Literature review on the release of micro-fragments from CHF with a focus on end-of-life

Re_fashion

ACKNOWLEDGEMENTS

We would like to thank all the stakeholders consulted who contributed to this study (listed in Appendix D).

SUMMARY

The contamination of natural environments by micro-fragments originating from Clothing, Household Linen and Footwear (CHF) is an environmental and public health issue of growing concern. The term “micro-fragments” is used here to encompass all emissions, whether of synthetic, man-made or natural origin, including both the microfibres released by textiles and the microparticles generated by footwear abrasion, in response to the limitations of existing definitions, which still too often exclude non-plastic fibres.

While the scientific literature has focused predominantly on emissions occurring during the production and use phases, particularly during washing, end-of-life stages remain a significant blind spot, even though public policies are strongly steering the sector towards circularity. This report aims to provide a state of play of current knowledge and gaps regarding the release of micro-fragments along CHF recovery pathways—second-hand, mechanical recycling (closed loop and open loop), thermomechanical recycling and chemical recycling—based on a systematic review of the available literature, complemented by interviews with stakeholders from the sector.

With regard to extending the lifespan of CHF, the few studies available suggest that textile ageing affects the propensity of textiles to release micro-fragments, particularly during washing and under UV exposure. However, this work is carried out under laboratory conditions that do not reproduce real wearing conditions, which considerably limits the robustness of the conclusions. The release potential associated with natural ageing in use therefore remains very poorly characterised, particularly for natural, man-made and bio-based fibres.

The results relating to recycling processes highlight emissions at two distinct levels: during the operations themselves (cutting, unravelling, grinding, unravelling, tearing), and indirectly through the properties of recycled fibres incorporated into finished products, whose behaviour in terms of release during use remains insufficiently documented to allow definitive conclusions at this stage. Among the processes studied, the chemical route appears to be the one with the lowest impacts, both during recycling and during the incorporation of recycled materials, insofar as it yields fibres whose quality is assumed to be equivalent to that of virgin fibres; however, the available data remain insufficient to confirm this.

Footwear, and soles in particular, remain a persistent blind spot: their contribution to emissions is likely significant, but no standardised method currently makes it possible to quantify it, and the technical requirements imposed on incorporated recycled materials—identical to those applying to virgin soles—are likely to constitute a limiting factor in potential impacts.

These results highlight the urgent need to develop standardised measurement protocols covering the entire life cycle and all receiving environments (water, air and soil), as well as to conduct targeted studies on the impact of recycling processes and material ageing. They also call for raising awareness and training stakeholders in the downstream sector on micro-fragment issues and on best practices for limiting them. Lastly, a collaborative approach bringing together researchers, industry players and public authorities appears essential to share knowledge and co-develop appropriate solutions. This report does not call into question the overall environmental benefits of circularity, but it does underline the need to better characterise its impacts in terms of micro-fragment emissions.

Report prepared by: JED INNOVATION and REFASHION

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ABBREVIATIONS & ACRONYMS

LCA	Life Cycle Assessment
APPLIA	European Association of Home Appliances
BIOTA	**The set of living organisms (fauna and flora) of a region,** forming an **autonomous unit of living matter**
CETIA	Technology Center dedicated to the recyclability of textile and leather products
CTTN	Research Institute for Cleaning and Maintenance
ECHA	European Chemicals Agency
EVA	Ethylene Vinyl Acetate
IGDD	Institute for Sustainable Development Management
ISO	International Organization for Standardization
IPC	Institute of Plastics and Composites
JRC	Joint Research Centre (Centre Commun de Recherche de la Commission européenne)
MFC	MicroFiber Consortium
MariLCA	Marine Litter Life Cycle Assessment
RRM	Recycled Raw Material
OCS	Operation Clean Sweep
PA	Polyamide
PEFCR	Product Environmental Footprint Category Rules
PES	Polyester
PET/PES	Polyethylene Terephthalate
PFAS	Per- and polyfluoroalkyl substances
PU	Polyurethane
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals (règlement européen sur les substances chimiques)
TDS	Total Dissolved Solid
TLC	Textiles, Linges de maison et Chaussures
TOC	Total Organic Content
WRAP	Waste and Resources Action Programme

I. Introduction & context

This section sets out the foundations needed to understand Part 2, devoted to the impacts of recovery pathways. Information on the other life-cycle stages, definitions and standards is presented in Section III and the appendices.

A. Context and challenges

i. *Widespread and underestimated pollution*

The issue of microplastics occupies an increasingly important place in environmental debates, especially in the textile sector. According to recent studies, **between 15% and 35% of microplastics present in the environment could come from synthetic textiles**[1], an estimate that concerns only synthetic fibres and excludes natural and man-made fibres, which are nonetheless just as present and potentially impactful. These figures should be treated with caution, as they can vary significantly depending on the sources and definitions used.

Although the figures systematically mention synthetic textiles (including the textile uppers of the shoes concerned), the impacts of footwear and especially **soles are poorly documented** (likely to be classified as tyre emissions). Only the Fraunhofer study[2] mentions shoe wear as the 7th leading cause of microplastic production.

For clothing, household linen and footwear (CHF), emissions can therefore take several forms (fibres, fragments, dust, particles) and have different chemical natures (synthetic, natural, man-made). **We use the term "micro-fragments" to encompass all these emissions**, although the definitions, regulations and studies cited more often refer to microplastics or microfibres.

ii. *Three affected environments, three challenges*

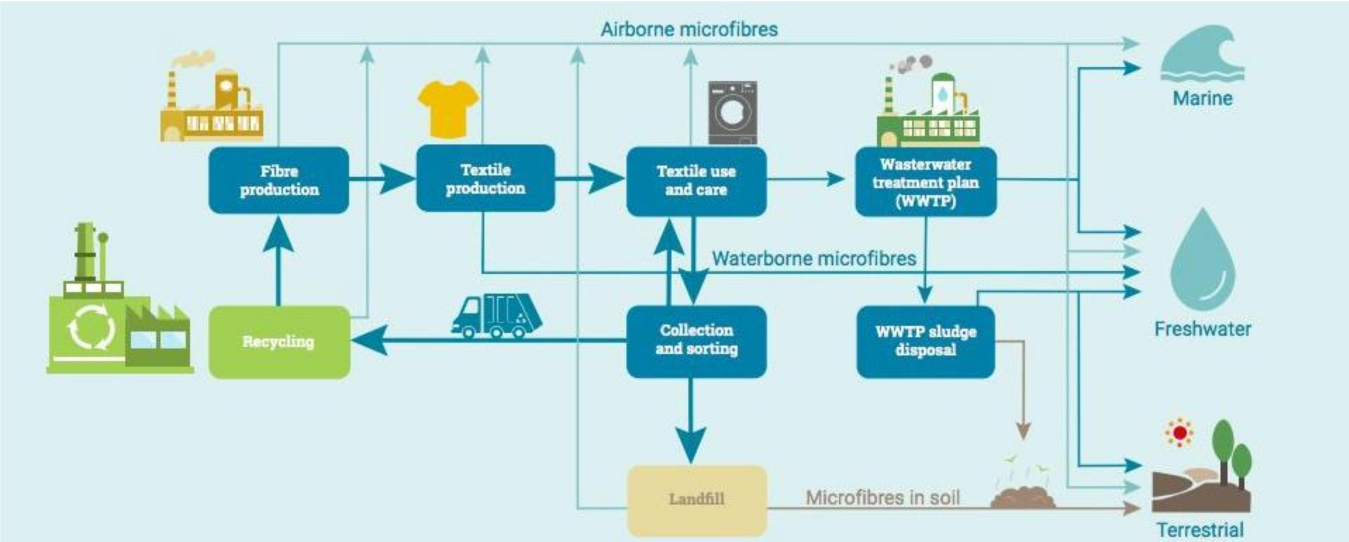

Figure 1: Sources and potential dispersal pathways of micro-fragments[3]-textile example

[1] https://www.eea.europa.eu/en/analysis/publications/microplastics-from-textiles-towards-a-circular-economy-for-textiles-in-europe

[2] Kunststoffe in der Umwelt: mikro und makroplastik, Bertling and al; Fraunhofer Institute publication, 2018

[3] Microfiber Pollution in the Earth System, Liu and al, Reviews of Environmental Contamination and Toxicology (2022) 260:13

The flows of micro-fragment emissions are found in **three environments of the biosphere**, each raising specific measurement and assessment challenges:

The aquatic environment concentrates most studies, with estimates of up to 3 billion tonnes/year of microplastics entering oceans and rivers[4]. It is by far the best documented environment, notably through studies on emissions during domestic washing.

The terrestrial environment reveals worrying contamination: an ADEME study in 2025[5] detected microplastics in **76% of the French soils analysed**. The share attributable to CHF remains poorly quantified, but the ubiquity of this pollution underlines the urgency of a better understanding of sources.

The airborne environment remains the least quantified. However, a study conducted between 2016 and 2022 shows that cellulosic fibres would be around **2.5 times more numerous than synthetic fibres in the atmosphere**[6], although the trend is gradually reversing. This airborne pollution raises specific health issues, particularly in occupational settings.

The distribution of micro-fragments across the three environments is not known with certainty and many sampling and measurement difficulties still exist. However, **one thing is certain: the impacts of these micro-fragments are real in all three ecosystems**[7].

iii. Health impacts: beyond microplastics

Beyond environmental impacts, micro-fragments pose **proven health risks, whatever their origin and composition**. This reality is too often obscured by the exclusive focus on synthetic microplastics.

Natural fibres, often perceived as harmless, are nonetheless linked to recognised pathologies. **Byssinosis[8],** an occupational lung disease due to chronic exposure to cotton, flax or hemp dust, is the best documented example. Recent studies (2025)[9] recall the importance of action and rehabilitation plans for this disease, which is still present in the textile industry.

Man-made and natural fibres also show harmful effects on fauna. Studies on bivalves[10] and earthworms[11] reveal that bio-based microfibres can sometimes be just as impactful as their synthetic counterparts, challenging the idea that "natural" materials are harmless.

A key figure that is often overlooked: contrary to popular belief, **around 70% of micro-fragments are believed to be of natural origin** according to many studies compiled by MFC[12]. This reality highlights the importance of a comprehensive approach that is not limited to microplastics alone.

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[4] https://www.e-a.earth/wp-content/uploads/2024/05/EA_2024_Update_Primary_Microplastics.pdf

[5] https://infos.ademe.fr/economie-circulaire-dechets/2025/microplastiques-une-contamination-potentiellement-importante-des-sols-francais/

[6] Man-made natural and regenerated cellulosic fibres greatly outnumber microplastic fibres in the atmosphere, Finnegan and al., Environmental Pollution 310 (2022)

[7] 7 Microfibres: the invisible pollution from textiles, The First Sentier MUFG Sustainable Investment Institute, 2022

[8] 8 https://lemedecin.fr/medical/pathologies/byssinose.html

[9] 9 Strategic overview of rehabilitation practices and action plans for byssinosis: A holistic review; Vaishali and al.; Clinical Epidemiology and Global Health Vol 33, 2025

[10] On the horns of a dilemma: Evaluation of synthetic and natural textile microfibre effects on the physiology of the pacific oyster Crassostrea gigas, Detrée and al., Environmental Pollution Volume 331, Part 2, 15 August 2023

[11] Are Biobased Microfibers Less Harmful than Conventional Plastic Microfibers: Evidence from Earthworms, Courtene Jones and al., Environ. Sci. Technol. 2024, 58, 20366−20377

[12] 12 Micro Fiber Consortium: Behind The Break 2025

iv. *Life cycle: an imbalance in knowledge*

Micro-fragments are emitted **throughout the life cycle of a textile**, from production to end-of-life. Based on the work of "The First Sentier MUFG Sustainable Investment Institute" [7] and on the data from Boucher and Friot (2017), an approximate distribution can be estimated:

- **~50% of emissions: production** (spinning, weaving/knitting, finishing)
- **~25% of emissions: wearing** (friction, mechanical wear)
- **~25% of emissions: washing** (the best documented stage)
- **End-of-life: almost no data**

Please note that the confidence intervals for these estimates are extremely wide, and there is a lack of systemic studies enabling precise quantification of flows at each stage.

