circula·tex

# REPORT ON TECHNOLOGY AND NOVEL SOLUTIONS ANALYSIS

## Deliverable 3.1

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# TABLE OF ABBREVIATIONS

| Abbreviation | Definition |
| --- | --- |
| M | Month |
| EU | European Union |
| WP | Work Package |
| KPI | Key Performance Indicator |
| EC | European Commission |
| ESPR | Ecodesign for Sustainable Products Regulation |
| EPR | Extended Producer Responsibility |
| IPR | Intellectual Property Rights |
| IP | Intellectual Property |
| GDPR | General Data Protection Regulation |
| EUTT | European Union Technical Textile |
| EoL | End-Of-Life |
| 5R | 5R Framework (Reuse, Repair, Refurbish, Remanufacture and Repurpose) |
| AI | Artificial Intelligence |
| NIR | Near-Infrared (Spectroscopy) |
| DPP | Digital Product Passport |
| PRO | Producer Responsibility Organisation |
| TRL | Technology Readiness Level |
| LCA | Life Cycle Assessment |
| LCC | Life Cycle Costing |
| S-LCA | Social Life Cycle Assessment |
| JRC | Joint Research Centre |

# EXECUTIVE SUMMARY

Deliverable D3.1 presents the results of Task 3.1 "*Technology scouting and definition of the best available solutions*", developed within the Circula-TEX project, to identify, analyse, assess and prioritise technologies supporting textile circularity and end-of-life textile management systems.

The activities resulted in the creation of a **Technology Assessment Database containing 138 technologies** and operational solutions associated with the main textile circularity pathways. Conceived as a **living and continuously updateable tool** rather than a static inventory, the database provides a structured repository of technologies relevant to textile circular systems and supports future technology monitoring, comparative assessment, strategic decision-making and investment-oriented evaluations. The work progressively evolved from what initially appeared to be a technology collection exercise into the development of **a broader technology intelligence framework**. During the implementation of the task, the consortium recognised that textile circularity systems are characterised by highly fragmented technologies, heterogeneous industrial processes, multiple innovation sources and rapidly evolving technological domains. Traditional technology scouting approaches therefore proved insufficient to capture the complexity of the sector. To address these challenges, the project developed an integrated **methodology combining patent intelligence, multi-source analysis, AI-supported information extraction, Human-expert validation and operational value chain mapping**.

A key outcome of the activities was the recognition that technologies cannot be effectively assessed independently from the operational context in which they are applied. As a consequence, the mapping of textile end-of-life value chains progressively became the methodological backbone of the entire assessment framework. The consortium developed and validated ten operational value chain maps covering collection and sorting activities and the main circular pathways associated with the 5R framework, including Collection and Sorting, Recycling (Mechanical, Chemical, Thermomechanical, Thermochemical), Reuse, Repair, Refurbishing, Remanufacturing and Repurposing processes. The value chain maps were used to define system boundaries, identify operational stages, structure patent searches, generate targeted keyword strategies, classify technologies and improve comparability across the different circular pathways analysed.

Building on the technology database, the consortium developed and tested a **prioritisation framework** aimed at identifying the most relevant and promising technologies for textile circularity. Through a structured evaluation process combining technical expertise, multi-criteria

assessment and validation activities, the initial portfolio of technologies was progressively filtered and ranked according to their circularity contribution, innovation potential, applicability and industrial relevance. This process enabled the identification of representative technologies and emerging innovation domains that will constitute the basis for the next phases of WP3, including sustainability assessment, circular value chain redesign, eco-design activities and may support future EPR-related decision-making processes.

The technology scouting activities revealed several strategic insights regarding the future evolution of textile circularity systems. One of the most significant findings concerns the **central role of collection and sorting activities as enabling functions for the entire circular ecosystem**. The analysis demonstrated that the effectiveness of R-strategies pathways depends heavily on the quality of material identification, classification and separation processes. Consequently, advanced sorting technologies, automated material recognition systems, sensor-based solutions and AI-supported classification tools emerged among the most strategic technological domains identified during the assessment. The work also highlighted that the management of **heterogeneous textile waste streams** remains one of the major barriers to textile circularity. Technologies capable of handling mixed fibres, blended materials and complex textile products consistently emerged among the most promising solutions identified within the database. This finding suggests that future innovation efforts should focus not only on improving individual recovery processes, but also on increasing the capability of circular systems to manage real-world textile waste streams characterised by high levels of material complexity.

Another important outcome concerns the **different levels of technological maturity and innovation intensity observed across the analysed value chains**. While recycling pathways are increasingly characterised by technological acceleration, automation and process engineering developments (while mechanical recycling appears to be evolving through industrial optimisation, whereas chemical recycling is progressing through rapid technological experimentation and innovation), other pathways such as reuse, repair, refurbishing and repurposing remain strongly dependent on organisational models, logistics, design capabilities and human expertise. This observation confirms that textile circularity cannot be achieved through technological innovation alone, but requires the simultaneous development of operational, organisational and business-model innovations.

The analysis further revealed a growing **convergence among technological domains** that have traditionally been considered separate. Several emerging solutions increasingly combine mechanical processing, chemical treatments, advanced sensing systems, automation and digital intelligence within integrated technological architectures. This suggests that future technological breakthroughs are likely to emerge from the **integration of complementary technologies rather than from isolated innovations**.

The technology prioritisation process also demonstrated that technological novelty alone is not sufficient to determine strategic relevance. Industrial applicability, scalability, compatibility with existing infrastructures and adaptability to real textile waste streams frequently emerged as more important factors than technological sophistication itself. As a result, the highest-ranked technologies were generally characterised not only by innovation potential, but also by their ability to support practical implementation within industrial circular textile systems.

Beyond the technologies identified, Task 3.1 generated important methodological lessons regarding the assessment of innovation in textile circularity. The work demonstrated the limitations of relying exclusively on patents, highlighted the importance of integrating multiple information sources, confirmed the indispensable role of expert judgement in technology evaluation, and showed the value of AI-supported tools for large-scale information processing and technology intelligence activities.

Overall, Deliverable D3.1 provides both a comprehensive overview of the current technological landscape supporting textile circularity and a robust methodological framework for future technology assessment activities. The resulting Technology Assessment Database, value chain maps and prioritisation methodology constitute key assets for the subsequent activities of WP3 and other activities of the project, supporting sustainability assessments, circular value chain redesign, eco-design strategies and the future implementation of evidence-based circular economy, strategies, EPR schemes and support mechanisms by Producer Responsibility Organisations (PROs) within the textile sector.

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# 1.INTRODUCTION

## 1.1.OBJECTIVES OF THE REPORT

The transition towards a circular textile system requires not only the development of new circular strategies and policy instruments, but also a comprehensive understanding of the technologies, processes, and operational solutions currently available for textile end-of-life (EoL) management and circular value chain implementation.

In recent years, increasing regulatory pressure, growing environmental concerns, and the progressive development of Extended Producer Responsibility (EPR) schemes have accelerated the need for structured knowledge on technologies capable of supporting textile circularity, material recovery, reuse-oriented systems, and the reintegration of secondary raw materials into industrial applications.

Within this context, Work Package 3 (WP3) of the Circula-TEX project focuses first of all on the **identification and assessment of best promising solutions associated with textile circularity pathways**. In particular, Task 3.1 "Technologies scouting and definition of the best available solutions" aims to identify, analyse, classify, and preliminarily assess technologies and innovative solutions applicable to textile circularity and textile EoL management.

The activities developed within the task address **multiple circular pathways**, including recycling, reuse, repair, refurbishing, remanufacturing, and repurposing, considering both industrially established technologies (especially those with the highest potential for further development and diffusion) and emerging solutions. The work focuses on the identification of technologies associated with the different operational stages of textile circular systems, ranging from collection and sorting activities to pretreatment and treatment processes related to the different 5R pathways considered within the project.

The core objective of Task 3.1 is the development of a **structured Technology Assessment database** capable of providing a broad and continuously updatable overview of technologies, processes, and operational solutions relevant for textile circularity applications. The database was conceived not only as a project output, but also as a *practical support tool for future technology monitoring, comparative analysis, strategic assessment activities, industrial decision-making processes, and investment-oriented evaluations related to circular textile systems*.

In particular, the Technology Assessment database aims to support:

- the identification of promising technologies and operational solutions;
- the comparison of technologies across different circular pathways and operational stages;
- the understanding of emerging technological trends and innovation domains;
- the identification of technological gaps and criticalities;

- future industrial and strategic evaluations performed by stakeholders, including actors involved in EPR implementation and Producer Responsibility Organisations (PROs).

To support this objective, the project developed an integrated technology scouting and assessment approach combining different complementary methodologies, including:

- patent analysis;
- technical and scientific multi-source analysis;
- AI-supported document exploration and classification;
- expert-based review and validation activities.

The methodological framework was progressively refined during the task activities in order to improve the consistency, comparability and relevance of the identified results across the different value chains and technology domains. In particular, the work highlighted the limitations of traditional technology scouting approaches when applied to textile circularity systems, especially due to the fragmentation of technologies, the heterogeneity of operational processes, and the difficulty of linking patents and technical information to specific circular applications and industrial stages.

During the development of the task, the operational mapping of textile end-of-life value chains progressively became a fundamental enabling activity for the technology scouting process itself. Although not initially conceived as the main output of the task, the mapping activities became essential to:

- define the system boundaries of the assessment activities;
- identify operational stages and process interconnections;
- support the construction of targeted keyword strategies and IPC-based patent searches;
- connect technologies to specific operational steps and circular functions;
- improve the consistency and comparability of the technology scouting activities across the different circular pathways.

The resulting value chain mappings were structured according to the 5R framework adopted within the project and cover multiple textile circularity pathways, including recycling, reuse, repair, refurbishing, remanufacturing, and repurposing activities.

The activities developed within Task 3.1 also support the broader objectives of WP3 and provide methodological and technical inputs for the subsequent project tasks, particularly:

- the environmental, economic, and social sustainability assessments developed in Task 3.2;
- the circular value chain redesign activities developed in Task 3.3;
- the eco-design and EPR analyses developed in Task 3.4.

Finally, this deliverable presents the methodological approach adopted within Task 3.1, the operational value chain mappings developed during the project activities, the technology scouting workflows implemented for patent and multi-source analyses, and the preliminary results emerging from the identification and assessment of technologies, technical solutions, and innovation trends related to textile circularity systems.

## 1.2. GUIDE TO THE READER

The current deliverable documents the activities carried out within Task 3.1 of the project and presents both the methodological framework developed for technology scouting and assessment and the main outputs generated during the task.

*Section 2* introduces the overall objectives of Task 3.1 and describes the **conceptual and methodological framework** developed to support the identification, assessment and prioritisation of technologies relevant to textile circularity systems. It describes the technology intelligence methodology implemented during the task. This includes the patent analysis workflow, the multi-source analysis approach, the integration of AI-supported tools and the procedures adopted for identifying, filtering and validating relevant technologies. Particular attention is given to the challenges associated with technology scouting in highly fragmented and rapidly evolving circular textile ecosystems.

*Section 3* presents the methodology developed for defining the system boundaries of the assessment activities and for **mapping textile EoL value chains**. The section explains how the consortium progressively adopted an operational approach structured around the 5R framework and how value chain mapping became a key enabling activity for technology scouting, patent analysis and technology classification.

*Section 4* focuses on the **Technology Assessment Database** provides a comprehensive overview of the 138 technologies identified across the analysed circular textile pathways. Beyond the description of the database structure, the section examines the resulting technology landscape, highlighting technology maturity levels, emerging innovation domains, key technological trends and the main insights arising from the assessment of textile circularity solutions.

Finally, Section 5 presents the evaluation, ranking and prioritisation activities developed by the consortium. The section describes the assessment framework, the evaluation criteria and weighting mechanisms adopted, and the expert-based process used to compare technologies across the different value chains. Building on the Technology Assessment Database, **the section identifies the most promising technologies and innovation domains** emerging from the analysis, highlighting those considered particularly relevant for future industrial implementation, sustainability assessment activities and circular textile system development.

# 2. CONCEPTUAL FRAMEWORK FOR TECHNOLOGY SCOUTING IN CIRCULAR TEXTILE SYSTEMS

## 2.1. THE OVERALL APPROACH TO THE TECHNOLOGY ASSESSMENT

The technology assessment activities developed within Task 3.1 were designed to support the identification and organization of technologies and operational solutions applicable, at now, to textile circularity systems and textile EoL management. The spectrum of the analysis was intentionally kept very broad, ranging to all different continents of the planet. After the technologies identification by mean of the very different sources analysed, the work progressively evolved towards the evaluation, comparison and prioritisation of the identified technologies, with the aim of **identifying the most promising solutions** for future industrial application, circular value chain integration and strategic investment-oriented assessment activities.

The overall approach was developed to address the high complexity and fragmentation of circular textile systems, where technologies are distributed across multiple operational stages, involve heterogeneous industrial processes, and often overlap between different circular pathways.

The activities were carried out through the direct collaboration of the three partners involved in Task 3.1 activities - **Next Technology Tecnotessile Società Nazionale di Ricerca r.l. (NTT), Centro Tessile Cotoniero e Abbigliamento Spa (COT) and Centre Scientifique & Technique dell'Industrie Textile Belge Asbl (CTB)** - each contributing to specific circular pathways, operational stages and technology domains according to their technical expertise and responsibilities within the project.

The activities were coordinated by NTT as Task leader, through a dedicated multidisciplinary internal team composed of four researchers and technical experts working on technology scouting coordination; operational value chain mapping; patent analysis; multi-source analysis (literature, websites, scientific publications, project technical reports and deliverables); technology assessment framework development; AI-supported technology exploration activities.

