BEHIND THE BREAK

EXPLORING FIBRE FRAGMENTATION

2025

The Microfibre Consortium

FASHION FOR GOOD

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ABOUT **US**

Fashion for Good unites the entire fashion ecosystem, from brands, retailers, suppliers, innovators, and funders to collaborate and drive change towards a regenerative industry. At the core, Fashion for Good enables disruptive innovators on their journey to scale, providing hands-on support, connection to capital, and access to a robust ecosystem of experts. This work brings the most powerful innovations to market faster to create decisive system change. Through its coalition of partners, Fashion for Good designs and executes catalytic interventions and new ways of value creation that drive towards the right side of history as the new economy emerges.

This transformative work is made possible by the support of Laudes Foundation, co-founder William McDonough and corporate partners, adidas, Arvind Limited, BESTSELLER, Birla Cellulose, C&A, CHANEL, Inditex, Kering, Levi Strauss & Co., Norrøna, ON, Otto Group, Paradise Textiles, Patagonia, PDS Limited, PVH Corp., Reformation, Shahi Exports, Target, Teijin Frontier, and Zalando.

The Microfibre Consortium (TMC) is a non-profit, science-led, organisation with a vision to work towards zero impact from fibre fragmentation from textiles to the natural environment. TMC works to connect and translate deep academic research with the reality of commercial supply chain production. TMC's goal is to offer solutions to brands, retailers and manufacturers to transform textile production for the greater good of our ecosystems. Driven by research, with industry change at its core, TMC addresses the issue of fibre fragmentation, convening the global textiles sector to limit fibre fragmentation and fibre fragment pollution. Through interventions in design and development and in manufacturing TMC takes a holistic approach creating change for the whole product lifecycle.

THE SCOPE OF THIS REPORT

In early 2024, Fashion for Good and The Microfibre Consortium joined forces to address the issue of fibre fragmentation. Building on a solid foundation of existing knowledge, this collaboration aims to investigate the key drivers of fibre fragmentation, provide an overview of the critical gaps and identify the action required to advance industry-wide interventions and solutions. Although fibre fragmentation is an issue that spans multiple industries, this initiative focuses on the textile and fashion value chains, aligning with the mission of Fashion for Good and its partners. This report provides a comprehensive overview of fibre fragmentation within the fashion and textile industry, highlighting recent developments, critical insights, and the emerging opportunities for meaningful action.

Beyond this report, FFG and TMC have launched a homonymous project **'Behind the Break: Exploring Fibre Fragmentation',** a landmark study investigating the key drivers of fibre fragmentation. The project brings together major fashion brands and manufacturers including adidas, Bestseller, C&A, Inditex, Kering, Levi Strauss & Co., Norrona, ON, Paradise Textiles, and Positive Materials, with Under Armour joining as a project partner. Testing will be conducted across three laboratories - Paradise Textiles, Under Armour, and IMPACT+ Network from Northumbria University—to analyse fibre fragmentation in cotton knit, cotton woven, and polyester knit fabrics. The research aims to challenge root causes and assumptions, address data gaps, and validate test methods. Tackling the issue at the source, this project will advance the industry knowledge needed to mitigate fibre fragment pollution.

ABBREVIATIONS

AATCC	American Association of Textile Chemists and Colorists
ASTM	American Society for Testing and Materials
C2CPII	Cradle to Cradle Products Innovation Institute
CEN	European Committee for Standardization
CH_4	Methane
CO_2	Carbon Dioxide
CSRD	Corporate Sustainability Reporting Directive
DIA	Dynamic Image Analysis
ECCC	Environment and Climate Change Canada
EPR	Extended Producer Responsibility
ESPR	Ecodesign for Sustainable Products Regulation
ESRS	European Sustainability Reporting Standards
ETP	Effluent Treatment Plant
EU	European Union
FFG	Fashion for Good
FT-IR	Fourier Transform Infrared
GCD	Green Claims Directive
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
MMCF	Man-Made Cellulosic Fibre
MMF	Man-Made Fibre
NFRD	Non-Financial Reporting Directive
PAH	Polycyclic Aromatic Hydrocarbon
PBS	Poly(butylene succinate)
PCB	Polychlorinated Biphenyls
PCL	Polycaprolactone
PEF	Product Environmental Footprint
PFAS	Polyfluorinated Alkyl Compounds
PLM	Polarising Light Microscopy
QCL-IR	Quantum Cascade Laser Infrared
REACH	Regulation on the Registration, Evaluation, Authorisation and Restriction of Chemicals
R&D	Research & Development
SEM	Scanning Electron Microscopy
TMC	The Microfibre Consortium
TSS	Total Suspended Solids
US	United States
WFD	Waste Framework Directive
ZDHC	Zero Discharge of Hazardous Chemicals
µm	Micrometre
mm	Millimetre

KEY WORDS

Aerobic degradation: The breakdown of organic pollutants by microorganisms when oxygen is present.

Anthropogenic: Resulting from the influence of human beings on nature.

Bioaccumulation: The accumulation over time of a substance and especially a contaminant (such as a pesticide or heavy metal) in a living organism.

Bioavailable: The degree and rate at which a substance is absorbed into a living system or is made available at the site of physiological activity.

Biobased: A product wholly or partly derived from biomass, such as plants, trees or animals.

Biodegradation: Biodegradation is the breakdown of organic materials by microorganisms into simpler substances like CO_2, CH_4, water, biomass, and mineral salts under under oxygen-rich or oxygen-deprived conditions, defined by specific timeframes and environmental conditions.

Biomass: The biodegradable fraction of products, waste and residues from agriculture (including vegetal and animal substances), forestry and related industries, as well as the biodegradable fraction of industrial and municipal waste.

Biota: All the organisms living in a particular environment, including plants, animals, and microorganisms.

Brightfield Microscopy: Uses light to illuminate a sample placed on a glass slide and creates an image. The light passes through the sample, and an objective magnifies the image and projects it onto an eyepiece or a camera.

Cellulose I: The primary component of natural plant fibres, the cellulose found in nature.

Cellulose II: Called regenerated cellulose, describes the cellulose prepared by precipitating the dissolved cellulose into an aqueous medium. It is prepared using the mercerisation process, treating native cellulose in caustic soda.

Effluent Treatment Plants: A treatment facility/plant that reduces, alters, or eliminates pollutants in wastewater discharge prior to release of the water into the environment via a combination of various treatment processes (e.g. physical, chemical and biological). Wastewater treatment plants may be privately owned and operated by the enterprise creating the wastewater, or they may be owned and operated by a private or public third-party.

End-of-Use: The stage where products are no longer usable or wanted, so are either discarded, recycled, or repurposed.

Environmental Compartment: The different parts of the environments where fibre fragments can move through, accumulate, and interact with ecosystems. These include air, water, terrestrial, and biota.

Emission: The production and discharge of something, especially gas.

Fibre: A material which is transformed into yarn (and typically into fabric and then finished products).

Fibre Characterisation: Microscopic and analytical techniques used to identify and evaluate the physical and chemical properties of a fibre(s) within a sample, including composition, structure, and morphology in order to determine its type.

Fibre Fragment: Any processed fibrous material broken from a textile structure during production, use, end-of-use, as well as through its subsequent breakage in the natural environment.

Fibre Fragmentation: The process of fibre loss from a textile product during its life cycle and / or through its subsequent breakage in the natural environment. This is also referred to as fibre shedding.

Fibre Loss: Quantity of fibres that unintentionally leaves a managed product or waste management system during manufacture, consumer use/wear and end-of-use.

Fibre Release: Fractions of fibre loss that are ultimately released into different environmental compartments: water, air, terrestrial environments.

Food Dilution: The process where ingested particles occupy space in the gut, reducing the available space for essential digestive processes and potentially hindering proper food intake or nutrient acquisition.

Gravimetric Analysis: A class of lab techniques used to determine the mass or percentage mass of a substance by measuring a change in mass.

GyroWash: James Heal's equipment for conducting the colour fastness test.

Hydrophobic: Water repelling

Life Cycle: Consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal.

Man-Made Fibre: A material whose chemical composition, structure, and properties are significantly modified during the manufacturing process. They can derive from synthetic or natural polymers.

Membrane Filtration: Filtration process that uses a selective barrier, called a membrane, to separate particles based on their size, allowing smaller molecules to pass through while retaining larger ones.

Mechanism of Toxicity: Describe how the exposure of the chemical and physical properties of a toxicant leads to adverse effects in an organism.

Microscope: An instrument that makes an enlarged image of a small object, thus revealing details too small to be seen by the unaided eye.

Morphology: In biology, the study of the size, shape, and structure of animals, plants, and microorganisms and of the relationships of their constituent parts.

Nanoparticle: Ultrafine nano-object with all external dimensions in the nanoscale (nm; 1 nm = 10-9 metre) where the lengths of the longest and the shortest axes of the nano-object do not differ significantly.

Natural Fibre: A material that is produced by geological processes, or from the bodies of plants or animals. Examples include cotton, wool, silk, and flax.

Oxidative Stress: A condition that may occur when there are too many unstable molecules called free radicals in the body and not enough antioxidants to get rid of them. This can lead to cell and tissue damage.

Pathway: A route by which fibres are released to the environment following loss from a textile product. Different types of transfer pathways lead from loss to release. For example, wastewater, air or soil.

Polarising Light Microscopy: A technique which employs the use of polarising filters to obtain substantial optical property information about the material which is being observed.

Processed Fibre: Any fibre which undergoes some form of chemical or mechanical processing to be used for the fashion and textile industry. This includes natural fibres which are mechanically or chemically processed from their raw unprocessed within the environment, as well as Man-Made fibres derived from synthetic or natural polymers.

Raw Fibre: Textile fibres, as cotton or wool, or textile filaments, as silk or nylon, that have received no manipulation or treatment.

Root Cause: Determination of the variables that cause unintentional fibre loss and could be addressed through process improvement of material design and development to prevent it occurring during manufacture, use or end-of-use.

Secondary Clarifiers: Filtration process in which microorganisms and solids from treated wastewater settle at the bottom, forming activated sludge. The clarified water is then returned to the aeration tank with the cycle repeating until the effluent is clean before sent for filtration and/or disinfection. Waste sludge is removed and thickened prior to the digestion process.

Shedding: The process by which textile fibres are unintentionally lost from a textile. Also referred to as (fibre) loss.

Softener: A finishing agent that when applied to textile material improves its handle giving a pleasing touch.

Source: The origin of fibre fragments, including manufacturing, consumer use and end-of-use stages.

Synthetic Fibre: A Man-Made Fibre derived from fossil-fuels. Examples include polyester, polyethylene, acrylic, and elastane.

Terrestrial Environment: Covers the soil and soil/air interface and the associated biological communities.

Total Suspended Solids: A measure of the suspended solids in wastewater, effluent, or water bodies.

Translocation: The process where organisms ingest particles, which then move from the gut into other organs, potentially causing biological issues.

Ultrafiltration: One of membrane filtration techniques in which external hydrostatic pressure pushes a liquid through a semipermeable membrane that is capable of removing target compounds from the bulk solution.

1dtex: The dtex number indicates how many grams a sewing thread of 10,000 m length weighs. Example 1 gram for 10,000 meters of fibre.

EXECUTIVE SUMMARY

Fibre fragments are released into the environment at various stages of a textile's lifecycle, including manufacturing, processing, use, and end-of-use. These fibre fragments are recognised as pollutants with proven impact on the environment and human health. Within the fashion and textile industry, a highly effective and critical approach to addressing fibre fragmentation is at its source by developing textiles with a lower propensity to shed. This involves understanding the root causes of fibre shedding and using this knowledge to inform changes in textile design and manufacturing. However, given the complexity of the problem, which spans the entire lifecycle of a textile, this approach cannot address the issue in isolation. A portfolio approach is required, implementing various interventions across the entire value chain, including industrial-level filtration systems and consumer-level interventions.

While significant progress has been made to understand fibre fragment pollution, critical knowledge gaps remain, hindering progress within the industry. Table 1 provides an overview of these gaps, which will be expanded upon throughout the report.

Table 1: Knowledge gaps on Fibre Fragmentation

TOPICS	KNOWLEDGE GAPS
Sources	• Impact of drying, wearing, and environmental (UV) exposure during the use stage on fibre loss • Impact of diverse practices within the use stage (hand washing, dry cleaning, line drying) • Impact of the manufacturing and use stage on airborne fibre pollution • Impact of end-of-use practices on fibre pollution to air, water and biota
Pathways	• Airborne fibre fragments and their interaction with terrestrial environments and biota • Connection between wastewater pathways and fibre pollution in terrestrial environments • Connection between indoor contamination and other subsequent environmental compartments
Root Causes	• Impact of textile design and manufacturing factors, such as yarn type, spinning method, staple length and the various processing steps (pretreatment, dyeing, finishing)
Biodegradation	• Impact of environmental conditions within compartments where fibre fragments are most likely to accumulate • Impact of environmental conditions and material properties in water-based testing (especially in marine environments) • Impact of various mechanical and chemical processing methods on the ability of fibre fragments to biodegrade
Toxicity	• Relationship between fibre size and toxicological effects • Impact of the by-products and nanoparticles which form during the biodegradation process • Understanding the mechanisms and processes that drive the toxicity of fibre fragments, including the roles of their physical characteristics (e.g., size, shape) and chemical properties (e.g., additives or adsorbed contaminants) • Toxicological effects in terrestrial environments (e.g., agricultural fields) and atmospheric exposure pathways (e.g., inhalation).

Researchers, industry stakeholders, and policymakers are actively working to address knowledge gaps, alongside exploring solutions to mitigate fibre fragment pollution. During the research conducted in the lead-up to this report, it became clear that across geographies and areas of expertise, it is essential to align on common goals and directions to advance progress in all areas. This alignment is specifically critical to tackle four priority topics, which can subsequently contribute to informing policy and the development of targeted solutions and innovations in the space:

Test Methods: Testing driven by a clear purpose that supports the needs of those conducting the test, ensuring the data collected is comparable and reliable across stakeholders and organisations. This approach will lead to actionable mitigation strategies and the development of best practices.

Sources & pathways: Identifying the most significant hotspots for fibre release into different environmental compartments, especially focusing on understudied pathways such as air and terrestrial environments. This will enable prioritisation of research and intervention efforts.

Root Causes: Conducting targeted research to address key knowledge gaps and advance the overall understanding of fibre fragmentation, with a focus on designing fabrics with a lower propensity to shed.

Impact: Bridging the gap between the industry and scientific community to conduct research that evaluates the true impact of fibre fragment pollution on human health and the environment.

DEFINITION

The **lack of a standardised definition in the fashion and textile industry** creates ambiguity, hindering efforts to address fibre fragmentation. The common term ‘microfibre’ clashes with existing industry terminology, which refers to a fine synthetic yarn with a count of 1 dtex or less, emphasising diameter rather than length or size. Similarly, the term ‘microplastic’ is also widely used, but it is reductive, as it typically only applies to synthetic particles. For this reason, this report uses the term ‘**fibre fragment**’ as it captures fibres which shed from all fibre types, the fibrous structure of particles released from textiles, and reflects the action by which a fibre is released from the main textile construction. However, the discourse extends beyond naming conventions to the inclusion of specifications in the definition, such as size limits and the classification of sources, to distinguish between raw, unprocessed natural fibres found in the environment, and those that undergo mechanical or chemical processing. Many advocate for adding terms like ‘processed’ or ‘modified’ within the definition.

A clear working definition, with any relevant specifications, is essential to guide research, ensure comparability and inform policy discussions.

HOW WE AIM TO CONTRIBUTE

By proposing the following working definition for the scope of the collaboration between Fashion for Good and The Microfibre Consortium:

Fibre fragments: Any processed* fibrous material broken from a textile structure during production, use, end-of-use, as well as through its subsequent breakage in the natural environment.

* Processed is intended to encompass fibres that have undergone any form of mechanical or chemical processing. This includes natural fibres that are no longer in their raw, unprocessed state as found in the environment, as well as Man-Made fibres derived from synthetic and natural polymers. See Section 1 on Definition.

PROPOSED INDUSTRY ACTION

To adopt a clear overarching definition which captures all fibre types that have undergone any form of mechanical or chemical processing within the fashion and textile value chain. To supplement the overarching definition, it is important to include further specifications—such as size limits and diameter thresholds—if relevant, based on the scope and purpose of the study to ensure clarity and context. Clearly stating these are crucial to ensuring findings are communicated, understood, and actionable.

SOURCES AND PATHWAYS

The sources and pathways of fibre fragment pollution are complex and interconnected. **Despite significant progress, there are still gaps in understanding the contributions from each source and how the fragments travel across different environmental compartments, including water, air, and terrestrial environments.** These gaps hinder the ability to accurately assess exposure and risk, and subsequently develop effective interventions. To address this, a lifecycle approach is essential, enabling a comprehensive evaluation of the various pathways and timeframes involved in fibre fragmentation—from the direct release to their redistribution into other key environmental compartments (water, air, terrestrial) and living organisms (biota):

Water: Existing research has predominantly focused on fibre fragmentation during washing, particularly machine washing common in the Global North. Alternative washing methods, such as handwashing prevalent in the Global South remain underexplored. Further research that includes diverse washing practices is necessary to build a more global and comprehensive understanding of the sources and pathways of fibre fragments.

Air: Airborne fibre fragments have received comparatively less attention, despite their significant role in pollution as they travel through environmental compartments. Addressing this knowledge gap is vital for understanding the full extent of fibre fragment pollution.

Terrestrial: The terrestrial environment, and its connection to air, water, and biota remains largely unexplored. Investigating how fibre fragments interact with terrestrial ecosystems at various environmental touchpoints is essential for understanding their broader impact.

HOW WE AIM TO CONTRIBUTE

TMC is assessing the feasibility of developing a standardised test method to measure fibre fragment pollution to air during a garment's use stage. This work is being conducted in collaboration with IMPACT+ research team and Northumbria University and will contribute to assessing the risks associated with airborne fibre fragments.

PROPOSED INDUSTRY ACTION

Stakeholders within the fashion and textile industry, including brands and manufacturers, should design garments that promote better practices by incorporating current knowledge on fibre fragmentation alongside other impact metrics.

ROOT CAUSES

Fibre fragmentation occurs across the entire textile's lifecycle, with the textile itself serving as the ultimate source of fibre fragments. **Understanding why certain fabrics shed more than others is crucial for enabling the development of effective interventions within textile design and manufacturing.** Despite ongoing research efforts, significant knowledge gaps persist, hindering progress. Bridging these gaps is critical, yet several barriers exist:

Testing Methods: Existing methods are designed to assess fibre loss under simulated washing conditions using fabric swatches to enable root cause understanding. However, these do not provide sufficient data for product-level analysis as well as understand the shedding behaviour via atmospheric pathways.

Standardisation: The variety of methodologies and design of experiments used across the industry complicates the generation of comparable data across studies.

Interdependence of Factors: Fabrics behave differently, and the interdependence of factors along the supply chain (e.g., fabric construction, dyeing, finishing) makes it difficult to generalise results across fabrics. While identifying trends to prioritise key influencing variables is essential, strategies should be informed by both broad data and the unique characteristics of each fabric.

Balancing Commercial Needs: Research must align with industry needs, ensuring solutions do not compromise the fabric's overall quality, durability, or market appeal.

HOW WE AIM TO CONTRIBUTE

Behind the Break: Exploring Fibre Fragmentation, is a landmark study investigating the key drivers of fibre fragmentation. It will test the influence of individual manufacturing factors on a fabric's propensity to shed, within real supply chain conditions, to cover data gaps as well as challenge current assumptions derived from existing databases and research findings.

TMC is developing a research strategy based on the results of their root-cause analysis conducted in 2024, to further validate findings in commercial supply chain conditions.