MFC has developed a complete qualitative mapping of emission pathways along the life cycle[13], identifying direct flows and redistribution flows in the three environments (water, air, soil). This mapping is presented in detail in Section III. While the various pathways are more or less well identified, reliable quantitative data are sorely lacking, especially for production and end-of-life stages.

The paradox of current research is that the vast majority of studies focus on emissions after washing—the phase that is easiest to study in the laboratory via ISO standards—even though this phase would account for only around 25% of total emissions. The production phase (estimated 50%) remains largely under-studied.

A 2024 review study covering 57 articles[14] reveals a major methodological problem: **81% of studies are inconclusive** regarding the impact of design parameters on micro-fragment emissions. This situation is explained by:

- Non-standardised methodologies making comparisons impossible;
- Multiple experimental biases;
- A lack of reproducibility of results;
- Excessive focus on washing, to the detriment of the other stages.

v. *Footwear: the forgotten one*

There is **no systematic study on micro-fragment emissions over the full life cycle of a shoe**. The few existing studies concern sole wear in use (assimilated to tyre emissions), but the production phases of soles, textile uppers, and above all end-of-life, are totally absent from the literature.

In this report, we assimilate textile uppers to clothing textiles and household linen, although this assumption has major limitations: uppers do not undergo the same constraints (no domestic washing, different friction) and often use complex composite materials.

No standardised measurement method is available for footwear, whether for uppers or soles, and regardless of the environment concerned (water, air or soil).

[13] 13 Micro Fiber Consortium: Behind The Break 2025

[14] Emission of fibres from textiles: A critical and systematic review of mechanisms of release during machine washing, Tedesco and al., Science of The Total Environment, Volume 955, 10 December 2024

vi. *End-of-life: the blind spot of studies*

This overall finding highlights **a major gap: the end-of-life of CHF remains a blind spot** in terms of micro-fragment emissions. Yet this is precisely the stage at which crucial issues arise from a circular economy perspective.

The **reuse** and the processes of **recycling**, while beneficial in reducing environmental impacts and especially the consumption of virgin resources, **can also contribute to the release of micro-fragments into the environment**:

- Do cutting, shredding, unravelling and tearing operations generate significant emissions?
- Does ageing of second-hand textiles increase their propensity to emit micro-fragments?
- Do recycled materials incorporated into new products behave differently in terms of emissions?
- What are the emission flows in the different recycling technologies (mechanical, thermomechanical, chemical)?

These fundamental questions remain largely unanswered, even though public policies (AGEC, European Green Deal) and industrial strategies are increasingly geared towards circularity.

This report therefore proposes a specific focus on the downstream phases of the CHF life cycle: reuse and recycling (mechanical, thermomechanical, chemical). The aim is to:

1. **Highlight what is known**: gather the rare existing studies on end-of-life emissions

2. **Identify what is missing**: map knowledge gaps and research needs

3. **Ask the right questions**: guide future work to reconcile circularity and limitation of micro-fragment emissions

4. **Propose improvement levers**: identify action levers to reduce impacts

Section II of this report therefore forms the core of the study, systematically exploring each end-of-life pathway and its potential impact in terms of micro-fragment emissions.

B. Definition framework

i. *Micro-fragments, microfibres, microplastics: what are we talking about?*

As noted above, given the diversity of CHF products and compositions, **we use the term “micro-fragments” to group together all emissions: microfibres—natural, man-made or synthetic—and microplastics.**

Consensus on size

Despite variations depending on the source, **a consensus is emerging on the maximum size: 5 mm in at least one dimension**. The main international definitions converge on this limit, with nuances for fibres.

ORGANISATIONS	ADOPTED SIZE	SPECIFIC FEATURES
ECHA/REACH[15,16]	Particles: 0,1 µm - 5 mm Fibres: 0,3 µm - 15 mm	Length/diameter > 3
MICROFIBER CONSORTIUM[17]	< 5 mm	L/D ratio > 100 for microfibres
WRAP[18]	Length < 5 mm	Textile definition
IGDD/PEFCR[19,20]	< 5 mm in all directions	Microplastics and microfibres

Table 1: main definitions

The notion of shape factor (length/diameter ratio) remains more variable across definitions, making comparisons between studies difficult. Some use a ratio of 3, others 100, depending on whether they refer to microplastics in general or textile microfibres specifically.

More details on definitions are provided in Appendix A.

ii. Classification of materials and regulatory ambiguities

For textiles, a classic distinction is made between:

- **Natural materials** (cotton, wool, flax) – unmodified natural polymers
- **Man-made materials** (viscose, lyocell, acetate) – chemically modified natural polymers
- **Synthetic materials** (polyester, polyamide, acrylic) – synthetic polymers

The European REACH definition of microplastics includes **synthetic polymers or chemically modified natural polymers**[21]. A **grey area remains regarding the classification of** man-made fibres (viscose, lyocell) as plastic fibres. Views differ depending on the source. For footwear, the natural rubber used in soles is not clearly positioned either.

Organic natural fibres (animal or plant) are excluded from regulatory definitions because they are not chemically modified, although they account for **~70% of emitted micro-fragments** according to MFC[22]. This predominance is explained by the massive use of natural and cellulosic fibres and by their greater inclination to fragment, because they are often used as staple fibres and in weavings that release more than continuous filaments.

[15] ECHA, Background document to RAC and SEAC opinions on intentionally added microplastics, 2020
[16] RÈGLEMENT (UE) 2023/2055 DE LA COMMISSION du 25 septembre 2023
[17] Micro Fiber Consortium: Behind The Break 2025
[18] WRAP - Textile derived microfibre release: Investigating the current evidence base. Textile derived microfibre release, 2019
[19] [19] IGDD, La pollution par les microplastiques d'origine textile, Rapport n° 014908-01, Septembre 2023

[20] [20] Implementation of microplastics and microfibers impact in the EF (physical effects on BIOTA impact category), Draft Working Document Oct 2025

[21] [21] RÈGLEMENT (UE) 2023/2055 DE LA COMMISSION du 25 septembre 2023

[22] [22] Micro Fiber Consortium: Behind The Break 2025

In the remainder of this report, we will use the following terms:

- **Microfibres**: fibres released by textiles or shoe uppers, regardless of material (natural, man-made and synthetic)
- **Microparticules**: particles released by shoe soles, regardless of material (natural, man-made and synthetic)
- **Micro-fragments**: umbrella term covering the two types of release mentioned above, namely microfibres and microparticles.

For more details on definitions, debates and ambiguities, see Appendix A.

C. Methods and regulatory framework: the essentials

i. Measurement standards: focus on washing

Main finding: Most standards concern measurement of micro-fragments **after washing**. No standardised method exists for sampling in the atmosphere or in soils. No method is available for footwear.

Three ISO standards currently form the foundation:

- **ISO 4484-1:2023** – Material loss from fabrics during washing
- **ISO 4484-2** – Qualitative and quantitative evaluation of microplastics (solid, liquid and airborne samples)
- **ISO 4484-3:2023** – Measurement of mass at the outlet of the washing machine

Critical limitations: These standards cover only **plastic** micro-fragments (with no equivalent for natural and man-made fibres) and exclude footwear. MFC identifies many other proprietary methods[23], making comparisons between studies almost impossible.

ii. Cadre Regulatory framework: towards gradual consideration

REACH (UE, 2023)[24]: Restriction on intentionally added microplastics. **CHF products are not explicitly included** at this stage, because the microplastics present are considered non-intentional. Natural fibres are not covered.

AGEC law (France, 2024)[25]: Similar ban. An obligation for washing machines to be fitted with microfibre filters was planned from the 1st of January 2025, but the implementing decree had not yet been published at the date of this study.

PEFCR Apparel & Footwear 3.1 (EU, 2025)[26]: Within the restrictive framework of the European Product Environmental Footprint methodology, the Technical Secretariat of the PEFCR Apparel & Footwear nevertheless added the first impact module for fibre fragments, with inventory, impact factors and examples. Every PEF study on the textile and footwear sectors must now measure microplastic releases in addition to the classic indicators. These impact factors are based on the results of the MariLCA project, which should be updated in 2026[27].

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[23] 23 Micro Fiber Consortium: Behind The Break 2025

[24] https://trade.ec.europa.eu/access-to-markets/fr/news/restriction-des-microplastiques-dans-lue-partir-du-17-octobre-2023

[25] https://www.legifrance.gouv.fr/jorf/article_jo/JORFARTI000041553847
[26] https://pefapparelandfootwear.eu/
[27] 27 https://marilca.org/

French environmental labelling[28]: Includes an additional non-LCA microfibre criterion (70% biodegradability + 30% release) based on the declared composition of garments and factors from the MariLCA project. The “Microfibres” supplement is added directly to the environmental cost expressed in points.

For more details on the standards, their limits and the regulatory context, see Appendix B: measurement methodologies and standards.

[28] https://www.ecologie.gouv.fr/politiques-publiques/affichage-environnemental-vetements

II. The impacts of recovery pathways

Section II of this report aims to fill the identified gaps by providing a state of play of knowledge and gaps concerning end-of-life impacts: reuse and recycling of CHF.

This chapter focuses on impacts after sorting. The diagram below summarises the different potential destinies of used CHF. Elimination/energy recovery outlets are excluded from the study.

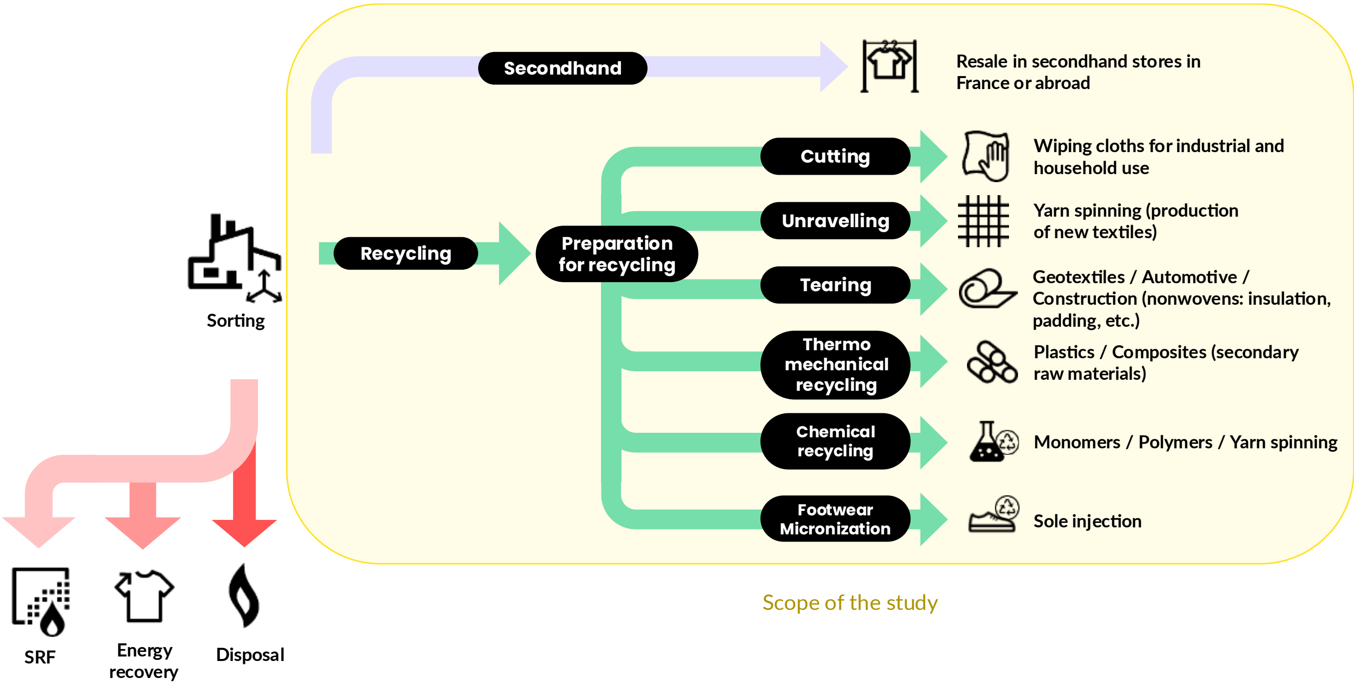

Figure 2: The destiny of used CHF after sorting

A. Second-hand

For the purposes of this study, reuse before and after sorting are examined in the same way and viewed from the perspective of extending the lifespan of CHF.