In parallel, COT and CTB contributed through dedicated technical teams composed respectively of at least three experts each, supporting all the activities. During the implementation of the task, the activities were progressively distributed among the different members of the teams according to their specific technical expertise and operational background. For example, as described in Section 2.3, the growing complexity of the patent intelligence activities also led to the progressive establishment of a dedicated cross-partner patent expert group involving specialised researchers from NTT, CTB and COT.

The activities of Task 3.1 officially **started in March 2025**, in accordance with the project Gantt planning and continued intensively until June 2026 through a continuous and iterative development process.

Due to the methodological complexity of the task and the large amount of technologies, documents and operational pathways analysed, the activities required a high level of effort and coordination among the involved partners.

Throughout the development of the task, regular internal coordination and technical alignment **meetings were organised on an almost monthly basis**, mainly as part of the WP3 Coordination Meetings, coordinated by NTT in its role as WP3 leader.

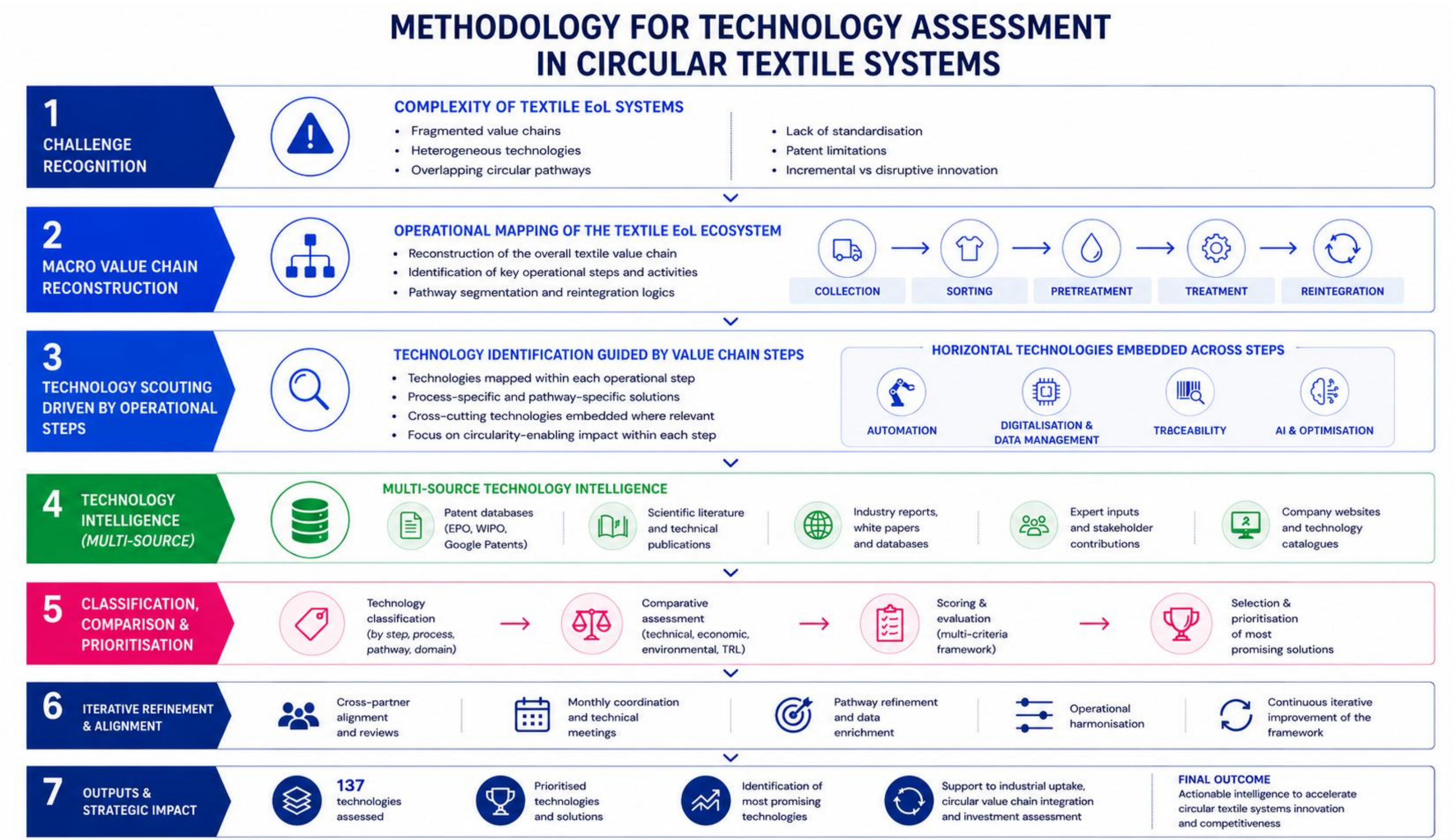



*Figure 1 - Overview of the methodological framework developed within Task 3.1, from technology scouting and value chain mapping activities to technology assessment, ranking and identification of the most promising technologies*

### 2.1.1. INITIAL OBJECTIVES, ORGANISATIONAL STRUCTURE OF THE TASK, THE TECHNOLOGY DATABASE

At the beginning of Task 3.1, the technology assessment activities were initially conceived as a structured technology scouting and classification process focused on the identification, collection and evaluation of technologies and operational solutions applicable to textile circularity systems and textile EoL management pathways.

From the very beginning of the activities, the consortium progressively understood that the main challenge was not only related to identifying technologies, but rather to **understanding how to structure the overall technology assessment framework itself**.

Several methodological questions rapidly emerged during the first coordination activities, including:

- ***which technologies should actually be considered relevant for textile circularity systems;***
- ***how to distinguish textile-specific technologies from broader industrial technologies;***
- ***whether the assessment should focus only on specifically circular technologies or also on conventional technologies applicable within circular pathways;***
- ***how to classify technologies operating across multiple operational stages;***
- ***how to organise and compare technologies belonging to very different circular pathways;***
- ***how to collect reliable technical and industrial information;***
- ***how to manage the extremely large number of potentially relevant patents and technical documents.***

In this context, one of the first core activities of Task 3.1 became the construction of a common ***Technology Assessment Tool*** intended to serve as the main operational framework for the entire task.

As detailed in Section 4.1, the Consortium progressively developed a shared Excel-based structure aimed at:

- standardising the collection of technology-related information;
- organising technologies according to value chain stages;
- harmonising the descriptors used by partners;
- supporting future comparison and evaluation activities
- Prioritising technologies according to their relevance and development/scalability potential.

The Technology Assessment Tool was therefore conceived not as a simple repository of technologies, but as a structured framework capable of supporting the technology classification, comparison, the strategic assessment activities of circular technologies and their selection.

The structure of the Technology Assessment Tool was progressively refined throughout the activities as the consortium progressively improved its understanding of the complexity of textile circular systems and the heterogeneity of the technologies analysed. As described in section 4.1, the final version was validated in September, 2025.

### 2.1.2. EMERGING CHALLENGES IN TEXTILE CIRCULARITY TECHNOLOGY SCOUTING

During the first months of the activities, the consortium progressively realised that textile circularity systems could not be effectively analysed through generic technology collection approaches alone.

The textile sector appeared highly fragmented from an operational perspective, with:

- multiple circular pathways;
- heterogeneous industrial processes;
- overlapping technologies;
- different operational logics depending on the specific circular application considered.

For this reason, the consortium progressively decided to first reconstruct and map the overall macro textile value chain before proceeding with large-scale technology assessment activities.

On the basis of this macro-level mapping exercise, the consortium explored different possible approaches for structuring the technology scouting activities. In particular, the analysis considered whether technologies should be assessed according to specific value chain phases or operational activities, or through more transversal perspectives, focusing on enabling technologies capable of supporting circularity across multiple stages of the textile system (e.g. horizontal technological domains such as automation, digitalisation, traceability, data management, and AI-based optimisation systems).

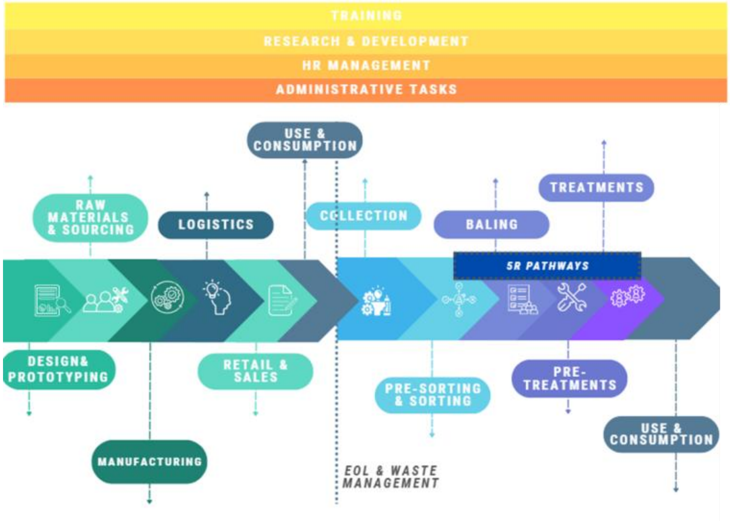



*Figure 2 - High-level representation of the overall Textile value chain and circular end-of-life ecosystem*

As detailed in Section 2.2, in line with Circula-TEX objectives, the Consortium chose to activities focused on the second part of the textile system, namely the **textile End-of-Life (EoL) management stages** (as in the representation above-EoL&Waste management) , starting from collection and sorting activities and subsequently analysing the different circular pathways associated with textile valorisation and reintegration processes. This represented a fundamental methodological decision for the definition of the system boundaries of Task 3.1, allowing the Consortium to delimit the scope of the assessment activities to the core part of the novel value chain, where the 5Rs play their role, and progressively structure the technology scouting framework around the operational stages most directly connected to textile circularity implementation and EoL management processes.

Within this framework, the consortium progressively structured the analysis according to:

- collection and sorting activities;
- pretreatment stages;
- treatment stages;
- reintegration pathways.

The operational decomposition of the EoL system progressively became the central enabling activity for all subsequent technology scouting and assessment activities and beyond (other project tasks).

In particular, the consortium progressively identified the need to separately analyse the different circular pathways due to their strong technological and operational differences. The pathways were therefore divided among the partners according to their technical expertise and previous knowledge. In the following the responsibility assignation for each partner involved:

*Table 1 - Allocation of Textile value chain responsibilities among partners involved in the task 3.1*

| VALUE CHAIN STAGES (of interest for the Technology Assessment) | LEAD PARTNER |
| --- | --- |
| **Collection** | COT |
| **Sorting** | COT |
| Pretreatments (**R – Recycling – Chemical, Thermochemical, Thermomechanical**) | CTB |
| Pretreatments (**R – Mechanical**) | NTT |
| Pretreatments (**R – Reuse**) | COT |
| Pretreatments (**R – Repair**) | CTB |
| Pretreatments (**R – Repurpose**) | NTT |
| Pretreatments (**R – Remanufacturing**) | NTT |
| Pretreatments (**R – Refurbish**) | NTT |
| Treatments (**Recycling – Mechanical**) | NTT |
| Treatments (**Recycling – Chemical**) | CTB |
| Treatments (**Recycling – Thermochemical**) | COT |
| Treatments (**Recycling – Thermomechanical**) | COT |
| Treatments (**R – Reuse**) | COT |
| Treatments (**R – Repair**) | CTB |
| Treatments (**R – Repurpose**) | NTT |
| Treatments (**R – Remanufacturing**) | NTT |
| Treatments (**R – Refurbish**) | NTT |

The initial mapping activities were developed in continuity with an operational mapping framework already available within NTT for mechanical recycling systems, based on operational steps; process decomposition; flow-based analysis; connection between inputs, outputs and technologies. Starting from this approach, the consortium progressively extended the methodology to all the other circular pathways. The activities progressively highlighted that technologies could not be analysed independently from the operational steps in which they are applied.

This led to the progressive emergence of an operationally-driven assessment framework based on:

- process-specific decomposition;
- operational granularity;
- pathway-specific analysis;
- technology traceability across operational stages.

As the activities progressed and the complexity of the pathways became clearer, the consortium progressively refined and expanded the mapping activities through iterative cross-review and technical alignment activities among the partners.

The value chain mapping activities progressively became the methodological backbone of the entire technology assessment framework.

For this reason, the value chain maps progressively became essential to:

- structure the Technology Database;
- connect technologies to operational steps;
- define consistent technology categories;
- support patent search activities;
- identify keywords and IPC/CPC classes for the patent analysis;
- improve the consistency and comparability of the assessment activities.

Details of the activities performed for the mapping exercise and their results are reported in Section 3.

### 2.1.3. PARALLEL DEVELOPMENT OF PATHWAY MAPPING AND PATENT ANALYSIS ACTIVITIES

In parallel with the operational mapping activities, the consortium launched dedicated patent scouting activities structured according to the pathway assignments distributed among the partners. Each partner progressively developed patent scouting activities associated with its assigned circular pathways, as represented in Table 1 - Allocation of Textile value chain responsibilities among partners involved in the task 3.1.

At the beginning of the activities, the consortium harmonised the patent analysis methodologies through a common structure based on:

- IPC/CPC classifications;
- keywords strategy;
- operational filtering;
- shared validation logic.

For this purpose, a dedicated cross-partner **"patent experts" working group** was also progressively established involving NTT, COT and CTB, with the objective of:

- monitoring the evolution of the patent scouting;
- discussing methodological refinements;
- comparing intermediate results;
- aligning operational classifications and filtering approaches.

However, as the activities progressed, the consortium progressively observed that the different circular pathways followed significantly different technological trajectories and innovation dynamics. As a consequence, the patent scouting methodologies progressively diverged among the partners according to:

- the technological maturity of the pathways;
- the different innovation patterns;
- the specificity of the industrial applications;
- the different structure of patent landscapes associated with each pathway.