PROPOSED INDUSTRY ACTION

Support collaborative effort to consolidate findings across key ecosystem players to identify potential correlations between the different data sources, assess if findings are complementary, and address any discrepancies.

Raise awareness across the industry to promote further research into the knowledge gaps within key manufacturing stages (both mechanical and chemical), enabling the development of best practices for textile design and manufacturing.

TEST METHODS

A range of standardised test methods are used to assess fibre fragmentation in textiles, but there is ongoing discourse on their best-use cases and their inherent limitations. Key concerns include the depth of analysis, data consistency, accessibility, and inability to address all sources of fibre fragments.

A fundamental consideration when employing test methods is understanding the purpose of the data collected and how it will be utilised. Existing methods have been designed to understand root causes by enabling fabric-to-fabric comparisons of their propensity to shed fibres, which helps identify key influencing factors. Therefore, from an environmental and human health perspective, this data alone does not provide information on the environmental consequences of fibre fragments within the environment. From a policy perspective, the data is not applicable to a finished product as significant assumptions are required to extrapolate fibre loss from a fabric swatch to an entire product. Furthermore, current test methods do not account for fibre release into the air. From an industry perspective, the primary objective is to produce textiles with a lower propensity to shed. While the data generated can inform this goal , there is ongoing debate about the level of analysis required. Gravimetric analysis measures the fibre loss by weight, offering clear and straightforward insights into shedding behaviour of fabrics. However, fabric characterisation techniques could offer additional understanding of fibre composition, morphology, and the presence of other polymers and additives. **These contaminants, which have no relation to the true shedding behaviour of the fabric, may skew results by contributing to the total weight of fibre discharge. Currently, the extent of this error remains uncertain, adding a significant 'noise' factor to the data.** To address these concerns, several steps could be taken:

Evaluation of limitations: Assess the limitations of available test methods to clarify the best use case. Compare data collected using different test methods to assess how the test methods can be improved or complement each other.

Account for other key sources: Create standardised test methods that account for other key pathways, such as air, to gain a more realistic understanding of the extent of fibre fragments released into the environment, and subsequently develop effective mitigation interventions at key hotspots.

Standardised Testing Protocols: Establish clear testing protocols including a robust and appropriate definition for the scope of the work. Adding, if relevant, supplementary specifications to enable consistency and comparability of the collected data.

Accessibility: Make test methods scalable and accessible for widespread adoption across the supply chain, driving manufacturers and brands to introduce testing protocols within their regular operations.

HOW WE AIM TO CONTRIBUTE

This Report contributes to this topic by casting light on the differences and best use cases for each existing test method. See Chapter 4: Test Methods.

The collaborative project Behind the Break: Exploring Fibre Fragmentation will generate data stemming from the testing of various fabric archetypes, leveraging multiple test methods, including existing quantification methods and fibre characterisation techniques. This approach will not only identify the best use cases and limitations of each method but will also explore whether test methods can complement one another to address those limitations. Additionally, the project will investigate the ‘noise factor’ introduced by contaminants—such as other polymers or additives—within a sample, providing greater clarity on the extent to which these elements skew results and how this error can be mitigated.

TMC and ZDHC have collaborated to tackle the issue of fibre fragments within wastewater. They have identified a correlation between Total Suspended Solids (TSS) and fibre fragment concentrations, offering a promising approach for simplifying monitoring processes in wastewater treatments. Building on this work, they are now planning to conduct further studies to validate the correlation and build confidence in the use of TSS as an indicator for fibre fragments in wastewater.

PROPOSED INDUSTRY ACTION

The industry is encouraged to come together through a panel of experts or working groups to evaluate the scalability, cost-effectiveness, accessibility and deployment of current test methods. This should lead to establishing testing protocols which are required for different studies and work scopes.

It is crucial for the industry to align on standardised testing protocols, determining which methods should be implemented (individually or in combination) as part of routine quality control for brands, retailers, and manufacturers. Such alignment will enable better monitoring on the production of textiles with a lower propensity to shed.

SOLUTIONS PORTFOLIO

The key strategy to address fibre fragmentation at its source is the understanding of root causes to inform more responsible textile design and manufacturing. However, given that fabrics will continue to shed even if at a lower rate, interventions across the value chain are needed, from industrial-level filtration systems and consumer-level interventions. **Thinking systemically and following a ‘solutions portfolio’ approach is key to significantly mitigate the issue of fibre fragmentation.**

Root Causes: Textile design and manufacturing factors significantly influence fibre fragmentation. Understanding the extent of the influence of each given factor is crucial for reducing fibre loss throughout the lifecycle of a textile. For example, pretreatments that reduce protruding fibres like biopolishing, alternative dyeing that maintain the integrity of the fabric, and abrasion-resistant finishes show promise, but more research is required to identify best practices.

Industrial-Level Filtration: Air and water filtration systems help reduce the amount of fibre fragments released into the environment, though high costs and the required expertise limit their accessibility and effectiveness across facilities, especially in smaller operations. Monitoring TSS levels have shown to serve as a reliable proxy, offering a cost-effective way to track effluent quality.

Consumer-Level Interventions: Domestic filtration technologies (e.g., washing machine filters) and consumer behaviour changes (e.g., gentler wash cycles) provide a straightforward approach for individuals to contribute to mitigating fibre fragment pollution. Public awareness campaigns are needed to educate consumers on the environmental benefits of adopting these simple actions.

Innovation: Innovations designed to reduce a textile's propensity to shed are still in their early stages. Further validation is required to assess their efficacy, costs, commercial viability, and wider environmental impact implications such as increased CO_2 emissions. Fibre fragment pollution is not yet recognised in Life Cycle Assessments (LCA), which are commonly used by the industry as a tool to assess the environmental impact of new innovations and strengthen the case for their adoption.

HOW WE AIM TO CONTRIBUTE

The project Behind the Break: Exploring Fibre Fragmentation Project will test the influence of individual design or manufacturing factors (one at the time) in a matrix-based approach to reveal the drivers of fibre shedding. These insights will become key levers to support brands and manufacturers in understanding the interventions that can be made at a design level. Additionally, this knowledge base could inform the development of new solutions that target specific root causes to reduce fibre fragmentation.

TMC and ZDHC are collaborating to empower the manufacturing community with robust approaches to tracking and mitigating fibre fragmentation in manufacturing effluent with the intent to set maximum allowable limits for fibre fragments in discharged effluent.

PROPOSED INDUSTRY ACTION

Develop a framework to validate potential solutions against conventional benchmarks across laboratory, pilot, and industrial scale to assess the benefits of the technology across impact, performance & cost with the aim to build a solution's portfolio for the wider industry.

Engage with experts within the space to assess facility hotspots and develop bespoke strategies and interventions to address fibre fragmentation in the supply chain with existing validated solutions.

BIODEGRADATION AND TOXICITY

Significant knowledge gaps remain regarding the environmental impact of fibre fragments, both in terms of biodegradability and toxicity. A clear distinction is needed between these two aspects to consider the by-products and nanoparticles that persist in the environment and may pose risks.

BIODEGRADATION

Enhancing the biodegradability of textiles is considered a potential solution to fibre fragment pollution, as biodegradable fibre fragments are less likely to persist and accumulate in the environment. However, biodegradation is influenced by various factors, including environmental conditions, material properties, and the mechanical and chemical processes employed during manufacturing. This complexity leads to variability in biodegradation rates, complicating accurate assessments.

Laboratory testing limitations: Current laboratory tests often fail to replicate real-world conditions and take into account the transient nature of fibre fragments as they move through the environment. There is a need for more comprehensive experiments that better reflect harsh or diverse environments and include representative organisms from specific ecosystems. Without this, there is a gap between lab results and actual biodegradation in nature, hindering the reliability and applicability of results.

Standardisation Gaps: The absence of standardised methodologies and testing criteria for biodegradability continues to create uncertainty in biodegradability claims. Existing metrics, such as molecular weight reduction, only measure partial breakdown and do not assess the full transformation of materials into harmless by-products. There is a need to establish clear, standardised testing criteria and thresholds for biodegradability, ensuring transparent and accurate claims.

TOXICITY

The toxicity of fibre fragments varies depending on factors such as material composition, chemical treatments, and environmental interactions. However, their toxicity remains underexplored, with the mechanisms behind their effects—which may be physical or chemical—still not fully understood. This hinders the ability to address the potential risks they pose.

Lack of Standardisation: Fibre fragments are distinct from microplastics and are highly heterogeneous in physical properties and chemical profiles, making it difficult to establish consistent baselines and controls. Harmonising testing materials, such as standardised reference fibres, would improve comparability and reliability across studies. Collaboration between academia and the fashion and textile industry is needed to ensure transparency around material specifications and the chemicals and processes used.

Environmental Relevance: Many studies use high concentrations of fibre fragments that do not reflect conditions in the natural environment, and existing research has largely focused on aquatic environments, overlooking terrestrial and atmospheric pathways. Experimental test designs should better reflect diverse environments where fibre fragments accumulate, as their behaviour and impacts vary significantly across different contexts.

HOW WE AIM TO CONTRIBUTE

Bridge the gap between industry and science by convening industry-relevant academic research, ensuring an open communication channel is created in which key information can be exchanged. This information can support the better design of experiments.

PROPOSED INDUSTRY ACTION

Researchers should collaborate more closely with the industry to improve and support the quality of studies by providing insights into materials, chemicals, and processes used within the fashion and textile industry. This collaboration could lead to:

- Creating a pool of standardised test materials and reference fibre fragments characterised by their physical and chemical properties. These materials could serve as benchmarks to evaluate biodegradability and toxicity under various conditions, enhancing the consistency and comparability across studies.
- Ensure transparency into the chemicals and processes used throughout textile manufacturing to better reflect textiles in their processed state and better understand the drivers of toxicity and biodegradability.

REGULATION

As awareness on the impact of fibre fragments grows, policymakers are under increasing pressure to act. However, progress on tangible interventions is still in its early stages due to the focus on plastic pollution and significant knowledge gaps. Most efforts related to fibre fragments from the fashion and textile industry are exploratory and concentrated in the Global North. Europe is leading the way with discussions on policies aimed at addressing fibre fragments across multiple stages, including manufacturing and product design. While progress is slightly slower in North America with efforts primarily focused on implementing washing machine filters.

Knowledge Gaps: There are significant knowledge gaps regarding the causes of fibre fragmentation and its impact on the environment and human health. Closing these gaps requires further research across the entire lifecycle of textiles. Collaboration between industry, government, and researchers is essential to inform future policies and regulations, ensuring that the latest scientific evidence is incorporated and the industry's readiness to meet regulatory requirements is assessed.

Test Methods: Existing methods assess fibre fragmentation under simulated laundering conditions using fabric swatches. While these methods provide valuable insights into the root causes, they hold limitations in regulating finished products as they require significant assumptions to extrapolate the data to reflect fibre loss at a product level and they fail to account for the fibre loss from other sources, such as air.

Impact: Existing methods focus on understanding the drivers of fibre fragmentation, but they fail to assess the environmental impact of fibre fragments. Biodegradability, chemical load, and toxicity must be considered in addition, and separately, to quantity.

HOW WE AIM TO CONTRIBUTE

TMC Policy Committee is leveraging scientific expertise to provide policymakers with comprehensive insights into the broader impacts of fibre fragmentation to ensure that policy decisions are rooted in a full understanding of the available science. This includes the status of science, test methods and potential solutions.

PROPOSED INDUSTRY ACTION

Drive momentum and awareness necessary to address the challenges posed by fibre fragments by ensuring that all fibre types are included in policy discussions, supporting the adoption of a unified definition, along with supplementary specifications to help create a consistent framework, and encouraging further research to close existing knowledge gaps. These combined efforts will drive meaningful progress in generating actionable insights needed to develop effective mitigation strategies.

Governments should incentivise the adoption of filtration systems in both residential and industrial facilities, where their potential to reduce fibre fragments entering the environment is better understood. Incentives could include subsidies, tax credits, or grants, particularly in regions where cost remains a barrier. Furthermore, Extended Producer Responsibility (EPR) frameworks could require appliance manufacturers to integrate and maintain fibre fragment filtration systems in their products, ensuring that consumer-level solutions are not only effective but also widely accessible.

INTRODUCTION

The fashion industry is a global force, producing over 100 billion garments per year.[1] Therefore, its widespread impact on the environment has long been a key topic of conversation. A growing concern gaining increased attention is the issue of environmental pollutants known as fibre fragments. In this report, we have deliberately chosen the term ‘fibre fragment’ over ‘microfibre’, defining it as “any processed fibrous material broken from a textile structure during production, use, end-of-use, as well as through its subsequent breakage in the natural environment’. The distinction of these terms and the rationale behind this definition will be explored in Chapter 1: Definition. While the definition of fibre fragments varies across industries and fields of research, the premise for the fashion and textile value chain is that fibre fragmentation is the process of fibre loss from a textile during its life cycle and their subsequent release into the environment. Fibre fragments have been found in almost every environment on earth, and numerous studies have not only demonstrated their highly persistent nature, but also their potential negative effect on the environment, organisms and human health.[2,3] This underscores the urgency of comprehensively addressing the issue.

The field of fibre fragmentation is complex and multifaceted, which has led to a diverse range of players across different geographies, each focusing on distinct areas within research, policy, and R&D. While these efforts are invaluable, there remains a lack of clarity around the roles and responsibilities of various stakeholders, established knowledge, and the remaining knowledge gaps. This lack of clarity has led to a limited strategic direction within the fashion and textile industry. The collaboration between Fashion for Good (FFG) and The Microfibre Consortium (TMC) led to a series of workshops which brought together experts in this space. The workshops dove into seven key topics related to fibre fragmentation, providing a framework for understanding this multifaceted issue, and forming the backbone of this report which highlights recent developments, critical insights, and the emerging opportunities for meaningful action. See Appendix for more information regarding the structure of the workshops. The topic is explored through the following chapters:

Chapter 1: **DEFINITION**

Chapter 2: **SOURCES AND PATHWAYS**

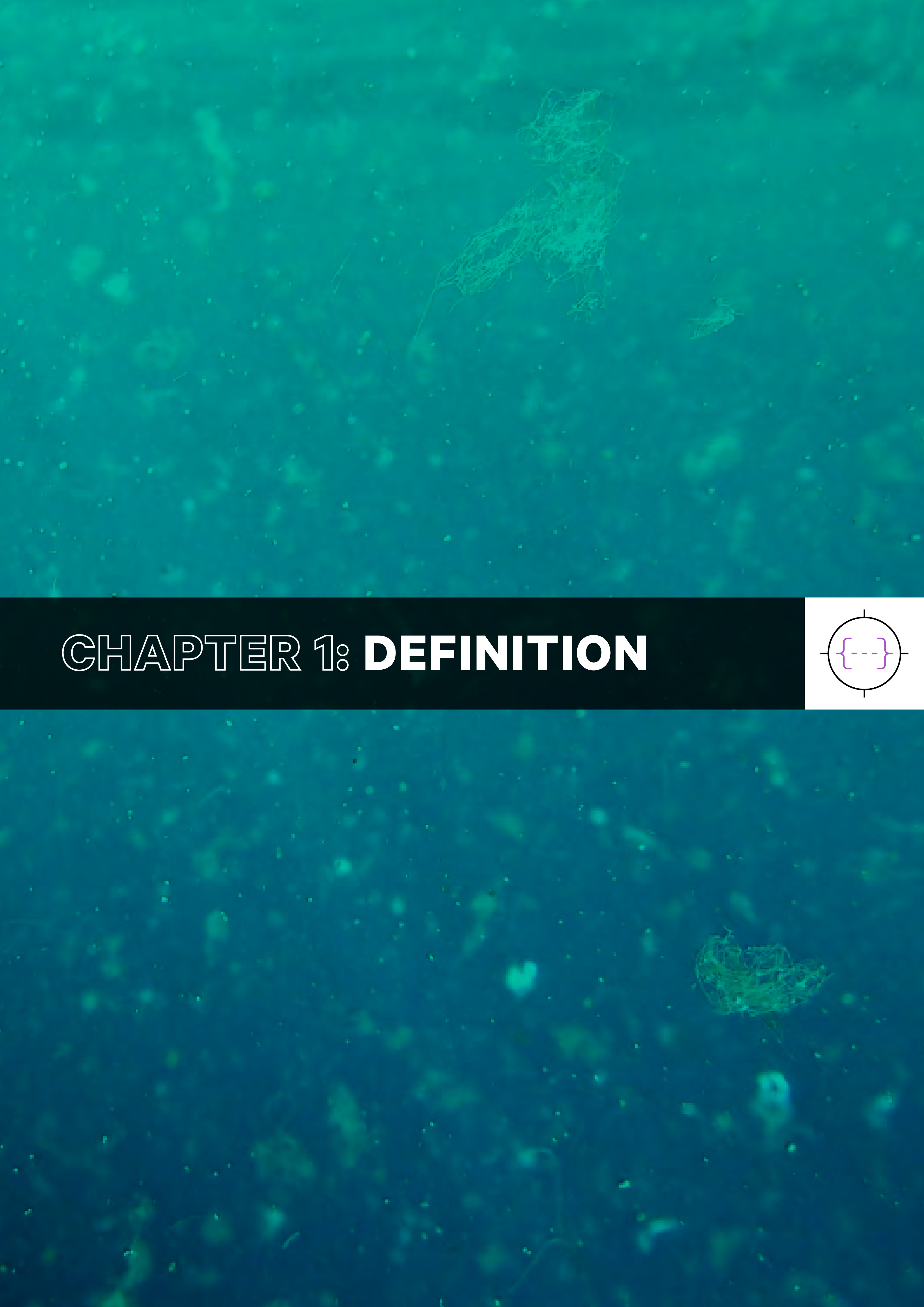
Chapter 3: **ROOT CAUSES**

Chapter 4: **TEST METHODS**

Chapter 5: **SOLUTION PORTFOLIO**

Chapter 6: **BIODEGRADATION AND TOXICITY**

Chapter 7: **REGULATION**



CHAPTER 1: DEFINITION

The emerging concern regarding the presence of fibre fragments (also commonly referred to as microfibres) in the environment is relatively recent, primarily brought to light by the pioneering work of Thompson, who reported their widespread presence in coastal sediments and waters in the UK.[4] Since then, their anthropogenic presence has been well-documented. They have been found in almost every environment on earth; marine and freshwater environments, wastewater, stormwater, terrestrial environments and air.[5] They are easily carried and dispersed, accumulating in diverse natural environments, demonstrated by their presence in remote regions far from urban areas, such as the Arctic and Mount Everest.[6,7] However, there remains a misunderstanding when it comes to the types of fibre fragments that dominate and persist in the environment, as well as the raw materials from which they originate.

Largely driven by the visible prevalence of plastic pollution, many environmental studies have previously focused on the detection of 'microplastic' matter or synthetic fibre fragments.[8] Consequently, non-synthetic fibres, such as natural fibres or Man-Made fibres derived from natural polymers (plants and animals) (see Figure 1), are often overlooked or undocumented; either because they fall outside the scope of such studies or due to a lack of appropriate knowledge, skills or instrumentation for their characterisation. This oversight has resulted in a general underestimation of fibre fragment concentrations across different fibre types, giving the misconception that fibre fragments are predominantly microplastics (synthetic).

These findings and the manner in which they are often reported in the media, creates a misleading narrative that synthetic clothing is the sole cause of fibre fragment pollution. Additionally, this narrative overlooks the findings of numerous forensic studies that provide unequivocal evidence to the contrary. Forensic studies have found that approximately 70% or more of all fibres are non-synthetic, with the vast majority originating from natural sources.[9,10,11,12,13]

Thankfully, a more holistic understanding of fibre fragment pollution is emerging. Recent environmental studies increasingly emphasise the importance of the full characterisation and identification of all fibre fragments encountered, contributing to a more accurate representation of the issue.[34] The findings of such studies align with on-land forensic studies, collectively supporting the growing body of evidence that fibre fragment pollution is not isolated to synthetic fibres.

