in REACH Annex XIII

For the PFAS identified as SVHC's (a very limited fraction of the PFAS group) it should in theory be possible to request information through the Substances of Concern In articles or complex objects (Products) (SCIP) database, but in practice, there is very little functional traceability for PFAS content in textiles that are being recycled or are entering the waste stage. As most types of PFAS are not classified, it is difficult to regulate the end of life treatment required for textiles with regards to PFAS.

Conclusion

The EU's textile landscape is marked by increasing consumption, import reliance, and growing used textile exports. In 2020, the average EU citizen consumed 6.0 kg of clothing, 6.1 kg of household textiles, and 2.7 kg of shoes. Despite this, the EU's own textile production was limited, at just 7.4 kg per person in 2017, indicating a reliance on imports , primarily from China, Bangladesh, and Türkiye. These imports are primarily finished textiles, clothing, footwear, and clothing accessories. Conversely, exports consist primarily of intermediate products, non-woven materials, fibres, technical textiles, premium fabrics. Used textile exports have surged from 550,000 to 1.7 million tonnes between 2000 and 2019. Most of these textiles are sent to Asia or Africa after use, where it is largely unknown to which extent it is re-exported, re-sold, recycled, landfilled or burned. The EU's textile recycling rate remains low at just 1%. Despite this, new EU regulations may spur higher rates, aligning with circular economy goals.

Polymeric PFAS has been used in a number of textile applications, primarily to increase the oil, water, and dirt repellence of the textile. Gore-Tex, which contains the fluoropolymer PTFE, is used in consumer and professional apparel as well as outdoor equipment, while Scotchgard™, a SCFP urethane, is used to treat home textiles. Technical textiles, from medical to mechanical applications use PFAS to improve the water, oil, and dirt resistance, as well as improve the mechanical properties of the overall textile.

The use of non-polymeric PFAS in textile applications is less well understood, as it is uncertain whether the presence of this type of PFAS in textiles is incidental due to residual contaminants from processing of polymeric PFAS or whether it is intentional. While the applications of PFAS in textiles has been well documented, the volumes of use for all applications, such as medical and footwear, has not. Similarly, the concentrations of PFAS used in these applications is not reported, which could be due to formulation protections by manufacturers and there is limited end of life information for textiles treated with PFAS.

3. Environmental and human health impacts of PFAS in textiles

This section is split into the following subsections: Section 3.1 (Environmental impacts) concentrates on the broader environmental impacts of the types of PFAS used in textiles as described in section 1.5. Section 3.2 (Release to the environment), focuses on the release of PFAS from textiles into the environment, explaining the pathways influencing the release of PFAS from textile products. Section 3.3 (Human health impacts) provides an overview of the known human health impacts of PFAS exposure and the potential combined effects. Section 3.4 (Exposure to humans), provides specific information on the human exposure of PFAS from textiles. Finally, Section 3.5 (Knowledge gaps and uncertainties) addresses the limitations and uncertainties in current assessments, highlighting the gaps in knowledge concerning PFAS in textiles. Note that this section is a rather brief overview of the environmental and human health impacts of PFAS in textiles and does not constitute a detailed or comprehensive assessment.

3.1. Environmental impacts

Degradation and persistence

According to the REACH Restriction Proposal, all PFAS are considered to be very persistent in the environment. This is because either they naturally persist for a long time or the products they break down into also last a long time (ECHA, 2023a).

PFAS can be defined as either "precursors" or "arrowheads". When PFAS precursors break down, they can form smaller PFAS pieces, called arrowheads, which are very stable and hard to break down and therefore persist in the environment for a long time (OECD, 2022). Both polymeric PFAS and non-polymeric PFAS precursors can degrade into arrowheads.

Many factors, such as their size, shape, the degree of fluorination and the conditions of the environment (e.g., temperature and pH) affect how fast PFAS break down (OECD, 2022). It is important to note that not all PFAS become arrowheads right away, but they can change into them over time, sometimes via intermediate stages. This makes it difficult to accurately understand and predict impacts of PFAS because they can have long-lasting effects which can change during their time in the environment (KEMI, 2022).

PFAS have different distribution properties to one another which mean that some are found in certain environments more than others. PFAS degradation products are often smaller and therefore more mobile than their PFAS precursors, as discussed later in this section (ECHA, 2023a). These exhibit efficient distribution through various environmental compartments (such as aquatic and atmospheric media), and are able to reach groundwater aquifers, serving as crucial drinking water sources, due to their high mobility in aqueous media (ECHA, 2023b).

Even if PFAS emissions were to halt immediately through regulatory action, the existing precursor stocks in the environment act as an enduring source of these transformed substances. Therefore, the longer these stocks accumulate, the less effective emission reduction efforts will be in diminishing their presence (ECHA, 2023a). According to Goldenman et al. (2019), the contamination might exhibit poor reversibility or even irreversibility which could lead to levels of contamination that may render natural resources, such as soil and water, unusable for an extended period into the future.

Whilst the degradation products/effects of certain PFAS in the environment are well known (particularly well-studied, legacy, non-polymeric PFAS such as PFOA and PFOS), relatively little is known about the effects of others, particularly polymeric PFAS which are widely used in textiles. Whilst polymeric PFAS are extremely stable (and therefore persistent) under ambient conditions, the long-term effects in the environment (i.e. potential degradation products) are not known (Lohmann et al., 2020).

Bioaccumulation

PFAS exhibit varying degrees of bioaccumulation in living organisms due to their bio-persistency (as described previously) and their tendency to accumulate in protein rich tissue. PFAS can be easily absorbed and distributed within tissues such as the liver, serum, and kidney (ECHA, 2023b). As a result, PFAS can accumulate in these tissues and build up over time (KEMI, 2022).

Short-chain PFAS tend to be less bioaccumulative than long-chain PFAS. However, studies suggest that short-chain PFCA are more efficiently taken up by plants compared to long-chain PFCA (ECHA, 2023a). There is limited evidence of how polymeric PFAS accumulates in organisms. However, there is an upper limit as to what can be taken up by organisms due to molecular size. Therefore, most of the polymeric PFAS compounds are not expected to bioaccumulate, as they are too large. However, they may be degraded to smaller substances with bioaccumulation potential.

Furthermore, PFAS concentrations in organisms can increase further up the food chain in animal species (biomagnification)[7]) (ECHA, 2023a). However, this is limited to studies for a small number of non-polymeric PFAS. Various PFAS substances accumulate differently in individual organisms, and their accumulation can also vary within the same organism. For example, short-chain PFAS tend to accumulate in above-ground plant parts, while long-chain PFAS accumulate in roots. This disparity is a result of the higher water solubility and lower molecular size of short-chain PFAS (ECHA, 2023a).

The European Human Biomonitoring Initiative (HBM4EU), amongst other studies, provides direct evidence that that a number of PFAS compounds can accumulate in humans. A study of PFAA in pregnant women revealed a positive correlation between the time elapsed since the most recent pregnancy and blood concentrations of certain PFAS, suggesting that bioaccumulation has occurred during the time between pregnancies (ECHA, 2023b). This is discussed further in section 3.3

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[7] Biomagnification is the progressive buildup of substances in living organisms as they consume contaminated prey or food sources.

Further research is needed to understand the complex relationship between chemical structure, accumulation patterns, and exposure routes of PFAS in the environment (ECHA, 2023a).

Mobility and long-range transport

Short-range mobility

The ability of PFAS to move in- and between environmental compartments[8] such as water, air and soil, contributes to their potential long-range transport, contamination of drinking water, and uptake in plants (ECHA, 2023a). Some non-polymeric PFAS have high mobility in soil which means they can enter the water course, potentially polluting ecosystems and drinking water. PFAS tend to be more mobile in soil and water when their carbon chain length is below eight. However, as the carbon chain length increases, their solubility tends to decrease. In general, short-chain PFAS, along with many long-chain PFAS, can be characterised as mobile in water (ECHA, 2023a).

Long-range transport

Certain non-polymeric PFAS can exhibit long-range transport potential in the air, which can result in (sometimes global) dispersal over long distances from their release points. As a result, PFAS discharges from specific regions have been reported to impact ecosystems further afield, including remote areas such as the Antarctic (ECHA, 2023a). It is worth noting that the residence time of PFAS in different compartments varies, and the transport to remote areas may experience time delays depending on the compartment's moving capacity (ECHA, 2023a).

Ecotoxicity

The available literature suggests that environmental exposure to a subset of PFASs is correlated to adverse effects in various environmentally relevant species e.g. invertebrates, fish, amphibians, birds, reptiles, mammals, plants or wildlife (Ankley et al., 2021; ECHA, 2023a).

As discussed in ECHA (2023a), the observed adverse effects occur on the molecular level (e.g. genotoxic effects), the organ-level (e.g. steatosis (fatty liver)) as well as organism level (e.g. mortality or reproduction) the latter of which may also have relevance at the population level. The studies evaluated for the ECHA (2023a) report suggest various endpoints associated with PFAS exposure in field studies, including changes in brain chemistry (e.g. brain hormone levels), oxidative stress (e.g. induction of antioxidant enzymes), reproduction (e.g. eggshell thinning), changes in metabolism, reduced biomass, endocrine activity (e.g. changes in hormone levels), or changes in immunologic parameters (e.g. a decreased antibody response).

Furthermore, it is known that certain PFAS can significantly disrupt some biological processes at the biochemical and molecular levels. PFAS exposure triggers an excessive generation of reactive oxygen species, leading to detrimental effects on plant cell structure and organelle functions. This exposure also disrupts various biochemical activities within

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[8] “Compartment" refers to a specific environmental or biological medium or location where PFAS can be found or can exist (e.g. surface water, groundwater, soil, sediment, biota, air etc.)

plant cells, including photosynthesis, gene expression, protein synthesis, and carbon and nitrogen metabolism (ECHA, 2023b).

The evidence, both under laboratory conditions and in the natural environment, suggests that certain PFAS compounds can interfere with the hormonal systems of animals and plants in the environment. This interference can cause harmful effects such as reduced fertility, changes in the balance of male and female offspring, and developmental problems in environmental species, among other effects. These impacts can therefore affect future generations of these species (ECHA, 2023a).

However, it should also be noted that, the available data on ecotoxicological effects of PFASs in the environment, while growing, is currently limited to a relatively small number of studies investigating a small subset of substances. For example, the ecotoxic effects of other PFAS which would be covered under the universal PFAS restriction, particularly polymeric PFAS, are not well known. Due to the limitations of the studies, a clear link between PFASs measurements in the environment, or PFAS-body-burdens in the animals and the observed effects can rarely be established (ECHA, 2023a). Moreover, it is noted that most studies investigate the aquatic toxicity of PFAS, leaving a considerable gap of knowledge regarding the toxicity towards terrestrial organisms (ECHA, 2023a).

It is also important to note that the large number of different PFAS with heterogenous properties (e.g. due to different functional groups) makes the assessment of their ecotoxicity very complex, and only certain PFAS (i.e. PFOS) has been systematically monitored in the European environment under the Water Framework Directive. However, new environmental quality standards are under development for a number of PFAS compounds under the Environmental Quality Standards Directive (EQSD) (JRC, 2021). If added to the Water Framework Directive this will introduce monitoring requirements in the European environment (SCHEER, 2022).

3.2. Release to the environment

During all life stages of textiles, including production, use and disposal, PFAS can be released through various processes. This can be through evaporation of volatile PFAS residues from production, shedding of particles and fibres through abrasion, release to water through washing of textiles, breakdown of SCFPs present in the fabric during use, through leaching from landfill residues as well as gaseous emission from combustion. Water-soluble residuals, like PFCAs, can also be washed out. These released PFAS may end up in surface water, sediments, drinking water, soil, food, dust and air, creating potential exposure sources for humans and other organisms (ECHA, 2023a).

After being released into the environment, the substances will undergo different partitioning, transport, and degradation processes. The outcome of these processes heavily relies on the specific properties of the substances, making it challenging to accurately predict the quantity of the substance that may be present in each environmental compartment (Wood, 2020). ECHA (2023a) estimated the emissions during the use phase (and the production phase), using either default information from the REACH methodology or more specific data, if available. The total annual PFAS emissions during manufacturing and use were estimated to be between 10,000 and 35,000 tonnes.

Production and manufacturing

Fluorochemical production

A major point source of PFAS emissions into the environment within the textiles value chain (encompassing both water and air) are fluorochemical production plants (FPPs) which are used to make the fluoropolymers (such as PFTE and PVDF) and other PFAS that are then later used in textiles manufacturing. According to the Annex XV restriction dossier, this is the fourth largest total source of PFAS emissions, however, not all of this can be attributed to textiles ECHA (2023a). PFAS processing aids have a high emissions potential as these are often fine powders or fluids that require special care during use and disposal (EEA, 2021).

Textiles manufacturing

The Annex XV restriction dossier identified three sets of activities during the textile production stage whereby PFAS can be released, including, manufacture of non-woven membranes, manufacture of mixtures (formulations) for textile treatment, and textile treating (ECHA, 2023a).

The release of PFAS into water and air during the textile manufacturing process is influenced by the daily production volume and the release factor to air and water. Wood (2020) estimated that 5% are released to air and 6% released to water during manufacturing.

A 1999 study by 3M found that there was an estimated 10-25% PFAS loss during surface treatments of textiles (3M, 1999). In studies performed on various Scotchgard™ formulations in lake sediment, soil samples, and wastewater treatment plant sludge, SCFPs were found in most samples, suggesting that SCFPs may be a long-term source of perfluoroalkyl acids in the environment (OECD, 2022). There is also evidence of substantial release of SCFP-containing fibres during washing and rinsing of SCFP treated textiles (OECD, 2022).

Polymeric PFAS formulations often contain shorter chain, non-polymeric PFAS to aid in the dispersion of the formulation. These non-polymeric PFAS do not bind to the textile in the same way as polymeric PFAS, leading to the increased possibility for environmental release either upon application or during the wetting of the article (OECD, 2022).

Use

Textiles treated with durable water repellent pose a potential source of PFAS release into the environment through multiple pathways. Firstly, high levels of volatile fluorotelomer alcohols (FTOHs) have been detected in outdoor clothing, indicating the possibility of PFAS emission into the air through abrasion during use.