The activities demonstrated that the recycling-related pathways, reuse-oriented pathways, sorting technologies and pretreatment systems required substantially different patent search logics, filtering strategies and technology interpretation approaches. This progressively transformed the framework from a fully standardised patent scouting activity into a more flexible pathway-specific technology intelligence process.

As discussed during the coordination meetings, only a limited percentage of the database fields could initially be filled directly using patent-derived information, while additional technical and industrial details often required complementary information sources such as brochures, reports and technical documentation.

More details in Sections 2.4.1.

### 2.1.4. COMPLEMENTARY MULTI-SOURCE ACTIVITIES AND AI-SUPPORTED EXPLORATION

As the activities progressed, the consortium progressively introduced complementary multi-source analysis activities to support and refine the patent scouting results. These activities were mainly developed to address some of the limitations observed during the patent analysis phase, particularly regarding the lack of operational and technical details, the difficulty in understanding the industrial applicability of certain technologies, and the identification of emerging technological trends not sufficiently represented within patent databases.

Rather than developing a conventional literature review approach, the consortium adopted a more exploratory and iterative methodology aimed at integrating heterogeneous technical and industrial information sources. **The activities combined scientific literature, technical and industrial reports, project deliverables, web-based technical documentation and targeted online searches, including Google Scholar exploration activities**.

The multi-source analysis activities were progressively integrated with AI-supported document exploration tools in order to accelerate large-scale exploratory searches and preliminary document screening activities. In particular, AI-supported approaches were used to support keyword refinement, preliminary document summarisation, extraction of technology-related information and comparison among technical solutions emerging from different sources.

However, throughout the activities, expert-based review and technical interpretation remained the foundations of the framework. **Human validation** activities were continuously required to interpret operational applications, evaluate the relevance of the identified technologies and connect the collected information to the operational structure of the textile circular pathways previously mapped by the consortium.

In this sense, the multi-source activities did not replace the patent analysis framework, but rather complemented and reinforced the overall technology assessment process by providing additional technical, operational and industrial insights useful for the refinement of the Technology Assessment Database and the identification of emerging innovation trends. As it will be described in the end of this document, the patent analysis proved to be very often poor in terms of technical references regarding the specific technology, not allowing a full understanding of the level of scalability/applicability of the technology itself. For such a reason, the multi-source analysis was intended as to complement and finalise the results of the patent analysis, to restitute and depict a clearer and more comprehensive picture of the technological panorama for the 5Rs development for EU the textile sector.

The multi-source activities progressively became particularly important for filling many of the fields included in the Technology Database that could not be populated directly through patent information alone.

### 2.1.5. Evolution towards technology evaluation and prioritisation

As the activities progressed, the Technology Assessment framework progressively evolved beyond a technology collection and mapping exercise. The progressive population of the Technology Database allowed to move towards:

- technology classification;
- technologies clustering;
- comparative assessment;
- evaluation criteria set up;
- prioritisation methodologies;
- identification of the most promising technologies in terms of potential for scalability-industrialisation.

By early 2026, the Technology Database included 138 technologies collected through patent and multi-source analyses.

At the same time, it was recognised that the available information was often heterogeneous and incomplete, particularly regarding industrial maturity and scalability aspects.

For this reason, a progressive evaluation and prioritisation framework was introduced based on: database cleaning and pre-selection activities; clustering by value chain and technology typology; scoring methodologies; pathway-oriented comparative analysis; identification of promising technologies for further investigation.

The final objective progressively became the identification of a restricted set of promising technologies to be further investigated through:

- additional technical analysis;

- interviews with technology providers and users;
- interaction with industrial and operational stakeholders.

The overall methodological evolution of Task 3.1 progressively transformed the Technology Assessment Tool into an integrated operational technology intelligence framework capable of supporting comparative analysis, prioritisation activities and strategic assessment of circular textile technologies across multiple End-of-Life value chains and operational pathways.

More details and results in Section 5.

## 2.2. Definition of System Boundaries: Integration with 5R Framework

The definition of the system boundaries progressively emerged as one of the most critical methodological activities within Task 3.1, as introduced in Section 2.1.2. During the first coordination phases, the consortium realised that textile circularity systems could not be approached through a generic technology scouting exercise due to the extreme complexity, fragmentation and heterogeneity of the textile sector. **The potential perimeter of the analysis could theoretically extend across the entire textile value chain**, including design, raw material sourcing, manufacturing, logistics, retail, use and end-of-life management.

At the same time, the potential perimeter could be built considering technologies operating from the design phase up to EoL management, including conventional manufacturing technologies, supply chain and logistics systems, retail and use-phase solutions, advanced manufacturing technologies, consumer-oriented circular business models, as well as waste management and textile valorisation technologies.

In fact, in parallel, other WP3 activities, particularly Task 3.3, explored several of these upstream dimensions of the textile system, including Design & Prototyping, Raw Materials & Sourcing, Manufacturing, Logistics, Retail & Sales and Use & Consumption stages.

However, during the first coordination activities, it was progressively recognised that extending the technology assessment to the entire textile system would have generated an excessively broad and heterogeneous analytical framework, making technology classification, comparison and prioritisation activities extremely difficult. As discussed during the WP3 meetings, one of the first methodological challenges was not simply identifying technologies, but, in line with Circula-TEX objectives, rather understanding which technologies should actually be considered relevant for textile circularity systems, how to distinguish textile-specific technologies from broader industrial technologies, and how to structure the assessment framework itself.

The consortium, thus, strategically decided to focus the assessment activities on technologies supporting textile EoL management and the subsequent reintegration of materials and products into circular value chains: also because **it was assumed that EoL management systems**

**currently represent one of the most critical enabling factors for accelerating textile circularity**.

As in Section 2.1.2, it was progressively understood that technologies could not be analysed independently from the operational stages and circular pathways in which they are applied. Different pathways were characterised by substantially different operational logics, industrial objectives, technological maturity levels and process structures. For this reason, textile circularity systems could not be treated as a single homogeneous technological domain.

Consequently, the consortium strategically decided to delimit the scope of Task 3.1 to the textile **End-of-Life (EoL) management macro-phase** and to the circular pathways associated with textile valorisation and reintegration processes. This methodological decision became one of the enabling conditions for structuring the overall technology assessment framework.

Another relevant methodological discussion concerned **the textile material scope of the analysis, in terms of fiber type**, and whether the assessment activities should focus only on selected textile fibres or include the broader variety of textile materials present in real waste streams. During the first phases of the activities, the consortium considered the possibility of limiting the analysis to specific fibre categories in order to simplify the scouting and assessment activities. However, this approach was progressively considered too restrictive and not fully representative of the actual complexity of textile circularity systems.

The consortium therefore decided to adopt a broad material scope, including different fibre typologies, blends and mixed-material textile products. This decision was mainly motivated by the assumption that one of the main barriers to textile circularity is precisely the heterogeneity of textile waste streams. Consequently, technologies capable of managing complex and mixed textile materials were considered particularly relevant within the assessment framework.

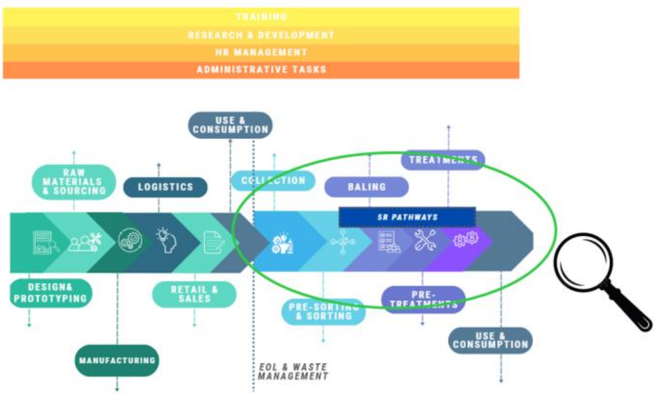
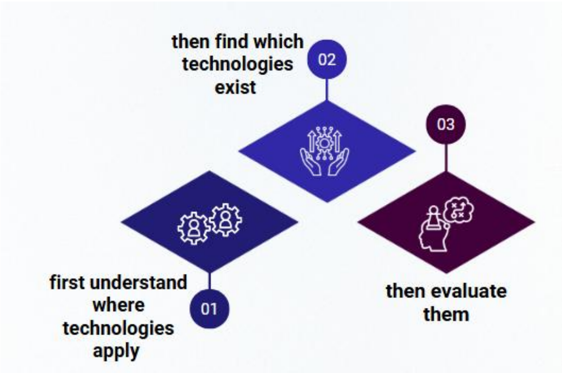



*Figure 3 - Focus on the system boundaries adopted within Task 3.1 for the technology scouting*

As described above, during the first phases of the task activities, it progressively emerged that the definition of the system boundaries could not be limited to a generic classification of circular pathways. In particular, the technology scouting activities highlighted the need for a much more operational and process-oriented approach capable of identifying:

- where technologies are positioned within textile circular systems and EOL related value chains;
- how technologies interact and characterise specific operational stages;
- which operational steps are associated with specific technological domains;
- which keywords, descriptors, and IPC classes are relevant for each process stage.




The mapping activities were therefore not developed exclusively as descriptive representations of textile circular systems, but mainly as operational tools supporting the identification, classification, and interpretation of technologies within the Technology Assessment activities. It is also because of this stringent need that the representation of the current EOL value chains was anticipated with respect to Task 3.3, and was included in the preliminary steps of Task 3.1.

## 2.3. TECHNOLOGY SCOUTING METHODOLOGY

The Circula-TEX project addresses complex and multi-layered challenges and objectives such as EPR harmonisation, eco-design, traceability, recycling, and labelling. For this reason, no single type of source of information would have been able to capture both the policy-operational landscape and the technological innovation scenario. Each method revealed its own limitations, making each source mutually necessary rather than merely complementary. Patent analysis, combined with multi-source analysis, proved to be an appropriate choice, since patents and scientific articles capture proprietary technological developments at any stage of development, whether the technology is still in its infancy or already well established. Through IPC/CPC codes, patents provide a structured and classification-based record of innovation. They reveal who is innovating, where and in which specific technological areas.

Understanding the patent landscape was crucial in several respects. It made it possible to map the actual level of technological maturity along each circular pathway, which often differs significantly from what is reported in technical documents or scientific articles. It also enabled the identification of the main innovation actors and geographical concentrations, highlighting which companies or institutions are leading development in specific areas.

By contrast, multi-source analysis facilitated the identification of established technologies based on reliable and documented sources.

Each circular pathway, under analysis such as mechanical recycling, chemical recycling, regeneration, sorting, etc. follows a different technological trajectory: innovation dynamics, maturity levels, and patent landscapes vary significantly from one pathway to another. This complexity could not be captured exclusively through literature or web sources, but also required pathway-specific investigations. The two analytical frameworks fulfilled different yet interrelated functions. Patent analysis provided the level of structured technological intelligence: a rigorous, classification-based map of who is innovating, in which areas, and with what implications in terms of intellectual property.

Multi-source analysis, on the other hand, filled the gaps in operational and industrial intelligence that patents are sometimes unable to cover, highlighting emerging trends, real-world applicability, and contextual distinctions that databases alone cannot capture. Neither of the two approaches would have been able, on its own, to fully meet the objectives of Circula-TEX within the WP3.

Together, they constituted a robust and layered technology assessment framework, capable of grounding the project's recommendations both in the formal record of innovation and in the living, constantly evolving reality of the circular economy in the textile sector.

### 2.3.1. PATENT ANALYSIS AND AI SUPPORT

#### 2.3.1.1. INTRODUCTION TO THE PATENT ANALYSIS

In general, the patent analysis constitutes an essential strategic tool for monitoring global innovation trends and assessing the state of the art in the EoL management of textile products. In a complex and fragmented market environment, the systematic study of patents is of primary importance. This activity provides three immediate and significant benefits: 1 - it enables the identification of competitors' strategic directions, 2 - ensures that the technologies under consideration can be deployed without infringing third-party rights (*Freedom to Operate*), 3- and highlights pre-existing solutions that may still offer practical value.

In addition, patent analysis supports the identification of *white spaces*, namely market areas that remain unoccupied by exclusive rights, thereby directing investment towards genuinely disruptive innovation pathways.

In order to address the considerable complexity of this information landscape, in general the operational workflow integrated traditional patent analysis methodologies with the support of a software platform specifically designed for intellectual property search, analysis, and management. Conventional methodologies rely on well-established and standardised criteria, including Boolean keyword searching, the use of international classification codes (such as IPC/CPC classes) assigned by patent offices, and the statistical mapping of patent activity to monitor filing trends over time and identify the leading industrial players. However, the traditional approach alone is constrained by the inherent rigidity of patent legal language, as applicants often adopt deliberately broad, vague, or highly specialised terminology in order to maximise legal protection and avoid disclosing the exact nature of the invention to competitors. As a result, relevant concepts may remain obscured within complex textual formulations.

Although the approach adopted at this stage remained predominantly traditional, it should be noted that an artificial intelligence component was already natively embedded within the platforms used for the preliminary search. Indeed, the contribution of AI was not limited to the initial scouting phase, but also extended to subsequent activities of comparative analysis and benchmarking through the use of software platforms based on large language models (LLMs).