Very few reports or articles have studied changes in the quantity of micro-fragments released over the life of a product.

i. *Impact of ageing of clothing/household linen/textile uppers on the release of micro-fragments*

A synthesis study conducted by APPLIA[29] shows that emissions often decrease after a first wash, then plateau after a certain number of washes (some studies go as far as 48 washes). However, in all the studies, the products are not worn under real-life conditions between washes, which limits the conclusions that can be drawn. Tests

[29] Updated Literature Review on Microplastics from Household Washing Machines (2020-2024), RISE Research Institutes of Sweden AB, 2024

on old garments (1 to 31 years old) also showed release peaks during the first wash after use. During this "first wash", garments worn in real-life conditions released up to twice as many micro-fragments as recent unworn garments, demonstrating the effect of wear during the use phase on the production of micro-fragments. These used garments also reach a release plateau when successive washes are carried out without an intermediate wearing phase, in a way similar to new garments. It should be noted that the main study on this topic[30] concerns cotton/polyester garments. The difference in micro-fragments release between new and old garments is more pronounced when the cotton content is high, suggesting that cotton is less resistant to natural ageing in use. This phenomenon has not been studied in depth and further research would undoubtedly be useful.

Impact of ageing on fibre quality

Studies, notably those by Dr. Nowack's teams[31,32], mainly on polyester fibres, show a degradation in fibre surface condition during ageing under UV exposure (reproducing outdoor use). This degradation is accompanied by the release of micro-fragments and especially nano-fragments with shapes different from those observed after washing. This release may occur in the aquatic environment (washing) but also in the air during wearing. Initial results show that the release potential during "natural" ageing could be greater than during machine washing.

Studies of the same kind would be valuable on natural materials, man-made materials and bio-based plastic materials.

ii. Impact of ageing of shoe soles on the release of micro-fragments

Although not studied in a systematic way, footwear use is a non-negligible source of micro-fragments. Work by the Fraunhofer Institute[33] even ranks shoe use as the 7th source of microplastic emissions, ahead of textile washing and packaging. Soles are mainly composed of synthetic materials and rubber partly of natural origin.

There are also a few studies on the impacts of running[34,35], but in general the literature is very sparse on this topic.

Among the parameters that lead to sole degradation and therefore the production of microparticles, the following can be noted depending on the polymers[36]:

- UV degradation: high UV exposure can lead to polymer chain breakage and therefore greater fragility/friability;
- Temperature: use of footwear at high temperatures increases abrasion rates;
- Fatigue resistance: shoe soles are highly stressed during walking or running. Materials with poor fatigue resistance are likely to induce increased micro-fragment emissions.

A specific point of attention highlighted in the studies is the impact not only of the micro-fragments as such, but above all, of the release of additives and molecules for which they are responsible. Micro-fragments from footwear enter the soil through leaching processes and can release various additives (present in large numbers

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30 Effect of the age of garments used under real-life conditions on microfibre release from polyester and cotton clothing, Fernandes and al., Environmental Pollution Volume 348, 2024

31 Formation of nanoparticles during accelerated UV degradation of fleece polyester textiles, Yang and al., NanoImpact 35 (2024) 100520

32 32 Characterization of fiber fragments released from polyester textiles during UV weathering, Pinlova and al., Environmental Pollution 322 (2023) 121012

33 Kunststoffe in der Umwelt: mikro und makroplastik, Bertling and al; Fraunhofer Institute publication, 2018

34 Microplastic accumulation on urban footpaths: microplastic deposition on concrete and asphalt surfaces after a single running event; Van Der Werf and al., International Journal of Environmental Science and Technology, Volume 23, article number 102

35 35 Plastics on the rocks: the invisible but harmful footprint of shoe soles; Cecchi; Comptes Rendus. Géoscience, Volume 355 (2023), pp. 135-144

36 36 https://wasserdreinull.de/en/blog/microplastics-from-shoe-soles/

in soles: anti-abrasion, anti-UV, processing agents, plasticisers, etc.) that may have negative impacts on the ecosystem[37,38] .

iii. Improvements levers

Further studies are needed on the influence of CHF lifespan on the release of micro-fragments.

Many studies exist on the impacts of production parameters on micro-fragment release during machine tests, but very few studies deal with ageing in real-life use of textiles, and even less with footwear.

Work could be launched on the different ageing factors and their impacts on release, not only in the marine environment but also in the air:

- Washing
- Exposure to climatic conditions: wind, humidity, UV
- Abrasion during use
- Impact of chemical pollution (micro-fragments as vectors for transporting chemicals)

In the case of shoe soles, all parameters (materials, additives, manufacturing) that can improve resistance to UV, temperature, fatigue and abrasion will help reduce micro-fragment emissions.

B. Recycling & incorporation of recycled material

This chapter examines the impact of the different types of recycling on micro-fragment release. The effects of processes on "immediate" release and the potential impacts of incorporating recycled material into finished products during use are also included.

As a reminder, there are currently three major recycling routes for textiles and household linen[39]:

- **Mechanical recycling:** all mechanical treatments (cutting, unravelling and tearing) used to obtain wiping cloths or garneted fibres;
- **Thermomechanical recycling:** a set of preparation and melting processes for mainly synthetic materials associated with one or more mechanical treatments (extrusion, injection, etc.), in order to produce pellets intended for plastics processing;
- **Chemical and enzymatic recycling:** all processes that transform polymer materials (synthetic or cellulosic) into purified polymers (dissolution), or into compounds derived from these polymers (monomers or oligomers).

For footwear, two processes are notable:

- Grinding the entire shoe, for recycling the whole shoe if it is mono-material, or recycling the different materials after a sorting stage of the ground fractions;
- Separation of the upper and the sole by cutting, tearing or delamination, for material recovery of the different components.

There are very few articles and studies dealing with these recycling aspects in connection with micro-fragments.

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[37] [37] Microplastics from shoe sole fragments cause oxidative stress in a plant (Vigna radiata) and impair soil environment Lee and al.; Journal of Hazardous Materials Volume 429, 5 May 2022,

[38] [38] Are your shoes safe for the environment? – Toxicity screening of leachates from microplastic fragments of shoe soles using freshwater organisms; Kim and al.; Journal of Hazardous Materials 421 (2022)

[39] [39]https://pro.refashion.fr/sites/default/files/rapport-etude/Revue%20des%20perturbateurs%20et%20facilitateurs%20au%20recyclage%20des%20TLC_VF_Refashion_2025.pdf

i. Material preparation

What we generally call material preparation includes unravelling for textiles, dismantling for footwear, and sizing/form reduction (cutting into strips, grinding/shredding). These preparation types are common to all recovery routes, whether in mechanical, thermomechanical or chemical recycling.

These stages are mainly responsible for direct emissions into the atmosphere via unravelling/dismantling workshops.

The unravelling operation, although never cited in the literature studied, was mentioned in various interviews conducted as part of this review as a stage likely to emit micro-fragments depending on the techniques used. Manual and/or coarse mechanical unravelling can lead to emissions. Some automatic unravelling lines are nevertheless equipped with extraction systems that limit the phenomenon.

The dismantling operation is not documented and was not mentioned in the interviews.

a. Cutting into strips

As shown by MFC, fabric cutting during garment manufacturing emits micro-fragments predominantly into the air. A recent study[40] shows that releases into the atmosphere during the cutting stage can be 50 times higher than the release measured during washing. These results can therefore be extrapolated to cutting stages prior to recycling. Since these cuts are often harsher/more brutal than in garment manufacturing, one may assume that their impact is likely even greater, although today no study provides a precise picture of this impact.

Regarding impacts on release during use of the final product, two main points can be noted:

- The wiping cloth obtained contains micro-fragments linked to the cutting stages.
- Studies have shown that “raw” textile edges (raw-cut edges) favour the release of micro-fragments during use and washing[41].

b. Grinding/shredding

Here, grinding is considered as a preparation stage within the various recycling processes for textiles, shoe uppers and soles. This stage may also be representative of preparation for recovery as SRF.

For footwear, especially soles, only the process called the “1st grinding step” in the CETIA study on sole recycling is referred to here[42]. Additional grinding stages leading to micronisation, devulcanisation, extrusion, etc. are detailed in the following paragraph.

Articles clearly highlight the impacts of the processes used in plastics recycling (all sectors combined), especially the grinding stage. These releases would represent around 3% of the total microplastics from plastic recycling[43,44,45]. This can occur in the workshop atmosphere and in process waters.

No article was identified dealing specifically with textiles made of natural or man-made materials, but in view of the emissions observed in simple cutting and in the grinding/shredding of plastics, there is no reason these processes would not induce micro-fragment emissions with other materials.

[40] Microfiber Release during Apparel Manufacturing process – A greater concern than Domestic Laundering, Balasaraswahi and al., Emerging Contaminants Available online 21 August 2025, 100559 In Press

[41] Microfiber Pollution: A Systematic Literature Review to Overcome the Complexities in Knit Design to Create Solutions for Knit Fabrics, Allen and al., Environ. Sci. Technol. 2024, 58, 4031−4045

[42] 42 Refashion - State of the art of recycling solutions for shoe soles - July 2025

[43] 43 Global discharge of microplastics from mechanical recycling of plastic waste, Suzuki and al., Env. Pollution Volume 348, 1 May 2024

[44] 44 The potential for a plastic recycling facility to release microplastic pollution and possible filtration remediation effectiveness, Brown abd al., Journal of Hazardous Materials Advances 10 (2023)

[45] 45 Waste plastic management: Recycling and the environmental health nexus, Nafiu and al., Cleaner Materials 15 (2025)

c. Improvement levers

The main improvement levers concern adaptations or modifications of the processes.

It has been shown that laser cutting has less impact than mechanical cutting[46,47]. Extraction systems at cutting and grinding points are also relevant.

With regard to wiping cloths, a first wash in a machine equipped with filters could be an interesting way to limit micro-fragment emissions into uncontrolled environments.

ii. Closed-loop mechanical recycling

Closed-loop mechanical recycling by unravelling consists in mechanically breaking down textiles to extract recycled fibres that are reintroduced into the manufacture of new products. Available studies suggest that these preparation stages can degrade fibre length and properties, which is likely to have an impact on future release behaviour.