Secondly, textiles are often subjected to vigorous, more regular, washing than other PFAS-containing products (OECD, 2022). During the use phase, the washing of PFAS-treated textiles can release fibres coated with fluorotelomer-based polymers and can subsequently enter the water-system and be washed away. The Annex XV restriction dossier identified the following three release groups that group the risk of PFAS losses through washing (ECHA, 2023):

- Release Group 1 (Indoors): This group includes items like clothing, high-visibility jackets, and medical textiles that are frequently cleaned or washed. They have a higher potential for releasing substances.
- Release Group 2 (Indoors): This category comprises items such as carpets, rugs, and curtains that are cleaned or washed less often compared to Group 1 items. They have a lower potential for releasing substances.
- Release Group 3 (Outdoors): This group includes treated textile or leather articles used outdoors, excluding those in Groups 1 and 2. Items like footwear, outdoor clothing, and technical textiles fall into this category. They may have a moderate potential for releasing substances when used in outdoor settings.

Finally, exposure to ultraviolet radiation, high temperatures, and humidity can lead to the degradation of durable water repellent polymers like FTOH, resulting in increased concentrations of PFAAs in textiles and its release (EEA, 2021).

End of life

The uncertainties surrounding PFAS emissions at the end of their useful life are multifaceted. Key challenges include the lack of clear connections between the usage of PFAS-containing products and their after use and subsequent categorisation as waste, as well as ambiguity regarding the methods employed during waste treatment processes.

Accurately identifying and assessing the sources of PFAS emissions is further complicated by incomplete knowledge of the pathways these substances follow and the limitations in measuring PFAS comprehensively (ECHA, 2023b). Furthermore, as discussed previously, the EU is a large exporter of used textiles (EEA, 2022a). As a result, many of the treatment methods and waste flows differ from those in the EU.

Even within the EU, there are discrepancies in how waste is treated between Member States and therefore how PFAS are emitted to the environment. Currently, it is estimated that the majority of used clothing and household textiles are still disposed of in mixed municipal waste streams, with, on average, 38% of used textiles collected separately in the EU (EEA, 2023b). The collection rate of used textiles in the EU varies significantly between Member States (from 4.5% in Latvia to 45% in the Netherlands (EEA, 2022a).

Incineration

Incineration is a common method of waste treatment for textiles in the EU (EEA, 2022a). However, the temperatures employed at municipal waste incinerators in the EU are typically around 850°C which is insufficient to completely destroy PFAS (Defra, 2013).

Incineration at a high temperature can be effective in breaking down and destroying PFAS compounds. However, to effectively degrade PFAS, incineration typically requires temperatures of at least 1,100°C. Longer-chain PFAS can be broken down at this temperature while some shorter-chain PFAS need even higher temperatures, around 1,450°C (Wood, 2020)[9]. Such high temperature incineration is typically reserved for controlled destruction of hazardous waste and thus there is often limited capacity to accept additional high-volume municipal waste streams such as textiles.

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[9] During incineration at these temperatures, PFAS is generally converted into carbon dioxide and hydrogen fluoride

Inadequate incineration, such as via lower temperature municipal incineration or burning in uncontrolled settings, can potentially lead to the release of PFAS and other hazardous substances (OECD, 2022). Furthermore, partial degradation can lead to the release of shorter chain PFAS. The incineration products of PFAS incineration at temperatures lower than 1,100°C remain uncertain and need further investigation (Wood, 2020).

Uncontrolled or open burning of textiles containing PFAS is likely to release PFAS compounds into the air, increasing the risk of long-range transportation of these harmful materials. While this practice is uncommon in the EU, it is prevalent in some of the countries to which used textiles are exported.

Landfilling

In landfills, products with fluorinated polymers, like textiles and furniture, can degrade into smaller, non-polymeric PFAS. PFAS can be released into landfill leachate years later (EEA, 2021). Studies in different European countries found varying levels of (selected) PFAS release into leachate, with Germany reporting 90 kg annually, Sweden 70 kg annually, and northern Spain approximately 1.2 kg per year in 2010 (Wood 2020).

These studies conclude that landfill leachate is not a major PFAS source compared to water and soil. Estimating Europe-wide yearly PFAS discharge, assuming the above figures and population data, yields between 430 kg to 3.7 tonnes which is likely to represent a small portion of the estimated total PFAS release of 10,000 to 35,000 tonnes (EEA, 2021). It is important to note that the EU collects and treats landfill leachate, but open and uncontrolled landfills are more common in countries to which after use textiles are often exported, presenting a greater risk in those regions.

Wastewater treatment

PFAS can enter the wastewater treatment facilities through washing of textiles. Wastewater treatment plants also receive leachate from landfills, which can increase the concentration of PFAS in the treated water by up to three times (ECHA, 2023b).

The unique properties of PFAS present significant challenges to wastewater treatment processes, which were not designed to handle such complex chemical families. As a result, it is generally assumed that wastewater treatment plants are not effective in managing PFAS. Instead, they act to partition PFAS between treated effluent and sewage sludge (Wood, 2020). It was found that these textile fibres are released into the environment, with over 95% ending up in sewage sludge and less than 5% in the discharged wastewater (Wood, 2020).

Within wastewater treatment plants, various types of fluoropolymers in nano- and microplastic form, as well as fluorinated sidechain polymers dispersed in water or adhering to particulate matter like dust, textile fibres, and paper fibres, can end up in sludge. Long-chain PFAS with limited or no solubility in water will also accumulate in the sludge (EEA, 2021).

The wastewater treatment plant's effluent is discharged directly into European surface waters, releasing PFAS into freshwater or marine environments. About two-thirds of the PFAS in sewage sludge are believed to remain undestroyed, as they're used on land for fertiliser, composted, or landfilled (ECHA, 2023b). As a result of this, some PFAS have found their way into food sources for wildlife, livestock and humans due to their extreme persistence, high mobility and bioaccumulation potential (ECHA, 2023b).

3.3. Human health impacts

Effects of non-polymeric PFAS

Non-polymeric PFAS are required to be registered under REACH and there are standard information requirements (depending on the annual tonnage) that need to be submitted to demonstrate safe use. However, there are no registration obligations for, polymeric substances, and toxicity information for these is limited. Indeed, most of the research concerning human health effects predominantly pertains to the toxicity of certain PFAS, notably PFOA and PFOS.

As of March 2023, 357 PFAS compounds were notified in the Classification and Labelling Inventory on the ECHA webpage with classifications for at least one of five endpoints[10]. Of these, 41 are harmonised classifications (ECHA, 2023a). This represents a relatively small proportion of the (more than) 10,000 total identified PFAS.

Human health effects stemming from extended exposure to certain PFAS include carcinogenicity, mutagenicity, reproductive toxicity, immunotoxicity and specific target organ toxicity (ECHA, 2023b). They can also harm organs, particularly the liver, by causing unhealthy fatty liver or “steatosis”. On a broader scale, some PFAS can reduce the effectiveness of vaccines, making them less capable of preventing diseases, and they increase the risk of infections in the lower respiratory tract, such as pneumonia. Furthermore, some PFAS can affect fertility and can elevate the risk of certain cancers, including thyroid issues and kidney cancers (ECHA, 2023a).

The European Food Safety Authority (EFSA) derived a Tolerable Daily Intake (TDI) using human epidemiological data rather than the usual process that relies on data from animal testing. However, this data is available for only four PFAS compounds (of which two are legacy compounds). Additionally, it is difficult to obtain immunotoxicological information from animal methods since the existing validated testing methods are not necessarily providing reliable data for PFAS. As a result, there is very limited knowledge about the potential harmful effects on the immune system for the numerous other PFAS compounds that exist (EFSA 2020).

Effects of polymeric PFAS

Conversely to non-polymeric PFAS, under REACH, polymeric substances are not required to be registered and have limited toxicity information. The properties of polymeric PFAS can vary significantly, which complicates linking them to specific health effects (ECHA, 2023a). Until recently, regulatory agencies have primarily concentrated on regulating and monitoring non-polymeric PFAS because they can readily be taken up by living organisms whereas substances with large molecular sizes (such as many polymers) are normally believed not to be bioavailable (taken up by organisms). This regulatory focus has led to more extensive research on non-polymeric PFAS. As a result, there is less historical data and scientific literature available for the effects of polymeric PFAS degradation products.

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[10] Carcinogenicity, mutagenicity, reproductive toxicity, immunotoxicity and/or specific target organ toxicity

Studies have indicated that some linear polymeric PFAS can be absorbed by the body into the bloodstream, though there is limited evidence to suggest negative human health impacts from this exposure (ECHA, 2023a). Nevertheless, long-term occupational exposure to PTFE spraying, lasting up to 28 years, has been linked to the development of granulomatous lung lesions, researchers believe these lesions result from the inhalation of PTFE particles rather than the degradation products caused by high temperatures (ECHA, 2023b).

It is also reported that inhalation of aerosolised waterproofing agents, sealants, and ski waxes containing polymeric PFAS, as well as inhaling the fumes produced by heating fluoropolymers (for instance, in an occupational setting involving heated PTFE in a plastic factory or from smoking cigarettes contaminated with ski wax), can lead to severe respiratory problems in humans (ECHA, 2023b).

Most polymeric PFAS are highly stable under ambient conditions, however, they can release harmful decomposition products when subjected to temperatures beyond their thermal stability threshold such as when they are incinerated in municipal incinerators which operate below the high temperatures required to mineralise (completely destroy) PFAS. However, specific toxicity data on these degradation products is limited (ECHA, 2023a). As discussed in the previous section certain, non-polymeric PFAS degradation products can cause health issues in humans (ECHA, 2023a).

Occupational exposure to degradation products of polymeric polytetrafluoroethylene (PTFE) can lead to severe toxic lung effects in humans. One of these degradation products is tetrafluoroethylene (TFE), which has been classified as specific target organ toxicity (STOT) RE 2 (toxicity to the kidneys) and has received a standardised classification as Carcinogen 1B (likely to be carcinogenic to humans) (ECHA, 2023b).

As discussed in section 3.1, the mechanisms of how polymeric PFAS degrade into non-polymeric forms in the environment are also uncertain. This uncertainty raises concerns about the potential uptake by humans and subsequently how this impacts human health.

Combined effects of co-occurring PFAS on human health

Multiple PFAS are found together in various environmental matrices (e.g. air, soil, sediment, water), drinking water, food, and human blood, leading to combined exposure to multiple types of PFAS. Many of these substances exhibit similar effects on organs such as the liver, kidney, thyroid, serum lipids, and immune system. The cumulative effects of PFAS are therefore concerning, but the lack of toxicity data for most PFAS makes precise modeling of their combined effects challenging (ECHA, 2023a).

As part of the European Human Biomonitoring Initiative (HBM4EU)[11], a study assessed PFAS levels in the blood serum or plasma of 1,957 adolescents across nine European countries. The findings indicated that a total of 14.3% of the teenagers surpassed the recommended threshold of 6.9 µg/L for the combined presence of PFOA, PFOS, PFNA, and perfluorohexanesulphonic acid (PFHxS). This threshold is based on the acceptable weekly intake set by EFSA (ECHA, 2023b). However, as discussed previously, there is very limited knowledge about the potential harmful effects on the immune system for the numerous other PFAS compounds that exist beyond these four PFAS (EFSA 2020).

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[11] https://www.hbm4eu.eu/

The prevalence of non-restricted PFSA and PFCA varies by research study which is likely due to diverse exposure patterns within distinct European subpopulations. However, comparing these studies is complicated by varying reporting limits, impacting the frequency of compound detection. In contrast to well-known PFOS, PFOA, PFHxS, and PFNA, non-restricted PFAA levels are generally lower in the European population (ECHA, 2023b).

As a result of the difficulty in measuring the combined effects, “concentration addition” has been suggested to estimate the combined or cumulative effect of multiple chemicals that may be present in a mixture. It assumes that each chemical in the mixture acts independently to produce its toxic effect, and their effects can be added together based on their concentrations, providing a worst-case estimation of combined toxicities. Due to the vast number of PFAS and the limited toxicological data, a comprehensive combined assessment for all PFAS is currently unfeasible (ECHA, 2023a). Therefore, it is crucial to consider the potential additive effects of different PFAS on the same target organs, which may increase the likelihood of exceeding effect thresholds or limit values compared to assessing individual substances in isolation (ECHA, 2023a). New environmental quality standards are under development for a number of PFAS compounds under the Drinking Water Directive to add a water quality standard for total PFAS. This will consider the total exposure to different PFAS compounds. However, an analytical method would need to be developed (SCHEER, 2022).

3.4. Exposure to humans

There has been extensive research involving biomonitoring studies and intake assessments for various exposure pathways for humans. These studies confirm that globally, humans are exposed to a diverse array of PFAS, with the most elevated levels observed among workers and residents near contaminated areas (ECHA, 2023b).

Workplace exposure

Human exposure is more prevalent during the production phase of the product’s lifecycle. Workers at fluorochemical and fluoropolymer production facilities also show elevated PFAAs levels in their blood, with instances such as the Rimar-Miteni factory in Italy (Veneto region) where PFOA levels were significantly high (ECHA, 2023b).

In environments containing large quantities of textiles, such as furnishings, carpets, and clothing, elevated levels of PFAS in indoor air and dust are expected. For example, high levels of FTOH have been reported in shops for outdoor wear and equipment (ECHA, 2023b). The employees of these stores were potentially exposed to PFOA through indoor air at levels comparable to their typical dietary intake of PFOA.

Textile manufacturing plants have shown even higher levels of FTOH, suggesting a potential for significant exposure among textile workers (ECHA, 2023b). In a study of a Chinese textile manufacturing plant, the levels of FTOH were reported to be 2-3 orders of magnitude higher than the levels measured in the abovementioned shops, indicating a potential of high exposure to textile workers (Heydebreck et al., 2016). Additionally, workers who require personal protective equipment (PPE) containing PFAS, such as firefighters, oil and gas worker and medical professionals tend to wear the equipment for long periods, heightening the risk of prolonged exposure to PFAS (Stantec, 2020).

Consumer and general population exposure

Throughout the use phase, PFAS can be emitted from textiles through various processes. These include the volatilisation[12] of PFAS residues, the shedding of particles and fibre fragments due to abrasion, natural degradation of PFAS within the fabric, and the leaching of water-soluble residues like PFCAs during washing (ECHA, 2023b).

Direct exposure to humans can occur through inhalation the dust of PFAS-coated textiles generated during use phase as well as through oral or dermal contact exposure. The latter two routes are particularly prevalent in children via object-to-mouth and hand-to-mouth exposure routes.