The use of LLMs was therefore positioned downstream of the search activity, with a function specifically aimed at the reprocessing, interpretation and structuring of data extracted from the patent landscape through the Orbit Intelligence platform. The datasets generated during the scouting phase are frequently presented in raw form and are often affected by issues arising from the rigidity and ambiguity of the legal-technical language that characterises patent documentation. This condition hinders the immediate, unambiguous, and coherent classification of information. Within this context, the LLM was employed as an advanced semantic post-processing tool: its role was not to identify patents, but rather to support the interpretative analysis of texts that had already been selected and processed by the platform. Through *Prompt Engineering* techniques, structured inputs were defined to guide the model in understanding the technical content of the descriptions and in interpreting the physical or engineering principles underlying the patented solutions, such as the rheological behaviour of fibres or the mechanical force vectors involved. This approach enabled the automated, consistent, and standardised extraction of key technical parameters, including the operating principle (*Working Principle*) and the underlying technology, thereby transforming extensive primary datasets into high-value, information-dense syntheses. The resulting outputs were subsequently subjected to critical evaluation by technicians and sector experts in order to identify only those solutions considered most promising and most relevant with respect to the objectives of the analysis. Nevertheless, the effectiveness of this automation remains strictly dependent on an expert review and validation phase, in accordance with a *Human-in-the-Loop* approach. Such validation is essential both to compensate for the so-called "genericity paradox" that affects many patent texts and to detect, albeit indirectly, the technological maturity of the solutions examined, which is rarely stated explicitly in the documentation. This cross-validation process made it possible to significantly refine the analysis of the identified documents, progressively narrowing the focus to a limited number of highly relevant technologies for the target sector and consolidating a robust knowledge base to support subsequent technology transfer activities towards the circularity industry.

### 2.3.1.2. PATENT ANALYSIS STEP BY STEP

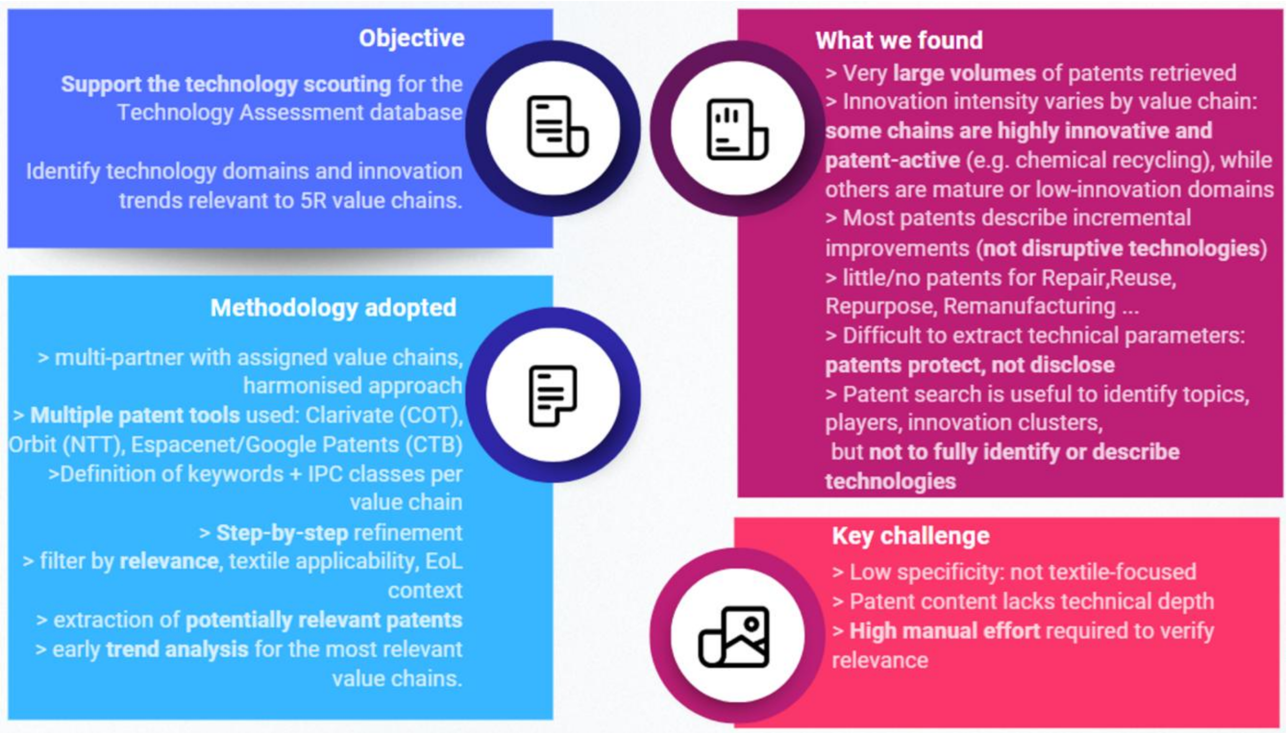



*Figure 4 - Schematic overview of the technology scouting methodology adopted in Task 3.1, including the main methodological challenges and enabling activities*

From what reported above, it is evident that in Circula-TEX the technology scouting process based on patent analysis was conceived as a progressive methodological pathway, initially grounded in a conventional patent search and subsequently reinforced through the use of AI tools and finally through the human evaluation, i.e. the expert technical review.

As already reported, the primary objective in Task 3.1 was to identify, select and systematise the most relevant technologies, transforming a very broad corpus of patent documents into an informative basis suitable for populating a technology database and supporting subsequent technology assessment activities within its structure as described in Section 4.1. This approach enabled the breadth of documentary research to be combined with the depth of qualitative analysis, thereby addressing several typical challenges associated with scouting processes, including the high volume of patents, the fragmentation of information, and the need to rapidly distinguish genuinely relevant solutions from those that are marginal or insufficiently documented.

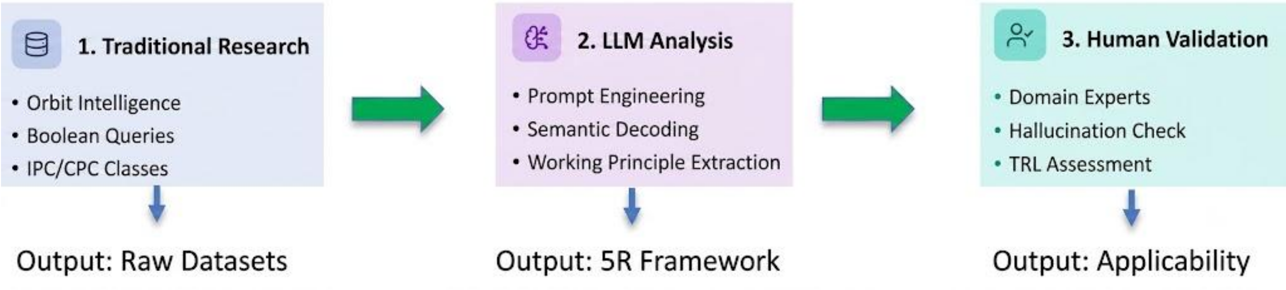



*Figure 5 - Three-step integration of traditional search methods with Large Language Models and expert review*

The first phase of the work involved the **implementation of a traditional patent search across platforms such as Clarivate and Orbit Intelligence**. In order to ensure consistency with the operational framework developed within the Task, the patent analysis activities were structured according to the value chain responsibilities assigned to the partners for the mapping activities (Table 1 - Allocation of Textile value chain responsibilities among partners involved in the task 3.1). NTT, CTB and COT therefore focused their initial patent investigations on selected case studies representative of the value chains under their responsibility. Rather than immediately extending the analysis to all value chains, an iterative approach was adopted, aimed at testing and refining the patent intelligence methodology. Each partner conducted one or more pilot patent analyses on a specific value chain segment. The objective was not only to identify technological trends and relevant patents, but also to validate a common methodological framework capable of generating comparable and meaningful results across the different circular pathways, finally leading to the definition of a dedicated tool for technologies assessment.

So, the technical activity started with the **reasoned selection of the IPC/CPC classes** considered most relevant to the technological domains of interest, the definition of keyword sets and synonyms, as well as the introduction of specific search parameters, including temporal boundaries, the presence or absence of territorial restrictions, and patent status. The search was configured to cover the period from 2010 onwards, without geographical restrictions and without the initial application of "dead or alive" filters, in order to obtain a broad and representative documentary basis. Once the keywords and filters had been defined, **several keyword-combination strategies** were adopted. In particular, **logical operators** such as "and", "or" and "not" were used to combine individual terms and construct complex search strings, thereby reducing the number of documents retrieved in the output.

During the initial phases, the objective was to define a common and homogeneous methodological approach among the partners, including shared criteria for IPC/CPC selection, keyword definition, filtering logic and interpretation of patent outputs. However, as the activities progressed and the first-round analyses were reviewed, the consortium recognised several methodological limitations and progressively refined the approach through iterative technical discussions and review meetings.

Early search outputs frequently generated excessively broad datasets, often with limited direct connection to concrete technologies or industrial applicability. For this reason, the consortium progressively refined the methodology through the adjustment of IPC/CPC classes, the revision of keyword combinations, the introduction of more selective search strings and the alignment of searches with the specific technological domains under investigation. In several cases, the searches initially generated datasets ranging from several hundred to more than one hundred thousand patent records, which were progressively narrowed down through cross-referencing procedures, AI-assisted filtering and expert technical review.

To address these issues, the team progressively converged on a workflow based on:

- definition of the technological scope starting from the mapped operational steps;
- identification of relevant IPC classes;
- construction of keywords and synonym combinations;
- cross-referencing between patent searches and value chain stages;
- AI-supported extraction and clustering of patent information;
- final expert-based human validation.

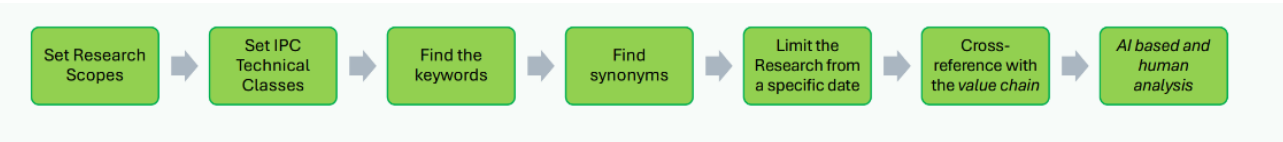



*Figure 6 - Workflow adopted for the patent analysis activities*

Although a common patent scouting workflow was progressively defined and shared among the partners involved in Task 3.1, the methodology was not applied in a completely identical manner across all analyses. In general terms, all partners followed the same core analytical structure as schematized above, however, the practical implementation of the workflow necessarily evolved according to the specific characteristics of the investigated value chains and technological domains. The consortium progressively recognised that **the strong heterogeneity among the analysed circular systems generated different methodological needs, levels of patentability and data availability**, making a fully rigid and standardised application of the workflow neither feasible nor methodologically appropriate.

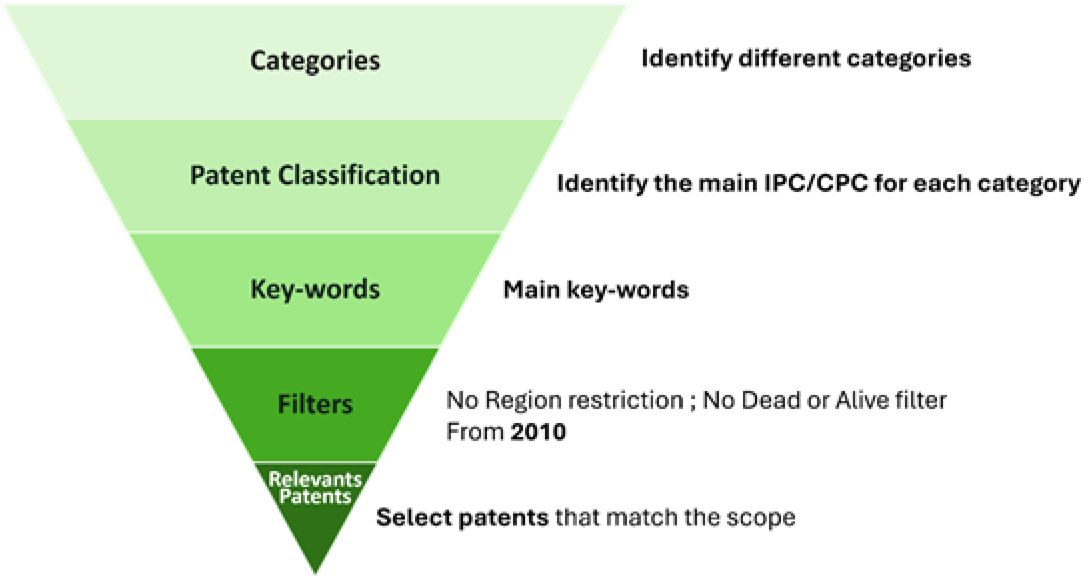



*Figure 7 - The patent search funnel: a step-by-step filtering strategy to identify relevant patents*

Once the first validated set of results had been obtained, the second phase focused on the **export of the selected patents** and the **launch of an analysis process supported by AI tools**. Specifically, appropriately designed prompts were used to query large language models (LLMs), with **the aim of analysing the abstracts of the identified documents at scale and producing concise yet informative summaries,** in particular data and information in line with the fields of the tool. This operation made it possible to extract key elements more efficiently, including the underlying technology, the operating principle, the main operational characteristics, and other relevant technical details. At this stage, AI was not used as a substitute for expert judgement, but rather as a tool to accelerate and support the preliminary analytical phase.

On the basis of the summaries derived from the abstracts, a subsequent reading and assessment activity was carried out in order to pre-select the most promising documents. This step forms part of a **two-stage filtering process**, whereby the analysis moves first from hundreds of technologies or documents to an intermediate shortlist and subsequently from that shortlist to an even more restricted set of high-potential solutions.

The selected patents, reduced to a few dozen, were then downloaded in full, thus enabling a second LLM-supported analysis no longer limited to abstracts and claims, but extended to the entire available text. This second analytical stage generated new summaries with a higher informational density, aimed at capturing not only the synthesis of the document but also the technical architecture of the solution, the operating modes, any plant configurations, and the distinguishing aspects in comparison with other related technologies.