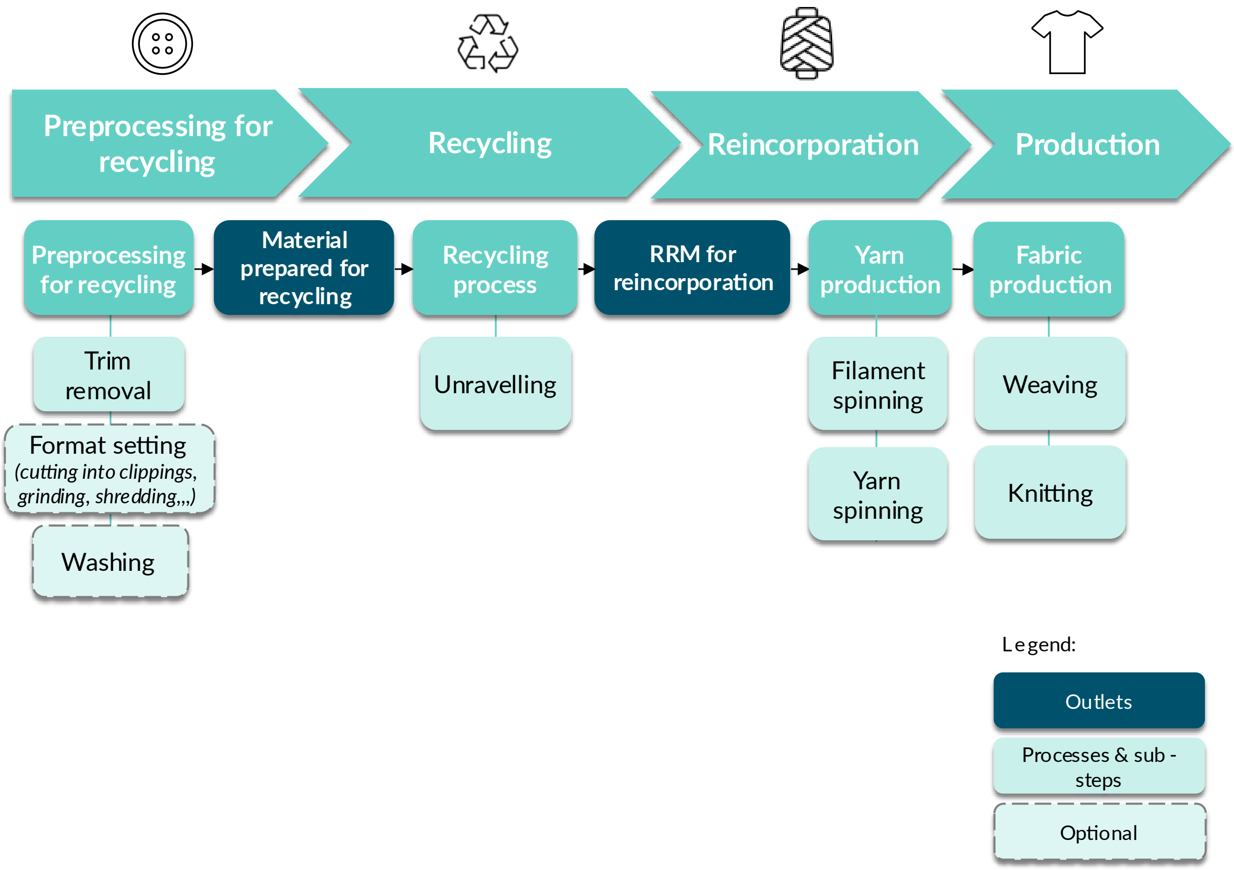

Figure 3: Closed-loop mechanical recycling

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[46] [46] The origin of microplastic fiber in polyester textiles: The textile production process matters, Caï and al, Journal of Cleaner Production 267 (2020) 121970

[47] Bibliographie de la these cifre tml « textile microplastic leak », Présentation de la méthode de thèse TML et de son étude bibliographique sur le relargage de fibres microplastiques. Cosne and al., 2024

a. Impact of textile unravelling

Unravelling notably involves tearing, which is often associated with refining operations such as mechanical carding or air blowing. All these stages release a quantity of dust, i.e. micro-fragments. There is currently no public study on the characterisation of this dust: quantity, size, shape.

This dust can be found both in the factory atmosphere and in the products themselves, or remain attached to the fibres.

b. Impacts of incorporating recycled raw materials

- Impacts on recycled raw materials: yarns

Several hypotheses suggest that mechanical recycling could have a negative impact: on the quality of the final product[48] on fibre mechanics and on fibre length[49]. The factors that may affect the quantity of released micro-fragments will be discussed in Section III for the design phase.

- Impacts on fabric and finished products (excluding nonwovens)

In view of the impacts on fibre quality (mechanics and length), it can be expected that mechanical recycling will have a negative impact on final product quality.

There are few studies directly dealing with micro-fragment emissions in relation to incorporation of recycled raw material. One may cite the study by Abbas et al[50], which examines the impact of incorporating recycled raw material produced by mechanical recycling into wool, polyester and acrylic textiles. This study clearly shows fibre degradation during recycling and therefore a marked increase in the release of micro-fragments during the use phase of products containing recycled raw material. Another study[51] shows the negative impact of introducing recycled fibres into textiles on abrasion tests (recycled cotton and flax fibres mixed with virgin cotton and viscose). Lastly, a very recent study[52] (2026) using PET shows a negative impact of incorporating recycled raw material produced by mechanical recycling (unravelling) on micro-fragment release when comparing products containing 30% recycled fibres several times over with products made from virgin fibres. For example, products containing PET fibres mechanically recycled three times in succession released three times more micro-fragments.

c. Improvement levers

If unravelling very probably generates micro-fragments, several mitigation routes can be considered to limit its effects. Dust capture instruments installed along the process can significantly reduce these emissions.

As proposed in K. Lindstrom's work[53], it is also possible to work on adding lubricants (such as polyethylene glycol, PEG) during the process. Tests performed on cotton, polyester or polycotton fabrics sprayed with PEG solutions diluted in water (concentration <1%) show that fibre length after unravelling can be increased by 50 to 100% compared with control tests, thus enabling spinning.

Then, as shown in Section III, in order to compensate for the potential increases in micro-fragments linked to fibre weakening during unravelling, adaptations can be made to spinning, weaving or knitting processes: working on the type of spinning (prioritising vortex or air-jet spinning), adapting fabric types, and possibly using softening

[48] [48] Transforming mechanically recycled cotton and linen from post-consumer textiles into quality ring yarns and knitted fabrics, Raiskio and al, Waste Management Bulletin, Vol 3, Issue 1, April 2025,76-86

[49] Mechanical Recycling of Textiles: dentifying Factors Impacting Fibre Quality, Lindstrom k., Doctorate PhD. 2025

[50] Serviceability and washing durability of recycled polyester, wool, and acrylic: Sustainability concerns and microfiber leaching, Abbas and al., Industrial Crops & Products 225 (2025) 120450

[51] Transforming mechanically recycled cotton and linen from post-consumer textiles into quality ring yarns and knitted fabrics, Raiskio and al, Waste Management Bulletin, Vol 3, Issue 1, April 2025,76-86

[52] Mechanically Recycled Textiles: A Source of Microplastic Fiber Emissions, Environ. Sci. Technol. 2026, 60, 1810−1818

[53] Improving Mechanical Textile Recycling by Lubricant Pre-Treatment to Mitigate Length Loss of Fibers, Lindstrom and al., Sustainability 2020, 12, 8706

chemical finishes and mechanical finishes such as calendering, singeing, shearing, and low-temperature, short-cycle dyeing processes.

However, data are lacking to truly assess the impact of closed-loop mechanical recycling. Studies should therefore be implemented to:

- Better quantify the impact of unravelling on the micro-fragment release of products resulting from this process: process parameters, different machines.
- Better quantify the different mitigation means and their impacts: chemical and mechanical.

iii. Open-loop mechanical recycling

Open-loop mechanical recycling for the manufacture of nonwovens consists in transforming end-of-life textiles into fibres through tearing processes, these materials then being integrated as raw material into lower value-added nonwoven products (insulation, padding, technical felts). While this outlet is currently one of the most industrially developed mechanical recycling routes, the heavy mechanical constraints imposed on the material and the diversity of materials processed raise questions that are still little explored regarding micro-fragment emissions generated and the behaviour of these finished products in terms of release throughout their own life cycle. In view of current volumes and projections, the focus of the study is on nonwovens. Recovery as wiping cloth was addressed in the preparation/cutting section.

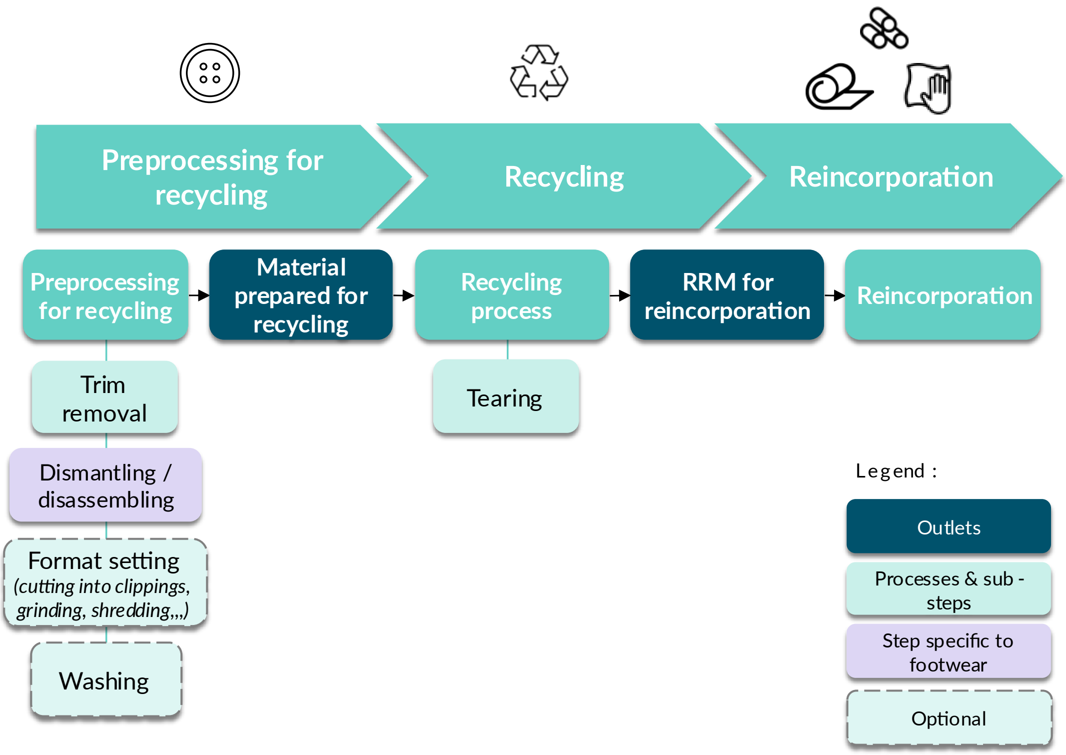

Figure 4: Open-loop recycling of textiles and footwear

a. Impact of tearing: nonwovens

The impacts of mechanical recycling have already been discussed in the previous section. However, it is important to note that fibres resulting from tearing for open-loop applications are shorter/more damaged than those obtained by unravelling. Since the process is more violent, the effects described in Chapter B.ii will be exacerbated, including emissions of micro-fragments into the atmosphere.

b. Impact of incorporation of recycled raw material: nonwovens

Nonwoven products as a whole are already identified as potential sources of micro-fragments, whether through production, single-use products and therefore rapid waste generation (masks, tea bags), or during their life cycle (filters, etc.)[54]. While there are no clear figures, a growing share of these nonwovens is made from recycled textiles.