DEFINITION UNPACKED

MICROPLASTICS

Microplastics are small pieces of plastic debris measuring 5mm or less, found in the environment from the disposal or breakdown of consumer products and industrial waste.[13] These particles can take various shapes, including spheres, pellets, foam, and irregular fragments. Therefore, also include synthetic fibre fragments. While the term microplastic was not yet used, microplastics were first observed in 1972 with numerous studies raising concerns about their potential environmental impact.[14] The term microplastic was eventually coined in 2004, and today are known to either originate as primary microplastics—tiny particles intentionally produced at small sizes—or secondary microplastics, which result from the degradation of larger plastic items such as textiles, bottles, or fishing nets.[15]

MICROFIBRES

Fibres are one of the most frequent particle shapes of microplastics detected in environmental samples, with textiles identified as a major source of release.[16] Studies show that approximately 35% of the primary microplastics in the ocean originate from textiles.[17] Therefore, the term 'microfibre' emerged to describe the thread-like, fibrous structures that shed from textiles, distinguishing them from microplastics which typically take on various other shapes. Additionally, research has shown that microfibres which persist in the environment are not limited to synthetics, making 'microplastic' too narrow a term to capture all fibre types. Thus, 'microfibre' became a commonly accepted term for these textile-derived pollutants.

FIBRE FRAGMENTS

Within the fashion and textile industry, the term 'microfibre' clashes with the industry terminology for a very fine synthetic yarn defined as having a count of 1dtex or less, specifically referring to the small diameter rather than the small length or size.[18] To avoid confusion, the term 'fibre fragment' is considered more appropriate as it also captures the notion that fibres shed from all fibre types, their fibrous structure, and reflects the action by which a fibre is released from the main textile construction.

Discourse over the terminology extends beyond naming conventions to the specifications that should be included within the definition. There is ongoing discussion around the size limits and the classification of sources in the definition, particularly regarding non-synthetic fibre fragments.

SIZE

An ongoing debate revolves around the size limits included within the definition. **Experts have voiced the need for flexibility in the size limits (minimum and maximum size limits) used within definitions to accommodate evolving research, while others advocate for stricter limitations to enhance consistency in testing and risk assessments.** Current size limits used within definitions are either not specified, or present a range of different size parameters such as, 'a diameter less than 50 μm, length ranging from 1 μm to 5 mm, and length to diameter ratio greater than 100', or 'less than 5 mm in all dimensions'.[19,20]

SOURCES

Evolving research has demonstrated that fibre fragments shed from all fibre types, and that non-synthetic fragments can persist in the environment similarly to synthetic fibre fragments.[2,21] This has stressed the need to consider fibre fragments from all fibre types. For example, one study quantifying the fibre population of 223 samples of river water and atmospheric deposition, demonstrated that over 70% of recovered fibres were non-synthetic.[22] Furthermore, research has also highlighted the potential ecological risks posed by non-synthetic fibre fragments. For example, a study demonstrated that cotton fibre fragments negatively affected the behaviour of silverside fish and reduced the growth of mysids.[23] **Despite this, research on non-synthetic fibre fragments remains relatively limited, due to the historical focus on plastic pollution.**

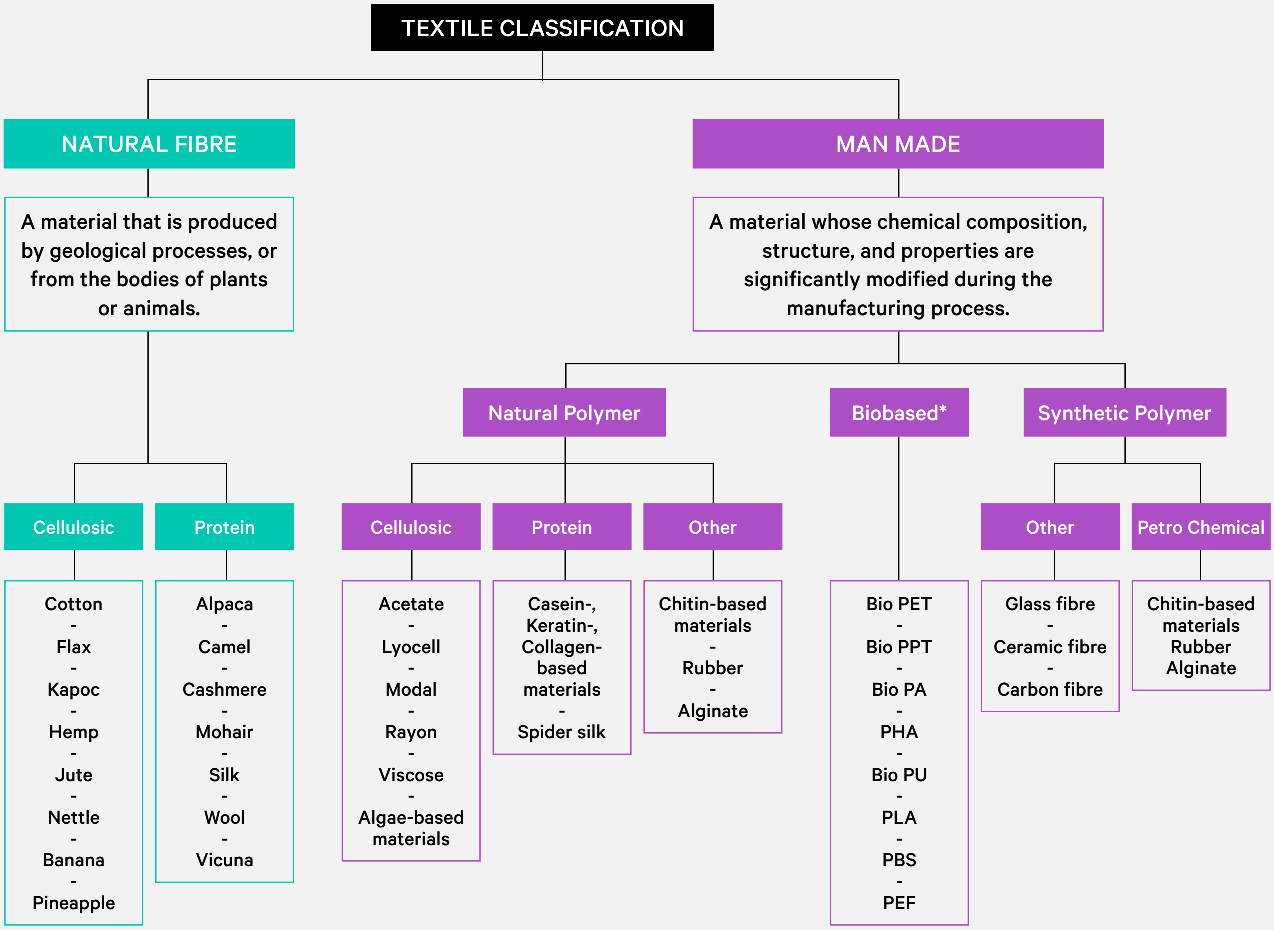
The persistence of non-synthetic fibre fragments in the environment has prompted a reassessment on the terminology used to classify the fibre types within the definition. **Some experts advise incorporating terms, such as 'processed' or 'modified' to encompass all chemically or mechanically processed fibres within the fashion and textile value chain.** This debate centres on the need to distinguish between natural fibres in their raw unprocessed state as found in the environment (directly derived from biomass such as plants, trees or animals) and those that undergo any form of mechanical and/or chemical processing during manufacturing.[24,25] This is because the different processing methods and treatments that fibres undergo throughout textile manufacturing have shown to increase fibre stability and resistance to biodegradation, subsequently increasing their persistence in the environment.[26,27,28] See Chapter 6: Biodegradation.

The term 'processed' more broadly refers to; Man-Made Fibres (MMFs) derived from synthetic polymers and natural polymers such as cellulosic and protein fibres which undergo significant chemical or mechanical modifications during their manufacturing processes.[29] Additionally, it includes natural fibres derived from cellulosic and protein fibres that undergo any form of processing—such as pretreatment, dyeing, and finishing.

Figure 1 illustrates the classification of textiles within the fashion and textile industry.

Figure 1: Textile Classification in the Fashion and Textile Industry

Note: This classification is not exhaustive of all fibre types.



*Another important term commonly used within the fashion and textile industry is 'biobased.' This refers to materials that are wholly or partially derived from biomass, such as plants, trees, or animals.[30] Biobased materials may include:

- Natural Fibres
- MMFs derived from natural polymers
- MMFs partly derived from synthetic polymers, such as a polyester-cotton blends that meet a specified minimum percentage of biocontent

Figure adapted from "Understanding 'Bio' Material Innovations: A Primer for the Fashion Industry, Biofabricate and Fashion for Good."

WORKSHOP OUTCOMES

During the workshop session, the group discussed the consequences of the lack of a standardised definition within the industry, leading to ambiguity and complicating collective efforts to understand, research, and mitigate the issue of fibre fragmentation. Workshop participants emphasised the importance of aligning on a broader, overarching definition to guide research and policy discussions within the fashion and textile industry.

The session aimed to establish a definition for the scope of the collaboration between TMC and FFG. The most significant points of divergence revolved around size limits, however, it is important to note that the opinions were largely dependent on the context of the work and research goals of the experts. A key question was raised: **'Should we be more concerned with what can be caught [by a filter] or what can cause harm [to humans and the environment]?'**

This revealed that from the perspective of environmental and health research, size limits play a critical role in understanding when fibre fragments become toxic to marine life or humans. For example, fibre fragments can lead to food dilution, where ingested particles take up space in the gut, reducing the space for the organism to carry out essential digestive processes and hindering proper food intake or nutrient acquisition.[31] Additionally, size can influence the risk of translocation, in which the ingested fragment can move into other organs and create other issues.[31] There is also evidence that the deposition and transfer of microplastics (including synthetic fibre fragments) and nanoplastics in the human respiratory system depend on particle size.[32] Therefore, specifying size limits is arguably important for identifying the thresholds at which fibre fragments cause harm and accumulate. Nonetheless, existing literature does not yet provide sufficient evidence on the relationship between fibre size and toxicological effects. Therefore, **it is important not to set specific size limits, as there may be fibre fragments that are above or below the size limit that are also potentially harmful.** Further research is needed to develop well-defined criteria for both upper and lower size limits.

From a testing perspective, establishing size limits is closely tied to the inherent capabilities of the filters used in relevant test methods. These size thresholds determine what can be captured and measured, thereby ensuring consistency in results across different studies.

From an industry perspective, it is important to recognise that fibre fragments continue to break down within the environment, with studies showing that they can reach nanoscale sizes.[33] Ultimately, the goal within the fashion and textile industry should be the development of fabrics with a lower propensity to shed, regardless of size thresholds. Therefore, fragments outside the proposed size limits should not be excluded from consideration.

The group concluded that specifications, such as size limits and diameter, should supplement the definition (if relevant) based on the scope and purpose of the study to ensure clarity and context. The definition, along with any supplementary specifications, should always be clearly stated so that findings can be communicated, compared with other research, and used to inform decision-making or guide further action. This is especially important given the need to carry out further research to fully understand the complexities around fibre fragmentation.

Taking these factors into account, the definition for the report is as follows:

Fibre fragments: Any processed* fibrous material broken from a textile structure during production, use, end-of-use, as well as through its subsequent breakage in the natural environment.

*The term 'processed' is intended to encompass all fibre types that have undergone any form of mechanical or chemical processing. This includes natural fibres that are no longer in their raw, unprocessed state as found in the environment, as well as Man-Made fibres derived from both synthetic and natural polymers. See Figure 1 for textile classification.

In line with this work, The Microfibre Consortium has also adopted this definition to ensure consistency across its workstreams. However, it is important to note that this working definition has not been officially adopted for industry-wide use at this stage and is intended to ensure clarity and consistency throughout this report.

CHAPTER 2: SOURCES AND PATHWAYS

Initially, research on fibre fragment pollution predominantly focused on the release of fibres during laundering (washing), as they entered the marine environment via wastewater. However, it has become evident that the sources and pathways of fibre fragment pollution are far more complex, with fibre fragments being detected across diverse environments and in hundreds of species.

SOURCES OF FIBRE FRAGMENTS

The sources of fibre fragmentation are where the particles originate, such as from manufacturing, consumer use, or end-of-use stages. Pathways, on the other hand, describes the mediums through which fibre fragments travel through the environment, via air, terrestrial or water bodies. A comprehensive understanding of these diverse sources and their pathways into the environment is essential for developing effective strategies to reduce fibre fragment pollution.

MANUFACTURING

Textile manufacturing is recognised as a major source of environmental pollution to wastewater and air.[1] Throughout textile manufacturing, materials undergo a variety of processes, including spinning, weaving, knitting, and processing (pretreatment, dyeing, and finishing). **These processes subject fabrics to both mechanical and chemical stresses, which can increase fibre loss from the main textile construction, making them a significant source of fibre fragments.** It has been shown that the dyeing stage can account for up to 95% of the total fibre emissions, and textile industry wastewater can contain fibre fragment concentrations up to a thousand times higher than those found in municipal wastewater.[34,35] While many textile manufacturing facilities have on-site effluent treatment plants (ETPs) designed to capture pollutants before they enter the environment, the effectiveness of these plants can vary. For example, a study showed ETPs can remove between 50% and 99% of fibre fragments from effluent, depending on the technology and operation of the plant.[34] However, even highly efficient ETPs can still allow significant quantities of pollutants to pass through due to the large volume of incoming wastewater. The complexities of ETP operations and their role in addressing fibre fragment pollution will be discussed further in Chapter 5: Solutions Portfolio.

CONSUMER USE

Washing: Early on, domestic washing was identified as a major source of fibre fragment pollution.[36] As the most documented source, washing has captured the attention of researchers and policymakers. The mechanical action of wash cycles generates fibre fragments, which are then released into wastewater. The annual global emission of synthetic fibre fragments from laundry alone has been estimated to be 5.69 million tons.[37] Consumer habits play a significant role in fibre fragmentation from textiles during washing. For example, detergent is believed to increase fibre fragmentation, with powder detergents potentially causing more damage than liquid detergents due to increased friction, although research findings vary.[38] In contrast, softeners have been found to reduce fibre fragmentation, potentially by reducing the friction between fibres.[39] Hotter and longer wash cycles result in more fibre fragmentation compared to cooler and shorter cycles, and filling the laundry drum to its full capacity can reduce fibre fragmentation per kilogram of clothing, as it decreases the water-to-fabric ratio.[40,41]

The type of washing machine used is also important, as top-loader washing machines are known to release greater numbers of fibre fragments than front-loading machines.[42] Additionally, factors such as abrasion and UV during consumer wear may also influence fibre fragmentation during subsequent washing over time. **It has been shown that garments shed the highest number of fibre fragments during the first wash cycles, making it crucial to understand the factors influencing fibre loss during washing.[36] However, studies have failed to take the effect of drying, wearing and environmental (UV) exposure into account.** Typically, a garment will be worn (indoors and outdoors), washed, dried and repeated. Research that has incorporated this approach indicates that whilst there is greater loss during the first wash, the level of fibre fragmentation then levels off and remains consistent.[42] To address fibre pollution from washing, technologies that can capture fibre fragments during washing are available, preventing them from entering wastewater systems, but efficiencies can vary.[35] See Chapter 5: Solutions Portfolio. Most of the existing research is focused on washing practices and the use of electric washing machines. However, this research is of limited relevance in the Global South where accessibility of machine washing is less common and a significant proportion of the population uses locally-specific practices, such as hand-washing. A study found that fibre fragmentation from hand-washing is comparable to that from machine-washing, yet fibre fragments released during hand-washing cannot be mitigated by laundry filtrations systems or wastewater treatment.[21] Additionally, studies are yet to investigate fibre loss from dry cleaning. This highlights critical gaps in understanding the respective contributions from different sources of fibre fragment pollution and, consequently developing appropriate interventions.

Drying: Electric machine drying is another important source of fibre fragment emissions into the air.[43,44,33] Research indicates that even a brief 15-minute tumble-drying cycle can release over 500,000 fibre fragments directly to air, often due to there being minimal filtration through exhaust vents.[45] Most of the research in this area is focused on machine drying, while the contribution from other drying methods such as line-drying on fibre fragmentation is unknown.

Wearing: Fibre fragmentation occurs during the wear of garments through the loss of loose surface fragments, abrasion caused by movement, and contact with other surfaces and/or weathering.[46,47,48,33] Through these mechanisms, fibre fragments are released directly to the air. **Although most of the more recent research on fibre fragments has focused on emission during washing, research indicates that fibre loss during wear could be the dominant source of fibre fragments present in the environment.**[49] Fibre fragmentation into the air is likely to be influenced by environmental conditions such as UV exposure, wind, humidity and temperature, as well as variations in human activity. While some research has shown that UV exposure can cause fragmentation of fibres, these effects are still poorly understood.[33]

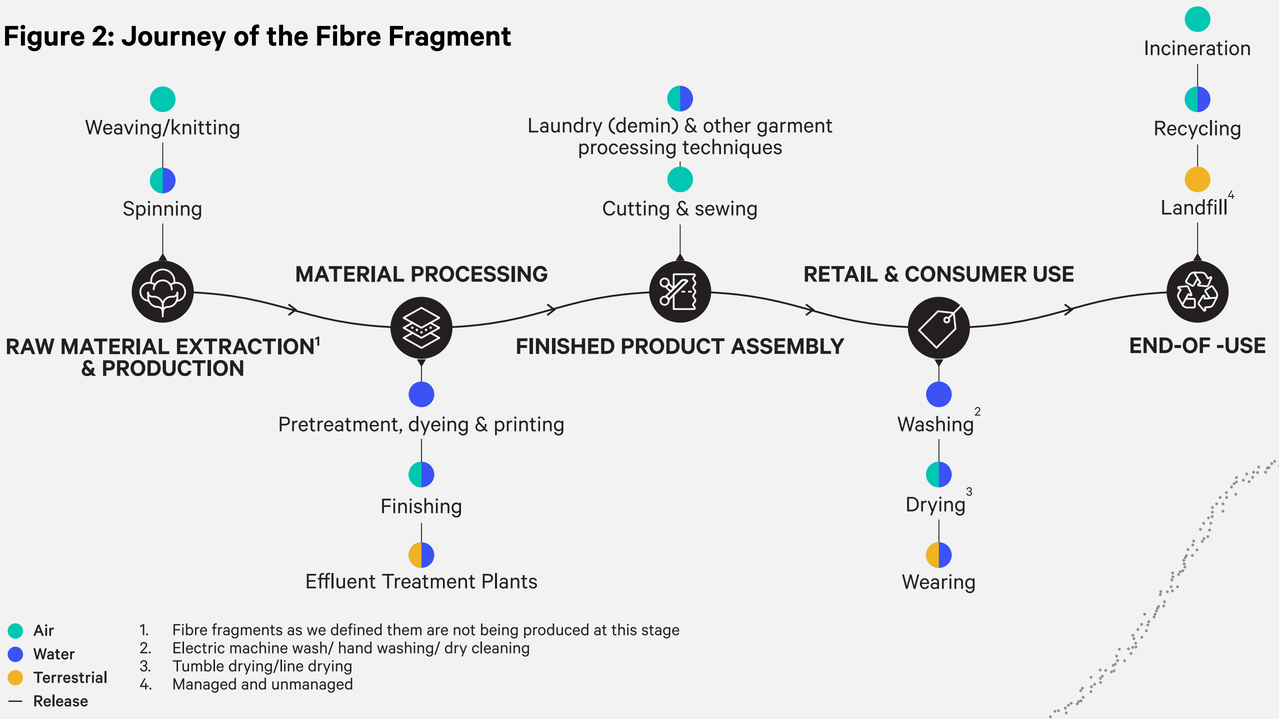
END-OF-USE

During the end-of-use stage, textile disposed of in landfills, sent to industrial composting facilities or littered, can degrade, providing another source of fibre fragments to the terrestrial environment.[50] When released to terrestrial environments, fibre fragments can impact terrestrial organisms, soil properties, microbial communities and plants.[51] As these fibres break down they can be released into the surrounding soil as small fragments and make their way into groundwater.[52] Rain or flooding may also cause fibre fragments emitted to land to be transferred to water bodies through run-off and soil erosion processes. While incineration should hardly ever be used as a disposal method due to its environmental implications, textiles can also be incinerated, which can release fibre fragments into the air that can then settle on land or water bodies, further spreading fibre fragment pollution. The unburned material that remains after incineration may also contain fibre fragments.[53] Moreover, a study on the recycling of plastic bottles demonstrates that the mechanical shredding during the size reduction stage generates significant microplastics.[54] This suggests that similar effects could occur during the mechanical recycling of textiles, where shredding processes might also lead to the release of fibre fragments. Nonetheless, **the end-of-use stage remains underexplored in comparison to other sources.**

PATHWAYS OF FIBRE FRAGMENTS

The key pathways through which fibre fragments enter the environment include air, water, terrestrial, and biota. Figure 2 illustrates the journey of a fibre fragment along the fashion and textile supply chain, and indicates the direct environmental pathways in which the majority of fibre fragments are released throughout each stage of a textile's lifecycle. In each of these primary environmental compartments, the fragments may ultimately interfere with the biota present.