The final phase of the process involved the contribution of expert technicians, who used the collected information to identify the most innovative technologies and **populate the technology database with the information considered most significant**. The technology database was first defined and then refined, by making its functioning centered on a set of technical and economic criteria, useful to the technologies prioritisation and, after, their consultation; the tool is conceived as to be kept alive and updated in time; it is also structured as to provide the opportunity to consult and select the different technologies according to one preferred parameter (or more than one). This enabled the preparation of a functional instrument for research activities, but for its application at operational level, servicing the European textile community. This was essential to ensure the final quality of the collected data, as it enabled the critical validation of the automatically extracted content, the selection of the elements genuinely relevant for technological comparison, and the integration of each item of information into a structure consistent with the project database. The human contribution therefore fulfilled a function of verification, interpretation and consolidation, making the overall workflow a clear example of effective integration between structured documentary research, automated analysis and specialised technical expertise.

In several of the domains analysed, **the initial cross-reference generated result sets ranging from a few hundred to nearly one thousand patents**. Faced with such volumes, the combined AI/human analysis made it possible to narrow the focus to a very limited number of patents considered genuinely relevant, while still allowing for the technical review of additional documents. It is also important to underline several significant methodological challenges, including the need for a data-cleaning phase, the identification of emerging patterns, the role of two-stage filtering, and the highly time-consuming nature of the overall process, particularly where information was incomplete or insufficiently transparent.

Overall, the work described represents an advanced model of patent-based technology scouting, in which conventional research based on patent classes, keywords and filters is enhanced through the combined use of AI tools integrated into the search platform and LLMs applied to the reading, summarisation and interpretation of patent content. The value of this approach lies in its ability to transform a very large documentary corpus into structured technical knowledge, progressively refined until it becomes suitable for the development of a reliable technology database. The continuous presence of human evaluation during the selection and final validation phases also ensures methodological robustness and practical coherence, preventing automation from generating excessive simplifications or uncontrolled interpretations. Looking ahead, this workflow provides a solid basis for subsequent grading activities, technology selection and, ultimately, the identification of the most promising solutions along the value chain under consideration.

### 2.3.2. TREND ANALYSIS

An additional methodological aspect progressively emerged during the activities concerns the role of trend analysis within patent-based technology scouting. In conventional patent intelligence practices, the most common approach consists of performing quantitative trend analyses aimed at identifying the evolution of technological domains, the growth of patent clusters, the geographical distribution of innovation activities and the most active industrial players. However, during the first phases of Task 3.1, it was recognised that this type of high-level trend analysis alone was not sufficient to reliably identify individual technologies suitable for detailed technical assessment and database population. In fact, the first round of patent analyses performed through platforms such as Clarivate and Orbit Intelligence mainly generated broad trend-oriented outputs related to the different value chains under investigation, including patent distributions, industrial actors, geographical concentrations and macro technological clusters.

While these analyses proved useful for the initial overview of the innovation landscape, they provided limited traceability to concrete technological solutions.

In fact, broad patent trend analyses frequently generated very large and heterogeneous datasets in which genuinely relevant technological solutions were diluted among incremental improvements, generic process descriptions or patents with limited practical applicability. For this reason, it was decided not to position trend analysis as the starting point of the scouting workflow, but rather as a more advanced interpretative activity to be performed after the first filtering and technical review phases.

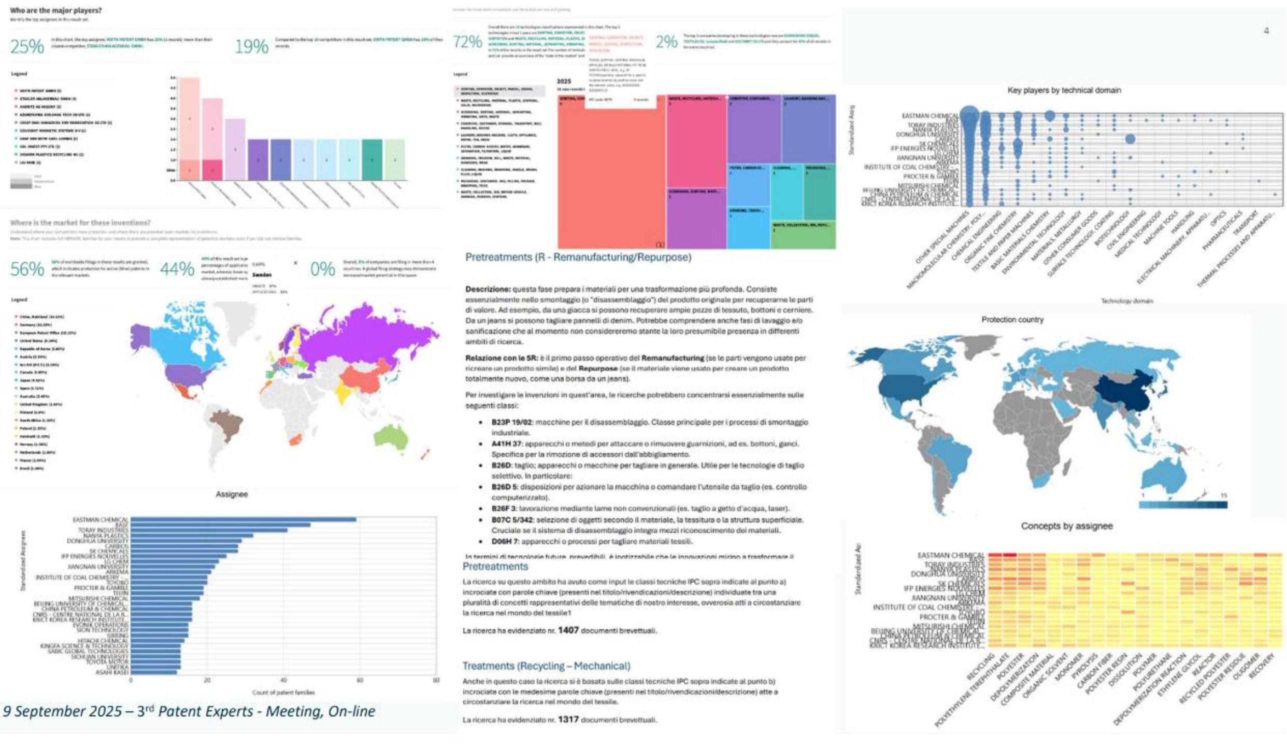



*Figure 8 - Examples of preliminary technological trends identified during the first round of patent analysis*

The progressive reduction of the documentary corpus through AI-assisted screening, expert evaluation and technical validation enabled a more reliable interpretation of technological trajectories and emerging innovation patterns. Only after narrowing the focus from hundreds or thousands of patents to more restricted and technically consistent subsets was it possible to identify meaningful trends, recurring technological approaches and potential future directions of the sector.

In this context, trend analysis evolved from a purely quantitative patent-landscaping exercise into a more qualitative technology intelligence activity aimed at understanding broader innovation dynamics.

The final results of these trend-analysis activities are reported in Section 4, where the identified technology clusters of the final database and their emerging technological trajectories are described, as well as in  Annex 1 (Annex 1.1, Annex 1.2, annex 1.3), where the final trend-analysis reports developed for each relevant value chain are presented in detail.

### 2.3.3. KEY CHALLENGES AND COMMON ISSUES

Patent analysis has represented a highly valuable tool for technology scouting, as it has enabled the identification of technological development trajectories, the mapping of key actors operating within a given domain, and the detection of areas characterised by higher inventive intensity. However, its use **as a primary source for the identification of innovative technologies has entailed several structural limitations** that required careful consideration. Indeed, an exclusively patent-based interpretation of the technological landscape may generate partial assessments that are not always fully aligned with the actual state of industrial and scientific innovation. The patent landscape literature has consistently shown that, while patent analysis is valuable for detecting trends and supporting strategic decision-making, it also requires significant methodological caution in the search, classification, and interpretation of results.

A first critical issue has concerned **patent ambiguity**: patent documents are generally drafted for legal and strategic purposes rather than with the objective of describing a technology in a linear and transparent manner. The language employed tends to be intentionally broad, abstract, or protective, in order to maximise the scope of protection and to cover possible application variants. This characteristic makes it difficult to accurately interpret the actual technical content of a patent, its degree of concrete novelty, and its real application boundaries. Furthermore, the gap between claims, description, and potential industrial implementations may generate interpretative ambiguity, leading either to an overestimation or to an underestimation of the innovative value of a given solution.

A second significant limitation has related to **incomplete Technology Readiness Level (TRL) data or industrialization stage**. The Technology Readiness Level (TRL) criterion has been assessed according to the official Horizon Europe TRL definitions adopted by the European Commission, ensuring consistency with the evaluation framework commonly applied in EU-funded research and innovation projects. As an intellectual property document, a patent rarely provides sufficient information to accurately position a technology along the Technology Readiness Level scale. In many cases, it is possible to derive the technical concept, the operating principle, or a proof of concept from a patent; however, it is generally not possible to determine whether the technology has been validated in the laboratory, tested in a relevant environment, or is already close to industrial deployment. Nevertheless, the TRL scale remains a central element of the technology database built within Circula-TEX activities, as it helps distinguish between a promising but still embryonic solution and a technology that is genuinely transferable to the market. The absence or incompleteness of such information therefore makes it difficult to assess the actual maturity of the identified solutions and may lead to the consideration of inventions that are still at a very early stage as concrete opportunities.

A further weakness has concerned **terminological inconsistency**: in patent documents, the same technology may be described using different terminology depending on the sector, the country, the applicant's strategy, or the historical evolution of the technical vocabulary. This has generated significant challenges in the definition of search strings, the construction of taxonomies, and the comparison of results. An overly restrictive search strategy risks excluding relevant documents that employ synonyms or unanticipated classifications. Conversely, an excessively broad search may generate informational noise and include patents that are only marginally relevant.

Another structural weakness has concerned **limited industrial transparency**. The fact that a technology has been patented does not necessarily imply that it has been developed, industrialised, adopted by the market, or integrated into actual production processes. Many companies routinely file patents for defensive, exploratory, or competitive positioning purposes, without any concrete intention of industrial exploitation in the short term. Moreover, patents do not provide complete information on implementation costs, operational reliability, regulatory barriers, scalability issues, commercial success, or experimental failures. For this reason, patent analysis alone offers only an indirect and, in some respects, incomplete representation of industrial dynamics.

From the methodological point of view, the main challenge encountered during the patent scouting activity was the difficulty of fully standardising the analysis procedure across all partners and value chain domains. This limitation was not only related to differences in analytical approaches among the involved teams, but mainly to the intrinsic heterogeneity of the circular textile value chains under investigation. The assigned domains covered highly diverse technological ecosystems — ranging from mechanical and thermochemical recycling processes to reuse, repair, remanufacturing and repurpose activities — each characterised by different levels of technological maturity, patentability, industrial codification and innovation dynamics. As a consequence, the applicability and effectiveness of patent-based analysis varied significantly depending on the analysed value chain. In some domains, particularly mechanical recycling and industrial processing technologies, patent searches generated extremely large datasets, often dominated by incremental improvements of existing machinery or process optimisation patents. In other domains, such as reuse or repair-related activities, partners encountered the opposite issue, namely the limited availability of patents directly associated with operational circular practices or service-oriented solutions.

Finally, one of the most significant critical issues for technology scouting has concerned the **difficulty of identifying disruptive technologies**. Truly disruptive technologies often emerge initially in hybrid, peripheral, or not yet recognisable forms within traditional patent categories. In some cases, the most radical innovations are not patented immediately, but instead first appear in scientific articles, prototypes, start-ups, industrial agreements, software platforms, proprietary know-how, or novel combinations of existing technologies. In addition, patent classification systems tend to describe the present rather than capture innovations that are still in the process of taking shape.

In conclusion, the intrinsic ambiguities of patents, the lack of complete data on technological maturity levels, terminological inconsistency, limited transparency regarding actual industrial application, and the difficulty of intercepting disruptive innovations have significantly complicated this phase of technology scouting. In order to increase the reliability of this activity, it has therefore been necessary to complement patent analysis with additional qualitative and quantitative sources, while also introducing a dedicated phase for the analysis and assessment of each individual technology identified by expert technical personnel.