For the same reasons as the impacts of mechanical recycling described above, it is predicted that nonwoven products incorporating recycled raw material release more micro-fragments than nonwoven products made from virgin material.

The ways in which nonwoven products are formed and consolidated (mechanical, chemical, thermal, etc.), and the process types associated with these approaches, can nevertheless be optimised or modified to limit release. These aspects would need to be studied more precisely in a dedicated study.

Some nonwoven products are bonded by adhesion, which could reduce release during production and use of these products, whether they include recycled raw material or not. This is notably the case for building insulation materials (excluding blown insulation), which contain a plastic binder between the textile fibres.

In this specific case of insulation material, the issue of micro-fragment emissions is less critical during the use phase because the product is in a location where it is not exposed to friction or climatic aggression (wind, UV). The point does, however, need to be considered during demolition and landfilling or recycling.

c. Improvement levers

Beyond the improvement levers described for unravelling, several elements can help limit the release of micro-fragments from nonwovens:

- Gentler processes during the use of recycled raw material: temperature, pressure, air flow (for medical products for example).
- Regular machine cleaning and efficient extraction systems.
- Use of binders to limit micro-fragment emissions.
- Some additives can also limit dust emissions.

iv. Thermomechanical recycling

In this chapter, open and closed loops are addressed together.

Sorting for recycling and preprocessing for textile recycling have been carried out, and possibly dismantling of uppers for footwear, the thermomechanical recycling process comprises the following stages[55]:

The densification stage consists in heating shredded textiles in a drum to agglomerate and densify them to facilitate their passage through extrusion/granulation.

[54] Nonwoven Fabrics: The Giant of Micro(nano)plastic Pollution Hidden in the Corners of Life; Tand and al; Environ. Sci. Technol. 2025, 59, 11429−11432
[55] 55 Le recyclage thermomécanique des textiles, Refashion, 2025

Granulation is a melting/extrusion/granulation stage that makes it possible to obtain material in the form of molten pellets.

Compounding is not a compulsory stage and depends on pellet quality after granulation and on the quality targeted for the final application. It consists in incorporating virgin thermoplastic material and additives to obtain pellets that can be used for the final application (thermoforming, spinning, etc.).

As the processes are very similar for textiles and footwear, they are treated together.

a. Process impacts

The pellet production process notably includes the preparation stage, whose impacts were described above, and an extrusion stage. This latter stage is not considered directly impactful in terms of micro-fragment emissions. However, it is critical for controlling the properties of the pellets that will be reused as recycled raw material.

b. Handling pellets

The main cause of micro-fragment emissions during the process is identified as the loss of plastic pellets, which can, through degradation, lead to the production of micro-fragments. Pellets rank third among the main sources of non-intentional plastic releases (after paints and tyres). These losses can occur at different stages: loading of compounding systems, post-extrusion recovery, transport on sites, maritime or land supply, etc.

In this context, in April 2025 a provisional agreement (pending final adoption) on a regulation relating to the prevention of plastic pellet losses was validated between the Council and the European Parliament[56,57,58]. A clear set of measures will be included in a risk management plan that must be developed by any facility where plastic pellets are handled. This agreement requires companies handling more than 1,500 t/year of pellets to have their good practices certified by an independent third party. For companies handling less than 1,500 t/year of pellets, i.e. the majority of CHF recycling companies, a self-declaration of compliance will be required. Given European procedures, this regulation is unlikely to apply before 2027 at best.

c. Impact of incorporation of recycled raw material

It is well known that thermomechanical recycling, notably because of oxidation processes, tends to affect the quality of recycled polymers: decrease in polymer molar mass and degradation of mechanical properties. In view of the factors that can affect micro-fragment release, one might therefore expect greater release from products made from recycled polymers. Conversely, incorporation of recycled raw material is rarely above 30% precisely in order to achieve mechanical properties meeting technical specifications and thus reduce the risk of faster degradation.

As previously, there are currently very few studies highlighting the impact of recycling on micro-fragment emissions from the finished product.

A first study compares the emissions of micro-fragments from textiles made from virgin PET and recycled bottle PET[59]: the differences are not significant. It should nevertheless be noted that bottle PET is initially of a higher technical quality than textile PET, so slight degradation during recycling still allows it to retain properties equivalent to textile PET.

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[56] [56] https://www.consilium.europa.eu/fr/press/press-releases/2025/04/08/plastic-pellet-losses-council-and-parliament-agree-on-new-rules-to-reduce-microplastic-pollution/pdf/

[57] https://www.surfrider.fr/press/lunion-europeenne-adopte-une-reglementation-inedite-sur-les-granules-plastiques-pour-reduire-la-pollution-aux-microplastiques-mais-les-derogations-et-delais-risquent-den-limiter-la/

[58] https://www.consilium.europa.eu/en/press/press-releases/2025/09/22/plastic-pellets-council-signs-off-regulation-to-reduce-pollution-from-microplastics/

[59] Differences in the release of microplastic fibers and fibrils from virgin and recycled polyester textiles, Gao and al., Resources, Conservation & Recycling 207 (2024)

MFC carried out a study[60] comparing 79 textile garments made from recycled raw material and 172 textile items made from virgin PET. The results show no difference in terms of micro-fragment emissions between recycled and virgin products. The rPET was most likely bottle-derived in view of current industrial practices.

In this same study, MFC listed several pieces of work, and the results can be contradictory. The majority are inconclusive or show no notable differences between virgin and recycled PET. Most do not mention the source of the recycled PET, which creates a problem for readability and interpretation of the results.

No study was found on other types of thermoplastic materials (PA, etc.), nor on the materials used for soles (TPU, EVA, rubber, various elastomers, PVC, etc.). In addition, as discussed previously, the effect of the use phase on wear and therefore on release is mentioned only very little in the studies. It would be relevant to look at the ageing of products containing recycled raw material.

d. Improvements levers

Among the improvement levers that can be cited:

- Regarding pellet handling, there is a manual called *Operation Clean Sweep*, developed in collaboration with the plastics federation, PlasticsEurope and Elipso, which lists and details guidelines and good practices to reduce plastic pellet losses into the environment[61].
- Regarding the properties of recycled raw material, there are currently two main avenues for limiting the effects of extrusion:
    - work on the extrusion process itself to limit oxidation conditions and improve the quality of recycled raw material.
    - add a recondensation step that lengthens polymer chains and therefore limits losses in mechanical properties.

v. *Chemical recycling*

Chemical recycling includes various families of processes:

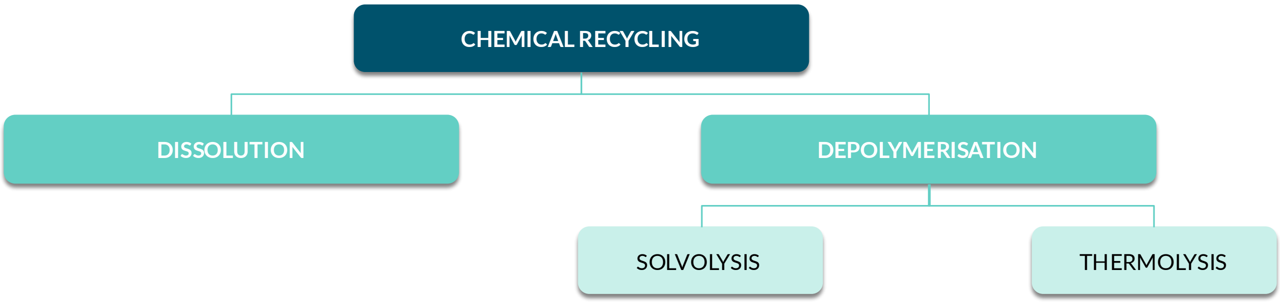

Figure 5: The main chemical recycling processes[62]

The figure above concerns only textiles and shoe uppers. Enzymatic depolymerisation processes, which are less widespread industrially, can also be added.
For footwear, the following processes can be assimilated to chemical recycling: chemical devulcanisation and de-cross-linking (PU, EVA)[63] .

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[60] 60 Technical Research Report: Recycled Polyester within the context of Fibre Fragmentation, MFC, 2023

[61] 61 https://www.opcleansweep.eu/application/files/1416/3004/9689/OCS_Manual_FR.pdf

[62] Le recyclage chimique des textiles, Refashion, 2024

[63] 63 https://pro.refashion.fr/sites/default/files/rapport-etude/etude_recyclage_semelles_CETIA_refashion2025.pdf

a. Process impacts

All these processes can be broken down into three major parts:

The first step is feedstock purification to remove dyes, impurities and finishes; the second relates to the chemical reaction or dissolution itself; and the third one is another purification of the materials obtained.

The most critical stages to produce micro-fragments are the first two. As chemical recycling processes are relatively recent, there are few specific studies on micro-fragment production during the process.

Nevertheless, one may cite a 2025 study by Manivannan et al.[64], which examined micro-fragment emissions in polycotton recycling processes. It showed that the most critical stage is the decolourisation stage (equivalent to a form of washing), before chemical treatment. In this case, basic hydrolysis, which preserves cotton but depolymerises PET, also emits fewer micro-fragments than acid hydrolysis, which preserves PET but degrades cotton into cellulose.

The feedstock purification stages are therefore likely to be the most emissive in terms of micro-fragments: impurities and washing may involve strong agitation and chemical or physical degradation.

The risks during the reaction stage are likely to be more related to incomplete reactions and residual impurities, or even materials that have not been depolymerised.

b. Impacts of incorporation of recycled raw material

Regarding products made following chemical recycling, although no study has been published so far, the fact is that the quality of the fibres and materials produced would be equivalent to virgin material. Micro-fragment emissions from a product containing recycled raw material should therefore be equivalent to those from a product made entirely of virgin material. This point remains to be validated for devulcanisation processes.

c. Improvement levers

The main improvement lever concerns the implementation of efficient filtration to prevent pollution of process waters.

The other improvement levers concern the processes and reactions directly and rely on optimisation of reaction and/or purification parameters (temperature, stirring, reaction time, etc.), to be studied case by case.

[64] [64] Textile Recycling's Hidden Problem: Surface-Modified Fiber Fragments Emitted at Every Stage, Manivannan and al., Environ Sci Technol. 2025

vi. *Footwear recycling*

This chapter focuses on the mechanical recycling of shoe soles. Thermomechanical and chemical recycling of soles is not dealt with specifically due to the lack of data. Even if the processes may vary, it can be assumed that the conclusions will be very close to those discussed in the previous chapters on textiles.

a. Micronisation of shoe soles

Micronisation is a mechanical process that reduces the particles of a material to a size on the order of a micron. Today it is used mainly in the recycling of shoe soles. It is an additional stage on top of the grinding already mentioned above.

By nature, the micronisation process is therefore likely to produce micro-fragments. The particle sizes obtained are generally below 1 mm, or even 0.5 mm, which clearly falls within the micro-fragment category according to the definitions in Section I.B. It is also worth noting that some studies rely on micronisation processes (especially cryogenic micronisation) to obtain microparticles similar to those recovered in oceans and then used in toxicity, degradation or similar studies.

b. Mechanical devulcanisation

Mechanical devulcanisation is akin to a form of grinding or shearing and therefore the conclusions are close to those discussed in Chapter II.B.

c. Impacts of incorporation of recycled raw materials

The products resulting from micronisation are then, in most cases, used as fillers in various applications or formulated with other plastic materials to reduce costs or add specific properties.