Figure 2: Journey of the Fibre Fragment



1. Fibre fragments as we defined them are not being produced at this stage
2. Electric machine wash/ hand washing/ dry cleaning
3. Tumble drying/line drying
4. Managed and unmanaged

WATER

Water is a key pathway through which fibre fragments travel, facilitating movement across different environments. During washing and textile manufacturing, fibres are released into wastewater, where they enter sewage systems. These fibres can then be discharged from ETPs into natural water bodies, including rivers, lakes, and oceans. Additionally, runoff from land, during rainfall or flooding, can also carry fibre fragments into different water bodies.[5] **ETPs can capture over 90% of fibre fragments, yet even highly efficient facilities can still emit high numbers of fibre fragments to the environment.** Moreover, during very high flow conditions, sewage overflows are designed to release untreated sewage into rivers to reduce pressure.[56] A study of municipal ETPs in Budapest predicted an emission of between 0.44 – 1.53 billion fibre fragments per month from a single plant.[57] Additionally, only around 20% of global wastewater undergoes treatment at ETPs.[58]

AIR

During the manufacturing and use stages, a significant number of fibre fragments are released into the atmosphere within both indoor and outdoor environments.[59] Within indoor environments, they can settle on the floor and surfaces, contaminate food or be inhaled by humans. **Studies on atmospheric fibre fragment concentrations have found that concentrations are much greater in indoor air than outdoor air, which increases the potential of human exposure.**[60] Whereas in outdoor environments, fibre fragments are likely subjected to longer distances as they are carried by the wind to settle on land and water surfaces.[61] Nonetheless, limited attention has been given to air, despite fibre fragment pollution being found in remote, non-urban locations. The presence of fibre fragments in such locations is scientific demonstration of their ability to naturally move through the air in the absence of external agitation forces, which allows them to be transported from the air to terrestrial and aquatic environments.[62]

TERRESTRIAL

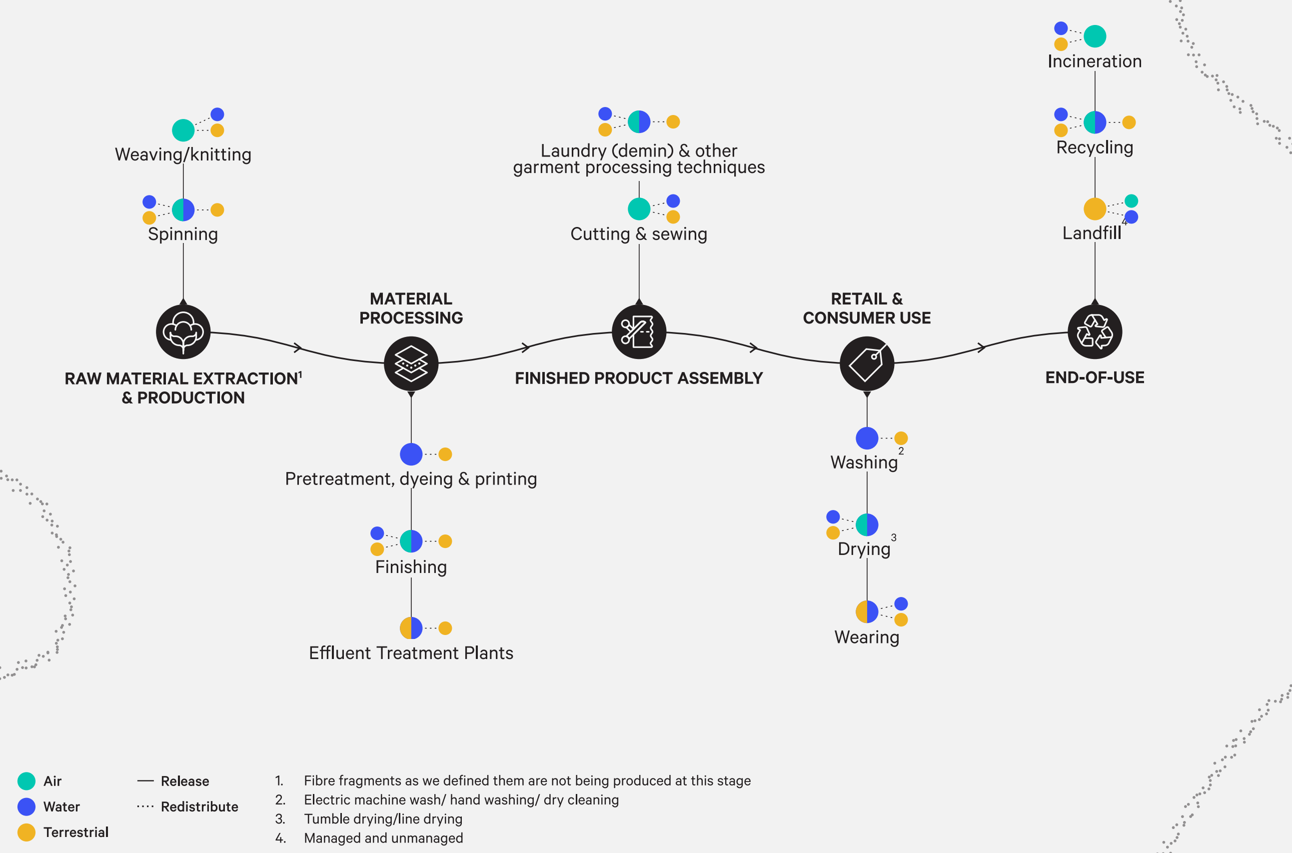
Fibre fragments are found in the terrestrial environments of land and soil, which is now identified as a pathway and reservoir for fibre fragments.[63] **Fibre fragments can be deposited to soil from the air, the breakdown of textiles in landfill or through the application of sewage sludge,** a byproduct of treated wastewater. Therefore, ETPs offer a direct pathway for fibre fragments to be reintroduced to the terrestrial environment when sewage sludge containing fibre fragments are applied to agricultural land as a soil amendment.[64]

BIOTA

Biota refers to all the organisms living in a particular environment, including plants, animals, and microorganisms.[65] **It has been identified as a pathway for fibre fragments when airborne fibres are inhaled or when fibres are ingested through feeding or drinking or by consuming contaminated organisms.** Upon ingestion, fibre fragments can accumulate in the gut, and fragments within a certain size threshold can then enter the bloodstream.[66] Once in the bloodstream, they can translocate to other organs, potentially affecting tissues and organs.[67] Finally, fibre fragments can also move through the food chain after ingestion, potentially impacting human or animal health.[68]

Once fibre fragments enter the environment, they may continue to break down or undergo large-scale transport across different environments, contributing to widespread pollution. Figure 3 uses the previous graphic, highlighting the key environmental pathways in which the majority of fibre fragments are released throughout each stage of a textile's lifecycle (depicted by larger circles), followed by the secondary environmental compartment in which the fibre fragment may be redistributed (depicted by smaller circles). For example, within material processing, the finishing step may include both mechanical and chemical processes. In the case of chemical finishing, the primary environmental compartment is water (blue), which can then be redistributed into terrestrial environment (yellow). This redistribution adds complexity to understanding the true extent to which fibre fragments accumulate and behave in each environment.

Figure 3: Redistribution Pathways



1. Fibre fragments as we defined them are not being produced at this stage
2. Electric machine wash/ hand washing/ dry cleaning
3. Tumble drying/line drying
4. Managed and unmanaged

There are still significant research gaps with regards to the sources and pathways of fibre fragmentation. Most existing research has concentrated on fibre release during washing and its impact on water systems.[69] Therefore, the total amount of fibre fragment pollution to the environment, and the relative contributions of their source(s) and/or pathways is unclear. **A notable barrier is the absence of a standardised test method to quantify airborne fibre fragments, limiting our understanding of this source and relevant pathways.** Given that fibre fragments can undergo long-range transport across environments, all geographical locations must be considered and research should not be isolated to the Global North. It is essential that these gaps are addressed so that targeted and appropriate mitigation solutions can be developed.

WORKSHOP OUTCOMES

The workshop aimed to collaboratively identify key knowledge gaps in the context of the fashion and textile industry. **A major concern raised was the lack of data on the impact of manufacturing as a significant source of fibre fragments, which impedes efforts to design textiles with a lower propensity to shed.** With regards to sources, gaps in understanding airborne fibre fragments during both the manufacturing process and the use stage were stressed as critical. The participants also acknowledged the need for more focus on use-stage practices in regions beyond the Global North, as these are often overlooked in existing research. Furthermore, the end-of-use stage was recognised as under-researched, despite its potential environmental impact. The variability in end-of-use scenarios, such as differences between landfill, incineration, and recycling processes, further complicates research and the development of best practices for the industry.

With regards to pathways, **water and wastewater pathways are somewhat better understood; however, gaps remain, particularly in understanding the connection between wastewater and terrestrial environments—** such as through the application of treated sewage sludge as fertiliser. Airborne fibre fragments and their interaction with soil and biota also require further investigation, with a particular focus on biological pathways like inhalation and bioaccumulation. Additionally, the issue of indoor contamination due to fibres shedding during manufacturing and wear, as well as its subsequent redistribution, is currently unexplored, but critical for understanding exposure risks.

Overall, it was clear that current research lacks a comprehensive understanding of the various sources and pathways through which fibre fragmentation occurs. As a result, the total amount of fibre fragment pollution within the environment, and the relative contributions of each source is still unclear. There is a need for research that spans the entire lifecycle of textiles—from cradle to grave—encompassing all sources and pathways. This should include an examination of time frames, such as the duration over which fibre fragments move between environmental compartments and living organisms, as well as the interconnectivity of different sources and pathways. This holistic approach would provide a clearer picture on how fibre fragments persist, accumulate, and change over time.

CHAPTER 3: ROOT CAUSES

Fibre fragmentation occurs at every stage of a textile's lifecycle, prompting the development of interventions to reduce fibre fragments from entering the environment in key steps such as manufacturing and consumer washing during the use stage. However, fibres will inevitably continue to shed, as the textile itself remains the ultimate source of fibre fragments. **Textile design and manufacturing are pivotal in influencing the textiles' propensity to shed fibre fragments.** Fabric design choices, such as fibre type, weave, and construction, can enhance resistance to abrasion and disruption, reducing the likelihood of fibre fragmentation. Similarly, manufacturing processes significantly influence shedding; mechanical treatments that involve abrasion and friction can weaken or damage fibres, while chemical treatments may compromise their integrity. Together, these factors highlight the importance of adopting more responsible textile design and manufacturing practices.

To effectively mitigate fibre fragment pollution, it is essential to understand the root causes at a product level and explore why some shed more than others. Addressing these root causes is a key lever to unlock more responsible textile design and manufacturing, ultimately leading to fabrics with a lower propensity to shed. See Chapter 5: Solutions Portfolio.

TEXTILE DESIGN AND MANUFACTURING

YARN TYPE AND CONSTRUCTION

Fabrics made from shorter, staple fibres are more likely to shed fragments compared to those made from longer, filament fibres.[70] This is typically the case for natural fibres like cotton or Man-Made cellulosic fibres, such as rayon and viscose, which tend to have a higher propensity to shed as they are often used in staple form, in contrast to synthetic fibres which are primarily filament-based. Fabric and yarn construction is another influencing factor; compact woven structures, using higher yarn twist, release fewer fragments than loose woven structures or knitted structures with lower yarn twist.[70] Most existing research into the root cause of fibre fragmentation has focused on the effects of textile design on fibre fragmentation during laundry, while the root causes behind fibre fragmentation to air are far less understood. Although some research has found that fabric composition and structure can influence fibre fragmentation to air as well as water, more research is needed to fully understand the effects.[70]

PROCESSING (PRETREATMENT, DYEING, AND FINISHING)

Finishing processes contribute to fibre fragmentation. Mechanical finishing techniques like brushing, which abrade the fabric surface to achieve softness, can increase fragmentation. A case study by The Microfibre Consortium (TMC), Taiwan Textile Research Institute (TTRI) and New Wide Group compared fibre fragmentation from fabrics produced with different levels of mechanical finishing. **Mechanical brushing was found to generate significantly more fibre fragments than those without, and this effect could be reduced by using fewer brushing passes.**[71] Similarly, chemical finishes, such as softeners and hydrophobic finishes may reduce fibre fragmentation by altering the friction or moisture management qualities of a fabric. The pretreatment and dyeing processes, including the relevant chemicals used, also influence fibre fragmentation.[34] **Processes that rely on high temperatures, water baths, and prolonged processing cycles can weaken fibre structure and increase swelling, all of which contribute to fibre fragmentation.** However, the full extent of their influence remains understudied, and further research is necessary to gain a comprehensive understanding.

RECYCLED FIBRES

Mechanically recycled fibres, typically shorter and weaker than virgin natural fibres, have shown a negative influence on fibre fragmentation.[72] However, conflicting results have been found in studies into the impact of recycling processes on fibre fragmentation, urging further research. Although many studies include recycled fabrics, textile specifications and production parameters are often omitted, meaning it is unclear if differences in fibre fragmentation are due to the presence of recycled fibres or another variable. Özkan and Gündoğdu (2020) is the only study assessing fabrics made from the same fabric structure in both polyester recycled from plastic bottles and virgin polyester and comparing the effect across staple and filament yarns.[72] Their study found that, on average, recycled polyester shed 2.3x more fibre fragments than virgin polyester, suggested to be due to the shorter fibre length and lower breaking strength of recycled polyester.[72] However, research conducted by TMC into recycled polyester compared fibre fragmentation from 251 recycled and virgin polyester fabrics across a wide range of fabric types and found no differences in fibre fragmentation between mechanically recycled and virgin polyester.[73] **These conflicting results among studies are likely due to variations in recycling processes, differences in fabric types, or inconsistencies across testing methodologies.** For example, the use of gravimetric analysis has the risk of overestimating fibre loss, as this method assumes all material shed originates from the fabric sample, potentially skewing results. See Section 4: Test Methods.

Most of the existing research into the effect of recycled fibres is focused on mechanically recycled polyester. Mechanical recycling is well-established and widely used for recycling textiles into new yarns by employing physical techniques such as shredding or melting of waste material. Chemical recycling uses chemical processes to break down waste material to a molecular level. Chemical recycling may produce fibres of different properties to mechanical recycling. **Theoretically chemically recycled fibres should perform as their virgin counterparts, but until relevant research has been conducted, it remains unknown if or how this process will influence fibre fragmentation.**

While it is acknowledged that all textiles have the potential to shed fibre fragments, the reasons why some fabrics shed more than others is not yet fully understood. **A growing body of evidence has highlighted the influence of factors such as fibre composition, fabric and yarn construction, and finishing processes. However, the intricate and incredibly complex nature of textile design means that significant gaps in knowledge persist.** Research efforts to explore these variables are often hindered by the lack of detailed fabric specifications or comparable data collected across studies, making it difficult to establish conclusions and industry best practices. Gaining a comprehensive understanding of how individual textile design and manufacturing variables contribute to fibre fragmentation is crucial for developing targeted mitigation strategies.

LARGE-SCALE INDUSTRY RESEARCH

The Microfibre Consortium houses The Microfibre Data Portal, the largest global database on fibre fragmentation globally. Signatories to The Microfibre 2030 Commitment are required to test fibre fragmentation from a number of textiles annually using the TMC Test Method that carries out gravimetric analysis to simulate domestic laundering. See Chapter 4: Test Methods. The fibre fragmentation test data is uploaded to The Microfibre Data Portal along with detailed specifications of the fabric being tested. Over 50 manufacturing variables are recorded for each fabric during this process, uploaded by the testing TMC signatory from the supplier. The variables recorded span the entire fabric production process, including fibre composition, yarn and fabric structure details, colouration methods and any mechanical and chemical finishes.

Over 1000 fabrics have been tested and uploaded to The Microfibre Data Portal. The detailed fabric specifications and underpinning standardised test data have enabled extensive, in-depth analysis to investigate the strength of effects and interactions of multiple fabric variables simultaneously. This is the first time such an extensive root cause analysis has been conducted due to the often limited data sets and lack of detailed technical specifications available in the more traditional academic research, in addition to the onset of advanced machine learning methods.

The initial findings show that, as supported by existing research, the use of knitted fabrics, staple yarns, natural fibre types like cotton or Man-Made cellulose, and mechanical brushing processes, tend to increase fibre fragmentation. **When comparing the strength of effects of each variable, finishing and fibre type were found to have stronger overall effects on fibre fragmentation than yarn type or fabric structure.** In particular, hydrophobic and softener chemical finishes were found to decrease fibre fragmentation, while hydrophilic chemical finishes were found to increase fibre fragmentation.

Whilst this analysis represents the most extensive root cause analysis of fibre fragmentation so far the results are influenced by existing data gaps in The Microfibre Data Portal. For example, the **current dataset is heavily skewed towards synthetic fibres, as over 50% of the tested fabrics are polyester-based, with limited fabrics submitted from non-synthetic fabrics (natural fibres and MMCFs).** This is reflective of where the topic began with its focus on synthetic fibres, in addition to the high proportion of TMC's signatory base of outdoor brands and retailers. Consequently, there is an urgent need to scale the testing of underrepresented fabrics to reduce existing data gaps and improve the solidity of root cause understanding.

Although there are observed differences in the average fibre fragments loss between fabrics of different fibre types, yarns and fabric structures, more specific, traditional, practical research is required to assess definitively whether these factors truly influence fibre fragmentation. Differences in shedding between different fibre types may be as a result of other factors, such as the yarn or fabric structures typically used in those fabrics, rather than fibre type itself. As TMC's dataset increases and data gaps are filled, the root cause analysis it enables will continue to improve in accuracy. The results will then support the textile industry in making informed, science-led, data-driven textile design changes to mitigate fibre fragmentation from the textile itself.

WORKSHOP OUTCOMES

There are currently a range of industry efforts aimed at better understanding the root causes of fibre fragmentation, across different fabric types, such as TMC's root cause analysis. Another example is the investigation led by Antoine Cosnes at DECATHLON which aims to explore how PET multifilament design impacts fibre shedding. Despite these efforts, significant knowledge gaps remain that must be addressed to resolve uncertainties around appropriate mitigation strategies at a textile design level.