As mentioned previously, the use of waterproofing textile sprays can result in respiratory issues for users (ECHA, 2023b). There is direct evidence of respiratory illness and other health problems due to short-term exposure to impregnating agents (EEA, 2021). The spray application of some SCFPs have been linked to acute lung injury due to the hydrolysis products of these substances (OECD, 2022).

There is relatively little knowledge on the uptake of the substances from textiles to the skin and lungs (EEA, 2019a). However, exposure via dermal contact is thought to be minor compared to dietary exposure and inhalation of dust (EEA, 2021).

The general population is exposed to PFAS through sources like drinking water, food, consumer products, and dust from PFAS that has entered the environment via the mechanisms discussed in section 3.2. Studies in the US and China have observed traces of PFAS in the blood from populations living close to fluorochemical manufacturing facilities suggesting that populations can be exposed via air or surface water (ECHA 2023a).

3.5. Knowledge gaps and uncertainties

Robust data on the hazardous properties of most PFAS is limited due to the sheer number of PFAS compounds. A small number of non-polymeric PFAS, particularly legacy PFAS such as PFOS and PFOA, which are known to affect the immune system, be reproductive toxins and suspected carcinogens, have been heavily researched and monitored. However, there has been less regulatory intervention on other PFAS, particularly polymeric PFAS and therefore there is, limited knowledge about the health effects of many others.

For non-polymeric PFAS, studies have revealed impacts on plant and animal systems. Observational studies in humans link high PFAS levels to impaired immunity, liver and cholesterol effects, and birth weight changes. This suggests that even low PFAS exposures could have adverse effects on ecosystems and humans, possibly spanning generations (ECHA, 2023a). However, further research is needed to better understand implications of wider PFAS exposure in humans and the environment, particularly as multiple PFAS are commonly found together which complicates our understanding of the combined effects of multiple PFAS.

Polymeric PFAS are widely used in textiles and can exhibit significant variations in their properties which can have different impacts on human health and the environment.

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[12] The process in which a substance changes from a liquid or solid state into a vapor or gas at a certain temperature or under specific conditions.

However, there is less historical data and scientific literature available for polymeric PFAS. Whilst polymeric PFAS are highly stable under ambient conditions, the available data does not allow for conclusive determination of the impacts within the environment, particularly in relation to degradation of products over time and on the identity of the main degradation of products. Polymeric PFAS can release harmful decomposition products when subjected to high temperatures such as in municipal incinerators. However, specific toxicity data on these degradation products is limited (ECHA, 2023a).

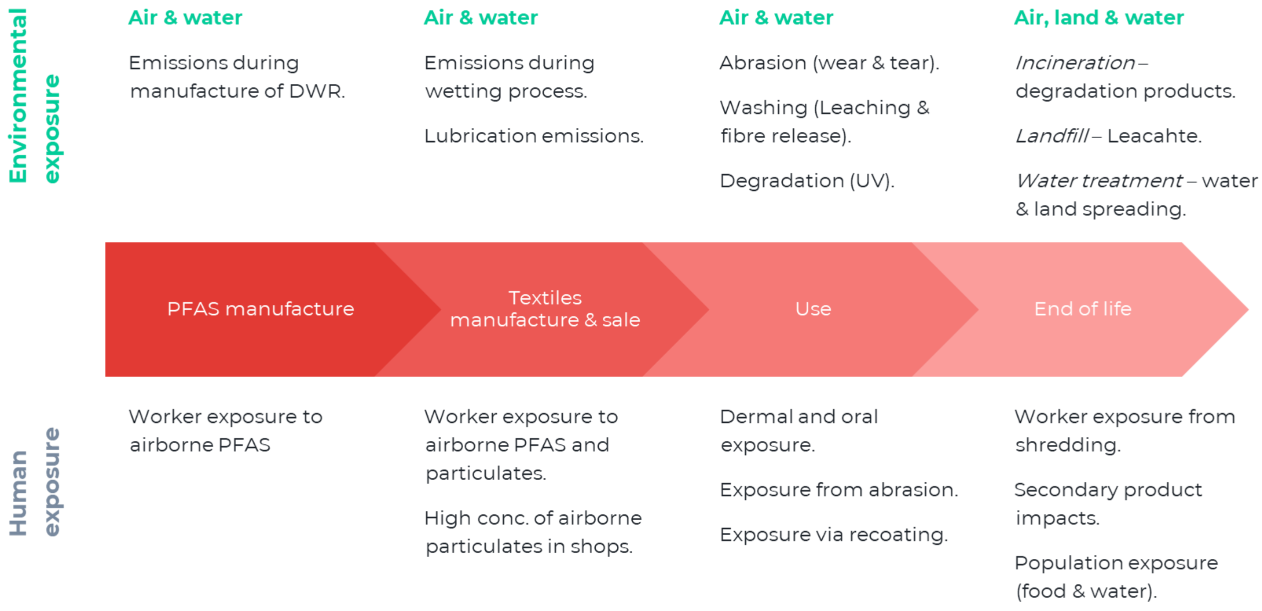
Conclusion

PFAS are becoming increasingly widespread in the environment due to their persistence, mobility, and tendency to accumulate in food chains. Non-polymeric PFAS exhibit high mobility and some can disperse globally, infiltrating ecosystems far from release points. Less is known about polymeric PFAS (which are more commonly used in textiles). They exhibit high stability under ambient conditions, but their behaviour in the environment are not well-documented.

Both polymeric and non-polymeric PFAS can degrade into persistent "arrowhead" compounds over varying timescales, sometimes via intermediate stages which makes predicting PFAS behaviour in the environment challenging. High-temperature processes like municipal incineration can release harmful decomposition products from both polymeric and non-polymeric PFAS.

Textiles are a major contributor to PFAS emissions throughout their lifecycle, including during production, use, and disposal. PFAS can be released to compartments (air, water, soil) through various processes, including production emissions, abrasion during use, washing, and end of life treatments. These PFAS have the potential to contaminate drinking water, indoor environments, and the wider ecosystem, posing potential risks to human and environmental health. Key release points are highlighted in Figure 3.1.

Figure 3.1 PFAS in the textiles lifecycle



Some PFAS have been shown to exhibit bioaccumulation in organisms due to their persistence and their tendency to attach to proteins, allowing them to accumulate in these tissues and build up over time. There is less evidence of how polymeric PFAS, and other less-studied PFAS accumulate in organisms.

Humans can be exposed to PFAS through various routes, including inhalation, oral contact, and dermal contact. Both workers in PFAS and textile manufacturing sectors and consumers of textiles are potentially at risk, while the general population can be exposed through food and drinking water.

The effects of non-polymeric and polymeric PFAS on human health are of significant concern. Non-polymeric PFAS have been associated with various adverse health effects. Limited toxicity data are available for polymeric PFAS, but some evidence suggests potential respiratory issues from inhalation exposure. Nevertheless, the degradation products of polymeric PFAS have been linked to human health impacts. However, a more comprehensive understanding of the degradation mechanisms in the environment is necessary to assess the effects of long-term exposure to these degradation products.

Combined exposure to multiple PFAS compounds is a concern due to their co-occurrence in various environmental sources and limited toxicity data for most PFAS. Estimating combined effects is therefore challenging, due to the vast number of PFAS and limited toxicological data, particularly for polymeric PFAS degradation products.

While legacy PFAS like PFOS and PFOA are well-studied, comprehensive information on the broader range of PFAS compounds is lacking. Continued research and regulatory measures are essential to understanding PFAS behaviour, particularly polymeric PFAS.

4. Implications of PFAS in textiles for the transition to a circular economy

The purpose of this chapter is to identify the key implications of PFAS used in textiles in the context of a circular economy. This chapter is split into the following sections: Section 4.1 explores the impacts of PFAS from the reuse of textiles, while Section 4.2 discusses how PFAS impacts textile recyclability. Section 4.3 examines the effects of PFAS beyond the EU. Section 4.4, discusses techniques for tracing PFAS within the textiles supply chain. Section 4.5 details current and emerging methods for separating and destroying PFAS in textiles. Section 4.6 considers alternative options to PFAS use, discussing their advantages, limitations, and environmental implications. Section 4.7 covers policy initiatives aimed at promoting PFAS substitution in textiles.

4.1. Reuse of textiles and the role of PFAS

Textiles reuse

The EU has mandated separate collection of textile waste by 2025, emphasising the need to prioritise reuse and recycling. EU directives, such as Article 10.4 of the Waste Framework Directive, requires that separately collected waste is neither incinerated nor landfilled. Additionally, Article 9.d of the Waste Framework Directive encourages systems for repairing and reusing textiles (EEA, 2019). Furthermore, The EU has set a deadline for Member States to establish specific targets for product reuse and recycling by 2024 (Åsa Östlund et al., 2020). The EU introduced Extended Producer Responsibility (EPR) requirements outlined in Directive (EU) 2018/851 (EEA, 2019) which require products to bear responsibility for, and therefore the costs of, the management of material with the incentive of designing out waste. This has been revised with the Ecodesign for Sustainable Products Regulation (ESPR) mandating EPR for textiles in all EU member states.[13] These laws are expected to increase the proportion of textiles to be reused in Europe.

However, uptake of EPR differs considerably by Member State. France is pioneering the implementation of EPR policies for end-of-use clothing, linen, and shoes, resulting in a 150% increase in post-consumer textile collection since 2007. Approximately 60% of collected textiles are reported to be reused, though only 4% are considered for high-value reuse in western markets. About 30% are recycled, mainly in Southeast Asia, and 8% are incinerated (EEA, 2019). Despite these improvements, the French system faces challenges, including unmet collection targets and financial sustainability issues (EEA, 2019).

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[13] Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL establishing a framework for setting ecodesign requirements for sustainable products and repealing Directive 2009/125/EC

Across the EU, various take-back and collection systems for reuse have been established by different entities, such as brands, charities, and public authorities. These systems have varying objectives, with brand-specific take-back schemes focusing on high-quality product resales, while general collection schemes aim to combine reuse, recycling, and waste treatment. Charities and professional collectors concentrate on re-wearable textiles, which are often pre-sorted for quality. Sorting can be performed (often manually) by the charity or by specialised third parties skilled in manual and automatic textile sorting (EEA, 2019). Charities and professional collectors tend to sell the best quality textiles in their second-hand shops while the rest are sold to wholesalers, who, in turn, distribute them globally (European Parliament, 2022).

Used textiles are often exported to EU countries specialising in sorting, exporting and wholesale centres, including France, Germany, Poland, the Netherlands, Belgium, Romania, Hungary, and Spain (European Parliament, 2022). Reusable clothes are manually sorted into numerous categories based on factors such as garment type, style, size, and season, and they are then sold in global second-hand markets (European Parliament, 2022). However, the practice of “reusing” textiles by exporting them faces key challenges (as discussed in section 4.3) (Canadian Environmental Law Association, 2019; Danish Environmental Protection Agency, 2015).

For textiles that cannot be reused directly, one option is to prepare the fabric for repurposing. Common applications include cutting waste clothes into industrial rags and cleaning cloths or as components of ‘new’ garments (EEA, 2019).

There is limited data available on the preparation of technical textiles for re-use, and it is reported that, despite some select examples, reuse of technical textiles is not common in practice. The reasons that contribute to this include (Textile Technology, 2019):

- Technical textiles typically reach the end of their life due to damage rather than changing fashion trends, making them less suitable for reuse.
- Protective clothing is often unsuitable for reuse as it serves a specific function and must be destroyed if it no longer functions as required or contains branding that cannot be reused. Medical textiles, are frequently contaminated and legally require special incineration processes, limiting opportunities for re-use.
- Technical textiles, especially those integrated into complex products like automobiles, are rarely disassembled at the end of their life due to financial reasons particularly when made with materials like carbon fibres that have strong adhesion to the matrix. This often leads to the shredding of products, making recycling of the fibrous components challenging and economically viable only for expensive materials.

Technical textiles in composite materials are usually not recoverable, particularly when made with materials like carbon fibres that have strong adhesion to the matrix. Separation is difficult and economically viable only for expensive fibre materials.

Impacts of PFAS on reuse

The presence of PFAS in durable (long-life) items such as textiles raises concerns when these items are reused. Reusing such items extends their lifespan, but it also heightens the potential for exposure to PFAS over time. This is a particularly noteworthy concern for legacy PFAS, which, despite being banned several years ago, can be detected in long-lasting textile products still in use such as bedding (Rodgers et al., 2022).

It is commonly assumed that the pathways for PFAS exposure during reuse are the same as those during their initial use (Danish Environmental Protection Agency, 2015). However, research indicates that the majority of volatile PFAS chemicals in clothing are released during the garment's regular use (Danish Environmental Protection Agency, 2015). As a result, reused products might pose fewer concerns in specific scenarios.

Nevertheless, there could be concerns when PFAS-containing textiles are repurposed for uses other than their original design. For instance, a shower curtain containing PFAS might present minimal risk during its intended use, but if the same material were repurposed as mulch[14] in a garden, it could significantly increase the potential risk of environmental exposure. Similarly, using items, like professional-grade PPE, designed for one group of professional users could pose a greater risk to health when used by more vulnerable users (e.g., pregnant women or children). However, such instances are relatively rare because most reused textiles typically serve the same purpose for which they were originally designed. Nonetheless, it is important to exercise caution to ensure that inappropriate reuse doesn't increase the potential risk to human health or the environment. This is of particular concern for textiles that are repurposed (e.g. as components of 'new' garments) where the end-use could differ from the primary use.

There are intervention points within the reuse cycle where PFAS-containing textiles can be removed from circulation (e.g. during sorting). However, this is almost always performed manually and there are therefore limited or no opportunities to identify products containing PFAS, beyond visual identification (as discussed in Section 4.5). In the many cases where identifying or separating potential PFAS-containing materials is not possible, precautions should be taken to minimise exposure risks.

To mitigate these risks, textiles should be directed to appropriate end uses. For instance, using safe textiles in the production of children's clothing is crucial. Hotel linen and terry cloth, which have undergone extensive washing, are considered advantageous for repurposing into children's clothing due to their softness and reduced residual chemicals, including PFAS (EEA, 2019). Proper labelling of products containing PFAS, and raising awareness among producers, brands, retailers, charities and product designers about material choices would help reduce the potential risk of exposure to the population (EEA, 2021).