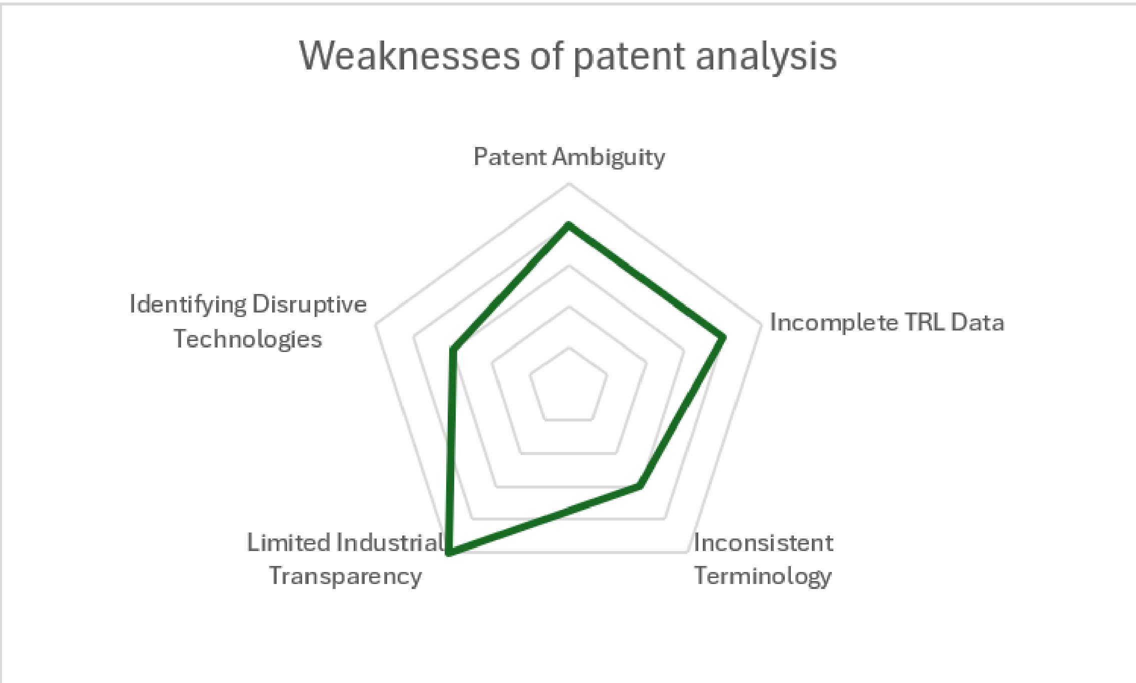


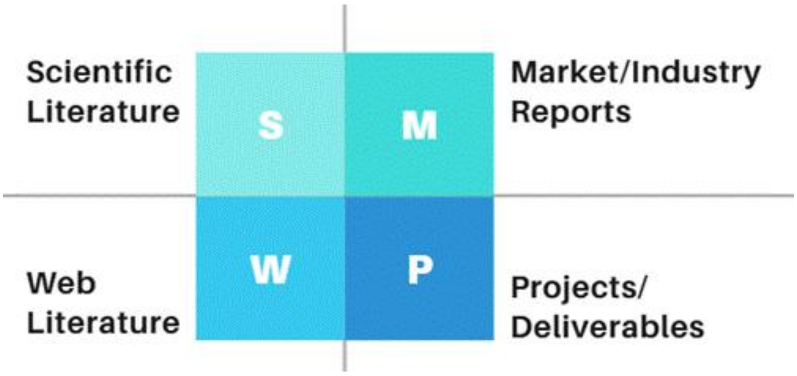

*Figure 9 - Dimensions of Weaknesses of patent analysis for technology scouting*

### 2.3.4. MULTI-SOURCE ANALYSIS AND AI SUPPORT

To bridge the information gaps described above, pragmatically map textile End-of-Life (EoL) technologies and avoid losing valuable technical and strategic information available across other highly relevant documentary and industrial sources beyond patents alone, the project progressively developed a structured multi-source research methodology. This approach extends the search beyond patent databases, capturing both peer-reviewed scientific literature and the technical-commercial documentation available on the web, with the explicit aim of validating the actual applicability and industrial scalability of the identified solutions.

This approach has the explicit objective of connecting formal scientific theory with the operational reality of the industry, exploring four main information quadrants:

- **Scientific Literature (S):** Peer-reviewed publications, specialized reviews, and research theses.
- **Market and Industrial Reports (M):** Technical documentation provided by leading companies and machinery manufacturers.
- **Web Literature (W):** Industry articles, specialized portals, and updated corporate websites.
- **Projects and Deliverables (P):** Results from other European or international research initiatives focused on the circular economy in textiles.




The operational workflow applied to the multi-source investigation methodology was not rigidly defined in advance; instead, it emerged and consolidated iteratively through practical activity and direct field experience. The sequential logical framework presented here represents, in fact, the culmination of a process developed as the work progressed.

This dynamic and empirical approach made it possible to structure the web and scientific literature research in a progressively more rigorous manner, preventing data fragmentation and optimally integrating all gathered sources. Each phase laid the groundwork for the next, moving from the internal, already validated knowledge base to a large-scale exploration of the global knowledge available online.

The final step, based on Gemini Deep Research, proved to be by far the most effective and widely adopted, establishing itself as a disruptive technology capable of synthesizing hundreds of unstructured sources and delivering directly actionable technical data. Below, the individual phases comprising this investigation methodology are explored in detail. The multi-source analysis activities were coordinated and progressively refined under the guidance of NTT, which had the main role in structuring the overall workflow and harmonising the methodological approach among the involved partners. As the scouting progressed, the methodology was continuously reiterated and adjusted according to the quality, consistency and usefulness of the retrieved results. NTT progressively refined the workflow by improving keyword strategies, reorganising source selection criteria, introducing more targeted AI-supported searches and strengthening the validation procedures.

The first step of the workflow focused on leveraging the documentary assets already available internally. To quickly scan files, interim reports, and deliverables saved on PCs or shared via the cloud, a custom application named the *Keywords Search Algorithm* was utilized.

The technical operating logic of the application is as follows:

1. The user maps the local or cloud folder containing the documents of interest for the Circula-TEX project.
2. A set of targeted keywords is entered (one per line), configuring the algorithm to automatically consider both the national language terms and their respective English counterparts (and vice versa).
3. The logical search type (AND or OR operator) is set before initiating processing.
4. the algorithm performs text analysis, maps the exact occurrences, and automatically generates an output file in .csv format containing the file references, the found keyword, the detected language, and the specific context of use.

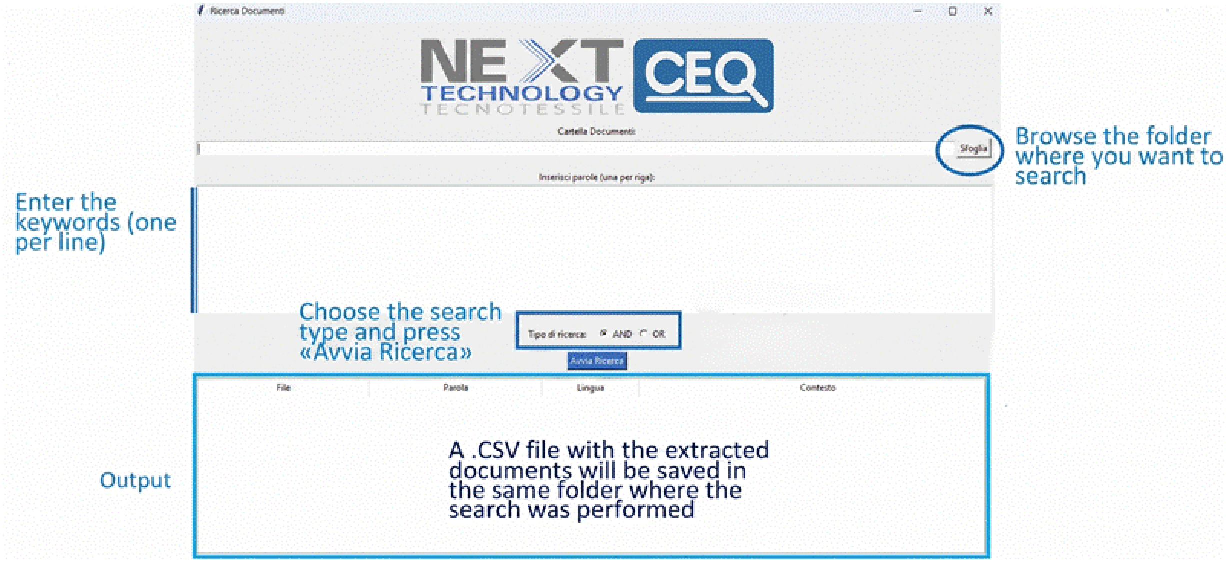



*Figure 10 - Keywords Search Algorithm Interface*

In the initial phase of the task, the organization of preliminary material was entrusted to a specialized custom module, the **AI Document Analyzer & Classifier**. This tool performed two key functions: on the one hand, the synthesis of lengthy scientific papers, industrial specifications, and user manuals; on the other, the automatic classification of documents by assigning tags based on the stages of the value chain (such as Pre-treatment and Treatment) and the categories of the 5R framework adopted in the project.

However, experimental activities demonstrated that the rapid evolution of commercial Large Language Models (LLMs) - equipped with advanced browsing and reasoning capabilities such as Gemini and its *Deep Research* extension - turned this specific tool redundant. The decision to transition from the legacy module to an advanced LLM represents a solid and scientifically justifiable methodological shift, grounded in significant strategic and operational innovation.

The inherent limitation of the AI Document Analyzer & Classifier tool lay in its static nature, as it required the user to manually search for, download, and upload each document into the interface.

Conversely, a next-generation LLM unifies the entire chain into a single operational step: it can actively search for sources across the web or academic databases, filter results in real time, extract technical parameters, and classify them instantly. This transitions the workflow from a fragmented process to a seamless pipeline, where classification occurs directly during the document discovery phase rather than downstream of it.

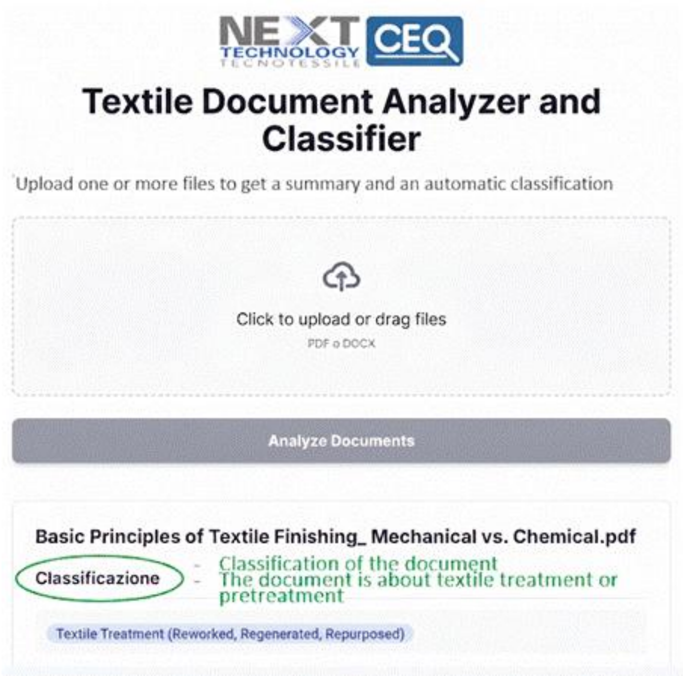



*Figure 11 - AI Document Analyzer & Classifier Interface*

This objective initially prompted the technical staff to engage with the most widespread screening methodologies for peer-reviewed scientific literature, initiating a testing phase based on the use of Google Scholar.

This approach represented a key intermediate step in the multi-source analysis workflow. It involved the manual drafting of advanced search strings based on Boolean logic, which were then used on Google Scholar to identify documents matching these keyword combinations.

Below is an example of a result obtained by combining keywords according to Boolean logic:

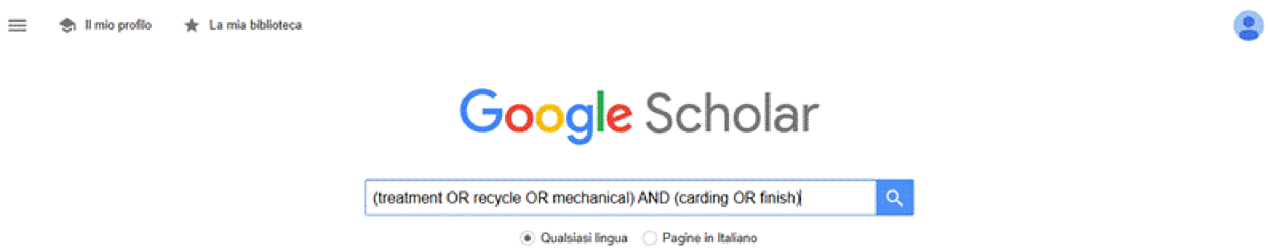



*Figure 12 - Example of Google Scholar*

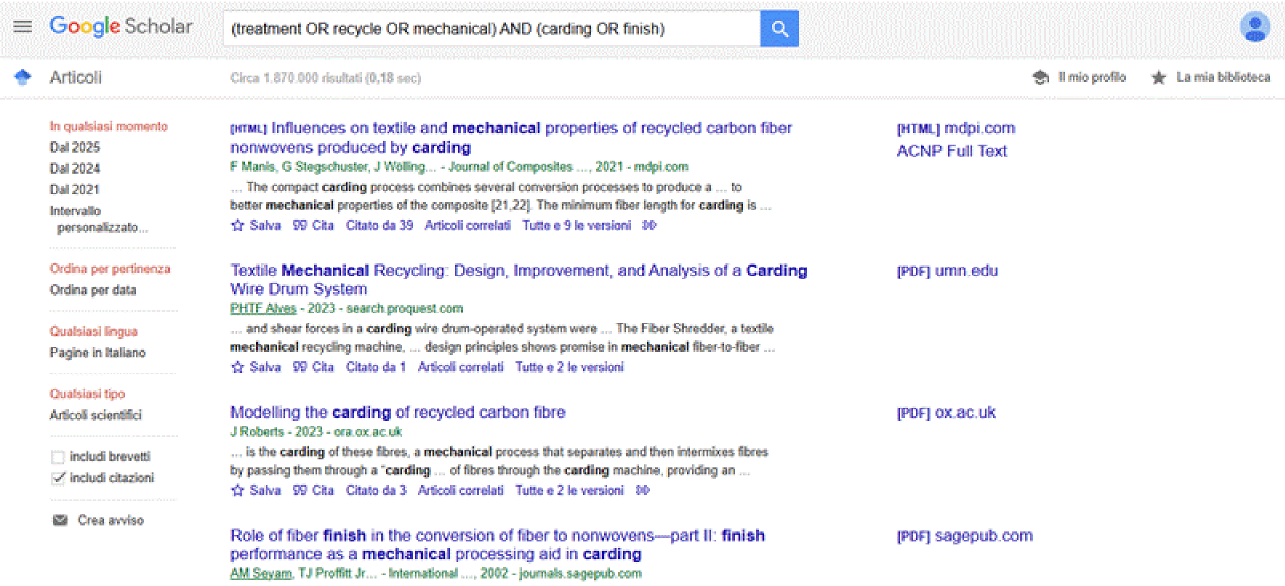


*Figure 13 - Example of a result obtained from a search with Google Scholar*

In line with the shortcomings already identified in the previously analyzed tools, field-testing this approach also revealed severe operational and structural limitations. The comparative analysis conducted throughout the process highlighted how relying on Google Scholar generated a significant bottleneck in terms of man-hours. This internal evaluation process guided the methodological evolution of the Task: here too, the adoption of an LLM - specifically the *Deep Research* feature integrated into the most advanced chatbots - proved to be the ultimate and genuinely effective tool for overcoming the identified limitations.