The workshop aimed to shed light on the key challenges hindering progress in understanding and addressing the root causes of fibre fragmentation, these include:

- **Balancing Research with Commercial Needs:** Aligning root cause research with commercial needs is essential. For example, studies have shown that tighter yarn twists may reduce fibre fragmentation.[70] However, even if these findings hold true, they may not be adopted for all fabric types, emphasising the need to ensure that such adjustments do not compromise the fabric's overall quality, durability, or market appeal.
- **Product-level analysis:** Existing test methods assess fibre loss from fabric swatches which requires significant assumptions to extrapolate the data to reflect fibre loss at a product level.
- **Standardising Experimental Designs:** The multitude of methodologies and testing protocols within root cause studies complicates the generation of comparable and reliable data across studies.
- **Challenges in Generalising Results:** Conducting statistical analyses on large datasets is essential to identify trends and prioritising key influencing variables. However, it's important to recognise that fabrics behave differently, and the interdependence of factors along the supply chain (e.g., fabric construction and dyeing methods) can limit our ability to generalise findings across different fabric types. Workshop participants highlighted the value of isolating individual variables for specific fabrics to gain deeper insights into their influences, ensuring that strategies are informed by both broad data and the unique characteristics of each fabric.

To address these gaps, TMC and FFG are collaborating on the **'Behind the Break' Project.** This initiative will investigate how individual variables related to textile design and manufacturing influence fibre shedding under real supply chain conditions. The study will focus on three fabric types: cotton knit, cotton woven, and polyester knit, with the aim of strengthening data correlation by comparing results across different methods. This approach will help uncover discrepancies, identify variations, and establish clearer data connections.

CHAPTER 4: TEST METHODS

The fashion and textile industry currently leverage various test methods to evaluate and understand the quantities and mechanisms of fibre fragmentation from textiles. It is now widely recognised that fibres shed into air and water through various sources, including manufacturing, use, and end-of-use. To fully understand the true scale and mechanisms of fibre fragmentation, test methods must capture all these sources. However, currently, they primarily focus on assessing fibre loss from a fabric specimen, following laundry simulation. Filtration of the wastewater allows industry professionals to determine fibre loss from the tested fabric specimen. **Today, standardised test methods to assess fibre fragmentation from other pathways, such as air, are still lacking.**

Existing test methods are typically carried out by various stakeholders. Some are conducted directly by brands in their laboratories, others through third-party labs, and others within manufacturing facilities equipped with specialised testing capabilities. These tests are designed to enable fabric-to-fabric comparisons, generating data that informs textile design and manufacturing processes with the goal of producing textiles with a lower propensity to shed. This report examines the test methods available, highlighting their benefits, limitations, and best use cases. Factors such as the depth of analysis, cost, and accessibility for industry stakeholders play a critical role in determining which test methods are used.

LAUNDERING TEST METHODS

Commonly used methods for assessing fibre fragmentation have been **designed to enable the direct comparison of fibre loss from fabric samples through quantitative and/or qualitative data, leading to a better understanding of the root causes of fibre shedding.** These are typically carried out using manual counting, gravimetric analysis or visual analysis.

COUNTING

Manual counting involves filtering wastewater to capture the fibre fragments lost from a fabric specimen, followed by manually counting the collected fibres with the aid of a microscope.[16] Often only a selected area of the filter is analysed, and the data is extrapolated to estimate total fibre loss. This can lead to inconsistent results, particularly when filters are overloaded with overlapping fibres, which may result in underestimation. This is especially the case for high shedding fabrics that lead to a higher rate of fibre loss. Automated counting provides a faster alternative through specialised softwares that reduce the variability of results collected between users. However, inconsistencies may persist when dealing with overlapping fibres.

GRAVIMETRIC ANALYSIS

Gravimetric analysis involves filtration, often assisted by a vacuum pump. This approach offers a straightforward and objective quantitative measurement by directly weighing the collected fibres, allowing for the calculation of weight loss as a percentage of the original fabric specimen. This overcomes the limitations of counting methods, as it can offer more consistent results, especially when fibres overlap or are indistinguishable.

The benefit of both counting and gravimetric analysis lies in their ability to produce reliable quantitative data, enabling a comprehensive analysis and greater understanding of the root causes of fibre fragmentation. Furthermore, the results generated are clear and facilitate a straightforward interpretation: fewer fibre fragments on the filter indicate a ‘better’ outcome regarding the shedding potential of a fabric. This simplicity is crucial for the fashion and textile industry. These tests can typically be conducted in any textile or testing laboratory globally, at relatively low-cost, and are therefore scalable. For this reason, gravimetric analysis has emerged as the most commonly used method to generate insights into the shedding behaviour of different fabrics. It now forms the basis for several established methods used within the industry. These test methods include the following (presented in an alphabetical order);

AATCC TM212-2021 is a standardised method developed by the American Association of Textile Chemists and Colorists (AATCC) to determine the fibres released from fabric specimens during the initial washing phase by simulating laundering using a machine which replicates the motion and agitation of a washing machine.[74] This method is most commonly recognised in the U.S and is aligned with ISO 4484-1 and the TMC Test Method as it follows the same general procedure, requiring four specimens per test. Additionally, the method offers the option to use a standardised detergent in the simulated laundering process, designed to reflect the most common detergents available to consumers.[75]

ISO 4484-1 is a standardised method developed by the European Committee for Standardization (CEN) and the International Organization for Standardization (ISO) to measure the material loss from a fabric sample, by weight, under simulated laundering conditions.[76] This method is most commonly recognised in Europe and follows the same general procedure as AATCC TM212 and the TMC Test Method, requiring four specimens per test and prohibits the inclusion of detergent.

ISO 4484-3 is a standardised method developed by ISO to measure the quantity of fibres shed from a fabric or garment through a typical domestic wash using an electric machine.[77] A domestic washing machine is used to find the quantity of fibre loss, by weight, to identify how much fibre would potentially be released into the wastewater bound for water treatment facilities through washing. This method can be repeated to collate the amount of fibre lost during multiple wash cycles and requires at least two specimens per test.

TMC Test Method is a method developed by TMC in collaboration with the University of Leeds and European Outdoor Group in 2017. The test method measures fibre loss by weight by mimicking simulated domestic laundering.[78] Although the TMC Test Method is not part of an internationally recognised standards body, it has been validated across the industry and is aligned with ISO 4484-1 and AATCC TM 212 as it follows the same general procedure. However, contrary to those methods, the TMC Test Method requires eight specimens per test and unlike AATCC TM 212 prohibits the inclusion of detergent.

VISUAL ANALYSIS

Visual analysis assesses fibre shedding by evaluating the quantity of fibre loss from a fabric after simulated laundry. This method eliminates the need for counting or mass measurements by relying on a microscope or magnification tool to make relative comparisons of fibre fragmentation between fabric samples, which are then ranked using a visual scale. **It is commonly used for quick and inexpensive testing, allowing supply chain stakeholders to make faster decisions about acceptable limits for fabric shedding and to design fabrics with a lower propensity to shed.** However, a significant limitation is the subjective nature of the assessment, as variability in interpretation by different assessors can affect the accuracy and reproducibility of results.

The Under Armour Test method was developed by Under Armour through the Proving Ground Testing Lab, and has now been formalised as DIN SPEC 19292.[79] It uses a visual analysis technique and was designed to support mills and designers to classify textile material based on their propensity to shed, in the early-stages of product development.[80] Using different equipment to ISO, AATCC and TMC test methods, the method involves agitating a fabric sample in water to simulate a wash environment, filtering the wastewater to collect fibres fragments on a paper filter, and then examining the fibres under a microscope. The samples are scored qualitatively using a 1-5 visual scale to compare material loss across fabrics.

Visual and gravimetric analyses are foundational approaches for studying fibre fragmentation, yet they may lack the depth needed for a comprehensive understanding of the true shedding behaviour of a fabric. Research has shown that non-textile particles, such as production residues or external contaminants adhering to textile surfaces, can also be released during laundering, distorting the results of weight-based analyses.[16] Therefore, a potential limitation is the risk of overestimating the fibres loss from the original fabric, by assuming that all material captured on filters originates from the fabric sample being assessed. Furthermore, these methods do not provide insights into specific fibre characteristics such as composition, morphology, size, and shape—details that may enhance the understanding of the mechanisms behind fibre fragmentation, particularly when blended fabrics are tested. The absence of these detailed insights has led to ongoing discussions about the level of analysis required to accurately assess the influence of each factor on fibre shedding.

FIBRE CHARACTERISATION TECHNIQUES

To better understand the mechanisms of shedding and types of particles within a sample, fibre characterisation methods are used to provide more detailed information about the composition, morphology, size, and shape of fibre fragments. These insights are crucial for various reasons. For instance, fibre composition, whether natural, synthetic, or blended, can reveal how different materials contribute to the overall shedding of a single fabric sample. Morphological analysis, which examines the structure and surface features of fibres, may shed light on the influence of mechanical or chemical stress on fibre loss. Similarly, analysing the size of fibres shed can help identify trends, such as the tendency of certain fabrics to produce smaller, harder-to-capture fragments.

DYNAMIC IMAGE ANALYSIS

Hohenstein, an international research and testing organisation, developed a test method known as DIN SPEC 4872.[81] This method is designed to assess fibre loss during washing and includes two additional optional steps for evaluating aerobic degradation in aqueous environments and ecotoxicity. The protocol for measuring fibre loss incorporates traditional gravimetric analysis, such as the TMC Test Method or AATCC TM212, but also integrates a fibre characterisation technique, Dynamic Image Analysis (DIA). **DIA provides detailed insights into fibre characteristics, as well as the total fibre quantity per gram of textile material, the average fibre length (µm), and the fibre length distribution.** An additional step in the method involves using sulphuric acid treatment to dissolve non-synthetic fibres, leaving synthetic fibres intact. For instance, in a polyester-cellulosic blend, this step allows for the determination of the percentage distribution between cellulosic and polyester fibres. However, a limitation of the dissolution method is that cellulosic fibres are excluded from further analysis, which may lead to incomplete characterisation, especially when fibre blends or unknown fibre types are present.

MICROSCOPY & SPECTROSCOPY

Beyond DIA, several other fibre characterisation techniques can be employed to gain a more detailed understanding of fibre fragments within a sample. **Brightfield microscopy** is useful for obtaining general information, such as, dimensions, mesh size, and the homogeneity of colour, providing an overview of the sample's physical characteristics.[82] This is critical for characterising natural fibres, such as cotton, wool, viscose, as their morphological properties are distinct. A more advanced microscopy method, **Polarising Light Microscopy (PLM)**, enables the differentiation of generic synthetic fibres e.g. acrylic, polyester, nylon, though it is unable to distinguish between similar types e.g. nylon 6 from nylon 6.6.[83]

There are also a range of methods that can provide insights beyond the fibre's generic type, but on the specific polymer composition and chemical additives present within a sample. The most used techniques for chemical analysis of fibre fragments are conventional **Fourier Transform Infrared (FT-IR) and Raman spectroscopy**, but these techniques have several limitations, most notably their ability to fully differentiate certain non-synthetic fibres with similar polymeric structures (e.g., cellulosic fibres). As well as, spatial resolution, measurement accuracy, throughput, photodamage, and fluorescence interference.[84] Emerging technologies include **Quantum Cascade Laser Infrared (QCL-IR)** spectroscopy, which excels in speed, sensitivity, and the ability to analyse specific polymers with higher precision than FT-IR.[85] **Optical Photothermal Infrared (O-PTIR) spectroscopy** is an emerging technique that provides chemical analysis via infrared spectroscopy, with a spatial resolution of ~500nm, around 10-30 times better than conventional FT-IR microspectroscopy. However, while these methods offer an unparalleled depth of detail, they are often costly, time-consuming and their complexity demands advanced technical expertise to carry out the analysis and interpretation, limiting their broader adoption within the industry. **Scanning Electron Microscopy (SEM)** can also be used in combination with other techniques to offer a high-resolution view of the sample, enabling an assessment of surface integrity (smooth or cracked), as well as the elemental composition, shape and size of the fibres.

A standardised test method which uses advanced fibre characterisation techniques is the **ISO 4484-2 method**[86] which was originally developed for microplastic analysis. The method combines optical microscopy and molecular spectroscopy to quantify and characterise microplastics through sample preparation, filtration, and analysis. Its strength lies in the detailed characterisation of microparticles, providing insights into morphology, size distribution, polymer composition, surface area, and estimated weight. This enables precise quantification of microplastics across various size classes (5-5000 μm). However, it has limitations in distinguishing between some non-synthetic fibres.

Table 2: Comparison of Established Test methods for assessing fibre fragments into water

TEST METHOD	THE MICROFIBRE CONSORTIUM	UNDER ARMOUR (DIN 19292)	HOHENSTEIN	AATCC TM 212 - 2021	ISO 4484-1	ISO 4484-2	ISO 4484-3
Overview	Measures material loss from fabrics during the initial wash.	Compares material loss between fabrics during the initial wash. A quick, inexpensive test to aid in early-stage product development.	Measures material loss from fabrics during the initial wash.	Measures material loss from fabrics during the initial wash. Includes the optional inclusion of detergent.	Measures material loss from fabrics during the initial wash.	Measures microplastic loss from fabrics during the initial wash.	Measures material loss from a fabric/ garment through a domestic washing machine. Can be repeated across multiple wash cycles.
Qualitative/ Quantitative	Quantitative	Qualitative	Quantitative & Semi-qualitative	Quantitative	Quantitative	Quantitative & Semi-qualitative	Quantitative
Number of Specimens required	8	8	4	4	4	4	≥2
Size detection limit	1.6µm	5µm	50µm	1.6µm	1.6µm	0.45µm, 0.8µm, 1µm, 5µm	10 ± 4µm
Ease of Use*	++	+++	+	++	++	+	+
Cost**	$$	$	$$$	$$	$$	$$$	$$$
Limitations	Does not differentiate fibre composition, polymer type and/ or chemical additives.	Subjective analysis. Does not differentiate fibre composition, polymer type and/or chemical additives. White or pale fabrics are not applicable for this method.	Does not differentiate between polymer types and/ or chemical additives. This method can only be performed by Hohenstin.	Does not differentiate fibre composition, polymer type and/or chemical additives.	Does not differentiate between polymer types and/ or chemical additives.	A relatively new test, therefore, it has not undergone extensive validation and is not CEN approved. Some non-synthetic fibres can't be fully characterised.	Does not differentiate between polymer types and/or chemical additives.

***Ease-of-use:** From most (+++) to least (+) easy to use, with the Under Armour test being the easiest, as anyone within the supply chain can be trained to carry out the test, compared to Hohenstein test, which can only be carried out at Hohenstein labs.

****Cost**: From most ($$$) to least ($) expensive, with the Under Armour test being the least expensive as it was designed to be inexpensive for its adoption within the supply chain, compared to the most expensive tests such as Hohenstein, ISO 4484-2, and ISO 4484-3, which require specific resources (i.e., testing equipment and trained lab technicians) to carry out the test.

CONSIDERATION FOR CURRENT TEST METHODS

While significant strides have been made in developing methods that simulate washing, several barriers still hinder progress in achieving a true understanding of fibre fragmentation—not only during washing, but across the entire lifecycle of a textile.

The variability in testing protocols used by industry stakeholders and researchers complicates the ability to generate comparable data to draw consistent conclusions across studies.[38] For instance, even the variations in filter types can influence the accuracy and consistency of results between studies. Filters with smaller pore sizes capture more fibre fragments but are prone to clogging, disrupting the analysis process. In contrast, filters with larger pores are less likely to clog but may miss smaller fibres, leading to an underestimation of the fibres loss. Additionally, the material of the filter can influence the drying, conditioning, and weighing — all key steps conducted during gravimetric analysis.

Moreover, **existing tests measure fibre loss from fabric swatches during the first simulated wash cycle. This approach limits the applicability of results at a product-level, as significant assumptions are needed to extrapolate fibre loss for an entire product.** Additionally, the washing conditions simulated in existing tests are based on washing practices in developed countries with widespread access to electric washing machines. This overlooks the diverse washing techniques used globally, particularly in the Global South, where hand washing is more common. Understanding the influence of these practices on fibre shedding is essential for designing solutions that are globally relevant, but no standardised methods are currently available to address these variations.

Next, **there is also a lack of standardised test methods to assess other critical pathways of fibre fragmentation, such as fibre loss into air** from mechanical process during manufacturing or abrasion during wear.[16] As a result, there is a gap in understanding the relative extent of fibre fragments released into the environment across different lifecycle stages.

Lastly, while current test methods measure fibre loss from fabric samples, **the data alone does not provide information on the environmental consequences of fibre fragments within the environment.** Biodegradability, chemical load, and toxicity will all affect the impact of a fibre fragment within specific environments (marine, freshwater, terrestrial, air) and should be considered in addition, and separately, to quantity.

WORKSHOP OUTCOMES

The workshop aimed to address the ongoing discourse on the best-use cases and inherent limitations of existing test methods. **Key concerns include the depth of analysis, data consistency, accessibility, and inability to address all sources of fibre fragments,** all of which complicate efforts in establishing a unified strategy for assessing fibre fragmentation.

A central theme of the discussion was the lack of consensus on the appropriate depth of analysis required to accurately assess fibre fragmentation and draw reliable conclusions. Some participants acknowledged the ability of gravimetric analyses, which quantify fibre loss for the identification of influencing variables and enabling fabric-to-fabric comparisons. In contrast, others advocated for more detailed analyses through fabric characterisation techniques to gain insights into fibre morphology or contaminants within the sample before drawing conclusions solely based on quantification results. However, the outcomes of fibre characterisation analyses remain less established, leaving uncertainties about which fragment size, shape, or type should be considered preferable in reducing the impact of fibre fragment pollution.

This complexity raised a fundamental question to consider when employing test methods: **"Why do we test? What is the purpose of the data collected? How will the data be used by stakeholders?"**

From an environmental and health perspective, there is a growing desire to understand how fibre fragments affect the environment and human health. These fragments can enter food webs and disrupt biological systems. This impact is dependent not only on size, but also chemical makeup of additives and the age or weathering of the fibre fragment. This is because additives, such as dyes or coatings, can alter how fragments behave in the environment, affecting their toxicity or persistence in the environment. Additionally, the age and weathering of fragments, influenced by factors like UV exposure or microbial activity, can change their physical and chemical properties. Therefore, **quantitative data from gravimetric analysis alone do not provide enough information on the consequences of fibre fragments within the environment.**

From a policy perspective, existing methods, such as the TMC Test Method, the ISO 4484-1, ISO 4484-2, and AATCC TM212, were designed to measure fibre loss from fabric swatches during simulated washing conditions. While these methods are intended to inform more responsible textile design and manufacturing choices to ultimately reduce shedding through the understanding of root causes, the data collected is not sufficient for regulating finished products at the consumer level. This limitation stems from the need to extrapolate the results to estimate fibre loss at the product level, as well as the failure to account for fibre fragmentation into other pathways, such as air.

From an industry perspective, the primary objective is to produce textiles with a lower propensity to shed. Consequently, data generated from test methods are crucial, as they provide valuable insights to support this goal. Nonetheless, there is still ongoing debate about the level of analysis required. Although gravimetric analysis offers clear and straightforward insights into the shedding behaviour of fabrics, this methodology alone might not provide a complete picture. Fabric characterisation techniques may offer additional understanding of fibre composition, morphology, and the presence of other polymers and/or additives. **These contaminants, which are unrelated to the fabric's true shedding behaviour, can skew results by contributing to the total weight of fibre discharge. Currently, the extent of this error remains uncertain, adding a significant 'noise' factor to the data.**

Furthermore, the accessibility of these test methods is critical for wider adoption. Key questions remain; What levers can be used to increase accessibility? Will government support be required, or is greater collaboration needed for the industry to move forward in the same direction.