4.2. Recycling of textiles and the role of PFAS

Textiles recycling

Compared to other sectors, the textile industry has been relatively slow to adopt circular economy practices, with only 3% of materials globally being recycled (Östlund, et al, 2020). However, as previously discussed, new or upcoming EU legislation is likely to increase reuse and recycling from 2024 onwards (Östlund et al., 2020; EEA, 2019).

Within the EU, a substantial portion of collected clothes (25 - 50%) are in poor condition and are either recycled, incinerated, or sent to landfills. As mentioned previously, France

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[14] A protective covering left on the ground to improve soil conditions and prevent weed growth.

has been a notable leader in implementing EPR policies for end-of-use clothing, resulting in a significant increase in textile collection and recycling, with a reported 90% recycling rate on consumer textiles. However, this figure includes textiles that are exported and for which we don’t know whether they are recycled or not (EEA, 2019).

In cases where textile fabric cannot be reused, high-quality fibre recycling through methods such as yarn respinning is a viable alternative (EEA, 2019). However, certain textiles are problematic especially those with coatings. Recent technological advancements in automated and semi-automated sorting have begun to address recycling obstacles. Scaling of automated sorting systems can efficiently categorise textile waste by colour and fibre type, essential for recycling. Semi-automated sorting employs handheld scanners to identify fabric types and accurately measure mixed fabrics (European Parliament, 2022).However, these are not widely adopted across the EU as they often incur high costs (Östlund, et al, 2020). To improve textile recycling, establishing large-scale collection systems and utilising both manual and automated sorting processes is essential.

Furthermore, despite advancements in sorting and recycling technologies, there are limitations as the type of textile (and its components) are ultimately critical for high quality recycling (EEA, 2019). New techniques for separating textiles and purifying them on a molecular level (chemical recycling) are being explored although this remains in development. Moreover, there is a need for technology that can trace the chemical content of textiles, especially additives like surface finishes, that remain in fabrics after their initial use (see Section 4.4). These improvements require thoughtful design planning to avoid contaminating used materials with substances that cannot be separated during recycling, while reducing complexity and minimising the use of persistent chemicals.

Despite the current lack of advanced textile recycling technologies, recent innovations show promise for future industrial-scale adoption. However, building the necessary infrastructure for efficient textile collection and sorting remains a significant challenge to be addressed by 2025 (Östlund, et al, 2020).

Technical textiles can pose problems with recycling depending on their application as they often contain high levels of PFAS which exacerbate the abovementioned problems. However, in many of their uses, these product waste streams are captured by industrial/ commercial waste collection systems which often have well-defined waste collections and treatment. However, recycling is often costly and therefore incineration or landfill is the preferred method unless a secondary use can be identified or materials have sufficient value. For example, in the case of electrolyser membranes, at end of life recovery is driven by the desire to recover the catalyst therefore waste is treated in order to maximise the value of materials (Hydrogen Europe, 2023).

Impacts of PFAS on recycling

Through recycling, humans and the environment are at greater risk of exposure to PFAS from one of the two following ways:

- Greater risk of contamination of secondary products; and
- Greater risk of PFAS release during recycling.

In addition to the environmental and human health impacts of recycling, regulations on restricted/banned substances can prevent recycling of materials containing those substances, which contravenes circular economy objectives.

Contamination of secondary products

Much like the practice of reuse, recycling of PFAS-treated textiles prolongs the duration that PFAS remain in circulation, thereby extending the potential for environmental and health risks (International Pollutants Elimination Network (IPEN), 2022).

However, recycling introduces a challenge not found in reuse: the heightened risk of contaminating secondary products. This contamination can lead to the incorporation of PFAS-containing textiles into a broader array of secondary products, some of which may expose humans and the environment to greater potential risks than the primary product would have done (IPEN, 2022). "PFAS super-spreader" products can distribute PFAS into a large number of products. Lohmann et al. (2020) cite an example of fluoropolymers found on items such as non-stick pans can break down at high temperatures during metal recycling, potentially releasing PFAS at high concentrations into secondary products. This could also be applicable for textiles that contain high levels of polymeric PFAS (e.g. some technical textiles with very high levels of PFAS).

Once recycled, it becomes challenging to trace the presence of PFAS in consumer products since there is no direct link to their original supply chain, and manufacturers of secondary products are likely to be unaware that their materials contain PFAS. Consequently, legacy PFAS may inadvertently find their way into products, even if their use has been restricted (IPEN, 2022). Recycling PFAS-treated textiles can therefore result in uncontrolled exposure, without any means of tracking their presence in other consumer goods produced from recycled materials (Jikta S et al., 2022).

To demonstrate this, consider the following scenarios where PFAS products are downcycled into lower-quality items. For instance, a waterproof coat containing high levels of PFAS might end up as filler material in children's toys or as building insulation. Among these secondary products, the risk of exposure varies. Children's toys, given their frequent contact with a more vulnerable population, present a notably higher risk of exposure. In contrast, insulation material might entail minimal exposure during its secondary use, as it has limited contact with humans or the environment over a long period of time.

Nonetheless, even insulation material presents a challenge when it reaches its end of life, as workers involved in demolition may be exposed to PFAS. The extended lifespan of such material thus poses a specific risk for exposure to legacy PFAS, which may occur many years after PFAS were banned from the initial product.

In both of these examples, end users, and ultimately, waste handlers, are often unaware of the presence of PFAS in these products, as neither were originally designed with PFAS in mind. Consequently, these materials may be repurposed in applications, or via processes, with higher risks of exposure and may inadvertently enter recycling or reuse loops, potentially perpetuating their presence indefinitely (IPEN, 2022).

It is worth noting that there is a substantial emphasis on promoting the reuse and recycling of textiles without sufficient consideration of the substances used in the treatment of the original textiles (Rouch, 2021). Without comprehensive sorting mechanisms, textiles containing PFAS can inadvertently enter waste streams, presenting a heightened risk of exposure to a larger population.

Release during recycling

Recycling processes can inadvertently perpetuate the presence of PFAS in new products, causing PFAS to be released into the environment and potentially impacting worker health (Reihart, et al, 2023). Two primary pathways of PFAS dissemination during recycling have been identified:

- Direct Worker Exposure: Workers in materials recovery facilities (MRFs) and processing facilities are at potential risk of direct PFAS exposure, particularly when handling materials with PFAS surface treatments.
- Air and Water Emissions: Emissions of PFAS into the air and water within MRFs and processing facilities contribute to environmental contamination as PFAS escape from the recycling process.

The recycling process for textiles involves several steps, including shredding and sorting. Worker exposure is most frequent during shredding, where residual PFAS may remain in recovered fibres, potentially concentrating in newly manufactured carpets and rugs. Hazardous substances (in dust) are often generated during the shredding and separation of blends and the removal of dyes, additives, and finishes, resulting in health impacts (Reihart, et al, 2023; National Institute of Standards and Technology (NIST), 2022). A range of PFAS, including polymeric and non-polymeric compounds, can be released during these processes directly to workers and to the surrounding environment. As discussed previously, workers involved in sorting at waste recycling plants have shown elevated levels of PFAS in serum and urine compared to control groups (Reihart, et al, 2023).

Recycling of fluoropolymers

Fluorospar, the primary ore used to obtain most fluorine-containing fine chemicals such as PFAS, has been designated as a critical raw material by the EU. This designation reflects the importance of preserving this crucial natural resource. Despite this designation, very little fluorine is currently recycled (EEA, 2021).

In the context of recycling, it should be noted that polymeric PFAS, such as PTFE in textiles are not commonly recycled. Nevertheless, it is possible to recycle polymeric PFAS like PTFE in certain applications. Current recycling efforts are primarily focused on production scrap since significant waste is generated during the production of fluorinated polymers. For example, commercial bakeries regularly remove fluoropolymer coatings from their baking forms after 12−24 months of use either via burning or blasting, with unknown emissions of PFAS and fluoropolymer particles to air, water, and soil, and then have the forms recoated, with uncertain emission control methods (Lohmann, R. et al, 2020). PTFE waste is ground into PTFE micro powder, which is used to reduce wear in mechanical devices, extending their lifespan. However, the fine nature of these particles raises concerns about their dispersion in the environment (Lohmann, R. et al, 2020).

Recycling fluoropolymers from consumer articles is not well-established due to the heterogenous nature of these materials which are mixed with other substances and fillers, making recycling more complicated (Lohmann, R. et al, 2020). It has been noted that successful scaled recycling processes for textiles containing PFAS have not been established (Office for Product Safety & Standards, 2023). Limited recycling processes exist for certain fibre types (NIST, 2022).However, surface-treated fabrics, in particular, are considered unsuitable for recycling (Danish Environmental Protection Agency, 2015). Consequently, most end-use materials are either landfilled or incinerated (EEA, 2021).

One potential solution is chemical recycling, which involves breaking down these polymers into monomers and rebuilding them into useful polymers. However, as of 2021, only one small-capacity plant in Germany has achieved this (EEA, 2021). Recently, there has been a push for plastic pyrolysis, a form of chemical recycling that operates at temperatures below 600 °C. This approach has gained attention in both the United States and Europe, and there have been investigations into small-scale plastic pyrolysis using mixed polymer inputs. Fluorinated polymers are likely to be processed in chemical recycling, but there is uncertainty about whether, and to what extent, volatile emissions are captured in this process (EEA, 2021).

Some polymeric textiles, like polyester, may be suitable for alternative chemical recycling (IPEN, 2022). There is ongoing research into a pilot-scale recycling method known as vacuum pyrolysis, which aims to regenerate monomers from industrial-scale fluoropolymer products (Lohmann et al, 2020).

Overall, research and demonstrations of technologies for recycling fluorinated polymers from both production waste and end of life products into safer products are currently lacking (EEA, 2021). There is a need for smart sorting solutions to identify materials and systems capable of detecting and separating potentially hazardous chemicals, as discussed in Section 4.6 (EEA, 2019).

Regulatory hurdles to recycling

The challenge of recycling is not only related to technical obstacles posed directly by PFAS but also regulatory hurdles. For example, industrial and commercial recycling facilities have specific criteria for accepting waste. If waste is suspected or known to contain persistent organic pollutants (POPs) such as certain PFAS (e.g. PFOS and PFOA) above legal concentration limits, it must be disposed in such a way that ensures such hazardous chemicals are irreversibly destroyed.

The Stockholm Convention (UNEP, 2019) mandates that when a chemical substance is prohibited or restricted (i.e. listed under Annex A or B of the Convention), wastes are not permitted to be subjected to disposal operations that may lead to recovery, recycling, reclamation, direct reuse or alternative uses of persistent organic pollutants. This means that wastes containing PFAS that are already listed under the Convention (e.g. PFOS, PFOA, PFHxS), or those that are in the process of being listed (e.g. long-chain PFCAs), may not be able to be recycled without mixing them with other material streams. Furthermore, the Convention states that material streams contaminated with this material cannot be mixed with other streams therefore they must be collected and treated separately. Co-collect products may therefore also be considered contaminated and dealt with in a similar way.

Another complication is dealing with materials sent for recycling when their chemical composition is unknown. Recyclers may reject uncontaminated feedstock materials due to concerns about potential contamination. In some cases, it may be necessary to identify and remove contaminants from materials, or to sort contaminated and non-contaminated waste. However, the lack of information about the presence of chemicals within products can make these options challenging as discussed in Section 4.4 (Friege et al., 2019).

Separate regulations often apply to chemicals used in different products, resulting in varying legal requirements based on the product or context. For example, the Toy Safety Directive 2009/48/EC[15] imposes limits on the concentration of certain chemicals (Friege et al., 2019). Furthermore, there are additional costs associated with dealing with hazardous substances in recycled materials. Monitoring material flows to identify contaminated materials can be limited by technical and financial barriers. This results in one of two outcomes: 1) valuable material may be disposed of, leading to a loss of value, or 2) the hazardous substance may continue to circulate indefinitely in material loops.

4.3. Impacts outside the EU

Within the EU, most textiles waste is systematically collected, processed and recorded. Although the management of textile waste in the EU is not as comprehensive as many other waste streams, it is comparatively well-documented (EEA, 2021). However, beyond the borders of the EU, the transparency and information available about the fate of used textiles become considerably scarcer.

While PFAS have notable impacts within the EU, it is important to recognise that this is a global issue. A substantial amount of PFAS and textiles consumed within the EU is imported from beyond the EU, and conversely, a significant portion of EU used textiles is exported. This interconnected flow of materials and products has both upstream and downstream environmental and social consequences, which are discussed in this section.

Imports

Within the EU there are strict rules around the production of chemicals such as PFAS for its own market (Brunn et al, 2023). However, the EU faces constraints in influencing production methods and related negative social and environmental impacts that occur elsewhere. As the EU relies heavily on textile imports, there are key challenges when it comes to ensuring that textile products entering the EU are subject to the same standards and can be traced.

Despite such constraints, there are several policy options which can influence production methods in other regions, some of which have already been proposed or put in place. Examples include policies related to eco-design requirements, green public procurement, standards and labelling, and waste management. Transparency and traceability through the value chain are also key as touched upon in section 4.4 (EEA, 2019). It is important that these items are identifiable so that they can be properly disposed of once it is waste, depending on how PFAS is classified moving forward (EEA, 2019).

Numerous studies have shown that products containing long-chain PFAS, even though they have faced recent restrictions within the EU, continue to be imported from countries outside the EU, particularly China, India and Bangladesh. In a study conducted in the United States, approximately half of the products analysed were found to have originated from China, with 75% of products containing long-chain PFAS being traced back to Chinese manufacturers. In contrast, products containing short-chain PFAS were sourced from a more diverse set of countries, including both China and the United States. This

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[15] Toy Safety Directive 2009/48/EC

distribution more closely mirrored the overall country of origin for all products examined in the study (Rodgers et al., 2022).

Exports

Discarded textiles in Europe, are an increasing waste and export problem. Rapidly increasing supply of second-hand clothes surpasses the demand in the EU, leading to an increasing share being exported, particularly to countries in East Asia and Africa. This export is usually motivated by the assumption that these materials will be reused and recycled, with supposed circularity benefits, and by the market value of used textiles.

However, this practice has sparked criticism, with some accusations that the influx of inexpensive second-hand clothing is contributing to the decline of local textile industries in recipient countries. Furthermore, many of the exported items are of such poor quality that they cannot be effectively reused. Essentially, used textiles including some of which is waste is being offloaded onto countries that lack the infrastructure to handle it. Reports have emerged of large clothing dumps in countries including Ghana and Chile, where the items are either landfilled or incinerated in open pits (European Parliament, 2022). It is not clear whether these originate from Europe or elsewhere.