The first major obstacle emerged regarding syntactic rigidity, where initial experimentation with Google Scholar revealed the inherent limitation of traditional search engines, which are strictly bound to exact keyword matching. In the textile recycling sector, terminology is notoriously fragmented: the same shredding or pulling process is described by authors using highly diverse synonyms. To ensure a comprehensive screening, researchers were forced to construct hyper-extended and complex Boolean strings; nevertheless, if an author used a jargon or unanticipated term, it resulted in the systematic exclusion of fundamental papers. This critical issue was radically resolved by Gemini Deep Research through the use of semantic search: the LLM interprets the underlying physical and engineering principles within the text and is therefore capable of capturing and mapping relevant studies, even if the technology is described using unusual or initially uncataloged terminology.

Furthermore, Google Scholar only returns a static list of titles and abstracts, compelling personnel to perform massive and time-consuming post-processing work. Specifically, to extract the required quantitative and granular data, technicians had to open each individual link, verify access permissions (open-access vs. paywall), download the PDF, and manually scan tables and graphs, resulting in hours of repetitive labor. Conversely, the advanced research agent overcomes this limitation by autonomously browsing the web and permitted academic databases. In doing so, it analyzes the full text of dozens of articles in parallel and performs targeted fact-checking, directly extracting only the technical parameters specified in the search prompt.

Finally, the technological transition enabled the recursive optimization and automation of the snowballing process—the methodological strategy that analyzes the bibliography of an authoritative article to identify additional related sources. When performed manually by a human operator, this search task translates into a continuous and burdensome cycle of copying and pasting bibliographic titles into the search engine. Gemini Deep Research, on the other hand, performs this citation mapping natively, recursively, and automatically: once a pivotal paper is identified, the algorithm immediately explores its bibliographic references, expanding the knowledge base within seconds and transforming a traditionally fragmented process into a seamless, rapid, and integrated research pipeline.

In conclusion, moving away from Boolean strings on Google Scholar did not represent a sudden shift in direction, but rather the logical outcome of process optimization driven by experimental evidence. Centralizing the workflow within the LLM made it possible to merge the systematic exploration of external sources (including industrial portals and major global databases like Scopus and Web of Science), full-text reading, and subsequent categorization according to the 5Rs into a single process. This transition eliminated manual uploading steps and ensured a natively structured and standardized output, reducing a complex activity to just a few minutes and optimizing the operational efficiency required to populate the Technology Assessment Database.


*Figure 14 - Example of using Gemini Deep Research*

The querying of the LLM was structured by providing the model with the keyword clusters extracted from the value chain analysis (e.g., Shredding, Carding, Carbonization, Spinning). To curb the natural verbosity of commercial language models and focus the output solely on actionable data, a strict constraint of selective conciseness was applied *('in the report, write only: document, link to the document, brief summary, and technology used')*. This instruction forced the model to exclude any conversational introductions, focusing exclusively on mapping the four core attributes required for the database.

A key element of the prompt engineering process was the inclusion of recursive validation questions and coverage checks *('have you investigated the entire scientific literature?')*. This approach made it possible to verify and calibrate the LLM's deep research algorithm, compelling it to look beyond isolated academic theory alone.

To eliminate manual post-processing times and enable the immediate importation of data into the database specifically structured for the technology census, the prompt pipeline integrated precise formatting and export instructions.

First, a native tabular structuring of the results was enforced, instructing the model to immediately generate summary tables to facilitate visual screening and critical validation by human experts (Human-in-the-Loop). To ensure seamless compatibility with spreadsheets and a smooth export process, a strict taxonomic constraint was applied to the models: the reports had to be delivered by filling out exclusively four predefined data fields *(Document; Link to document; Summary; Technology used)*, with the mandatory instruction to separate the columns using a semicolon (;) character.

Finally, the workflow was completed by including a request within the prompt to generate a pre-configured Python source code snippet. This code-driven automation made it possible to download and save the extracted data directly into a native .csv file, ensuring complete data interoperability and enabling a seamless, fast, and straightforward transfer into the Google Sheets platform (or Excel).

The research clusters and structured keywords included in the AI prompts were categorized as follows:

- ***Mechanical Recycling (Treatment):*** *Investigation focused on industrial shredding and regenerated spinning lines using keywords such as: Shredding (breakdown of textiles), Preparation of fibers (+ blending), Carding, Carbonization, Fiber layering – web formation, Bonding, Thermoforming, Combing, Preparation for spinning, Spinning, Doubling/Twisting, Warping/Weaving/Knitting, Dyeing, Finishing.*
- ***Remanufacturing & Refurbish (Pre-treatment):*** *Mapping of preliminary hygienic-functional restoration technologies using keywords such as: Cleaning, Sanitization, Odor neutralization, Inspection, De-linting.*
- ***Remanufacturing & Refurbish (Treatment):*** *Exploration of advanced, "like-new" quality restoration processes and structural defect management using keywords such as: Disassembly into components, Regeneration / Reconditioning, Re-Assembly, Defect management: Closures (repair / replacement), Fabric damage (patching / reweaving / reinforcement), Lining & padding replacement, Elastic parts replacement, Stains / color fading (treatment / re-dyeing), Stain removal, Pressing / Ironing, Labelling.*
- ***Repurpose (Pre-treatment):*** *Research focused on preliminary functional disassembly using keywords such as: Disassembly into components, Cleaning, Sanitization, Regeneration/Reconditioning.*

- ***Repurpose (Treatment):*** *Tailoring transformation technologies and equipment, upcycling, and circular design using keywords such as: cutting, sewing, Finishing, Transformation, Pressing / Ironing, Odor neutralization.*

The quantitative results of the scouting faithfully reflect the scientific rigor expressed by this workflow and sequential logical framework. The process kicked off with the aggregation of Multi-source Literature and the scanning of Partner Documentation through the search algorithm, which together enabled the mapping of an initial potential pool of over 300 resources. Subjected to a stringent Filtering & Selection phase supported by AI and subsequent expert validation, this source archive underwent a drastic screening aimed at eliminating generic or irrelevant contributions. However, the application of Deep Research during the Technology Identification and Technology Description phases made it possible to expand and bolster this knowledge base, leading the final database to integrate over 100 highly relevant technical-scientific documents (divided into peer-reviewed academic literature, verified patents, and industrial market reports). The parametric information and structured data obtained in this manner flow directly into populating the WP3 Technology Database, ensuring the availability of robust inputs for the subsequent life cycle assessments LCA/LCC (Task 3.2) and for the definition of Eco-design requirements and EPR policies (Task 3.4) within the Circula-TEX project.

### 2.3.5. KEY CHALLENGES AND COMMON ISSUES

Although the multi-source analysis proved fundamental to bridging the operational and industrial intelligence gaps that patents alone could not cover, implementing this AI-integrated approach raised a series of specific methodological challenges. During the execution of Task 3.1 activities, the consortium had to address and mitigate several structural criticalities, starting with the paradox of information abundance. Indeed, the simultaneous exploration of scientific databases, market reports and industrial portals generated massive volumes of data, demonstrating that an abundance of material does not necessarily equate to clarity or utility. On the contrary, one of the primary challenges was precisely filtering vast amounts of fragmented, inconsistent, or redundant information to identify technologies that were genuinely significant for textile circular systems, overcoming the limitations of corporate brochures or articles that often feature an excessively commercial slant and lack the engineering parameters necessary for Technology Assessment.

This issue is compounded by the terminological fragmentation of the sector, as terminology within the textile circularity ecosystem is not yet fully harmonized. The exact same technology or process, such as shredding or depolymerization, is described using markedly different vocabularies depending on whether the source is an academic paper, a machinery manufacturer's report, or a European directive. This creates significant heterogeneity that complicated the definition of initial search strings and made the transition to a semantic decoding approach via Prompt Engineering indispensable.

Furthermore, there is a major difficulty in evaluating the real industrial scalability of the analyzed solutions. Analyzing scientific or patent literature alone often tends to overestimate a technology's maturity level, as many solutions that appear revolutionary or high-performing in peer-reviewed papers turn out, in practice, to be theoretical concepts limited to laboratory environments or simple proofs of concept. Consequently, the critical challenge for the consortium was to determine whether a technology represented a concretely scalable solution at an industrial level, taking into account that even the most academically sophisticated technologies can prove economically unrealistic or difficult to adapt to the actual heterogeneity of real-world textile waste streams.

To be added to this the inherent limitations of Artificial Intelligence, linked in particular to the risk of computational hallucinations. Although the integration of tools based on language models has significantly accelerated large-scale screening phases, document synthesis, and information classification, entirely delegating data extraction to an algorithm carries the latent risk of generating plausible but completely inaccurate technical data, given that AI lacks the industrial experience necessary to independently judge the soundness of a technical parameter.

Precisely to mitigate the risks related to hallucinations and information overload, the compelling need for a Human-in-the-Loop approach ensured that human expertise remained absolutely indispensable throughout the entire workflow.

The role of the partners' technical teams was crucial in verifying whether the identified technology was truly innovative, effectively applicable to textile circular systems, and whether the automatically extracted technical information was entirely coherent and reliable. This human cross-checking made it possible to prevent computational model errors, ensuring the actual industrial applicability of the mapped solutions to establish a solid foundation for subsequent technology transfer. In conclusion, AI-supported multi-source analysis has proven to be a powerful methodological pillar for WP3, but it requires a continuous and careful balance between the efficiency of algorithmic automation and the indispensable critical interpretation by domain experts.

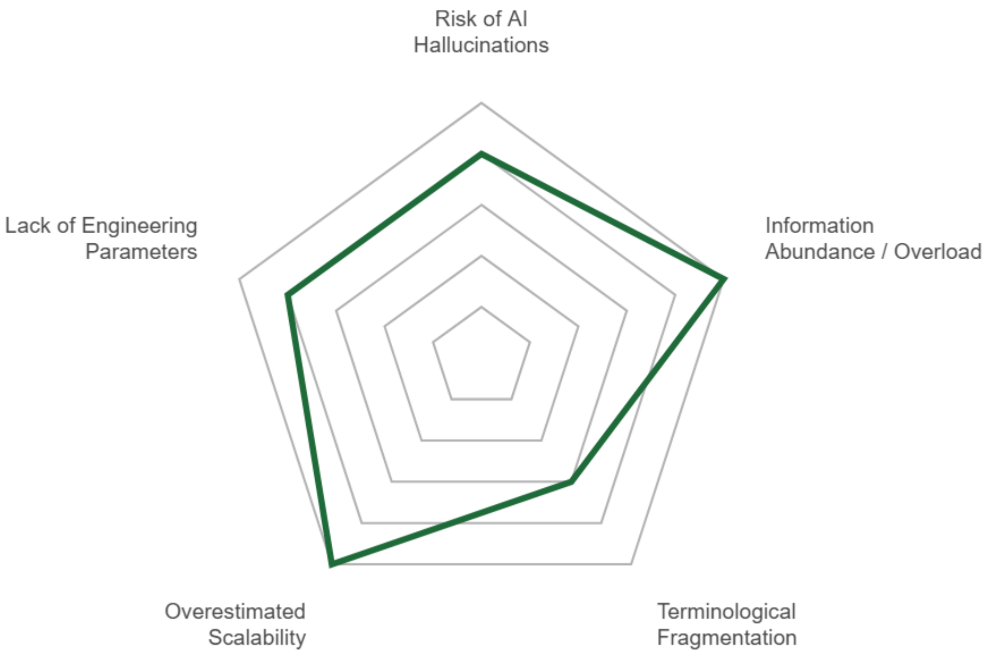



*Figure 15 - Dimensions of Weaknesses of multi-source analysis*

# 3. MAPPING OF TEXTILE END-OF-LIFE VALUE CHAINS

## 3.1. METHOD USED FOR VALUE CHAIN MAPPING

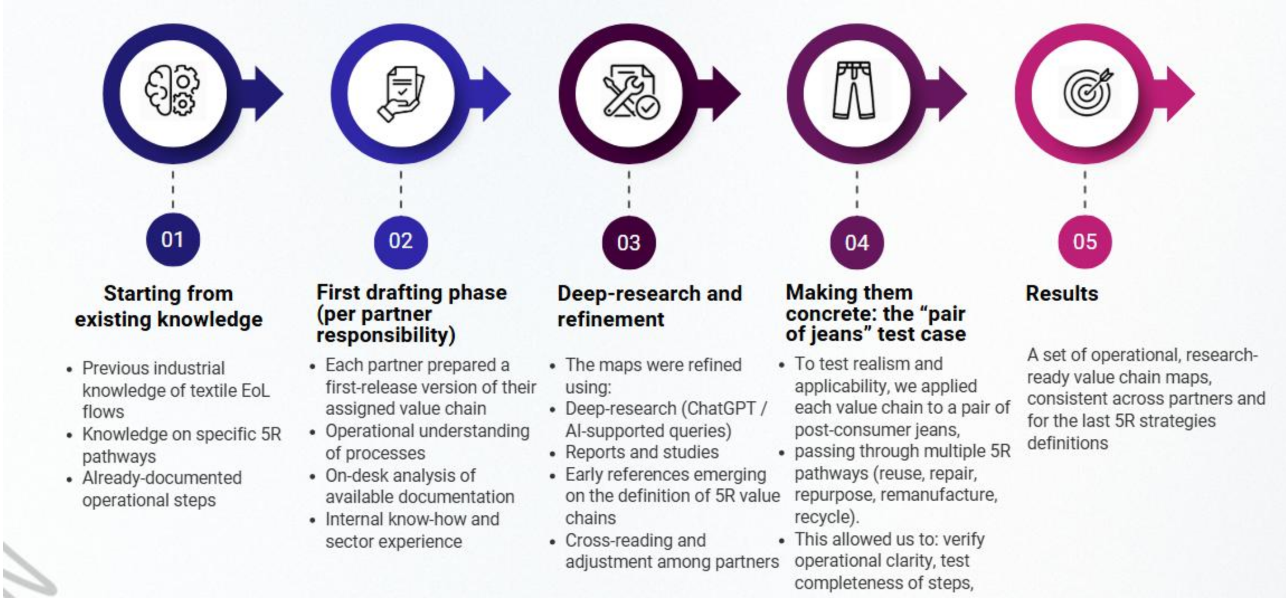



*Figure 16 - Schematic overview of the methodology adopted for the Textile value chain mapping activities*

The value chain mapping activities developed within Task 3.1 aimed to create a structured operational representation of textile EoL circular systems capable of supporting the technology scouting and assessment activities carried out within the project. The mappings were not conceived exclusively as descriptive representations of circular pathways, but mainly as operational tools enabling the identification, organization, and interpretation of technologies, processes, and operational functions associated with textile circularity systems.