In this case, degradation of the material in question will directly lead to the release of these micro-fragments. Attention must therefore be paid to the use, wear and end-of-life of these materials. In some cases, adding micronised material may also have a negative impact on the properties of the final product and therefore increase wear.

Preliminary tests were, for example, carried out by CETIA, Micropolymers, Elanova and CTC on the introduction of micronised rubber soles into slabs of virgin rubber matrix[65]. The results show that while processability is not critically affected, mechanical properties are degraded, especially abrasion resistance and therefore the potential release of micro-fragments.

These are only preliminary results, and several R&D projects are underway to achieve equivalent mechanical properties with or without the incorporation of micronised materials (better sorting of rubber grades, purification, cleaning, optimisation of formulation). Incorporation of recycled raw material is rarely above 30% in order to achieve mechanical properties that meet technical specifications and reduce the risk of faster degradation.

Furthermore, if the micronised material is remelted and mixed with virgin material, except in the case of an impact on mechanical properties, there should be no impact on the production of micro-fragments.

d. Improvements levers

During micronisation stages, several good practices can be implemented to prevent micro-fragment pollution:

- An appropriate filtration system to remove micro-fragments from the air circulating in the micronisation line;
- When filling micronised materials into big-bags after sieving, particular attention must be paid to dust removal using systems such as cyclones above the big-bags, and cleaning floors after a certain number of fillings to prevent the accumulation of micro-fragments in loading zones;

[65] 65 État de l'art des solutions de recyclage des semelles de chaussures en Europe, Refashion, 2025

- Incorporating the micronised materials directly on the production site avoids transport, load breaks and changes in packaging, thereby reducing the risk of leaks into the environment;
- In outdoor plant areas (truck filling zones for example), equip water drainage points with filtration systems.

C. Non-recoverable waste

Although this report studies issues of micro-fragment emissions linked to recycling and reuse, it seems important to mention, so as not to underestimate it, the emission source represented by CHF waste in landfills (formal or informal). Oxidation, UV degradation and abrasion phenomena alter the structural integrity of materials and therefore lead to the production of micro-fragments[66]. These phenomena are particularly present on seashores due to the combined action of sun, abrasion with sand and salt, and waves. They depend on the type of material. For example, for PET these degradation rates can reach 1 mm/year[67]. This may be enough to contribute significantly to the appearance of microplastics. As these rates are linked to biodegradability, they will be much higher for natural fibres. However, the persistence of materials in the environment must also be taken into account, as it is greater for synthetic materials, and even man-made materials, than for natural materials.

[66] A framework for the assessment of marine litter impacts in life cycle impact assessment, Woods and al., Ecological Indicators, 129 (2021)

[67] 67 Degradation Rates of Plastics in the Environment, Chamas and Al, ACS Sustainable Chem. Eng. 2020, 8, 3494−3511

III. The end-of-life into perspective with the other life-cycle stages

This section aims to place the previous analysis, which focused mainly on end-of-life recovery pathways, back into its overall context considering the entire life cycle.

A. Impact of textile production phases

MFC has produced a complete qualitative mapping of the types of emissions throughout this life cycle, highlighting for each stage the different direct emission flows and redistribution flows:

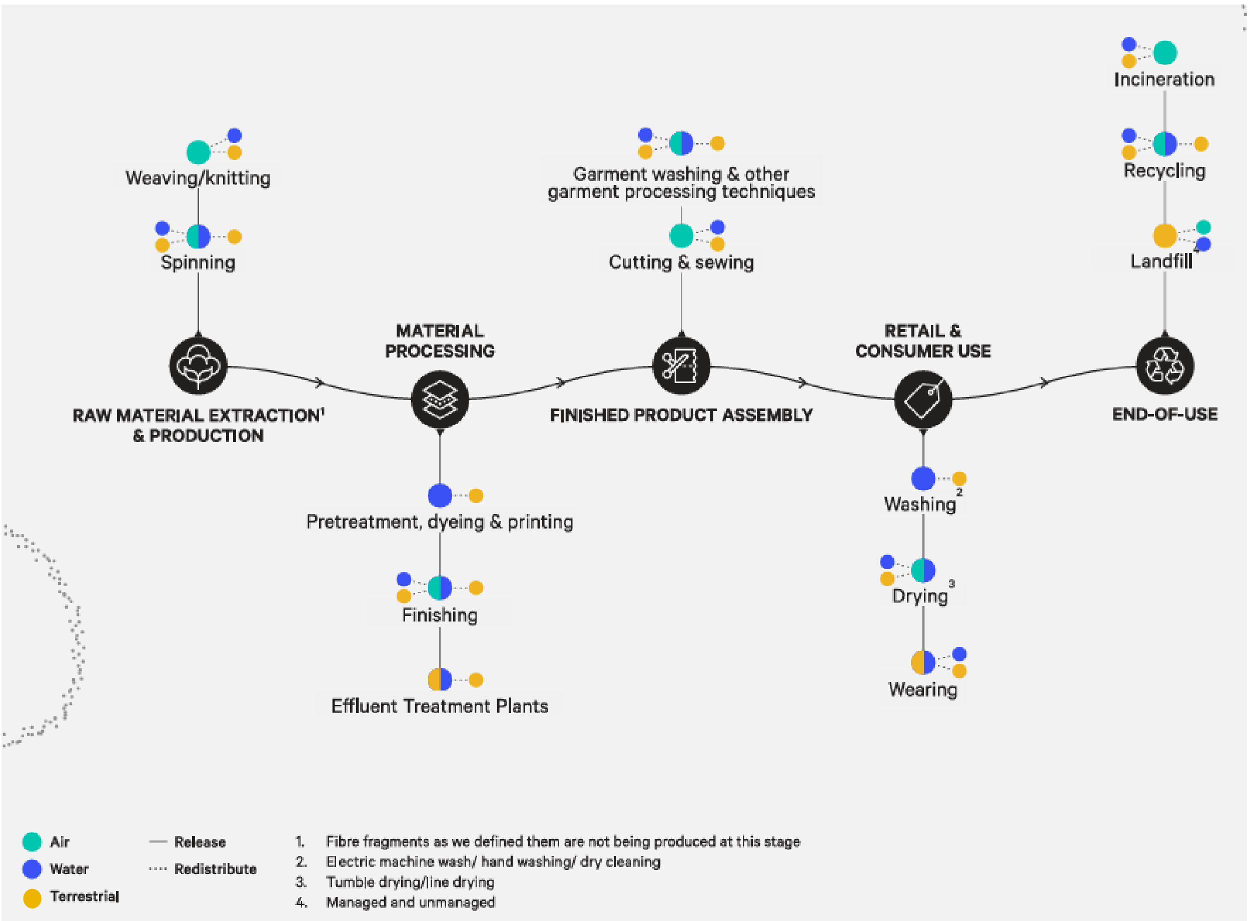

Figure 6 : Micro-fragment emission pathways

Although the different pathways are rather well identified, there are currently very few results providing a distribution of micro-fragment flows throughout this life cycle.

This chapter details the elements that may contribute to increasing or reducing the release of micro-fragments during the production stage. Many studies have dealt with the impact of different manufacturing process parameters on micro-fragment emissions. However, these results must be treated with caution. Indeed, it is very difficult to draw clear conclusions from these articles: for example, a 2024 review study on 57 articles shows that 81% of studies are inconclusive[68].

[68] 68 Emission of fibres from textiles: A critical and systematic review of mechanisms of release during machine washing, Tedesco and al., Science of The Total Environment, Volume 955, 10 December 2024

The table below summarises the conclusions of a broad panel of review articles (Appendix E). Most studies are based on measurements of micro-fragment emissions after washing. The impact of modifying these parameters on emissions during production (mainly into the air) is not studied.

Table 2: Impact of textile production parameters on the release of micro-fragments

	Reduces micro-fragment emissions	Increases micro-fragment emissions
Material	Synthetic fibres High tenacity High elongation	Natural, man-made fibres Natural/synthetic fibre blends Short fibres
Yarn/Filament	Filament Spun staple fibres of great length Spun staple fibres with high twist Vortex spinning process Low-hairiness yarns Yarns with high tensile strength Low-roughness yarns (smoother surface) Combed spinning process Fine / low linear density yarn	Spun staple fibres of short length Low twist rate Ring spinning / continuous spinning
Fabric	Woven (in the majority of studies) Knitted (in one study only) Dense fabric structure Good fabric abrasion resistance Stitching fabric edges to avoid loose yarns	Knitted (in the majority of studies) Low density "Loose" satin-type weave Presence of elastane
Mechanical finish	Shearing Calendering Singeing	Brushing Compaction Tribofinishing
Dyeing	Piece dyeing Yarn dyeing at low temperature and with short dyeing cycles	No dyeing
Chemical finish	Hydrophobic agents Softeners Laminates	Hydrophilic agents Agents increasing moisture absorption

B. Impact of footwear during production phases

It should be noted that no equivalent study on micro-fragment emissions during the life cycle of a shoe was identified. Like in the first parts of this report, the textile upper is assimilated to other clothing textiles and household linen products. This assumption obviously has certain limits, especially because textile uppers are not subject to the same constraints as clothing textiles or household linen during their use phase (especially wearing and washing).

Footwear production is carried out in several stages:

- Manufacture of the upper (the top part of the shoe),
- Manufacture of the sole,
- Assembly (joining the upper and the sole),
- Finishing.

As described earlier, this chapter mainly deals with sole production and its impact on micro-fragment generation.

Shoe soles are mainly manufactured through extrusion-moulding processes, after which the different layers may be assembled.

These processes may lead to micro-fragment emissions either directly, mainly through the production of waste during handling, storage and disposal; or indirectly, i.e. by affecting the physicochemical properties of soles, especially resistance to abrasion and ageing.

However, there is not yet a body of studies, comparable to those described for textiles, enabling a table of the different process stages and their impacts on microplastic release to be established.

C. Impacts of the use phase

The use phase of CHF is a significant source of micro-fragment emissions, although knowledge remains fragmentary. This subject was treated in more detail in Part II.A on second-hand.

As stated previously, 50% of the release of microfibres from garments is believed to occur during wearing (friction, mechanical wear) and washing. Studies generally show a decrease in emissions after the first washes, followed by a plateau. The same phenomenon seems to occur for textiles worn in real-life conditions, after a peak during the first post-wear wash due to different tear factors. These results remain limited because most studies do not reproduce real conditions of use between washes.

Beyond washing, the work of Dr. Nowack[69,70] on polyester reveals that UV exposure during wearing degrades the fibre surface and generates nano-fragments with shapes different from those observed after washing. The release potential during this "natural" ageing could be greater than that during machine washing, both in aquatic and airborne environments. These studies should be extended to natural, man-made and bio-based fibres.

Regarding footwear, daily sole wear is an underestimated source: Fraunhofer ranks it as the 7th source of microplastics, ahead of textile washing. UV degradation, high temperatures and mechanical fatigue accelerate emissions.

It is also important to note that micro-fragments, especially those made of natural materials, are major vectors for transporting chemical substances in airborne environments (where they also capture other pollutants) and aquatic environments[71]. In addition, many chemical species that were still authorised only a few years ago (certain phthalates, formaldehyde, PFAS, etc.) can be found in these micro-fragments. One study[72], carried out by teams from the Institute of Chemical Process Fundamentals of the Czech Academy of Sciences, examined the release of certain chemicals by new and used textiles. It shows that used garments release very small quantities of products (aluminium, zinc, cobalt, arsenic, lead, selenium, PFAS) not necessarily linked to their production but which may have been absorbed by textiles during the use phase. Quantities remain in the ppm range and will not necessarily pose a problem since they remain below regulatory thresholds. The most present products in new textiles remain essentially linked to production.