However, the export of used textiles to non-EU countries has varying impacts on local economies. For example, in African countries, the import of used textiles primarily serves local reuse and jobs and sorting due to a demand for affordable, second-hand European clothing over new items. Textiles unsuitable for reuse often end up in open landfills and informal waste disposal systems. Some African countries are considering banning imports of textiles waste to protect and boost local textile production, citing negative social and environmental impacts associated with imports (EEA, 2023b).

In contrast, in Asia, most used textiles are imported into designated economic zones for sorting and processing. Import for local reuse is limited, with a focus on local recycling, often resulting in downcycled products like industrial rags or filling. Some used textiles are re-exported for recycling in other Asian countries or for reuse in Africa or even in Europe. Textiles that cannot be recycled or re-exported may often end up in landfill.

The fate of EU-exported used textiles in receiving countries is highly uncertain as limited and mostly anecdotal evidence is available. Nevertheless, open waste burning, which is relatively rare in Europe, is a widespread practice in developing countries. It is estimated that 41% of global waste is disposed of in this manner. This type of burning often occurs with insufficient oxygen and at lower temperatures compared to controlled municipal incineration, leading to the release of PFAS emissions into the air as discussed in section 4.5 (EEA, 2021).

One significant problem is the lack of documentation regarding waste handling and related emissions for products ending up outside Europe. During recycling processes, health risks emerge due to dust produced by industrial shredders (EEA, 2021). Additionally, recycling systems in developing countries often recover lower-value textiles. Consequently, the likelihood of exporting materials to lower-quality recycling processes results in downcycling, which contradicts the broader circularity goals of the EU in terms of retaining materials within recycling loops.

The example of France illustrates that the introduction of EPR schemes has significantly boosted reuse and recycling rates. However, these figures are heavily reliant on exports. The reuse stream, in particular, has faced criticism and challenges, as some countries are banning the import of used textiles to bolster their own textile industries (SWITCH-Asia, 2022).

Exporting unsafe products for reuse raises ethical concerns, extending the issues discussed in section 4.1 to lower-income countries. There are serious concerns regarding the human health and environmental impacts of PFAS (EEA, 2021).

4.4. Tracing PFAS within textiles

Textile production in Europe is regulated through a patchwork of EU and national legislation, including on production methods and working conditions, along with the related labelling and marketing of the fibre composition of textile products (EC, 2019c). Further legislation on chemicals and specific articles also impacts textile production, selling to consumers, and the importing and exporting of the final product. Within the EU, for example, textile production is covered by the EU Regulation on Evaluation and Authorisation of Chemicals (REACH) (Regulation (EC) No 1907/2006)[16] and the Industrial Emissions Directive (IED) (Directive 2010/75/EU)[17].

Textiles produced outside the EU are also subject to some product policy, such as EU eco-label criteria and green public procurement criteria for textiles. However, this is to a lesser extent compared to textiles produced in Europe, since chemicals used in manufacturing outside of EU are not subject to registration or authorisation under REACH. Nevertheless, as noted previously, REACH does not cover polymers which make up the majority of PFAS in textiles.

Information on the amounts of non-polymeric and polymeric PFAS produced, used, and imported in the European Economic Area is limited, posing challenges for accurate assessments. The long, complex, and global nature of textile supply chains, coupled with a lack of reporting from manufacturers, has increased the difficulty of tracking chemicals like PFAS through the supply chain and into waste streams at the end of life (EEA, 2019c). Because safety data sheets only apply to chemical formulations, PFAS are not listed as components in textiles or in import/export logs, resulting in unclear tonnages of imported and exported PFAS containing articles (ECHA, 2023a). Similarly, the recovery of materials or the safe disposal of wastes is limited by a lack of clarity about what types of fluorinated polymers and levels of contaminants in products should be treated as hazardous wastes (EEA,2021).

The Zero Pollution Ambition for a toxic-free environment calls for the risks posed by very persistent chemicals to be addressed rapidly (EC, 2023). Potential hazards and their expected impacts are mainly analysed qualitatively because data are lacking on both hazards and exposure to the majority of PFAS, and particularly the risks to ecosystem health (EEA, 2021). Despite evidence indicating the potential for widespread and increasing exposure of the environment and humans to PFAS, comprehensive tracking of total PFAS emissions across the life cycle globally has not yet been undertaken (EHCA, 2023a). The complexity of the supply chain and the tracing of PFAS in textiles is illustrated in the figure below.

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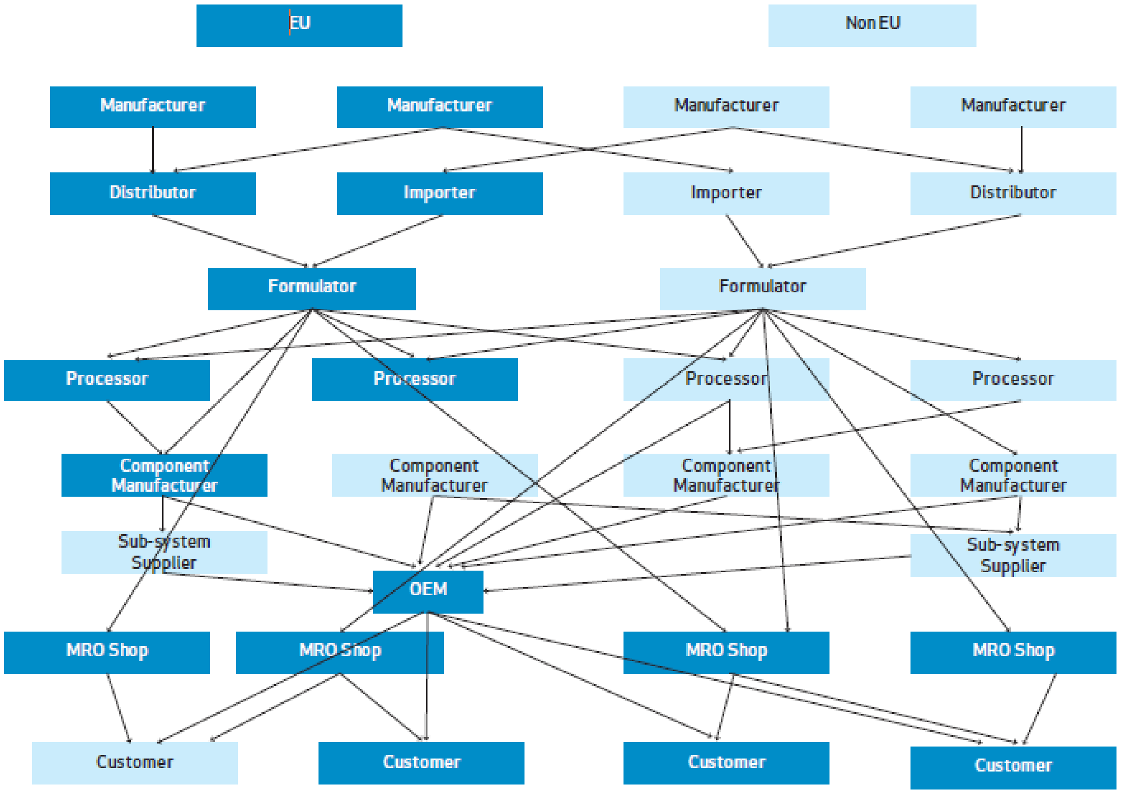
[16] Regulation (EC) No 1907/2006

[17] Directive 2010/75/EU

Figure 4.1 Illustration of supply chain complexity (ECHA/EASA, 2014)



Current tracing methods

Currently, the SCIP database is the main source of information on the substances contained within chemicals products, providing information on hazardous substances that are classified as hazardous according to Classification, Labelling and Packaging (CLP), are persistent/bioaccumulative/toxic (PBT), are listed under the Stockholm Convention or POPs Regulation, or are included on the SVHC candidate list when in a concentration above 0.1% w/w (RI.SE, 2022, ECHA, 2023f). While this does cover a relatively small number of non-polymeric PFAS (PFOA, PFOS, PFHxS, etc. as listed in the Stockholm Convention), the majority of non-polymeric PFAS and all polymeric PFAS are not included in safety data sheet reporting.

Consumer products such as textiles also have no regulatory obligation for a safety data sheet, even for banned PFAS, which significantly limits the ability to trace PFAS once incorporated into the final product (The Occupational Safety and Health Administration (OSHA), n.d.). Once PFAS is incorporated into the textile, there is limited, if any, testing the track the concentrations of PFAS during service life. A study by Rogers et al. (2022) investigated PFAS in textiles labelled as water- and/or stain-resistant and were able to regularly detect PFAS even in products with a green-certification. As green-certified products often do not consider PFAS and the concentrations of PFAS found were under the accepted limits, the results of the report where unsurprising to the researchers (Rogers et al,2022).

The Danish Ministry of Environment has created a letter template to assist Small and Medium Enterprises (SMEs) in acquiring information from their suppliers. This template is available in both English and Chinese (Danish Ministry of Environment, 2023a). Industry has positively responded to this initiative, and it has resulted in some success in improving the tracing of PFAS within the supply chain. However, one stakeholder credits this success might be influenced by the extensive media coverage of PFAS in Denmark which may not be the case in other regions (Danish Ministry of Environment, 2023b).

Testing for PFAS

At end of life, the majority of testing for PFAS is done in liquid mediums, specifically when investigating concentrations of PFAS in bottom ash or landfill leachate (Vogel, 2023). Screening for PFAS in the bottom ash of energy to waste plants has been analysed for PFAS concentrations, and some countries such as Norway monitor PFAS such as PFOS and PFOA in the flue gases of these plants as well (Vogel, 2023).

The most common technique used to detect PFAS in various mediums is liquid chromatography-mass spectroscopy (LC-MS), which can also be coupled with high resolution mass spectroscopy (HRMS) for very arcuate detection of non-target PFAS in aqueous samples (Brunn et. al, 2023). For aqueous samples, a good lab can achieve a limit of qualification (LoQ)[18] 1 ng/L of PFAS routinely. In solids such as composts, soils, and sludges a LoQ of 10 µg/kg has been achieved, however this LoQ is too high to determine any background PFAS contamination (i.e., PFAS that should not be in the tested sample but is a result of emissions) (Brunn et al., 2023). HRMS has been key in advanced detecting of PFAS present in the environment, as the technique is based on the detection of the mass of Cl atoms present in the substance. This technique has allowed for characterisation of various PFAS present in samples, not just those that have an analytical standard (Brase et al., 2021).

Currently, there is no direct regulatory activity requiring the testing of textiles for PFAS concentrations which has resulted in very limited reported testing conducted on consumer textiles. In the instances of testing for PFAS in textiles near the end of production or before being passed to the consumer, LC/MS is the preferred method of PFAS detection (eurofin, n.d.). Eurofin offers a range of testing for PFAS in textiles alongside LC/MS, including combustion ion chromatography for total fluorine screening and novel inhouse testing methods to find PFAS with C_6 or C_8 chemistries (eurofin, n.d.).

Future potential of tracing PFAS in the supply chain

In March 2022, the European Commission published a proposal[19] for an Ecodesign for Sustainable Products Regulation (ESPR), as a means of improving the circularity, energy performance and overall environmental sustainability of products. This adapts the existing Ecodesign Directive (2009/125/EC), which currently only covers energy-related products, by establishing a framework to set performance and information requirements for physical goods placed on the EU market (including textiles). This includes provisions for product durability, reusability, upgradability and reparability, presence of substances that inhibit circularity and recycled content. Clearly, as discussed in other sections of this report, this

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[18] The limit of qualification (LoQ) is the lowest concentration of the substance in question that can be quantitatively detected with a stated accuracy and precision.

[19] https://eur-lex.europa.eu/resource.html?uri=cellar:bb8539b7-b1b5-11ec-9d96-01aa75ed71a1.0001.02/DOC_1&format=PDF (accessed 15/02/2024)

is likely to have significant implications for the safe management of PFAS in the textiles sector, and the tracking of PFAS in this supply chain.

While significant knowledge gaps regarding PFAS in textiles and waste streams exist, there are several steps that could be taken to address and minimise these gaps. For example, the labelling of PFAS (specifically polymeric PFAS) within textile products by manufacturers would provide assistance for waste management to suitably manage these products at end of life (EEA, 2021). A number of ecolabelling programs also operate within the European Economic Area, such as the EU eco-label and Nordic Swan, which provide reliable and transparent information to consumer regarding the environmental and social impacts of the products they are purchasing (EEA, 2019c). Other labels include OEKO-TEX which prohibits the use of PFAS in textiles, leather and footwear and BIONIC-FINISH ECO from Rudolf in Germany is widely used. As a part of these ecolabelling schemes, manufacturers supply further information on the chemicals used in the final article, which could be extended to include information about PFAS in textiles.

Some companies have implemented internal tracing systems, however, these systems are not regulated by authorities or consistently shared across the supply chain. To improve on these tracing systems, technology such as radio frequency identification (RFID) tags with the unique data about the textile can be incorporated into product tags (Bylund and Andersson, 2022). The tag can then be scanned at points throughout the supply chain to provide information about the composition of the textile and potentially end of life management options. The main challenge with RFID currently is that the tags can be bulky and not optimal for wearable textiles and can easily be electrically duplicated for non-genuine products (Bylund and Andersson, 2022).

The EC has also recently proposed the implementation of a digital product passport (DPP) which will be used to store product-related data throughout the lifecycle of the product with the entire supply chain. The EC has identified the textile industry as a priority industry, and it is expected that the DPP will be approved in 2024 with products being added by 2026). While the information the DPP will provide for each industry is still not full established, with the ongoing regulatory activity around PFAS there is a good chance PFAS will be included as a substance that needs to be reported outside of the substances under Stockholm (wbcsd, 2023).

Barriers to tracing PFAS in textiles

In circular business models, much closer collaboration is needed among companies, both downstream and upstream in the value chain, and with customers than is typically the case in a linear system. To support collaboration, value must be created at all stages of a product’s value chain and lifecycle (EEA, 2019c). Industry could work to establish requirements and standards for the consistency of products, feedstocks, principles, processes, and reporting (Schumacher and Forster, 2022). This could include digital product identification that provides access to data that is needed to support circular pathways (Schumacher and Forster, 2022).