CHAPTER 5: SOLUTION PORTFOLIO

Tackling the challenge of fibre fragmentation requires the involvement of stakeholders across the entire supply chain, from raw material producers to consumers, as well as academia and policymakers. The key strategy to address fibre fragmentation at its source is the understanding of root causes. Identifying these factors can inform more responsible textile design and manufacturing, helping to produce fabrics with a lower propensity to shed. However, fabrics will continue to shed even if at a lower rate; therefore, interventions across the value chain are needed, from industrial-level filtration systems to consumer-level interventions. **Thinking systemically and adopting a 'solutions portfolio' approach is key to significantly mitigating the issue of fibre fragmentation.**

RESPONSIBLE TEXTILE DESIGN AND MANUFACTURING

Textile design and manufacturing factors play a crucial role in fibre fragmentation. Understanding the level of influence of each factor is essential to identify best practices in design and manufacturing as well as to steer the development of targeted solutions aimed at reducing fabric shedding. While research has provided valuable insights into the influence of different design or manufacturing factors (e.g., raw material, type of yarn, fabric construction), significant knowledge gaps persist. There is also uncertainty around the consistency of scientific data, which limits the ability to draw actionable recommendations. This uncertainty hinders the development of industry best practices and slows the progress of R&D efforts driving innovation aimed at mitigating fibre fragment pollution.

YARN TYPE AND CONSTRUCTION

Continuous filament fibres, known for their long, unbroken strands, release fewer fibre fragments than staple fibres, which are shorter and more prone to separation. For instance, polyester continuous filaments, when tightly twisted into yarns, enhance fibre cohesion, reducing shedding during use and washing.[87] Additionally, **thinner and denser yarns without sufficient twist have been associated with higher shedding rates during manufacturing and consumer use**, underscoring the need for careful design and subsequent yarn development at this stage.[34] Yarn preparation plays a critical role in fibre fragmentation, and rotor spinning—a widely used method in the textile industry—has been shown to notably contribute to fibre shedding.[87,88] This process involves sharp-edged opening rollers that untangle fibres before twisting them into yarn, which can lead to fibre damage. Optimising twist levels and integrating novel bonding techniques have proven to be potential solutions for enhancing yarn stability and reducing fragmentation.[70,89]

PROCESSING (PRETREATMENT, DYEING AND FINISHING)

Identifying the drivers of fibre fragmentation within processing is crucial for reducing fibre loss throughout the lifecycle of a textile. Research has demonstrated that different mechanical and chemical processes can either negatively or positively influence fibre fragmentation.

Conventional dyeing methods, which rely on high temperatures and prolonged processing times, weaken fibre cohesion and increase the likelihood of fibre fragmentation.[34,87] Therefore, innovations which reduce water use, lower dyeing temperatures, and have shorter processing times help preserve fibre strength and reduce shedding.[90,91] Emerging technologies, such as ultrasonic-assisted dyeing, and supercritical CO_2 dyeing, offer such alternatives by being less abrasive.[90] For instance, supercritical CO_2 eliminates the use of water-intensive dye baths and minimises surface abrasion. Similarly, ultrasonic dyeing enhances dye penetration without mechanically stressing fibres. Finishes aimed at reducing protruding fibres from fabrics can also significantly lower their shedding potential.[92,87] This includes singeing or enzymatic treatments such as biopolishing which target loose fibre ends.

Further research is required to understand how different finishes impact mechanical properties such as tensile, tear strength and friction, and subsequently their influence on fibre fragmentation.[93] Finishes that apply plasma treatments, nanofibre coatings, and cross-linking technologies are among the most promising solutions for enhancing fibre cohesion and durability, thereby reducing shedding.[87] Additionally, advanced coatings, such as hydrophobic layers and polymer-based anti-shed treatments, create smoother fabric surfaces that resist abrasion. However, the durability of these treatments across repeated laundering cycles also requires further investigation to ensure their long-term effectiveness in minimising the release of fibre fragments into the environment over time.

GARMENT PREPARATION

Cutting methods have been identified as a key factor influencing fibre fragmentation. Innovative methods such as laser cutting and ultrasonic cutting provide promising alternatives to conventional scissor cutting.[95] **Laser cutting reduces fibre shedding due to its precision, showing 3 to 31 times lower shedding rates than conventional scissor cutting.**[94,96] While ultrasonic cutting uses high-frequency vibrations to achieve clean cuts with minimal fibre loss. Beyond cutting techniques, preparation steps are being developed to address fibre shedding before garments leave the factory. For example, Jeanologia and Inditex are collaborating to develop the first industrial 'Air Fiber Washer', a technology designed to remove loose fibre fragments from garments at the factory level, before they reach the end consumer.[97] The system uses dynamic airflow to extract fibre fragments without employing water, designed to capture fibres that shed during initial domestic washes.

INNOVATIONS

Innovations designed to reduce a textile's propensity to shed are still in their early stages, facing several barriers. Firstly, high implementation costs present a significant challenge, particularly for small and medium-sized manufacturers, limiting the adoption of advanced solutions like ultrasonic cutting or plasma treatments. Secondly, **these innovations require further validation to confirm their efficacy and identify potential environmental trade-offs, such as increased CO_2 emissions.** Lastly, fibre fragment pollution is still not recognised as an impact category in LCAs, which are commonly used by the industry as a comprehensive tool to assess the environmental impact of new technologies and strengthen the case for their adoption. Therefore, despite its recognition as an environmental concern, it is often overlooked within the industry. Addressing these barriers will require collaboration across the supply chain, researchers, and regulatory bodies to encourage the development and adoption of solutions tailored to diverse production contexts. Sharing best practices, informed by rigorous testing and research, will further ensure that these innovations can be widely implemented and effectively reduce fibre fragmentation, while also supporting other sustainability agendas.

INDUSTRIAL-LEVEL FILTRATIONS

Industrial filtration systems play a critical role in reducing the amount of fibre pollutants released into the environment. These systems are designed to target two primary pathways: air and wastewater effluents. Both of these pathways represent significant contributors to fibre fragment pollution from manufacturing and require advanced and scalable solutions for effective management.

AIR FILTRATIONS

Airborne fibre fragments released during textile manufacturing contribute to fibre fragment pollution and pose health risks to workers. Implementing advanced industrial air filtration systems with a multi-stage approach, combining pre-filters, HEPA filtration, and proper ventilation, can significantly reduce airborne microfibres.[97] These systems not only help capture fibre fragments more effectively but also improve overall workplace air quality, safeguarding workers from prolonged exposure to high concentrations of airborne fibres during production processes.

WATER FILTRATION

ETPs play a pivotal role in reducing the release of fibre fragments into water bodies. Wastewater from textile manufacturing frequently contains significant concentrations of fibre fragments, necessitating the use of effective filtration technologies. Advanced methods, such as membrane filtrations, including ultrafiltration have shown promise in reducing fibre fragments in effluent.[87,98] These technologies employ selective barriers with specific pore sizes that separate particles based on size, allowing smaller molecules (e.g., dissolved salt or organic compounds) to pass through while retaining larger ones (e.g., fibre fragments and suspended solids). However, their high cost, energy requirements, and operational complexity limit accessibility for smaller facilities. Secondary clarifiers, which use sedimentation to remove suspended solids, provide a more affordable alternative. Although less effective at capturing smaller fragments, well-maintained systems with skilled operators can still achieve significant reductions with larger fibre fragments.[87]

Despite their critical role, the effectiveness and accessibility of ETPs vary significantly across the industry. Smaller operations in resource-constrained regions often lack the capital and expertise for advanced setups, leaving some facilities struggling to implement advanced setups and meet the required standards. This variability is further aggravated for those relying on communal ETPs, as implementing advanced filtration systems becomes more challenging. Furthermore, the high energy consumption of advanced filtration technologies raises concerns about their environmental footprint, underscoring the need to assess whether these solutions are not only effective, but also cost-efficient and energy-conscious.

Monitoring ETP performance is vital for reducing fibre fragment pollution. TSS monitoring has emerged as a cost-effective approach for indicating fibre fragment concentrations in effluents. **ZDHC and TMC have played a pivotal role in advancing the use of TSS by demonstrating that TSS data can serve as a reliable proxy for fibre fragment monitoring along with general effluent quality,** particularly in facilities lacking the resources for advanced analytical techniques.[99] Through ZDHC's Wastewater Guidelines, thresholds for TSS concentrations have now been established in line with sustainable effluent management practices. By achieving the aspirational limits for TSS, facilities can drastically reduce the fibre fragments discharged in their wastewater. This will not only improve fibre fragment capture rates, but also support compliance with broader environmental standards.

Modular filtration technologies, which allow facilities to scale their filtration capacity incrementally, provide a viable solution for reducing upfront costs, enabling broader adoption across the textile industry. An example is Regen® filter developed by Matter; a patented self-cleaning water filtration technology. The filter can be installed in any existing or new textile factory and was exclusively designed for textile manufacturers to capture fibre fragments. **To further improve filtration system effectiveness, capacity-building initiatives, such as training programs and technical support, as well as collaborative industry partnerships that incentivise the adoption of high-efficiency technologies are required.** These can be complemented with policy interventions, such as financial subsidies for smaller operators, and phased implementation schedules to further support equitable progress in pollution reduction.

CONSUMER-LEVEL INTERVENTIONS

Consumer-level interventions play an important role in reducing the release of fibre fragments into the environment through practical solutions focused on filtration technologies and behavioural changes.

CONSUMER-LEVEL FILTRATION TECHNOLOGIES

Filtration technologies designed for domestic use provide an additional barrier against fibre fragment pollution by capturing fibre fragments released during laundering, before they enter wastewater systems.[87] Washing machine filters, such as the PlanetCare filter, Matter's Gulp filter, Xeros' XFilter, and in-drum tools like the Cora Ball, are examples of consumer-level interventions that have demonstrated varying degrees of effectiveness. Additionally, washing bags, such as the GUPPYFRIEND, offer another accessible solution by reducing friction during the wash cycle and trapping fibre fragments within a bag. However, the effectiveness of these tools in reducing the fibre fragments released into the environment is contingent upon proper consumer handling, including regular cleaning and responsible disposal of the captured fibre fragments. Improper disposal, such as rinsing fibres down the drain or adding them to compost, risks reintroducing fibre fragments into the environment and negates the benefits of these filtration technologies. Environmental organisations recommend sealing captured fibre fragments in secure containers or bags before disposal with regular household waste.[87]

CHANGES IN LAUNDRY PRACTICES

Research identifies three key actions that consumers can take to minimise fibre fragmentation when washing their garments:

- **Reducing washing frequency:** Washing garments less frequently minimises mechanical stress and abrasion, primary drivers of fibre release.[87]
- **Lowering wash temperatures:** Washing at lower temperatures, such as 30°C instead of 40°C, helps preserve the integrity of fibres.[87]
- **Using gentle wash cycles and full loads:** Gentle wash cycles limit agitation, thereby reducing friction between garments.[87] Additionally, running full loads minimises fabric-to-fabric abrasion, further mitigating fibre release during washing.

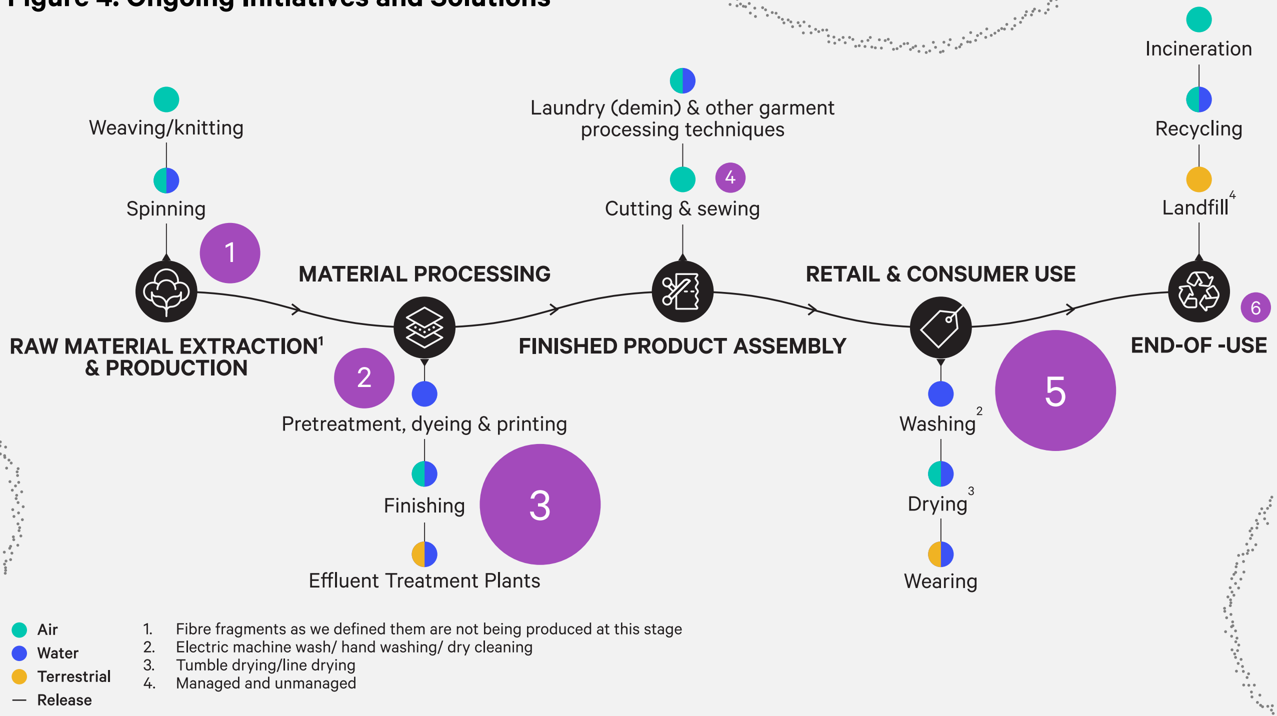
These small but impactful behavioural changes align with broader environmental goals, such as reduced water consumption and energy, as well as provide a straightforward way for individuals to contribute to mitigating fibre fragment pollution. **Public awareness is a critical factor in driving consumer-level interventions. Surveys suggest that many consumers remain unaware of the environmental impacts of fibre fragments or the role they play in mitigating their impacts.**[87] Targeted education campaigns, developed in collaboration with environmental organisations, governments, and appliance manufacturers, can help bridge this knowledge gap.

WORKSHOP OUTCOMES

The workshop focused on discussing both current and emerging solutions for addressing fibre fragmentation, and the potential challenges to their implementation. A key takeaway was the necessity of a 360-degree approach that encompasses all stages of the textile's lifecycle, and the importance of validating solutions to address any unintended consequences that may hinder broader sustainability efforts. For instance, trade-offs—such as increased energy consumption and CO_2 equivalent emissions linked to more intensive ETP processes—must be carefully evaluated. Ultimately, the workshop emphasised that **a single solution will not suffice; instead, a holistic approach is required, one that connects fibre fragmentation to other sustainability challenges.**

Several clusters of ongoing efforts are driving research, the development of mitigation strategies and innovative solutions to address fibre fragment pollution. While not exhaustive, Figure 4 illustrates the most prominent clusters along the journey of a fibre fragment.

Figure 4: Ongoing Initiatives and Solutions



1. Fibre fragments as we defined them are not being produced at this stage
2. Electric machine wash/ hand washing/ dry cleaning
3. Tumble drying/line drying
4. Managed and unmanaged

1 Root Causes:
Addressing fibre fragmentation at its source is increasingly recognised as the most effective long-term strategy. Initiatives are focused on examining the influence of various variables—such as fibre composition, yarn structure, and processing treatments—across different fabrics. The aim is to integrate these insights into textile design and manufacturing processes to minimise fibre fragmentation. Although this area of research is still in its early stages and significant knowledge gaps persist, substantial efforts are underway across various groups.

2 Industrial-level interventions:
Technologies initially developed for laundry interventions have been adapted for wet processing stages, including pretreatment, dyeing, and finishing. These solutions aim to reduce the release of fibre fragments before textiles reach consumers, mitigating pollution through industrial water pathways. While implementation efforts are increasing, gaps remain in understanding their full potential, as effectiveness at scale varies across facilities.

3 Effluent treatment plants:
ETPs are well-established in the industry, utilising a range of technologies to prevent pollutants from entering waterways. The focus is now on improving their efficiency, as well as developing reliable assessments for monitoring the capture of fibre fragments.

4 Garment Preparation:
Recognising that a higher amount of fibre fragments are released during the first wash after leaving the factory, technologies are being developed with air-based systems to extract loose fibres from garments before they reach consumers. However, these solutions are predominantly in R&D and have not yet been widely commercialised.

5 Consumer-Level Interventions:
A large focus in the use phase has been laundry interventions specifically to electric washing, with some solutions developed in collaboration with washing machine manufacturers and others independently developed for consumers to add to their washing machines. These interventions aim to capture fibre fragments before they enter the environment through water pathways and have been widely commercialised.

6 Biodegradation:
Enhancing the biodegradation of fibre fragments is a potential solution to reduce their persistence within the environment. R&D is being carried out into chemicals that enhance biodegradability, along with significant research to gain a better understanding on the true biodegradation potential across all processed fabrics.

Legend:
Figure 4 illustrates the clusters of initiatives and solutions along the journey of a fibre fragment. The size of each purple circle indicates the extent of work in that area:
- Smallest - Limited no. of initiatives
- Middle - Considerable no. of initiatives
- Largest - Well-established field

Despite these efforts, workshop participants emphasized that significant gaps in knowledge regarding the root causes of fibre fragmentation remain a key barrier to developing targeted solutions. This not only hinders the development of defined industry best practices, but also limits brand's ability to engage with internal teams or manufacturing facilities to educate them on the impact of their design and manufacturing choices. It was also noted that visual test methods, such as the Under Armour method, have proven effective in communicating potential solutions to designers by providing easy-to-read, data-driven insights into how their decisions can influence fibre fragmentation. This highlights the benefits of generating data with consideration for the diverse individuals at different stages of the supply chain, ensuring they can effectively interpret and act on the information.

Another notable barrier stressed by the workshop participants is the variation in ETP effectiveness across facilities and geographies, which complicates efforts to establish universal benchmarks or standards. While research suggests a correlation between TSS and fibre fragments, further studies are needed to confirm TSS as a reliable metric for assessing ETP performance in capturing fibre fragments. Defining acceptable levels of fibre fragments in discharged effluent is crucial for consistent benchmarking, tracking progress, and identifying effective solutions to reduce emissions.

CHAPTER 6:
BIODEGRADATION AND TOXICITY

BIODEGRADATION

Biodegradation is the breakdown of organic materials by microorganisms into simpler substances like CO_2, CH_4, H_2O, biomass, and mineral salts under under oxygen-rich or oxygen-deprived conditions, defined by specific timeframes and environmental conditions. Enhancing the biodegradability of textiles is viewed as a potential solution to fibre fragment pollution, as biodegradable fibre fragments are less likely to persist in the environment, thereby reducing their impact.[100] Note that this section of the report focuses on biodegradation within the natural environment, specifically referring to our definition, which centers on fibre fragments that shed during the lifecycle of textiles and their subsequent breakdown in natural environments. While we acknowledge that fibre fragments also end up in commercial or home compost environments, the topics of compostability and biodegradability of fibre fragments require individual attention. Therefore, compostability is out of scope.

Measuring the rate and extent of biodegradation within the natural environment is complex as it is influenced by a range of factors. These factors include environmental conditions, material properties, and the chemical and mechanical processes applied to a fabric during manufacturing.[26,,102,103] The interplay of factors means that biodegradation rates vary considerably, making it challenging for the industry to accurately assess a material's ability to biodegrade and estimate the time required for this process.