For synthetic materials, and footwear in particular, one major point of vigilance concerns the leaching of chemical additives (plasticisers, anti-UV, anti-abrasion agents) into soils, with documented toxic impacts on ecosystems. Quantitative data on changes in emissions over the life of a shoe are however sorely lacking.

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[69] Formation of nanoparticles during accelerated UV degradation of fleece polyester textiles, Yang and al., NanoImpact 35 (2024) 100520
[70] Characterization of fiber fragments released from polyester textiles during UV weathering, Pinlova and al., Environmental Pollution 322 (2023) 121012
[71] Natural Fibers: A Missing Link to Chemical Pollution Dispersion in Aquatic Environments, Ladewig and al., Environ. Sci. Technol. 2015, 49, 12609−12610
[72] 72 Hazardous Substances in Textiles: A Comparative Study on Chemical Leaching, Shtukaturova and al., Dorbrin Congress, 2025

IV. Overall conclusion and outlook

This report has made it possible to gather and synthesise the **rare studies available** on the release of micro-fragments, with a focus on the impact of recovery pathways for Clothing, Household Linen and Footwear (CHF). This study specifically concerns micro-fragments and does not call into question the positive environmental results highlighted in the study on the environmental impacts of the EPR sector for used CHF[73].

Several findings emerge:

- **The release of micro-fragments is a reality at all life-cycle stages**, but its quantification and distribution remain highly uncertain.
- **Recycling processes**, while virtuous in terms of waste reduction and resource preservation, can themselves generate micro-fragment emissions, especially during preparation stages (unravelling, cutting, grinding), and can affect the release of micro-fragments from products containing recycled raw material.
- **Footwear, and shoe soles in particular**, are a blind spot of studies: their contribution to micro-fragment emissions is poorly documented even though they represent a non-negligible source, particularly through abrasion and ageing.
- **Current measurement methods and standards** focus almost exclusively on washing-related emissions, leaving aside the other environments (air, soil) and the other life-cycle stages, especially end-of-life.

This work also highlights several gaps in knowledge and management of micro-fragment emissions during CHF recovery:

- **Lack of quantitative data**: there are few reliable data on the distribution of micro-fragment release across the different end-of-life pathways;
- **Few studies on the impact of ageing** of CHF on micro-fragment release under real conditions of use can be found. Moreover, existing studies are often difficult to compare because of different experimental protocols, weak standardisation of methodologies and a strong focus on post-wash measurements;
- **Insufficient research on the impact of recycling processes**: their direct impacts (release during operations) and indirect impacts (quality of recycled materials and increased release during use of finished products) remain poorly known.

Several action levers can be mobilised to reduce micro-fragment release during recovery stages:

- **Improve preparation and recycling processes**
    - Put in place dust capture and air filtration systems in unravelling, cutting and grinding workshops.
    - Optimise process parameters to limit fibre degradation and the production of micro-fragments in finished products containing recycled raw material.
- **Strengthen research on micro-fragment release during use and recovery of CHF**
    - Launch studies on the impact of CHF ageing and recycling processes on micro-fragment release.
    - Focus initially on mechanical recycling to better assess and optimise impacts.
    - Specifically, study release linked to footwear, especially soles, and solutions to reduce it.

[73] [73] Refashion – Étude relative aux impacts environnementaux de la filière REP TLC usagés issus de la consommation des ménages – Juin 2025

- **Raise awareness and train sector stakeholders (recyclers, industry players, consumers) on micro-fragment issues and good practices to limit them.**
- **Promote a comprehensive and collaborative approach**
    - Foster partnerships between researchers, industry players and public authorities to share knowledge and co-build solutions.
    - Encourage eco-design of CHF, integrating criteria of durability, recyclability and low micro-fragment emission from the design stage.

To reconcile circularity and limitation of micro-fragment emissions, it is essential to continue the work and ask:

- **What optimisations should be implemented** for each recycling process in order to minimise micro-fragment emissions while preserving the quality of recycled materials and the economic viability of recycling?
- **How can the extension of CHF lifespan be reconciled with control of micro-fragment emissions**? Can reuse, although beneficial for the environment compared with buying new, have a significant negative impact on the release of micro-fragments due to ageing of materials?

In conclusion, this report highlights the importance of filling knowledge gaps on end-of-life micro-fragment emissions from CHF, in order to weigh the overall benefits of recycling and reuse assessed at the life-cycle scale, while proposing concrete avenues to reduce their environmental and health impact.

V. Appendices

A. Appendix A: Definitions

i. Size

- IGDD[74]

In a 2023 report, IGDD does not take a clear position on the size definition of microplastics. The report recalls that most studies mention **5 mm** as the maximum **size** limit for the largest dimension. However, there is great variability in the dimensions chosen (which often depend on the measurement methods). The notion of shape factor (length/diameter ratio) is addressed for textiles but without a clear definition.

- ECHA[75]

In 2020, ECHA developed a definition for microplastics, refined in Commission REACH Regulation (EU) 2023/2055[76].

Microplastics are particles that contain solid polymers to which additives or other substances have been added and where more than 1% by mass of the particles have dimensions **between 0.1 µm and 5 mm, or, for fibres, a length between 0.3 µm and 15 mm**, and a **length/diameter ratio above 3**. Natural polymers that have not been chemically modified are excluded, as are polymers that are biodegradable or have a solubility above 2 g/L.

The polymer definition is the one defined under REACH.

As a reminder, this definition is not specific to textiles and is therefore more general. It is nevertheless used, for example, in the synthesis report commissioned by APPLIA on the impacts of washing[77].

- MicroFiber Consortium[78]

In its report *Behind the Break*, MFC highlights the debate over size limits, between those who want the broadest possible definition to maintain flexibility in the scope of research and those who want a finer definition so that studies can be properly compared. In the report, the proposed definitions are those of Liu et al.[79]. The definition of a microfibre is given as **a diameter > 50 µm, a length of 1 µm to 5 mm, and a length/diameter ratio above 100.** Another definition of microfibre given in the report is: fibres with dimensions of **less than 5 mm in all directions.**

- WRAP

In its 2019 report, WRAP[80] defines a microfibre as "any fibre of textile origin that measures **less than 5 mm along the length axis**, whether intentionally formed or created via a secondary process during production, processing, use or end-of-life."

- Technical Advisory Board (PEF)

[74] 74 IGDD, La pollution par les microplastiques d'origine textile, Rapport n° 014908-01, Septembre 2023

[75] 75 ECHA, Background document to RAC and SEAC opinions on intentionally added microplastics, 2020

[76] 76 RÈGLEMENT (UE) 2023/2055 DE LA COMMISSION du 25 septembre 2023

[77] RISE Report 2024: Updated literature review on microplastics from household front load/top load washing machines and other reference household washing machines (e.g. used for EN and ISO testing) (literature from 2020-2024)
[78] Micro Fiber Consortium: Behind The Break 2025
[79] 79 Liu, J., Yang, Y., Ding, J., Zhu, B. & Gao, W. Microfibers: a preliminary discussion on their definition and sources. Environ. Sci. Pollut. Res. 26, 29497–29501 (2019).

[80] 80 WRAP - Textile derived microfibre release: Investigating the current evidence base. Textile derived microfibre release, 2019

Finally, in a working document of the Technical Advisory Board for the European PEF method[81], which seeks to integrate a new impact category on microplastics and microfibres, a clear distinction is made between microplastics (microparticles of synthetic polymers) and microfibres (fragments of fibres of man-made or natural origin). In both cases, a size of <5 mm is given.

In conclusion, there is no clear definition regarding microfibre dimensions, **even though the maximum size of 5 mm comes up frequently for microfibres**. This confusion and variation in definitions makes comparisons between the different studies even more complex.

ii. Origin

In the case of microplastics in particular, two categories are defined: primary microplastics and secondary microplastics.

Here too, there are divergent definitions depending on the source.

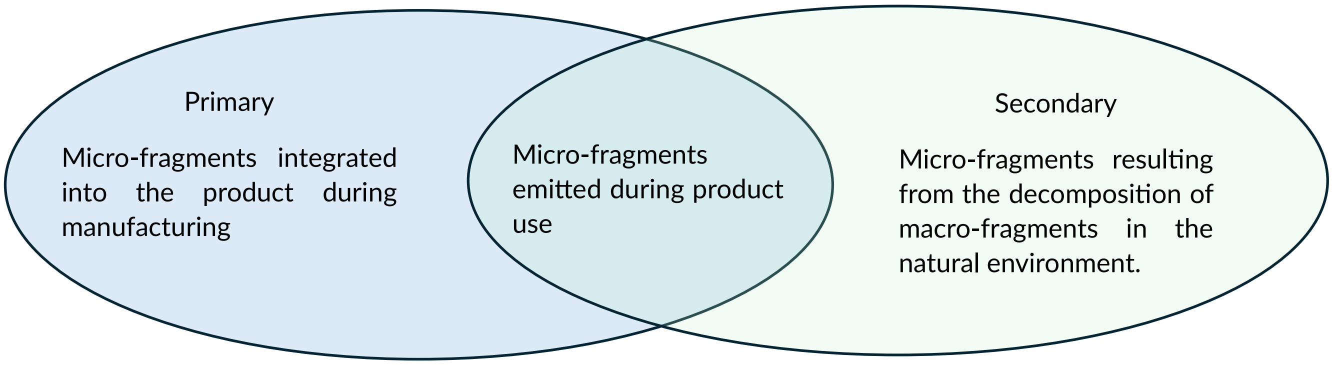

Figure 7: Definitions of primary and secondary micro-fragments

Although there is broad agreement that particles integrated into the product from the manufacturing stage are primary sources of microparticles, and that micro-fragments resulting from the decomposition of end-of-life products are secondary particles, there is divergence regarding the positioning of micro-fragments emitted during the product's lifetime. IGDD, for example, classifies the latter as secondary sources, whereas the International Union for Conservation of Nature and the ETC classify them as primary sources.

Among the main causes of release of secondary micro-fragments in the context of CHF are illegal dumping and uncontrolled disposal. Biological and environmental factors (aquatic environments, UV radiation) drive this transformation of macro-fragments into micro-fragments[82,83].
According to a 2018 report by the European Parliament[84], secondary microplastics (from various products, not only CHF) could represent up to 81% of ocean microplastics. We have no equivalent data on micro-fragments in the broader sense.

[81] [81] Implementation of microplastics and microfibers impact in the EF (physical effects on BIOTA impact category), Draft Working Document Oct 2025

[82] Understanding plastic degradation and microplastic formation in the environment: A review, Zhang and al., Env.pollution, Vol 274 2021

[83] From macro to micro: The key parameters influencing the degradation mechanism and the toxicity of microplastics in the environment, Kumari and al., Polymer Degradation and Stability Volume 233, 2025
[84] [84] https://www.europarl.europa.eu/topics/en/article/20181116STO19217/microplastics-sources-effects-and-eu-solutions

These definitions also reach limits in the context of recycling products and processes. For example, into which category should fibres emitted during recycling processes be classified, and the emissions from products resulting from reuse?

These definition issues, although not critical for the content of this study, may be a key element when drafting or interpreting potential regulations relying on these terms.

iii. Material

For textiles, it is common to distinguish natural, man-made and synthetic materials. For footwear, the upper and the sole are often treated separately and may be made of leather, textiles (cf. above), and other materials such as thermoplastic, rubber-like or thermosetting materials.