With companies moving towards circularity, barriers still exist for tracing PFAS within textiles and the textile supply chain. As mentioned, the use of RFID tags is hindered due to their size and ability to be counterfeited. The EU digital passport is a step towards providing information to consumers and end of life management, however, the reporting requirements will need to be extended to include substances such as polymeric PFAS and PFAS used solely in the manufacturing process. PFAS is also not considered under the green- and eco-label products, which is another area which could be tackled to further improve the ability to trace PFAS within the supply chain. The proposed ESPR (see above) will likely have implications for this aspect in the future, however. In addition to adding the capability to track PFAS throughout the supply chain, the sheer number of PFAS to track poses its own unique challenge.

Transparency must be gained through the entire production line in order to ensure a sustainable product from a life cycle perspective. Today's reporting formats contain a high degree of voluntary information and there is a risk that the most critical points are left out and that companies only report on the aspects where they perform well (Östlund et al, 2020). Systems for traceability and transparency need to cover the content described above under 'new business models to prolong the lifetime of garments', 'new production technology' and 'new material recycling technology'. The willingness to report substances used within textiles increases if the information requested is easily available and also being requested by other systems (Östlund et al, 2020).

The Danish Ministry ran a user survey for PFAS in textiles in 2023 which found that whilst larger textile corporations often have a decent knowledge of PFAS and understanding of how it may impact their business, SMEs often have limited resources to trace PFAS in their supply chain and act upon it. Some of the issues raised during consultation included (Danish Ministry of Environment, 2023b):

- Limited technical comprehension of PFAS, how it is used in products, and associated impacts.
- Difficulty in controlling suppliers and communicating requirements up the supply chain due to resource constraints. Bypassing tier 1 suppliers to reach tiers 2 and 3 is challenging, and even if attempted, tier 1 may not be aware of alternatives to PFAS.[20]
- Challenges in communicating specific requirements to suppliers and obtaining credible documentation about ingredient composition.
- Varying levels of priority in different regions, with some EU member states and certain Asian suppliers showing less concern.
- PFAS effectiveness often results in low concentrations that don't need to be disclosed on data sheets, making it difficult to obtain information about contents due to trade secrecy. Suppliers are hesitant to disclose ingredients, relying on external consultants under non-disclosure agreements to obtain information.
- Uncertainty about impending legislation and testing requirements, leading to confusion about responsibility for testing.
- Concerns about the functionality and durability of products without PFAS. Consumers will demand money back if product does not meet expectations.
- Competing demands and feeling overwhelmed with other requirements (e.g. GDPR), leading to action only when legally required, as there's little incentive to invest time in non-mandatory issues.

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[20] Tier 1 suppliers directly provide products or services to the primary company, while tier 2 and tier 3 suppliers represent successive levels of the supply chain, with tier 2 supplying tier 1 and tier 3 supplying tier 2, contributing to the overall production or service delivery process.

4.5. Separation and destruction technologies

As highlighted in earlier sections, it is essential to improve the treatment of textiles containing PFAS as we transition towards a more circular economy. The goal is to effectively separate PFAS from material cycles and permanently eliminate it while preserving the maximum material value of the textiles. PFAS substances within textiles are challenging to remove and dispose of due to their durable nature. The aim of this section is to identify the current and emerging separation and destruction technologies for PFAS in textile products.

Separation technologies

There are two primary methods for separating PFAS from the textile waste stream:

- By identifying and sorting products that contain PFAS and destroying the whole product; or
- By removing PFAS components from the product, so that they can be destroyed separately.

In a circular system, the second method is generally favoured, as it promotes increased textile recovery, while the complete destruction of entire product streams is often impractical due to destruction capacity constraints. However, the second method is usually more technically challenging. Both approaches are essential to ensure that PFAS is not perpetuated within a circular economy.

Identification, sorting, and separation processes can be carried out manually, semi-automatically, and automatically. In the textiles value chain, separation and sorting already occur at the end of the product's life, before reuse and recycling. These intervention points in the value chain present potential opportunities for implementing measures to separate high-risk products.

Identification and sorting of products

Identification and sorting can be undertaken in one of three ways: manually through visual inspection, semi-automatically using handheld scanners or fully automatically with the use of automated technology. The advantages and disadvantages of each are explored below.

Visual identification and sorting

Visual identification is the most straightforward method for identifying and sorting PFAS-containing textiles and doesn't require significant investment, using the tools and processes already common in the industry. However, it does demand additional training to enable staff to identify products that likely contain PFAS. The challenge lies in the fact that accurate identification through visual inspection alone is difficult. Current labelling practices do not aid in identifying PFAS-containing textiles. Moreover, aftermarket treatments for stain, soil, and grease repellence frequently include PFAS, which means textiles not previously flagged as PFAS-containing may also be contaminated (Antell et al., 2020). This complexity makes it challenging to identify PFAS-containing textiles (NIST, 2022).

The accuracy of this method is likely to be low, resulting in the under-detection of PFAS-containing textiles, as well as the potential for the incorrect sorting and treatment of textiles without PFAS, which results in mistakenly destroyed textiles and lost material value. While it is relatively easy to implement, it introduces new criteria that may affect the sorting process time.

Semi-automatic sorting (hand-held scanners)

Hand-held technology can be a valuable tool to aid in the manual identification and sorting of textiles. Handheld devices are already widely employed by the reuse/recycling sector to identify textile type and colours etc. However, these existing handheld devices are not equipped to identify PFAS.

Handheld X-ray fluorescence (XRF) machines can be employed to identify fluorine-containing products, such as PFAS. However, adopting this technology requires notable investment, as it comes at a relatively high cost, often in the thousands of Euros. Additionally, its operation requires radioactivity safety training and security measures, making it potentially inaccessible for smaller-scale operators.

Nonetheless, these machines may not be required for every individual item. In cases where employees are uncertain whether a textile contains PFAS, it can be sent for verification, which can significantly enhance the accuracy of the sorting process (NIST, 2022).

Automated

Automated systems are currently being developed and employed by larger-scale operators and are increasingly being developed for sorting of large volumes of mixed post-consumer textiles based on material composition. The EU Fibresort project is an example being piloted and demonstrated in Europe (Interreg, 2021; EEA, 2019).

However, current systems do not identify or sort textiles containing PFAS. Modification of existing systems to include XRF would therefore need to be developed which requires significant investment. However, once operational, the automated system would require less operational cost through lower employment of manual workers. Introduction of a fully automated system is highly expensive and is likely beyond the means of smaller-scale operators such as charities.

An overview of the key advantages and limitations of each technique is provided in Table 4.1 below:

Table 4.1 Advantages and disadvantages of key sorting techniques (Texaid, 2023)

Technique	Advantages	Limitations
Visual identification	Already widely implemented in sector Low capital cost	Labelling does not support identification of PFAS in textiles Requires knowledge of textiles likely to contain PFAS (training required) Low accuracy High operational cost

Semi-automatic (hand-held scanners)	Fits in with existing models Medium capital cost Higher accuracy	Requires investment in XRF scanners Requires training and safety protocols
Automated	Lower operating costs as less humans High accuracy	High capital cost

Separation

Once articles containing PFAS are identified, they can be sorted in one of two ways:

- **Sorting for Destruction:** Identifying and sorting products for destruction is a straightforward process. However, once identified, these products should follow a specific destruction route, as discussed later, rather than being directed to common municipal waste routes like landfill or low-temperature incineration. Complete destruction of entire product streams has limited capacity. Therefore it is preferable to minimise the quantity of products sent for destruction. In the context of a circular economy, it is also desirable to maximise the retention of valuable materials. Therefore, whenever feasible from both technical and economic perspectives, removing PFAS from contaminated materials is the preferred approach to reduce the overall quantity of material requiring destruction.
- **Removal of PFAS from Textiles:** The removal of PFAS from existing textiles is often integrated into the recycling process, although there are limited examples of scaled applications. As of 2014, recycling processes for textiles made of or containing PFAS had never been successfully established, and there continue to be significant barriers to recycling surface-treated textiles (Danish Environmental Protection Agency, 2015; Office for Product Safety & Standards, 2023). Nevertheless, there are opportunities for development. Treatment techniques can be applied to certain textiles during the recycling stages. For instance, during the recycling process, carpets are typically washed in an aqueous solution, and most PFAS removal (or mineralisation) technologies take place in an aqueous medium (Antell et al, 2020).

Destruction technologies

Once identified and separated, complete destruction (mineralisation) of PFAS is necessary to prevent its continued circulation within the environment. Treatment technologies for PFAS exploit a contaminants chemical and physical properties to immobilise or destroy the contaminant. The stability and surfactant nature of PFAS make the substances a challenge to remove, some treatments can be ineffective if not implemented fully and correctly (ITRC, 2023). This section explores the existing and emerging destruction technologies available to textiles.

Existing destruction techniques

Thermal treatment

Thermal treatment processes have proven to be effective in removing PFAS at scale. However, they come with significant costs and high energy consumption. Nevertheless, municipal incineration can potentially lead to PFAS emissions from combustion bottom ash or fly ash if the complete mineralisation of PFAS does not occur (Reihart et al, 2023).

Complete mineralisation of PFAS at lower temperatures is not guaranteed for all PFAS compounds, and addressing volatile fluorinated emissions during treatment remains a challenge for both gaseous and solid waste. In uncontrolled conditions, fluorinated polymers can thermally degrade to form a range of volatile and water-soluble PFAS compounds, as well as small particles. The thermal degradation of PTFE, for instance, begins at relatively low temperatures of less than 500 °C and results in the degradation into persistent and mobile PFAS (EEA, 2021).

Despite the growing body of research, a comprehensive understanding of how PFAS behave during thermal treatment is still lacking due to the complex chemistry of fluorine flames and the absence of a robust sampling methodology (Reihart et al, 2023).

The IED mandates that waste incineration plants should be designed to ensure that flue gases reach a temperature of at least 850 °C for two seconds to ensure the complete breakdown of toxic organic substances (EEA, 2021).

According to the OECD, PFAS within textiles can be effectively destroyed at high-temperature incineration, with approximately 90% destruction at around 850 degrees Celsius and 99.9% at 1000°C (OECD, 2022). Consequently, municipal treatment plants are, in theory, capable of destroying 90% of PFAS but are insufficient for adequately destroying PFAS if these materials were to be restricted. Peak temperatures in uncontrolled open burning systems reached only 250–620 °C (EEA, 2021) therefore do not sufficiently destroy PFAS.

PFAS destruction should therefore be undertaken via high-temperature incineration. Under the Stockholm Convention, if hazardous waste with a content of more than 1% of halogenated organic substances (such as banned PFAS), is incinerated or co-incinerated, the temperature should be at least 1100 °C with a minimum residence time of two seconds to mineralise (completely degrade) organic compounds. Therefore, were PFAS to be added to this list, any textiles treated with PFAS would need to be incinerated at high temperature to be compliant (Persistent Organic Pollutants Review Committee, 2023). Note that the adoption of the REACH restriction does not mean that measures under the Stockholm Convention is extended to all PFAS. The Restriction is focuses on the sale of products and not extend to waste handling.

The possibility of thermally degrading fluorinated polymers in cement kilns is currently being investigated, by use of calcium as a catalyst and fluoride as a scavenger, by the formation of calcium fluoride (CaF_2) captured in the cement to completely immobilise PFAS (EEA, 2021).

Long term storage

Whilst not considered to be a destruction technique, deep storage in abandoned mines and oil extraction fields is an option that is not commonly explored. It is often reserved for exceptional cases such as when mandated by court orders, due to its high cost and logistical complexity. Furthermore, it is not a permanent solution and the long-term effects within the environment are unknown (Lohmann et al, 2020).

Emerging destruction techniques

Photocatalysis

A technology that utilises the adsorption of a photon within the presence of a photocatalyst which accelerates the destruction reaction rate. The photocatalyst substances are generally semiconductors. Photocatalysis have enormous potential to treat organic contaminants in water and air. The technology is an advanced oxidation process, consequently it is applicable for the oxidation of a wide range of organic contaminants (Meegoda et al., 2022). The photodegradation can be performed with a wide range of wavelengths, which overcomes the problem that it has difficulty to destroy the C-F bond by direct photolysis.

Supercritical Water Oxidation (SCWO)

SCWO is an oxidation treatment process where media is transformed into water, carbon dioxide and a few other products depending on the waste stream being treated. The process can treat a range of products without dewatering and has already proven to be effective in the destruction of toxic and persistent organic contaminants (Meegoda et al., 2022). This is generally considered to be an environmentally friendly technology when compared to other destructive processes. The moderate temperatures (380 – 600ºC) prevents the formation of NOx and SOx compounds that are highly toxic. However, the technology is not economically viable to work with volumes larger than 50,000 gallons/day of waste, and the requirement to heat up large quantities of waste liquid inhibits the scalability of the technology.

Remediation techniques

PFAS released into the wider environment necessitates specialised and often challenging treatment procedures for removal. As detailed in Chapter 3, PFAS in textiles pose a particular concern for the water system. PFAS from textiles can find their way into the water system through:

- Rinse water from domestic washing and processing of textiles (manufacture, use and end of life),
- Landfill leachate requiring treatment, and
- Emissions via other compartments (e.g. via wear and tear or incineration emissions to air etc.)

Within the water system, remediation techniques can capture PFAS. However, traditional waste water treatment plants have not been developed to treat complex chemicals such as PFAS.

The issue of landfill leachate is particularly critical for legacy PFAS in textiles, as a substantial portion of textiles have been, and continue to be, landfilled in the EU. It should be noted that under the revised EU Landfill Directive, separately collected waste streams (which will include textiles from 2025) cannot be landfilled (EEA, 2019b). Nevertheless, the impact of legacy PFAS will persist. Another concern is that the average lifespan of landfill liners is shorter than that of most PFAS substances, which means that some PFAS compounds may continue to leach into the environment once the landfill liner has degraded (Brunn et al., 2023). Remediation is a crucial consideration for textile waste. Table 4.2 outlines the most commonly-used remediation techniques aimed at curbing the release of PFAS into water.