ASTM and ISO methods exist to measure the rate and extent of a material's biodegradation in various environments, including soil, commercial compost, seawater, and wastewater sludge, where fibre fragments are significant pollutants. For example, ASTM D6691-17 is used to assess plastic materials in marine environments.[104] **While these tests offer valuable insights, they have limitations in determining true biodegradability, as they are typically conducted under controlled laboratory conditions that do not fully replicate the complexities of real-world environments.** Moreover, measuring the by-products and nanoparticles which may form during the biodegradation process is challenging and remains underexplored. For example, fabrics may shed and continue to break down in the environment into nano-sized fibres that can persist undetected, regardless of whether the material is inherently biodegradable.[105] This raises questions around the definition of biodegradation and its endpoint, creating uncertainty on the claims made on a fabric's biodegradability.

ENVIRONMENTAL AND MATERIAL SPECIFIC FACTORS

Typically, the physical form and chemical structure of a material dictates whether it has the potential to biodegrade, while environmental conditions dictate whether this potential is realised in practice.[101] Biodegradation relies on access to moisture and the ability of microorganisms to break down molecules within a finished fabric, using them as a food source. For this process to occur effectively, the right environmental conditions are needed to allow microorganisms to thrive and support their microbial activity.[26] Factors such as temperature, moisture, nutrient availability, and oxygen levels are critical in determining the speed and efficiency of biodegradation. These environmental factors must align optimally to enable or accelerate the rate of biodegradation. Table 3 outlines the key environmental factors influencing biodegradation.

Table 3: Environmental-Specific Factors Influencing Biodegradation.[101]

FAVOURABLE ENVIRONMENTAL FACTORS	UNFAVOURABLE ENVIRONMENTAL FACTORS
Warm temperature	Cold temperature
High moisture	Dry conditions
Sufficient nutrients (nitrogen, phosphorous, iron, trace elements)	Insufficient nutrients (nitrogen, phosphorous, iron, trace elements)
Suitable oxygen levels	Unsuitable oxygen levels
Lots of sunlight	Little to no sunlight
Long time period	Short time period

In addition to environmental conditions, the material properties of the textile itself—both physical and chemical—play a significant role in determining its biodegradability.[101] Table 4 outlines the key material properties influencing biodegradation.

Table 4: Material-Specific Factors Influencing Biodegradation[101]

DECREASE BIODEGRADATION	INCREASE BIODEGRADATION
High crystallinity	Low crystallinity (Amorphous regions)
Insolubility in water	Solubility in water
Hydrophobicity	Hydrophilicity
Larger molecules	Smaller molecules
Molecular structure dissimilar to naturally occurring materials	Molecular structure similar to natural occurring materials
Less surface area	More surface area

When only considering the material properties of natural fibres in their raw, unprocessed state as found in the environment (directly from plants or animals), they are generally more prone to biodegradation under favourable environmental conditions. This is because they are primarily derived from biomass made up of natural occuring materials, like glucose and amino acids, which are common in the environment and easily utilised by microorganisms as a food source.[106] Additionally, natural fibres like cotton are hydrophilic, meaning they readily absorb water. This absorption creates an environment that encourages microbial activity, further speeding up the breakdown of the fibres and enhancing their biodegradability.

In contrast, synthetic fibres such as polyester are notably less prone to biodegradation, due to their inherent material properties. Its chemical composition, derived from fossil fuels, differs significantly from naturally occurring materials, hindering microbial breakdown.[101] Furthermore, polyester's hydrophobic nature repels water, and its high crystallinity reduces the surface area accessible to microorganisms, making it less susceptible to microbial activity.[26,106]

MECHANICAL AND CHEMICAL PROCESSING

When evaluating the biodegradability of materials from any fibre type, attention to the specimen form is crucial as the ability for a raw, unprocessed fibre may vary significantly from a finished fabric.[26,27,108] Finished fabrics undergo both mechanical and chemical processing to enhance material quality and refine their final handle for consumer appeal. However these processes can either hinder or enhance the biodegradability of the fabrics. Pretreatment steps, such as the mercerisation of cotton can cause structural modifications, converting cellulose I to cellulose II. This structural change increases the crystallinity and crosslinking, which in turn, can make it less susceptible to biodegradability.[103] However, some studies have also found no significant difference in biodegradability between mercerised and unprocessed cotton, demonstrating other factors also play a role.[26,25] Dyes also influence biodegradation rates due to the various chemical compounds, even when the material is inherently more susceptible to biodegradation.[27] For instance, a study on reactive dyes applied to cellulosic, wool, and nylon fibres found that the chemical structure of these dyes hindered biodegradation.[108] However, this research was limited to soil and composting environments and did not explore the relationship between physical and chemical changes on fibre surfaces and their biodegradation rates. Finishes have demonstrated a wide range of effects across the board. Antimicrobial finishes designed to resist microbial activity typically hinder or even prevent biodegradation.[107] Likewise, water-repellent finishes have shown to slow down the rate of biodegradation.[103,108,25] Whereas, softeners with surfactant properties can promote microbial adhesion to the fibre surface, accelerating the biodegradation process.[109,108] This variety of findings and conflicting data underscores the complexity of measuring the biodegradability of materials, highlighting the need for further research to fully understand how processing treatments influence fibre breakdown across different environments.

MISCONCEPTION OF BIOBASED MATERIALS

A common misconception is that all biobased materials are inherently biodegradable.[110] While biobased textiles are often partially or fully derived from biomass, this does not guarantee biodegradability. For example, biobased polyester (BioPET) is derived from biomass, but it is not biodegradable. In contrast, some synthetic derived from fossil fuels, such as Polycaprolactone (PCL), and poly(butylene succinate) (PBS),have shown to biodegrade under specific conditions.[111] This highlights the importance of distinguishing between biobased and biodegradable, as two properties that are not synonymous.

It is important to approach claims on biodegradability with caution to avoid common misconceptions on the biodegradability of different materials used within the fashion and textile industry. Biodegradability is not solely determined by a material's origin as within the natural environment microorganisms cannot distinguish between carbon derived from plants or animals and carbon from fossil fuels.[28] Various other factors come into play, such as environmental conditions, material properties, and the chemical and mechanical processes applied throughout manufacturing up until a finished fabric.

LIMITATIONS IN TESTING

Current test methods are conducted under controlled laboratory conditions, failing to replicate diverse and often harsher conditions that fibre fragments encounter in the natural environment. Fibre fragment pollution is transient, with many pathways into the environment, potentially ending up anywhere on earth. Therefore, biodegradation in real-world environments is far more complex and variable, creating a gap between lab results and actual biodegradation in nature. Laboratory conditions are limited and cannot take into account unknown factors such as the likely starting and stopping of the biodegradation of fibre fragments as they pass through different environments, but can only confirm or deny the inherent ability of a material to be fully mineralised in stable laboratory conditions, as well as compare how long the process takes from one material to another. In situ testing in actual environments can be useful in corroborating laboratory data, but is also limited in evaluating true microbial biodegradation versus disintegration. Additionally, as with lab studies, in situ tests only consider a small subset of potential environmental conditions. **This imbalance contributes to discrepancies between results drawn within a lab and actual environments, underscoring the need to develop a more comprehensive matrix of testing protocols that focus on the diverse environments in which fibre fragments may end up.** Furthermore, tests that are conducted before a fibre or fabric is fully processed, void of the chemicals and auxiliaries commonly used cannot be solely relied on for a complete understanding of how fibre fragments that shed from a garment truly degrade across different environmental compartments.

These gaps underscore the need for more targeted research specifically focused on fibre fragments, while also taking into account their transfer between various environments and where they are most likely to accumulate (refer to Figure 3).[50,112] **Most research has currently focused on the biodegradation of whole textiles or yarns, overlooking the degradation of fibre fragments, which are smaller, more persistent, and likely to be more mobile in the environment.** Testing limitations, coupled with the complexities of transient pollution in uncontrolled and endlessly variable environmental conditions, make it nearly impossible to predict the fate of fibre fragments once they enter the environment. Even highly biodegradable materials may persist if they do not reach moisture- or microorganism-rich environments. This has created uncertainty within the industry around biodegradability claims not fully representing real-world conditions. Since biodegradation potential depends on environmental conditions, it is essential to distinguish between a material's inherent ability to biodegrade and the likelihood of that potential being realised. This distinction is crucial when communicating biodegradability claims in consumer marketing for finished products.

CERTIFICATIONS AND STANDARDS

The emerging focus on circularity in the fashion industry has led to the development of new materials or treatments to enhance biodegradation and in parallel, the increase of biodegradability claims. Certifications like the Global Organic Textile Standard (GOTS) and Cradle to Cradle Certified® provide frameworks for substantiating these claims. For instance, GOTS applies to textiles made with at least 70% certified organic fibres, setting limits on environmental impacts, including biodegradability of chemical inputs used in wet processing (not to be confused with biodegradability of fibre fragments from finished fabrics).[114] Cradle to Cradle Certified® offers multiple levels of certification.[115] For example, at the lowest level (Bronze), at least 50% of a product's materials by weight must be compatible with either biodegradation or recycling pathways. One requirement is that the materials be biodegradable within a specified timeframe and to the extent outlined by a C2CPII-recognized compostability or biodegradability standard test.

UNCERTAINTY IN BIODEGRADABILITY CLAIMS

The absence of standardised methodologies, testing criteria, and thresholds for assessing the biodegradability continues to create uncertainty regarding claims.[112] For example, TMC emphasises that biodegradability claims should be based on tests demonstrating the full mineralisation of materials—breaking them down into CO_2 (or CO_2 and CH_4) and microbial biomass. A precise claim might state: *'This cotton fabric [including a brief summary of specifications on weight, yarn type, dyeing process and functional finishes] achieves 86% biodegradation in marine environments after 42 days at 30°C, based on ASTM D6691 testing,' rather than a vague assertion like 'cotton biodegrades'.* Such specificity ensures transparent communication about the true environmental impact of a fabric.

Additionally, metrics such as molecular weight reduction that can be generated from in situ tests, are insufficient evidence alone as they only measure the partial breakdown and not the complete transformation of materials into harmless by-products or nanoparticles. This concern is particularly relevant with the introduction of chemical additives that enhance biodegradability by attracting microbial populations to textile surfaces.[113] The potential for complete biodegradation must be scientifically proven. These additives may improve biodegradation rates, but also must be evaluated to ensure that they do not introduce additional toxicological risks beyond the inherent dangers of fibre fragments polluting the environment, and their by-products should be confirmed as not harmful to ecosystems. It is important to acknowledge that a chemical safe for one species might be toxic to another, highlighting the need to separately assess biodegradability and toxicity and using appropriate target species relevant to the affected ecosystems.

To avoid misleading claims and prevent uncertainty around biodegradation, the fashion and textile industry must be cautious when using terminology that implies biodegradability. **Clear distinction needs to be made between biodegradation potential, toxicity of chemicals and possible by-products (including nanoparticles) that persist within the environment.** Additionally, the industry needs to align on appropriate testing methodologies and metrics, giving reasonable consideration to the timeframes and real-world environments, as well as take into account any processing carried out up to the finished product. With these considerations in mind, the textile and fashion industry can gain a better understanding on the biodegradation of fibre fragments, and guide innovation to focus on creating safer, and less harmful textiles.

TOXICITY

Fibre fragments are among the most prevalent anthropogenic particles found in habitats and wildlife globally.[8] Despite this, their toxicity remains underexplored compared to other microplastic types, such as microplastic spheres.[116,117] **Studies have shown observable effects of fibre fragments on organisms, yet the mechanisms behind these effects—which may be physical or chemical—are not fully understood.** This gap in knowledge is amplified by the unique physical properties of fibre fragments, such as increased surface area and flexibility, which likely influences their environmental fate and interactions with organisms when testing these particles in laboratory settings. This underscores the urgent need to move beyond simply describing the impacts of fibre fragments and focus on understanding their mechanisms and processes which influence the toxicity i.e., whether the physical particle, a chemical (or set of chemicals), or these factors together are driving effects. Such research will be essential for more accurately assessing risks and developing effective mitigation strategies.

HUMAN HEALTH

Studies have shown detailed effects from fibre fragments, including adverse impacts to animals and humans. Impacts have been observed at different levels, from the subcellular level to growth and survival.[118] Early research on the effects of fibre fragments primarily focused on occupational exposures, with lung inflammation and other respiratory diseases reported among textile workers. The harmful impact of synthetic fibre fragments in workplace environments has been documented for nearly 50 years, while concerns about health risks from natural fibres date back even longer.[119,120,121] For instance, health impairments caused by cotton 'dust' were first documented in 1818, noting lung illnesses in cardroom workers and recommending ventilation measures to mitigate these effects.[121]

ANIMAL HEALTH

Fibre fragments cause harm to a range of wildlife through ingestion, translocation, and accumulation. Fibre fragments in the digestive tracts of aquatic and terrestrial organisms can lead to blockages, reduced nutrient uptake, reduced growth, and subsequent malnutrition or mortality.[122,123,124,125] For example, studies have shown that ingestion of nylon fibres by mussels *(Mytilus edulis)* impacts their energy acquisition.[124] Physical damages, such as intestinal abrasion, are also observed.[123] In regards to translocation and oxidative stress, studies show that smaller fibres can translocate from the gut to other tissues, leading to oxidative stress and inflammation.[126,127] Oxidative stress has been observed at low environmentally-relevant concentrations of fibre fragments.[128] Additionally, inhaled fibres can deposit in the respiratory system, leading to chronic inflammation and potential respiratory diseases, as evidenced by human workplace exposure data.[129] Recently, non-human species have also been reported as inhaling fibre fragments, and in fishes fibres may cause greater respiratory stress than other microplastics.[130,131] Recent studies show that polyester fibres break down into nanoplastics and can cause changes in gene expression related to muscle function in fish, similar to nanoparticles from other plastic product types.[132] Moreover, studies have shown that exposure to fibres disrupts key physiological processes, including changes to behaviour as well as impair reproduction, leading to multi-generational effects.[133,134,135]

CHEMICAL TOXICITY

Although studies do not typically differentiate between the impacts from the physical particle or associated chemicals, fibre fragments act as chemical vectors, releasing harmful substances from both chemicals used throughout manufacturing processes as well as pollutants from the environment. Processed fibres typically contain chemical treatments, with chemicals such as Polyfluorinated Alkyl compounds (PFAs), flame retardants, and dyes, some of which are known to be toxic, bioaccumulative, and persistent.[136,137,138,139] Some chemicals, even if they are only used as processing agents, remain on textiles, or for some chemicals, such as PFAs, release of these chemicals can increase over time as garments age.[140]

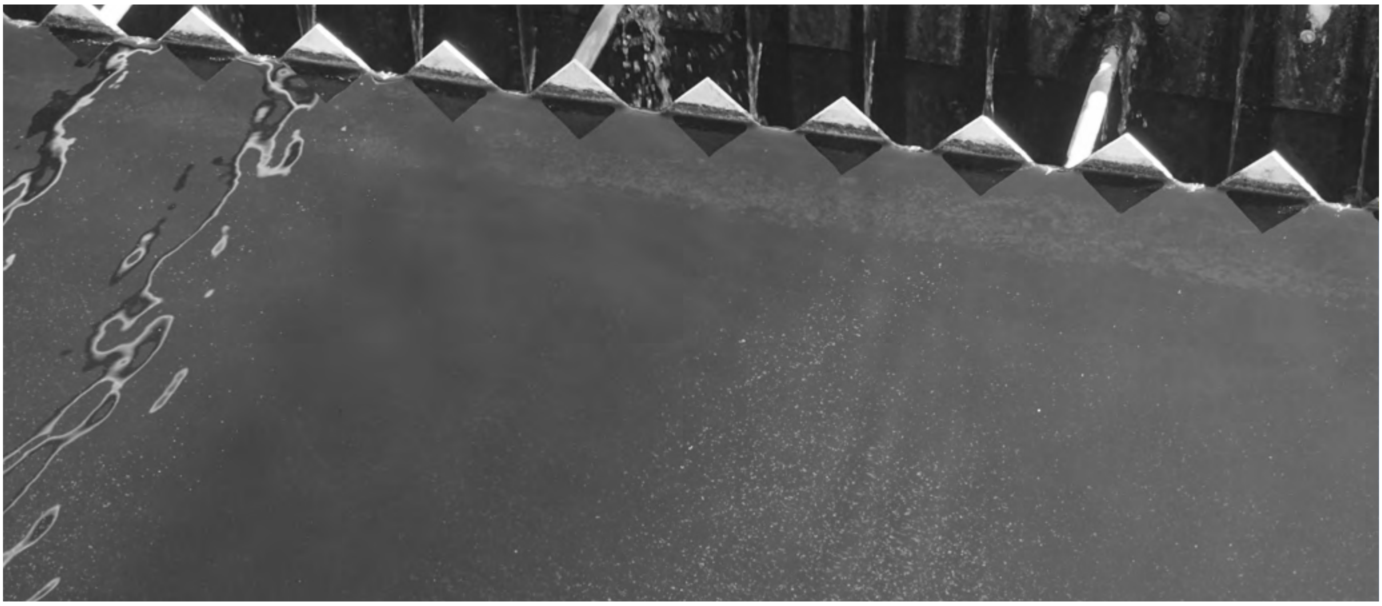
ADHERENCE OF ENVIRONMENTAL POLLUTANTS TO FIBRE FRAGMENTS

Fibre fragments have the ability to attract and adhere to environmental pollutants due to their high surface area and the properties of the polymers they are made from. This includes contaminants such as heavy metals, Polychlorinated Biphenyls (PCBs), Polycyclic Aromatic Hydrocarbons (PAHs), and other hydrophobic pollutants. When ingested, they become bioavailable, meaning they can be absorbed by the organism.[141,142] Due to high concentrations of chemicals, ingestion of fibre fragments may lead to increased bioaccumulation (chemical buildup). This buildup can be more significant than if the organism were simply exposed to the same pollutants directly in water.

WEATHERED FIBRES

Natural weathering alters fibre surface morphology and chemical composition. Increased surface area and weathers may increase toxicity due to changes to sorption behaviour, the process by which fibre fragments or microplastics take up and retain substances from their environment like chemicals, contaminants, or moisture from the surrounding medium. Different chemical leachates, including additives and degradation products, may leech at different rates depending on different weathering.[139]

Fibre fragments are distinct from other microplastics due to their unique physical properties and complex chemical profiles. Addressing fibre fragment toxicity requires improved testing protocols, environmentally relevant designs, and collaboration with the textile sector. Given that textiles are a major source of fibre fragments in the environment, and their observed presence in the human body, understanding and mitigating their impacts on ecosystems and human health remain critical priorities.



WORKSHOP OUTCOMES

The workshop solely focused on the topic of toxicity, with participants noting that current research predominantly concentrates on synthetic fibres, leaving other fibre types underrepresented in the exploration of fibre fragment toxicity. The primary aim of the workshop was to identify research challenges and prioritise strategies to enhance the appropriate design of testing approaches and protocols.

The workshop underscored several key barriers that continue to hinder comprehensive toxicity assessments of fibre fragments, including:

- **Lack of standardisation:** Fibre fragments are heterogeneous, varying in length, size, material, and chemical composition, making it difficult to establish consistent baselines or controls.
- **Environmental relevance:** Many studies use high concentrations of fibres or pristine fibres, which do not always reflect conditions in natural environments.
- **Complexity of fibre fragmentation:** The physical and chemical effects of fibre fragmentation are not well understood, requiring careful experimental designs to disentangle these effects.
- **Underexplored pathways:** Most research has focused on aquatic systems, with limited attention to terrestrial environments (e.g., agricultural fields) and atmospheric exposure pathways (e.g., inhalation).