As regards micro-fragments, material definitions are sometimes less clear and mostly based on the definition of microplastics.

The EU includes in the definition of microplastics **synthetic polymers or chemically modified natural polymers**[85]. In that framework, man-made fibres would be considered plastic compounds. Their currently low quantity compared with the other fibre types does not lead to a major change in the conclusions. In 2023, man-made fibre production accounted for 6% of total fibre production, which is of the same order of magnitude as the figures obtained in Refashion's 2023 characterisation study[86].

As stated above, organic natural fibres (animal or plant) are excluded from the definition of microplastics because they are not chemically transformed. To clarify what is meant by chemical transformation, one may rely on the legal definition of plastic published by IPC[87]: a natural polymer is considered not chemically modified when its "**chemical structure remains unchanged**, even if it has undergone a chemical process or treatment or a physical process of mineralogical transformation, for example to remove impurities". In this framework, **viscose and lyocell are not considered plastics, unlike cellulose acetate fibres**.

The term chemical transformation nevertheless remains ambiguous, as some processes may modify the chemical or physical structure of natural materials, especially at the surface (mercerisation for example, or some water-repellent treatments).

ECHA also highlighted in a 2020 report[88] the difficulties of definition around the term plastic and the problem of non-standardised definitions. As mentioned above, the PEF Technical Advisory Board excludes man-made materials from the definition of microplastic. The PEF TAB considers two major families: microplastics (particles of synthetic polymers) and microfibres (fragments of fibres of natural and man-made origin). Synthetic microfibres are considered microplastics.

As with man-made fibres, ambiguities also remain regarding the classification of natural rubber that may be used in shoe soles.

The term micro-fragments includes all these small fibres and fragments, regardless of their material, emitted notably by textiles and footwear.

For various historical or methodological reasons, micro-fragments from natural fibres are currently less studied than those from synthetic fibres[89](Figure 3).

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[85] RÈGLEMENT (UE) 2023/2055 DE LA COMMISSION du 25 septembre 2023

[86] https://refashion.fr/pro/sites/default/files/rapport-etude/Synthèse_Etude_Caractérisation_Refashion_2023_FR.pdf

[87] [87] https://www.ct-ipc.com/blog-ipc/la-definition-juridique-du-plastique/

[88] Background document to rac and seac opinions on intentionally added microplastics, Committee for Risk Assessment (RAC), ECHA, 2020

[89] Natural Fibers: Why Are They Still the Missing Thread in the Textile, Fiber Pollution Story? Stanton and al., *Environ. Sci. Technol.* 2024, 58, 12763−12766

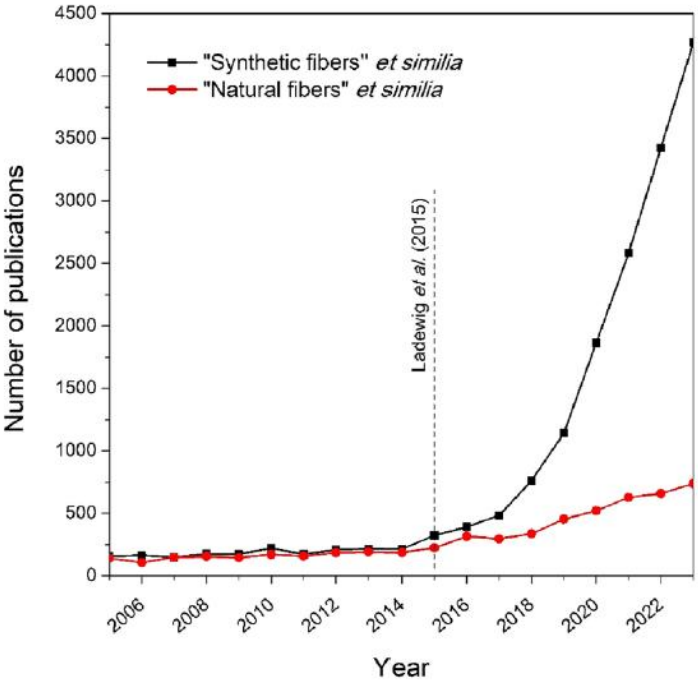

Figure 8: Evolution of the number of publications on micro-fragments

Yet micro-fragments from natural fibres should not be underestimated. According to MFC's Behind the Break report[90], the quantity of microfibres of natural origin is believed to be higher than that of plastic microfibres. One study[91], comparing airborne micro-fragment emissions between 2016 and 2022, shows that cellulosic fibres are around 2.5 times more numerous than synthetic fibres. The trend nevertheless points to an increase in the proportion of synthetic fibres, and a crossover in the emission curves could occur between 2025 and 2030. Please note that these figures take into account all micro-fragments, without distinguishing their origin.

The same trends have been observed in certain marine environments. A study[92]by Stanton et al., carried out in England at river and atmospheric sampling sites, shows that natural fibres account for 93.8% of the fibres analysed and are absent from only 9.7% of samples.

One final point that seems worth clarifying when discussing materials in relation to micro-fragments is biodegradability. This is a major difference between material types.

[90] 90 Micro Fiber Consortium: Behind The Break 2025

[91] Man-made natural and regenerated cellulosic fibres greatly outnumber microplastic fibres in the atmosphere, Finnegan and al., Environmental Pollution 310 (2022)

[92] Freshwater and airborne textile fibre populations are dominated by 'natural', not microplastic, fibres, Stanton and al., Science of the Total Environment 666 (2019)

B. Appendix B: measurement methodologies and standards

i. *Measurement methodologies*

The standard "ISO 4484-1:2023 – Textiles and textile products – Microplastics of textile origin – Part 1: Determination of material loss from fabrics during washing" is a laboratory test method that can be used to assess the propensity of fabrics (containing synthetic materials) to release plastic microfibres during washing and in what quantities. It was the subject of inter-laboratory trials to which CTTN (participant in TC 38/WG 34) contributed. The standard was published in February 2023.

The standard "ISO 4484-2 – Textiles and textile products – Microplastics of textile origin – Part 2: Qualitative and quantitative evaluation of microplastics" is more comprehensive and proposes an analytical method for evaluating microplastics in order to determine their number, morphology, size distribution and type (nature, colour). It applies to samples of different physical natures: solid, liquid or airborne samples.

The size definition is that given in the REACH definition. Natural and biodegradable polymers are, however, excluded from this standard.

The standard "ISO 4484-3:2023 – Textiles and textile products – Microplastics of textile origin – Part 3: Measurement of the mass of collected materials released by finished textile products using the domestic washing method" describes a method for measuring the mass of materials at the outlet of the discharge hose of a standardised washing machine compliant with ISO 6330 during the washing process. It applies to finished textile products.

In its report *Behind The Break*, MFC identified and compared a set of standards and measurement methods (not applicable to cut fabrics and textile products), presented in Table 3.

Table 3: comparative table of the different methods for measuring micro-fragments

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.

Beyond these standardised methods, which are very focused on washing, many technical studies rely on proprietary methods and specific sampling types. This again makes most direct comparisons between studies difficult. Experts are strongly calling for more standardisation.

ii. The limits of measurement methodologies and standards

Table 3 describes a series of methodologies/standards for measuring the quantity of micro-fragments, but essentially in water. In the context of a complete study of the life-cycle impact of a product, there is therefore currently a lack of standardised or harmonised methods for measuring micro-fragments in air primarily, and in soils.
No measurement method is available for footwear.

These difficulties in implementing methods are linked to several factors[93]:

- sampling strategies: choice of sampling volumes and locations in order to be representative, selection of sampling tools (notably to recover small fragment sizes).
- purification and sample preparation methods: some purification methods, for example, use oxidative or “digestion” processes some of which partially degrade certain categories of fibres.
- counting methods, which are often limited by the tools available and the representativeness of samples. The difficulties on this point notably limit studies to quantitative studies (mass of micro-fragments) rather than qualitative studies (materials, morphology).

These limitations and the lack of methods and standards make comparisons between studies even more difficult and may also explain data discrepancies or some differences in conclusions between articles and studies.

[93] Are We Underestimating Anthropogenic Microfiber Pollution? A Critical Review of Occurrence, Methods, and Reporting; Atheya and al., Environmental Toxicology and Chemistry—Volume 41, Number 4—pp. 822–837, 2022

C. Appendix C: Regulatory context and environmental labelling

i. REACH

On 25 September 2023, under the REACH regulation, the European Commission adopted the restriction on microplastics sold on their own or intentionally added. The definitions of microplastics are those mentioned above, namely particles of synthetic polymer smaller than 5 mm that are organic, insoluble in water and resistant to degradation. A transitional period was put in place for the application of the sales ban. CHF products are not explicitly included in this list at this stage[94], as the microplastics present are considered not intentionally added. To date, other types of micro-fragments (especially those made of natural material) are not addressed in the REACH regulation.

ii. France

In France, the AGEC law included a provision introducing these prohibitions from 2024[95]: "The placing on the market of any substance in the state of a microplastic, as such or in a mixture, intentionally present at a concentration equal to or greater than 0.01%, considered as the ratio between the mass of microplastic and the total mass of the sample of material containing that microplastic, is ended. Natural microplastics that have not been chemically modified or are biodegradable are not concerned."

France was also supposed to introduce, from January 2025, an obligation for washing machines sold in France to have a microfibre filter. The implementing decree has still not been published to date, and no schedule has been announced.

iii. PEFCR

The JRC is currently carrying out work, based on the MariLCA project[96], to integrate a new impact category into life cycle analyses: physical effects on BIOTA, in aquatic, terrestrial and airborne environments alike.

Some limits have been raised: lack of data on the impact of microplastics on human health, availability of data and harmonisation across databases, and the issue of shape factors.

iv. French environmental labelling

The textile environmental labelling scheme, deployed since 1 October 2025[97] on a voluntary basis, goes beyond the use of the LCA method (based on the latest version of the PEFCR Apparel and Footwear) and includes a supplement on microfibres covering both the biodegradable character of the fibre (70% of the calculation) and the product's ability to release fibres into the environment (30%). The calculation is based solely on product composition.

94 https://trade.ec.europa.eu/access-to-markets/fr/news/restriction-des-microplastiques-dans-lue-partir-du-17-octobre-2023

95 https://www.legifrance.gouv.fr/jorf/article_jo/JORFARTI000041553847

96 https://marilca.org/

97 https://www.ecologie.gouv.fr/politiques-publiques/affichage-environnemental-vetements

D. Appendix D: List of stakeholders interviewed

Skateholder category	Stakeholder
Research organisations / centres	Microfiber Consortium
	Gemtex Laboratory
	EMPA-SwissFederal Laboratory for material science and technologies
	Caen-IFREMER University
	European Outdoor Group (EOG)
Technical centres	CETI
	CTC
	CETIA
Recyclers and experts	Lavoisier Circular Transition
	Ecobalyse
	The8Impact

E. Appendix E: Bibliographic references specific to the impacts of textile production on the release of micro-fragments

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- Synthetic textile and microfiber pollution: a review on mitigation strategies; Ramasamy and al.; Environmental Science and Pollution Research, Volume 28, pages 41596–41611, (2021)
- The origin of microplastic fiber in polyester textiles: The textile production process matters; Cai and al.; Journal of Cleaner Production 267 (2020) 121970
- Microplastic pollution of textile origin ; IGDD
- CIFRE TLM thesis bibliography “Textile microplastic leaks”; COSNE Antoine and al . Presentation of the TML thesis methodology and its bibliographic study on the release of microplastic fibres. 23 pages.
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