Table 4.2 – PFAS remediation technologies (Waldemar et al., 2022)

Technique	Advantages	Disadvantages
Adsorption through granulated active carbon	Easily scaled.	Contaminants are not fully degraded (mineralised). Costly regeneration of adsorbent.
Resin	Fast and selective removal.	High material costs. Costly regeneration of adsorbent.
Membrane filtration, nanofiltration	High removal rate. Easily scaled.	High operational costs. Requires further disposal of the collected concentrate.
Reverse Osmosis with Plasma Treatment	High removal rate and complete PFAS destruction.	High energy usage and not particularly scalable mainly due to high costs.
Laccase treatment	Good removal potential and low energy requirement.	Lengthy implementation period.
Mechanochemical milling	Up to 99% PFAS destruction.	Not commercially viable. Further development needed.
Electrochemical treatment	Operates at ambient temperatures and pressures.	Only tested at a small scale.
Pyrolysis/Gasification	Excellent destruction capability and requires a small land area to set up units.	Gasification requires high temperatures over 1000ºC. High energy costs.

4.6. Substitution options

Market trends within the textile industry suggest that there are several PFAS alternatives in use and in development (Östlund et al, 2020). Substitution activities for PFAS can be traced back to 2000 when PFOS usage was restricted, and 3M stopped production of associated products. As further PFAS have been added to the Stockholm Convention and Annex XVII restrictions under EU REACH, the need for alternatives has increased (Hill et al, 2017).

In general, PFAS free technologies are more sensitive chemistries and can require numerous trials for manufacturers to achieve a suitable quality textile (RI.SE, 2022). As PFAS in textiles are most typically used for their water/oil/stain/etc. repellence, it is important to ensure that the alternative chemistry not only meets the accepted performance in these areas but is compatible with the textile as well. PFAS-free alternative chemistries in textiles are subjected to a number of laboratory tests, including resistance to surface wetting, determination of water repellence, oil repellence, wetting and spreading measurements, and liquid uptake measurements (RI.SE, 2020). Nonfluorinated finishes provide little to no oil repellence, however the water repellence they offer is close to that of the PFAS finishes (Hill et al, 2017).

The following summarises alternatives for PFAS in textiles that have been identified. Note that the focus of these alternatives is ‘safer’ substitutions to avoid providing regrettable substitutions.

- Paraffin waxes[21]:
    - **Textile type:** can be used for all textile types, primarily used for jackets, cloth shoes, and professional equipment such as clothing and tents.
    - **Properties:** wax based treatments are viable and perform well in terms of water repellence, however these treatments do not perform well as stain repellence treatments (Gilchrist, 2023). The incorporation of metal salts into paraffin waxes can improve the water repellence, as the metal salts will orient to the textile and leave the hydrophobic tails to repel water.
    - **Barriers:** paraffin waxes can range from biocompatible to toxic, regulated waxes such as chloroparaffins. Textiles treated with paraffin waxes must be used within a specific temperature range or there is a risk the wax can melt.
- Hyperbranched (or dendritic[22]) hydrophobic polymers and comb polymers[23]:
    - **Textile type:** can be used for all textile types and can be applied post manufacturing or incorporated into the fibres of the textile.
    - **Properties:** can reach up to superhydrophobic properties (a water contact angle greater than 150º) when applied to textiles, affording great water resistance.
    - **Barriers:** hydrocarbons themselves come with their own unique environmental hazard profiles;
- Silicones and siloxanes:
    - **Textile type**: can be used for all textile types.
    - **Properties:** The rough, rigid surface patterning of silicones and siloxanes allows for an effective repellence of liquids.
    - **Barriers:** silicone and siloxane based treatments pose human and aquatic toxicity risks, and have been identified as regrettable substitutions for PFAS in textiles previously, with a potential phase-out as siloxane precursors D4, D5, and D6 are under regulatory scrutiny (Gilchrist, 2023).

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[21] Paraffin waxes are a melt on wax that can come from either fossil or renewable sources.

[22] Dendritic polymers are hyperbranched polymers with perfect branching, i.e., every single branching point is identical and to the same generation.

[23] Comb polymers are a type of linear polymer with a low density of side chains.

- Nanomaterials[24]:
  - **Textile type:** Can be used for all textile types, most commonly used for leathers, footwear, and clothing fabric protection sprays.
  - **Properties:** The nano silica in silicon dioxide nanoparticles adheres to the textile and forms nano-sized air pockets that water cannot penetrate which creates a hydrophobic surface (Department of Toxic Substances Control (California), 2022). Titanium dioxide nanoparticles are hydrophobic which makes them useful for preventing water-based stains to textiles.
  - **Barriers:** with nanomaterials, the individual components of the nanomaterial need to be considered separately for risks and hazards, and the size scale of the final particle must be carefully selected to avoid migration from the textile and penetration of organism's cells.
- Polyurethanes:
  - **Textile type:** can be used for all textile types, commonly used for more heavy-duty applications.
  - **Properties:** The isocyanate/polyol combination can be tuned to afford various properties and hydrophilic segments can be incorporated into the polymer to make the polymerization water based, which is considered a greener chemistry. Polyurethanes can be used to treat fabrics for water repellence and spot-removal.
  - **Barriers:** Isocyanate based chemistries have been investigated, but due to the chemical risks and regulations under REACH these substances are not used. The hazards for polyurethanes are dependent on the isocyanate/polyol combination used during polymer synthesis (Department of Toxic Substances Control (California), 2022).
- Melamine:
  - **Textile type:** can be used for all textile types, most commonly used for clothing.
  - **Properties**: as a surface coating, melamine based polymers can be used as stain repellent treatments on textiles and can be tuned to various textile applications by changing the polymer type.
  - **Barriers:** melamine has been classified as potentially carcinogenic to humans and can potentially cause damage to the kidneys and bladder. Melamine resins are commonly formed in conjunction with formaldehyde as well, which is a known carcinogen, and results in a high chance of exposure.

Research has also been conducted where the inherent textile fibre properties and the fabric construction can repel water without needing an additive coating such as natural wools, eliminating the need for a durable water repellent coating at all (RI.SE, 2022).

There is significant work being done to implement alternatives to PFAS in textiles already, and PFAS is not critical for most classes of textiles (such as durable water repellent

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[24] Nanomaterials are not necessarily a chemical group but rather a mixture of substances.

clothing and footwear sold to average consumers). Lists of alternatives for PFAS in textiles are available to manufacturers, and a number of manufacturers in the textile industry have products on the market that are PFAS free (Glüge et al., 2021). For example, a number of carpet manufacturers offer PFAS free stain protected carpets, such as Aquafil and their fibres based on a nylon-6 fibre called Econyl StayClean, Universal Fibers and their sulfonated nylon copolymer yarn, Tarkett's 'Tandus Centiva' brand which is treated with a fluorine free soil protection product, and the Condor Group which offers polyamide carpets (Glüge et al., 2021).

4.7. Initiatives to support substitution

In line with the European Green Deal[25] and Chemicals Strategy for Sustainability[26], several policy initiatives are being explored and developed by EU authorities to help the chemical industry with substitution. These include the safe and sustainable by design (SSbD) framework and the essential use concept, which are explored in this section in the context of how they may support substitution of PFAS in textiles.

Other relevant policy initiatives, not included in detail here, are the ECHA resources on how to substitute, which include guidance, online training, networks, and information on funding and technical support (ECHA, 2023a). Notably, the European Commission recently shared a tender for a project looking to identify and evaluate options to strengthen the role of substitution planning in the context of REACH and other EU chemicals legislation (European Commission, 2023a), which could in future help with PFAS substitution in textiles. More broadly, research and innovation funding, promoting upskilling, support of public-private partnerships, and other commitments under the Strategy for Sustainable and Circular Textiles (European Commission, 2022) may also support substitution.

SSbD – The European Commission set out a commitment in 2020 (in the context of the Chemicals Strategy for Sustainability) to develop EU SSbD criteria for chemicals, and to ensure the development, commercialisation, deployment, and uptake of SSbD substances, materials, and products (European Commission, 2020). The concept of SSbD is a pre-market / (re-)design phase approach to support the development of alternatives to harmful chemicals which are inherently safe and sustainable. This challenges traditional substitution approaches which often focus on functionality and performance of alternatives, which can lead to oversight of unknown hazards, in turn leading to regrettable substitution (if hazards are identified after the alternative has already been placed on the market and incorporated into product manufacturing). In contrast, the SSbD approach requires there to be a certain weight of evidence that a specific chemical (in a specific application) lacks specific environmental and human health hazards and other negative environmental / human health impacts, to improve confidence that the substance can be used as a safer and more sustainable alternative.

In July 2022, the Joint Research Centre (JRC) published a SSbD framework for the definition of criteria and evaluation procedure for chemicals and materials (JRC, 2022). This framework was formally adopted as a recommendation by the Commission in

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[25] European Green Deal

[26] Chemicals Strategy for Sustainability

December 2022 (European Commission, 2022a) and outlines how chemicals can be identified as SSbD, according to a five step assessment:

1. Hazard assessment (intrinsic properties of the chemical).
2. Human health and safety aspects in the production and processing phase (occupational health and safety aspects, e.g. exposure and associated risks, from material extraction through to waste management).
3. Human health and environmental aspects in the final application phase (application/use-specific exposure to the chemical and the associated risks).
4. Environmental sustainability assessment (environmental impacts, including and beyond those related to toxicity, along the entire life cycle).
5. Social and economic sustainability assessment (socio-economic impacts).

The SSbD framework, including these steps and general principles thereof, can be used by researchers and developers to create / discover new suitable alternatives, and by users of chemicals to identify existing suitable alternatives through an alternatives assessment. For example, there is an ongoing (2023 – 2025) Horizon Europe project to develop SSbD coating alternatives to substitute PFAS in food packaging and upholstery textiles (VTT Technical Research Centre of Finland, 2023). The project is undertaking chemical development, formulation, coating, and validation, with SSbD analysis including life cycle assessment, life cycle cost, environmental footprint, and toxicology. The SSbD framework was also applied in a scientific paper that assessed the safety and sustainability of nanomaterial alternatives[27] to PFAS in non-stick coatings for cooking utensils to show that the alternatives have a high probability to be safer and more sustainable (Pizzol et al., 2023).

Scrutinising some current / past PFAS substitution efforts can shed light on how SSbD could have facilitated better substitution. For example, RI.SE (2022) highlight that substitution of PFAS with polysiloxane or silicone may be regrettable substitution, as these chemicals may emit hazardous cyclic siloxanes (D4, D5, and D6) during manufacture. If the SSbD framework had been applied before implementing polysilixane and silicone as substitutes, it is likely that step one of the SSbD framework would have failed, discouraging their substitution, and encouraging research and development of other alternatives.

The SSbD framework has been tested in the context of the textiles sector by Novozymes as reported in June 2023 (JRC, 2023). The third case study in the report looks at an enzyme (pectate lyase) used in scouring cotton yarns and fabrics to reduce energy and chemical consumption in the process. Novozymes found challenges with the hazard-based assessment in step one of the SSbD assessment (as their substance did not pass the step), as well as finding data on exposure (noting it would be difficult for small and medium-sized enterprises (SMEs) to obtain such data), and modelling for the product environmental footprint calculation for step four.

Notably, the framework is still being tested, both by the JRC and industry (e.g. members of the SSbD network), which will ultimately feed into a guidance report (expected in 2024) and a revised framework (expected in 2025). It is therefore too early to fully predict the

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[27] In this instance, the nanomaterial alternative is a nanocomposite coating comprised of silica carbide and titanium dioxide (SiC-TiO_2).

extent which the framework can be used to support PFAS substitution, but it is thought to be significant. If, ultimately, there ends up being a list of PFAS alternatives that are SSbD, this could simplify alternatives assessments by industry to a great extent. This could have a similar effect to the existing MarketPlace tool run by ChemSec (2023), which lists safer alternatives to PFAS (although the criteria for identification of these alternatives is not SSbD). While the specific impact of ChemSec MarketPlace on PFAS substitution cannot be quantified, it is worth noting that such information is of high demand to industry. In 2018, ChemSec published that the site attracts 4,000 users a month (ChemSec, 2018).

Further testing and refinement of the SSbD framework (e.g. defining of specific criteria) will be important to facilitate utilisation by industry. In addition to the work by the JRC on the topic, the Partnership for the Assessment of Risks from Chemicals (PARC) has a thematic area to support the operationalisation of the SSbD framework (through knowledge sharing and education, as well as the development of a toolbox to give guidance to users about functionality, chemical safety, environmental sustainability, and socio-economic aspects) (EU-Parc, 2023). This further work on the concept of SSbD is important due to its complexity, as it requires collaboration of environmental scientists, toxicologists, product/chemical designers, chemists, supply chain experts, and material scientists (Hale et al., 2022). Industry representatives have also commented that data gaps, tools, and expertise are significant challenges for them to overcome in implementing the framework (Chemical Watch, 2023).

Similar guidance tools are being developed for specific sectors which could be more widely applied. For example, The AFFIRM group[28] have developed a guideline document for "brands, manufacturers, and suppliers of raw materials and chemicals to align on a common approach and definition for the phaseout of PFAS from materials used in the production of apparel, footwear, accessories, and related products. It includes a harmonised implementation and verification approach based on supply chain communication, documentation, and laboratory analytical testing" (AFFIRM Group, 2023). The Danish ministry for environment has also developed guidance documents which include a quick guide for textiles and factsheets for retailers and buyers (Danish Ministry of Environment, 2023a).

The essential use concept – Another policy tool that has been considered and could support the substitution of PFAS is the concept of 'essential use', which indicates that the most harmful chemicals should only be used where essential for society. The concept was first introduced in the Montreal Protocol, which saw the phasing out of 98% of ozone-depleting substances between 1989 and 2019.[29] It has more recently been considered in the context of PFAS substitution, both in academia (Cousins et al., 2019; Brunn et al., 2023) and in policy (European Commission, 2020). The concept can help with substitution by asking the questions: 1) whether substitution is needed (is the use of the substance critical for the functioning of society and/or necessary for health and safety); and 2)

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[28] https://afirm-group.com/

[29] Decision IV/25 of the protocol states that use of a controlled substance should qualify as "essential" only if:

it is necessary for the health, safety or is critical for the functioning of society (encompassing cultural and intellectual aspects); and there are no available technically and economically feasible alternatives or substitutes that are acceptable from the standpoint of environment and health. It also requires that the production and consumption, if any, of a controlled substance for essential uses should be permitted only if: all economically feasible steps have been taken to minimise the essential use and any associated emission of the controlled substance; and the controlled substance is not available in sufficient quantity and quality from existing stocks of banked or recycled controlled substances, also bearing in mind the developing countries' need for controlled substances.

whether sustainable substitution can be achieved (are there alternatives that are available and acceptable from the perspective of human health and the environment.