To overcome these barriers, several strategies were discussed, these include:

- **Develop harmonised testing protocols:** To overcome the lack of standardisation, researchers should share validated methods, such as those for fibre preparation, determining appropriate dosing. Collaboration with the industry could support the development of reference fibres with consistent properties to ensure comparability across experiments.
- **Industry collaboration:** Researchers should collaborate more closely with the industry to gain insights into the chemicals and processes used throughout textile manufacturing to better reflect textiles in their processed state, further enhancing the quality of controls.
- **Improving environmental relevance:** Researchers should focus on concentrations that reflect natural environmental exposure scenarios, such water, soil, and wastewater.
- **Refine experimental designs:** Disentangling the physical and chemical effects requires careful experimental designs. Experimental designs should incorporate comparisons of different types of fibres (dyed vs. undyed, virgin vs. weathered) to understand their respective impacts on toxicity. Incorporating chronic exposure durations and co-exposures to chemical stressors like dyes, plasticizers, and finishes will better capture effects from realistic fibre fragment mixtures. Testing by chemical classes, and improved reporting on chemicals is required.
- **Expand research on pathways:** Research gaps in different exposure pathways must be explored in future toxicity assessments. These studies should focus on fibre fragments hotspots, such as wastewater effluents or biosolid-rich soils, to capture all realistic exposure scenarios.
- **Expand research on fibre types:** As research has predominantly focused on microplastics, collaboration with researchers in ecotoxicology, material science, microbiology and others can help refine experimental designs and identify key drivers of toxicity. A lot can be learnt from other experimental work conducted on microplastics to overcome challenges faced, such as characterising fibres.

CHAPTER 7: REGULATION

As awareness of the extent of fibre fragment pollution grows, policymakers are under increasing pressure to take action. To date, regulatory efforts have largely targeted plastic pollution and, by extension, microplastics across various industries. However, recent research has expanded its focus to include fibre fragments from the fashion industry, broadening the scope beyond synthetics to all fibre types. **Despite this progress, tangible policy interventions beyond plastic pollution remain in their early stages, with most advancements being exploratory and concentrated in the Global North.**

In the Global South, fibre fragmentation is not yet a priority for policymakers, with only a few key studies conducted to initiate awareness within the supply chain. In the Global North, Europe is leading policy discussions on addressing fibre fragments across multiple stages of the supply chain, from manufacturing to product design. Whereas, progress in North America has been slower, with efforts primarily centered on washing machine filters and consumer-level interventions. In all regions, the development of appropriate regulation is hindered due to significant knowledge gaps, creating uncertainty around the industry's readiness for regulation. This underscores the urgent need for a greater collaboration between fashion and textile industry, policymakers and researchers. This will help ensure that the latest scientific research is considered and drive the development of appropriate regulations that address all fibre types and the development of interventions across the whole value chain.

EUROPE

In Europe, existing regulations still predominantly target plastic pollution and microplastics. However, the impact of fibre fragments is gaining recognition with upcoming policies working towards addressing fibre fragments at multiple stages throughout a textile's life cycle.

France is the only country which has a national legislation specifically targeting fibre fragments from the fashion and textile industry. Article 23 in France's Anti-Waste Law for a Circular Economy (AGEC law) implemented in 2022, mandates that all new washing machines sold from January 1, 2025, must include a filter or other solutions to capture synthetic fibre fragments, preventing their release into wastewater.[143] Additionally, the AGEC law mandates verified environmental labelling for textile products containing more than 50% synthetic fibres by weight. The label must state 'releases plastic microfibres into the environment during washing'.

The rest of the regulatory landscape in Europe includes policies that aim to minimise microplastic release. Key policies include, The Plastic Strategy (2018), which aims to limit the intentional addition of microplastic particles to products, such as cosmetics.[144] This led to the restriction of intentionally added microplastics, such as microbeads in cosmetics under REACH (2023).[145] However, unintentionally added microplastics, in products such as tyres, paints, or textiles are not directly addressed under this legislation, although they are being assessed through different regulatory pathways outside of this specific REACH restriction. Additionally, the regulation on 'Preventing pellet losses to reduce microplastic pollution' (2023) proposes several measures across the entire plastic supply chain.[146] This proposal is not yet finalised, but it represents a proactive regulatory framework supporting the EU's Zero Pollution Action Plan, which targets a 30% reduction in microplastic emissions by 2030.[147] However, this legislation is also not specific to the fashion and textile industry.

The EU Textile Strategy (2022) includes numerous measures aimed at reducing the environmental impact and improving the sustainability of textiles across production, use, and disposal phases.[148] Under this strategy there are several key regulations and legislative initiatives that have the potential to address fibre fragments from all fibre types in the future. These include:

The Ecodesign for Sustainable Products Regulation (ESPR) (2024) is a market access legislation that sets a framework to establish ecodesign requirements for all products placed on the European Union (EU) market, whether produced inside or outside the EU.[149] All companies will have to comply if they want to sell their products in the EU market. **Under the ESPR, the upcoming Delegated Act for Apparel Textiles may set requirements to tackle microplastics and fibre fragment release.** However, progress has been delayed due to the broad product grouping of textiles, complicating the creation of specific, one-size-fits-all ecodesign requirements to address the unique challenges of each product type.

The Corporate Sustainability Reporting Directive (CSRD) (2023) aims to enhance sustainability and transparency for companies operating within the EU by broadening the scope to include more companies and requiring disclosure on a wider variety of sustainability problems, as well as their effect on financial performance.[150] **Under the Pollution (E2) in the European Sustainability Reporting Standards (ESRS), it requires companies to disclose the pollutants emitted through their operations, including microplastics generated or used.** This requirement appears to encompass both the intentional addition of microplastics and their unintentional release into the environment.

The Waste Framework Directive (WFD) aims to protect the environment and human health through prevention and reduction of waste, by reducing overall impacts of resource use and improving resource efficiency.[151] **In 2023, the European Commission presented a proposal to revise the waste framework directive, specifically targeting the food and textile industry.** The proposal considers the potential inclusion of microplastics release as a criterion for adjusting Extended Producer Responsibility fees. These fees would be paid by producers based on the environmental impact associated with their products.

The Green Claims Directive (GCD) (2022) is awaiting adoption for 2025, and aims to ensure that general or voluntary claims are reliable, comparable and verifiable across Europe.[152] All sustainability labels must be based on a certification scheme that is established by a public or third party authorities. There will also be minimum criteria for environmental claims, and will be based on learnings from Product Environmental Footprint (PEF). **PEF is a standard that provides a framework for evaluating environmental impacts across product categories, including textiles.[153] While still evolving, the standard, which is due to be released in 2025, will include fibre fragment pollution as an additional voluntary criteria** following requirements of the European institutions outlined in the Green Claims Directive.

The Microfibre Consortium Policy Committee (composed of predominantly brands, retailers and laboratories) is playing a role by leveraging scientific expertise to provide policymakers with comprehensive insights into the broader impacts of fibre fragmentation, ensuring that policy decisions are based on a thorough understanding of the science. However, in the meantime, immediate actions—such as encouraging the implementation of filtration systems—are necessary, as their capabilities at reducing fibre fragments from entering the environment are better understood. Taking these proactive steps can provide tangible environmental benefits while broader, long-term solutions continue to be developed.

NORTH AMERICA

In North America, the U.S. has made slightly more progress, particularly on the inclusion of all fibre types in legislative discussions. While Canada remains in a more exploratory phase, working within its broader efforts to tackle plastic waste and pollution. In both nations, there is currently no emphasis on the integration of mandatory testing protocols, standards or labelling requirements (although their implementation would significantly impact the fashion and textile industry), however these processes have been considered and discussed. Similarly to Europe, the development of appropriate regulation is hindered due to significant knowledge gaps, creating uncertainty around the industry's readiness for regulation.

UNITED STATES

Legislative efforts aimed at addressing microplastics and synthetic fibre fragments emerged at the state level with bills focused on labelling requirements in California, Connecticut and New York. Neither of the bills passed, however, Connecticut's HB 5360, also known as 'An Act Concerning Clothing Fibre Pollution' (2018) led to a working group focused on raising consumer awareness around fibre fragment pollution that originated from the fashion and textile industry.[154]

Save Our Seas 2.0 Act (2020) expanded on its 2018 predecessor with the aim to combat ocean plastic pollution more comprehensively by improving waste management practices, funding research, and promoting international collaboration.[155] Section 132 of the Act directed the Interagency Marine Debris Coordinating Committee (IMDCC) to develop a report on 'Microfibre Pollution', providing Congress with an overview and action plan for federal agencies and stakeholders.[156] The report adopts the definition of 'solid, polymeric, fibrous materials, including plastic and non-plastic fibres, less than 5 millimetres in all dimensions.' It acknowledges the fashion industry's terminology of 'microfibre' referring to a fine yarn, recommends the shift to the term 'fibre fragment' and excludes an aspect ratio requirement to keep a more broad and inclusive definition. Moreover, it highlights key research gaps on root causes of fibre fragmentation, the variations in fibre properties and chemical additives and their influence on the toxicological impact, as well as the need to assess the effectiveness and feasibility of various technologies that would capture and remove fibre fragments from known pathways. Finally, it underscores the need for multi-stakeholder collaboration to advance research required to inform the development of textiles with a lower propensity to shed, biodegradable solutions and effective filters, as well as addressing the toxicological risks of additives and the development of accurate labeling for biodegradable products.

California advanced its efforts with the Statewide Microplastic Strategy (2022), providing a roadmap for managing microplastic pollution, particularly in aquatic systems and coastal areas, through prevention, research, and collaborations involving state agencies and external partners.[157] The strategy also highlighted the importance of taking precautionary measures while expanding scientific research on the impact of microplastics.

By 2024, the U.S. introduced several initiatives to address synthetic fibre fragments exclusively to the textile industry. This included The Fighting Fibres Act of 2024 that was introduced by Senator Jeff Merkley and developed with the support from organisations like The 5 Gyres Institute and Ocean Conservancy.[158] The Act would require all new washing machines sold in the U.S. from 2030 to include filtration systems and would also commission research on the impact of fibre fragments in water to improve understanding and mitigation strategies.

CANADA

Canada has made significant steps to tackling plastic waste and pollution from various industries via the Ocean Plastics Charter and Zero Plastic Waste Strategy (2018).[159] Since then, federal support has driven exploratory research on fibre fragments from the fashion and textile industry, laying the groundwork for future policies. These efforts have focused on evaluating solutions and engaging stakeholders in mitigation efforts. For example, a study investigated the effectiveness of washing machine filters, finding an average weekly lint capture of 6.4 grams—equivalent to between 179,200 and 2,707,200 fibre fragments, further informing policy decisions aimed at reducing fibre fragment pollution from laundering.[160]

Bill 279 (2021) was introduced in Ontario, requiring all new residential washing machines in Ontario to be equipped with fibre fragment filter technology of 100 microns or smaller.[161]

In 2023 the Canadian House of Commons introduced Bill C-337, establishing a national strategy to reduce textile waste.[162] This bill acknowledged the significant contribution of microplastics released into the environment via the textile waste sent to landfills in Canada.

In early 2024, Environment and Climate Change Canada (ECCC) released a consultation document specific to the textile industry.[163] A key concern is the limited data on textile waste sources and quantities, hindering efforts to address and understand the scope of textile and apparel pollution. The report calls for further research into textile waste streams, the development of recycling options, and the need for enhancing product durability to extend lifespan through reuse and repair. It acknowledges the decline in repair habits attributing to a lack of skills and time, along with the influence of fast fashion. Additionally, it addresses Canada's limited recycling infrastructure and the absence of national or provincial Extended Producer Responsibility (EPR) programmes and voluntary take-back programmes. Notably, fibre fragment emissions from all fibre types are recognised, along with the importance of washing machine filters and design standards, signaling a broader awareness of the risks they pose.

Later on in 2024, ECCC partnered with Ocean Diagnostics and Raincoast Conservation Foundation on a report examining the issue of fibre fragment pollution more in-depth, outlining key challenges and recommendations for Canada.[164] It recommends the shift of the term 'microfibre' to 'fibre fragment' and stressed the need for a clear definition to support comparability across sectors. Additionally, it highlights inconsistencies in fibre fragment identification and quantification methods and for the need for studies to better capture both synthetic and non-synthetic fibres. Through assessing Canadian science research on microplastics, the report found fibre fragments to be a key environmental contaminant across various ecosystems, identifying research gaps such as limited studies on semi-synthetic fibres, inconsistent methodologies, and poor data on certain environments such as groundwater, snow, ice, and terrestrial environments. Finally, it proposes a framework for addressing fibre fragment pollution, focusing on improved textile design and manufacturing, consumer interventions, and environmental management interventions such as wastewater treatments.

WORKSHOP OUTCOMES

The workshop focused solely on regulatory efforts in North America due to the development of the regulatory landscape within Europe being better understood. This session provided an overview of the current regulatory landscape and explored potential opportunities for the industry and the government to collaborate in order to advance education, science and solutions together. Three collaboration points were the following;

1. **Enhancing research:** Closing knowledge data is crucial for informing future regulatory frameworks. Collaboration is critical to fund and design studies that have standardised testing protocols, in order to collect more reliable data on the factors influencing fibre fragmentation, the true extent of fibre fragment pollution, and subsequently their impact on the ecosystem and human health.
2. **Holistic approach:** The lack of progress on fibre fragments from all fibre types is attributed to lack of awareness and alignment in previous research. Collaboration is necessary to drive research and raising awareness on all fibre types to allow the issue to be tackled with a more holistic approach.
3. **Consistent engagement:** Engagement between the industry, government, and researchers is critical to assess the industry's readiness to meet regulatory requirements proactively and whether the government has sufficient reliable data to create laws. This collaboration may include regular engagements through site visits, joint workshops, and open discussions addressing potential regulatory obstacles and data gaps that require attention.

Notably, discussions with the TMC Policy Committee on regulatory developments in Europe closely aligned with these key points. While Europe is further along in regulatory efforts, several ongoing challenges mirror those identified in North America:

- **Knowledge gaps:** Significant knowledge gaps remain regarding factors influencing fibre fragmentation and its environmental and human health impacts. More research is needed across all textile lifecycle stages to support sound regulatory measures.
- **Test methods:** Existing methods assess fibre loss from fabric swatches under simulated laundering conditions, offering useful insights but limited applicability to finished products at the consumer level. Additionally, no standardised test method currently assesses key pathways such as airborne fibre release.
- **Accounting for impact:** Current methods do not account for the biodegradability, chemical load, and toxicity of fibre fragments, all of which influence environmental impact across marine, freshwater, terrestrial, and atmospheric ecosystems.
- **Textile value chain complexity:** The global and fragmented nature of the textile supply chain complicates fibre fragmentation management within corporate sustainability strategies. The lack of coordination among stakeholders makes it challenging to align efforts and implement effective mitigation strategies.

By identifying these common barriers and opportunities, both the North American and European discussions highlight the need for global collaboration to drive effective policy interventions and industry-wide solutions.

CLOSING **REMARKS**

Tackling fibre fragment pollution is a complex challenge that spans the entire textile and fashion value chain. As demonstrated throughout this report, addressing the issue involves diverse areas of expertise and multi-stakeholders commitment —including researchers, policymakers, brands, and manufacturers— who actively work together to understand the extent of fibre fragments released into the environment, assess their risks to human health and ecosystems, and explore mitigation strategies. However, current efforts remain scattered due to differing geographical contexts, approaches and priorities — in relation to how fibre fragmentation aligns with broader sustainability goals. Additionally, significant knowledge gaps persist, hindering effective action and systemic progress.

In this technically and scientifically charged topic, industry and science must unite in open dialogue to exchange knowledge, guide decision-making and encourage best practices. Efforts must move from siloed initiatives toward cohesive strategies which focus on what is truly needed to drive progress on priority areas and dedicate funding for critical research; to fill knowledge gaps, develop robust test methods and leverage the best available science to inform R&D for targeted solutions. By reducing uncertainties and defining clearer action steps, the industry can take more decisive strides toward mitigating fibre fragment pollution.

APPENDIX

The workshop series took place between 7th and 24th October 2024, with each session dedicated to exploring one of the key topics of fibre fragmentation. Each workshop involved up to ten active participants and a facilitator who guided the discussions. Participants were carefully selected from an ecosystem map based on criteria such as their expertise, role within the ecosystem, and relevance to the specific topic being addressed. Each session addressed two to three guiding questions or topics, designed to uncover areas of consensus, divergence, and knowledge gaps. The insights gathered from these discussions were integrated into this report and played a crucial role in shaping the recommendations shared for future research and collaboration aimed at advancing industry-wide efforts to address fibre fragmentation effectively.

SESSION	FACILITATOR	ACTIVE PARTICIPANT
Session 1: **Definition**	Fashion for Good and The Microfibre Consortium	• Josephine Pratiwi (Quantis) • R. Rathinamoorthy (VIT-Chennai) • Diana Wyman (Ex AATCC, REI) • Krystle Moody-Wood (Materevolve) • Lewis Shuler (Paradise Textiles) • Libby Sommer (Libby Sommer LLC) • Lisa Erdle (The 5 Gyres Institute)
Session 2: **Sources & Pathways**	Josephine Pratiwi (Quantis - Sustainability Consultant)	• Vajira Subasingha (adidas) • Miranda Prendergast-Miller (Northumbria University) • Lisa Erdle (The 5 Gyres Institute) • Judith Weis (Rutgers University) • Nadim Saadi (MariLCA) • Ben Williams (University of West of England)
Session 3: **Root Causes**	Dr R. Rathinamoorthy (VIT-Chennai - Associate Professor	• Antoine Cosne (Decathlon) • Bernd Nowack, (EMPA) • Alice Hazlehurst (University of Leeds) • Hector Alonso Fernandez (Inditex) • Courtney Oswald (Under Armour)
Session 4: **Test Methods**	Diana Wyman (REI - Senior Test Engineer)	• Candace Davidow (Under Armour) • Vajira Subasingha (adidas) • Helen Warburton (James Heal) • Annika Bahm (Hohenstein) • Alice Hazlehurst (University of Leeds) • Dimitri Deheyn (UC San Diego) • Tiziano Battistini (Aquafil)

SESSION	FACILITATOR	ACTIVE PARTICIPANT
Session 5: **Regulation**	Krystle Moody-Wood (Materevolve - Founder & Principal Consultant)	• Nizanna Bathersfield & Romell Nandi (US Environmental Trash Free Waters Program) • Carlie Herring (NOAA Marine Debris Program) • Anna Posacka (Ocean Diagnostics) • Lisa Erdle (The 5 Gyres Institute) • Analoli Del Cueto Menendez (Ohana Public Affairs) • Joel Chung & Vanessa Evans (Environment and Climate Change Canada) • Patrick Jurney & Aliya Rubinstein (The Nature Conservancy)
Session 6: **Solutions Portfolio**	Lewis Shuler (Paradise Textiles - Head of Advanced Concepts)	• Begoña Garcia (Jeanologia) • Aliya Rubinstein & Patrick Jurney (The Nature Conservancy) • Sarah Abbott and Alexander Law (Matter Industries) • Stephen Hayes (Xeros) • Janne Koopmans (ZDHC) • Hector Alonso Fernandez (Inditex) • Jimmy Summers (Elevate Textiles)
Session 7: **Toxicity**	Libby Sommer (Libby Sommer LLC - Principal Consultant) Lisa Erdle (The 5 Gyres Institute - Director of Science & Innovation)	• Bethanie Carney Almroth (University of Gothenburg) • Andy Booth (SINTEF) • Jennifer Provencher (ECCC) • Lauren Miki Kashiwabara (Oregon State University) • Leah Thornton Hampton (Southern California Coastal Water Research Project)
Session 8: **Future Direction**	Fashion for Good and The Microfibre Consortium	• Josephine Pratiwi (Quantis) • Dr R. Rathinamoorthy (VIT-Chennai) • Diana Wyman (REI) • Krystle Moody-Wood (Materevolve) • Lewis Shuler (Paradise Textiles) • Libby Sommer (Libby Sommer LLC) • Lisa Erdle (The 5 Gyres Institute)

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