If the use of the chemical is not critical/necessary (question 1), the concept suggests that the use should be ceased without the need for substitution (i.e. it should be accepted to lose the functionality provided by the chemical, the product component containing the chemical, or potentially the final product as an entirety). The question is relevant to PFAS in a number of applications, for example, Cousins et al. (2019) note that in textiles such as casual clothing, the liquid repellence properties offered by PFAS are “nice-to-have” rather than critical/necessary, meaning it may be easier / more feasible for industry to remove PFAS from the products rather than substitute. On the other hand, they categorise the use of PFAS in occupational protective clothing as essential, suggesting that suitable alternatives for this clothing category are not yet available.

The second question under the essential use concept is similar to alternatives assessment / analysis of alternatives, which is already a well-established approach, e.g. under REACH (ECHA, 2023a). It requires that if alternatives are available, and are acceptable from the perspective of human health and the environment, then substitution should be undertaken.

One academic paper looks at the potential to combine the essential use concept with the concept of functional substitution[30] (Roy et al., 2022). To build on question 1 mentioned above, the authors propose that the first step of the essential use concept should be to ask whether the functional use of the chemical of concern is necessary for performance in the application. This step may help highlight non-essential uses even before considering criticality/necessity (which are likely to be more complex to assess). To complement this, the concept of functional substitution could be used to define performance criteria, to identify a range of performance outcomes for alternatives that can fulfil the technical function of the chemical of concern, and answer the second question (above) by looking at alternatives which fulfil the chemical function, end-use function, and/or function as a service.

Importantly, the essential use concept is currently under review by the European Commission, and further information on the concept and its potential role in EU policy is uncertain at the time of writing. This follows the support study by WSP on the concept which was published in April 2023 (WSP, 2023). When the concept is further developed it may help industry to remove and/or substitute PFAS in textiles.

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[30] Functional substitution aims to shift the focus of substitution from chemistry (e.g. identifying alternatives with similar chemical properties, which may therefore have similar toxicological properties) to functionality at different levels (chemical function, end-use function, and function as a service), which encourages the consideration of non-chemical alternatives such as different products or processes.

5. Overall conclusions

The textile industry plays a significant role in global fluoropolymer demand. It is likely to be the most polluting consumer sector with respect to PFAS, both globally and in Europe, therefore it is a key sector and consumption area to address in terms of curbing PFAS emissions. As the sector transitions towards circularity in the coming years, products are increasingly being reused and recycled and this material is kept in use for longer which results in continued negative effects of PFAS release.

PFAS are present in textiles in both polymeric and non-polymeric forms. However current knowledge is focussed on a relatively small number of non-polymeric PFAS which are known to harm the environment and human health. The impacts of many PFAS compounds (including polymeric PFAS) are less well understood, particularly in terms of their long-term behaviour in the environment. Both forms of PFAS can be released at each of the various stages of textile product lifecycles, contaminating water, soil, and air. They degrade into smaller PFAS molecules which persist in the environment thereby posing potential risks to both human health and the environment in the long term.

Human exposure to PFAS occurs through multiple pathways, including ingestion, inhalation, oral contact, and dermal contact. Health impacts are strongly suspected for PFAS as a group but these have only been directly assessed and demonstrated for a relatively small number of individual PFAS compounds. However, regulating on a one-by-one basis has led to regrettable substitution which has led to the proposal for a restriction on all PFAS (universal PFAS restriction).

Through recycling, PFAS is at greater risk of exposure to humans and the environment due to the increased risk of contamination of secondary products; and greater risk of PFAS release during recycling. Once recycled, it becomes challenging to trace the presence of PFAS in consumer products since there is no direct link to their supply chain, and manufacturers of secondary products may not be aware that their materials contain PFAS. Consequently, these materials may be repurposed in applications, or via processes, with higher risks of exposure to end-users and/or, waste handlers and may inadvertently enter recycling or reuse loops, potentially perpetuating their presence indefinitely.

Recycling also acts to disperse PFAS in a greater number of products potentially with greater risk of exposure than when the original product was initially designed. On the other hand, regulations designed to protect secondary product users currently hinder the retention of valuable materials within the economy and contravenes the circular economy targets as recyclers do not have the information they need to manage it in the safest and most efficient manner.

Regulations related to PFAS in textiles are evolving, with REACH regulations currently requiring registration for non-polymeric PFAS produced or imported in quantities above one tonne per year, but not for polymeric PFAS or finished products (articles) unless they are on the SVHC list. As a result, there is limited communication throughout the supply chain as there is no legal obligation to provide information, and it relies on voluntary information sharing.

The supply chain for textiles is complex and there is a lack of transparency in how information is shared from producer to consumer and subsequently to waste handler. As such, recyclers may reject uncontaminated feedstock materials due to concerns about potential contamination. In some cases, it may be necessary to identify and remove contaminants from materials, or to sort contaminated and non-contaminated waste. However, the lack of information about the presence of chemicals within products can make these options challenging. This requires improvements in the design of products; transmission of data; identification, separation, sorting and recycling systems; and developing the technology and capacity to destroy it effectively.

Current tracing methods and tools, such as the SCIP database, provide information on a limited number of PFAS but are insufficient in covering the majority, especially polymeric PFAS. The lack of regulatory requirements for testing textiles for PFAS concentrations hampers the monitoring of consumer products. Efforts to improve tracing methods include initiatives like the Danish Ministry of Environment's letter template for SMEs and internal tracing systems undertaken by some companies. Future potential solutions could involve ecolabeling programs, internal tracing systems, and emerging technologies like RFID tags and digital product passports.

Barriers to tracing PFAS in textiles include limitations in reporting requirements, the large number of PFAS to track challenges with developing consistent labelling and the use of RFID tags. Closer collaboration among companies in circular business models would improve data transmission, along with the establishment of requirements and standards for consistency in reporting. Transparency throughout the production line is crucial for a sustainable product, but businesses face challenges due to limited technical comprehension, resource constraints, commercial sensitivity and varying regional priorities. Addressing the complexities of PFAS tracing in textiles requires a multi-faceted approach involving regulatory enhancements, industry collaboration, and the adoption of advanced technologies to ensure transparency, sustainability, and safer end of life management practices in the textile supply chain.

After use or at end of life, European textile waste is incinerated, landfilled, or exported to less regulated destinations, raising concerns about end of life treatment and environmental contamination from PFAS. Within the EU, there is uncertainty as to whether municipal incineration sufficiently mineralises PFAS. Therefore, high temperature incineration (the only proven scaled destruction technology) is necessary although there is limited capacity to destroy the high volumes of affected material. Therefore, alternative solutions such as the use of cement kilns is being investigated alongside other emerging techniques such as photocatalysis and supercritical water oxidation which have lower environmental impacts than incineration. Further investigation is required better understand these treatment methods and develop capacity to suitably destroy PFAS at scale.

Europe is facing challenges with its growing export of used mainly to Africa and Asia. The fate of these textiles in receiving countries is uncertain but less stringent regulation and infrastructure to deal with the part of this which is waste is likely to exacerbate the issues identified within the EU. Furthermore, open burning and open dumping is likely to increase the spread of degraded PFAS. Open waste burning, which is relatively rare in Europe is a widespread practice in some developing countries. This type of burning occurs at lower temperatures compared to controlled municipal incineration, leading to the release of PFAS emissions into the air.

Ultimately it is necessary to phase out PFAS by substituting with alternatives. The textile industry is actively exploring alternatives to PFAS, evident in the market trends and ongoing research and development. PFAS-free technologies, including paraffin waxes, hyperbranched hydrophobic polymers, silicones, nanomaterials, polyurethanes, and melamine, are being investigated. Rigorous laboratory tests ensure these alternatives meet performance standards, particularly in water and oil repellence.

Initiatives such as the European Green Deal and its accompanying Chemicals Strategy for Sustainability underscore the regulatory push for PFAS substitution. The Safe and Sustainable by Design (SSbD) framework, focusing on pre-market design to ensure inherent safety and sustainability of alternatives, is in development. However, challenges and refinements persist in its application. The essential use concept also prompts evaluation of alternatives when available and acceptable from health and environmental perspectives. Some textile manufacturers have already introduced PFAS-free products, showcasing an industry response to the evolving landscape. Guidelines and tools for phaseout are being developed to align on a common approach for PFAS elimination.

Despite this, challenges remain, including potential regrettable substitutions, such as the use of silicones emitting hazardous cyclic siloxanes. Ongoing testing and refinement of frameworks like SSbD are crucial for wider industry adoption. The impact of the essential use concept on PFAS substitution awaits further review.

List of abbreviations

Abbreviation	Name
ATSDR	Agency for Toxic Substances and Disease Registry
CAGR	Compound Annual Growth Rate
CLP	Classification, Labelling and Packaging
DPP	Digital product passport
DWD	Drinking Water Directive
EA	Environment Agency
EASA	European Aviation Safety Agency
EC	European Commission
ECHA	European Chemicals Agency
EEA	European Environment Agency
EEB	European Environmental Bureau
EFSA	European Food Safety Authority
EP	European Parliament
EPR	Extended Producer Responsibility
EQSD	Environmental Quality Standards Directive
ESPR	Ecodesign for Sustainable Products Regulation
EU	European Union
EURATEX	European Apparel and Textile Confederation
FASA	Perfluoroalkane sulphonamides
FFPM/FFKM	Perfluorinated elastomers
FPM/FKM	Fluoroelastomers (vinyldiene flouride based)
FPPs	Fluorochemical production plants
FPs	Fluoropolymers

Abbreviation	Name
FTEOS	Fluorotelomer ethoxylates
FTMACs	Fluorotelomer methacrylates
FTOHs	Fluorotelomer alcohols
FTs	Fluorotelomers
GDPR	General Data Protection Regulation
HBM4EU	European Human Biomonitoring Initiative
HRMS	High resolution mass spectroscopy
IED	Industrial Emissions Directive
IPEN	International Pollutants Elimination Network
ITRC	Interstate Technology and Regulatory Council
JRC	Joint Research Centre
KEMI	Swedish Chemicals Agency
LC-MS	Liquid chromatography-mass spectroscopy
LoQ	Limit of qualification
NIEHS	National Institute of Environmental Health Sciences
NIST	National Institute of Standards and Technology
OECD	Organisation for Economic Co-operation and Development
OSHA	The Occupational Safety and Health Administration
PASF	Perfluoroalkane sulfonyl fluoride
PBT	Persistent/bioaccumulative/toxic
PFAAs	Perfluoroalkyl acids
PFAS	Per- and polyfluoroalkyl substances
PFBA	Perfluorobutanoic acid
PFCAs	Perfluoroalkyl carboxylic acids
PFDA	Perfluorodecanoic acid

Abbreviation	Name
PFHpA	Perfluoroheptanoic acid
PFHxA	Perfluoroparohexanoic acid
PFNA	Perfluorononanoic acid
PFNS	Perfluorononanesulfonic acids
PFOA	Perfluorooctanoic acid
PFOS	Perfluorooctane sulfonate
PFPE	Polymeric perfluoropolyethers
PFPeA	Perfluoropentanoic acid
PFPeS	Perfluoropentanesulfonic acids
PFSAs	Perfluoroalkyl sulfonic acids
PFTrA	Perfluorotridecanoic acid
POPs	Persistent organic pollutants
PPE	Personal protection equipment
PRODCOM	PRODuction COMmunautaire' (Community Production)
PTFE	Polytetrafluoroethylene
PVDF	Polyvinylidene fluoride
PVF	Polyvinyl fluoride
RAC	Committee for Risk Assessment
REACH	Registration, evaluation, authorisation and restricion of chemicals
RFID	Radio frequency identification
RI.SE	Research Institutes of Sweden
SCFPs	Side chain fluorinated polymers
SCIP	Substances of Concern In articles as such or in complex objects (Products)
SEAC	Committee for socio-economic analysis
SMEs	Small and medium-sized enterprises

Abbreviation	Name
SSbD	Safe and sustainable by design
STOT	Specific target organ toxicity
SVHC	Substance of very high concern
TDI	Tolerable daily intake
TFE	Tetrafluoroethylene
US EPA	United States Environmental Protection Agency
WBCSD	World Business Council for Sustainable Development
XRF	X-ray fluorescence

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Annex A. Key Terms

A list of key terms employed for the literature review are listed in the table below. Initial search was conducted by combining the search terms in the following formula. Terms within each column were combined with an 'OR' function to systematically, and efficiently gather data. More targeted searches within this formula were used to plug data gaps :

'Term 1' AND 'Term 2' AND 'Term 3'

Table A.1 Systematic literature search keywords

Term 1	Term 2	Term 3
PFAS	Home textiles	Circular economy
	Consumer apparel	Waste
	Professional apparel	Recycling
	Technical textiles	Reuse
	Textiles	Mechanical recycling
	Clothing	Chemical recycling
	Consumer	Continued release
	Homewares	Emerging technology
	Leather	Abatement
	Protection sprays	Substitution
	Shoes	Safe and sustainable by design (SSbD)
		Human health
		Environment

Annex B. Search keywords

Summary table of the different textile categories and key technical functions of PFAS as based on information (Wood. 2020).

Table B.1 Systematic literature search keywords

Textile category	Sub-category	Technical function of PFAS
Home textiles	Carpets and rugs	Water and oil repellence
	Curtains and blinds	Water and oil repellence
	Upholstery	Water and oil repellence
Consumer apparel and accessories	Indoor and outdoor clothing	Water repellence
	Sports wear	Water and oil repellence
	Footwear	Water and oil repellence
	Accessories e.g. umbrellas	Water repellence
Professional apparel	Professional sports wear and footwear	Water and oil repellence
	PPE for industrial applications	Water and oil repellence
Technical textiles	Outdoor technical textiles e.g. canvas, awnings, tents etc.	Water and oil repellence, stain resistance and soil protection
	Medical application e.g. surgical gowns, curtains.	Water and oil repellence and stain protection
	High performance membranes	Water and oil repellence, stain resistance and flame retardancy
Leather	Leather based goods	Water and oil repellence
	Indoor and outdoor wear	Water and oil repellence
	Footwear	Water and oil repellence
Other	Home fabric treatments – leather	Water and oil repellence and stain and soil resistance

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