As described in Section 2, during the first phases of the task activities, it progressively emerged that existing generic representations of textile circular systems were insufficient for the objectives of the technology assessment process. For this reason, the partners agreed to progressively develop a process-oriented mapping methodology based on the operational decomposition of textile circular systems into interconnected process stages and operational functions.

The resulting approach followed a function-oriented logic conceptually aligned with process modelling methodologies such as IDEF0, enabling the structured representation of operational stages, process relationships, inputs and outputs, and technology domains across the different circular pathways. Although the mappings were not developed as formal IDEF0 diagrams, the adopted logic allowed the progressive decomposition of complex textile circular systems into operationally identifiable activities and process functions.

This methodological approach originated from an initial operational mapping exercise developed by NTT on the mechanical recycling pathway, which served as a first reference model for structuring process phases, operational steps, and technology positioning across the subsequent value chain mappings.

The mapping activities were mainly developed by the three partners directly involved in the technology scouting activities - NTT, COT, and CTB - with each partner contributing to specific circular pathways and operational domains according to their technical expertise and responsibilities within the task (referring to the Table 1 - Allocation of Textile value chain responsibilities among partners involved in the task 3.1).

The methodology adopted for the value chain mapping activities combined multiple complementary approaches, including:

- previous technical and industrial knowledge of textile circular systems;
- desk research and technical literature analysis;
- analysis of industrial case studies;
- AI-supported deep research activities;
- iterative partner review and validation processes.

Within each pathway, the operational flows were progressively decomposed into more detailed operational stages in order to identify the specific activities where technologies are applied. Particular attention was dedicated to distinguishing:

- collection activities;
- sorting activities;
- pretreatment stages;
- treatment stages;
- output generation and reintegration phases.

As the activities progressed, **the operational mappings progressively became one of the enabling elements of the overall technology assessment methodology**. In particular, the value chain structures became essential to:

- define the system boundaries of the assessment activities (as described in Section 2.2);
- identify operational interconnections between process stages;
- structure the classification of technologies;
- support the identification of targeted keywords for patent searches and improve the selection of IPC classes (as described in Section 2.3);
- connect patents and technical documents to specific operational functions;
- harmonize the scouting activities performed by the different partners.

In order to ensure methodological consistency and visual homogeneity among the different value chain mappings, a common free-access process mapping tool (**Draw.io)** was selected and shared among partners for the development of the graphical representations.

To facilitate interpretation and validation of the mappings, representative product-based logic and industrial case studies were progressively integrated into the methodology at the end of the year 2025. Several mappings were therefore associated with practical examples and real industrial applications in order to improve the interpretation of the operational differences among the various circular pathways and technological stages.

The methodology also included iterative validation activities involving cross-review sessions among project partners and discussions with external stakeholders during consortium meetings. These activities aimed to improve the operational consistency of the mappings and verify the representativeness of the identified stages with respect to real industrial practices and textile circularity systems.

Within the recycling pathways, the operational structures were further differentiated according to the specific technological and process characteristics associated with:

- **Collection and sorting**
- **mechanical recycling;**
- **chemical recycling;**
- **thermochemical recycling;**
- **thermomechanical recycling.**

Similarly, dedicated operational mappings were developed for **reuse**-oriented pathways, including **repair**, **refurbishing**, **remanufacturing**, and **repurposing** systems, considering the different operational logics and process requirements associated with each circular strategy.

## 3.2. DESCRIPTION OF TEXTILE EOL VALUE CHAINS

The following sections present the results of the value chain mapping methodology described above, developed through a progressive and collaborative process involving operational analysis, literature review, and cross-partner validation activities.

For each EoL value chain analysed within Task 3.1, the objective is both to represent process flows and to provide a structured and operational interpretation of the different circular pathways relevant for textile waste management and valorisation. The value chains were therefore defined through the integration of multiple information sources, including scientific literature, industrial reports, technical documentation, existing sector frameworks, and project-internal activities. Particular attention was given to ensuring alignment with the activities developed within WP1, especially Task 1.4, in order to maintain methodological consistency with the broader project framework and with the circular strategies previously identified by the consortium.

Each subsection includes:

- a structured definition of the analysed value chain;
- a graphical representation of the operational flow;
- a description of the main pretreatment and treatment stages;
- representative examples supporting the interpretation of the pathway (for selected value chains).

The proposed definitions were developed by combining authoritative and recent sources currently available in the textile circularity domain with the operational perspective emerging from the project activities. The main reports selected for creating the "definition" sections of each value chain are listed in the "references and Bibliography" section.

For each value chain, the deliverable includes a simplified visual representation specifically designed to facilitate readability and understanding of the operational logic and material flows. In parallel, the complete technical mapping developed through Draw.io is provided in the Annex 2 as supporting material for detailed operational analysis and methodological traceability.

In order to improve the interpretability of the mappings, several value chains are also accompanied by practical examples illustrating the evolution of a representative textile product through the operational flow. For example, within the repurpose value chain, the transformation of a pair of jeans into a different textile product is used to concretely illustrate all the operational steps, inputs and outputs of the value chain, i.e. component selection, disassembly, reconstruction and reintegration activities to produce the final item across the mapped operational stages.

### 3.2.1. COLLECTION AND SORTING

#### 3.2.1.1. DEFINITION

Collection and sorting is the first value recovery stage of the circular textile value chain through which post-use, post-consumer, unsold, or discarded textile products are separately collected, protected, screened, identified, classified, and directed into the most appropriate circular pathway according to their condition, composition, quality, functionality and reuse-potential.

It represents the common upstream segment of the EoL textile management system shared across all the circular value chains analysed in this study. It functions as the entry point of Textile waste and it directs toward the most appropriate pathway. For the purpose of this document, the collection and sorting value chain is considered to end at the stage where textile products and materials are directed toward their most appropriate subsequent circular pathway. Any specific pre-treatment, preparation, or transformation processes required for reuse, repair, refurbishment, remanufacturing, repurposing, or recycling are considered part of the respective downstream value chains and are therefore outside the scope of this definition.

#### 3.2.1.2. MAP OF COLLECTION AND SORTING VALUE CHAIN. DESCRIPTION OF OPERATIONAL STEPS AND FLOWS

**Collection activities** include the organized gathering, handling, storage, transport, and protection of textiles through systems such as take-back schemes, collection bins, retail return systems, kerbside collection, charities, municipal collection systems, and commercial operators. Collection systems should minimize contamination, moisture exposure, physical damage, and material loss in order to maintain the quality and usability of the collected textiles and maximize their circular value potential.

**Sorting activities** include the inspection, assessment, separation, grading, and preparation of textiles into defined streams for subsequent circular operations.

To perform this role effectively, sorting systems should activize a robust "Hierarchical decision-making process" for the classification and allocation of textile products and materials according to their most appropriate subsequent use pathway. This includes assessing characteristics such as **product condition, durability, level of contamination, material composition, fibre blends, colour, functionality, presence of non-textile elements, and recyclability potential**.

Sorting may be performed manually, automatically or through hybrid systems and typically involves identifying the condition, material composition, product type, colour, functionality, contamination level, and recyclability of each item.

Collection and sorting function as a critical enabling interface between product end-of-use and circular value retention. Their effectiveness directly influences the quality, scalability, economic viability, and environmental performance of circular textile systems, particularly reuse and fibre-to-fibre recycling. High-quality collection and sorting systems are essential to creating reliable secondary material streams, supporting reverse logistics, increasing resource efficiency, reducing waste generation, and enabling circular business models across the textile value network.

Within the scope of Task 3.1, the mapping activities focused specifically on the collection and sorting value chain for post-consumer textiles (see Figure 17. The original map, illustrated by Draw.io in Annex 2). However, it should be acknowledged that other textile flows also exist, including post-industrial textile flows, unsold textiles, retail returns, and brand take-back programmes. These flows can involve different stakeholders, ownership conditions, quality levels, traceability requirements, collection channels, and operational steps, and may therefore follow partially different collection, handling, sorting, and routing processes compared to post-consumer textile flows.

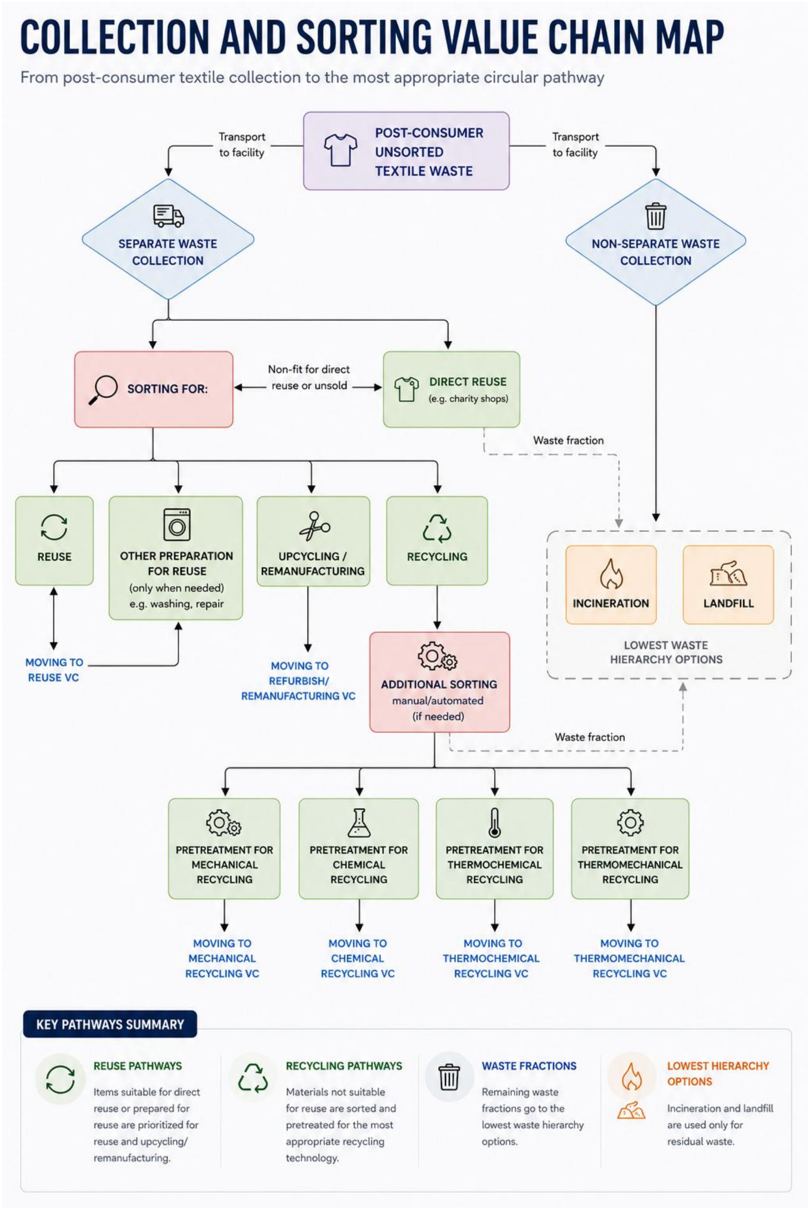



*Figure 17 - Collection and Sorting value chain. Visual representation derived from the operational mapping activities*

## 3.2.2. RECYCLING PATHWAYS

### 3.2.2.1. MECHANICAL RECYCLING

#### 3.2.2.1.1. DEFINITION

The mechanical recycling value chain is a material recovery pathway within the circular textile economy in which textile waste is physically reprocessed to recover fibrous materials and generate secondary raw materials for new textile or industrial applications, without fundamentally modifying the chemical structure of the constituent fibres or polymers.

The value chain primarily addresses post-consumer, post-industrial and pre-consumer textile waste streams that are no longer suitable for reuse but still retain recoverable material value. Its objective is to extend the useful life of textile materials **by reintegrating recovered fibres into manufacturing systems** while reducing dependence on virgin raw materials and limiting textile waste disposal. A defining characteristic of mechanical recycling is the **preservation of the fibrous nature of textile materials** throughout the recovery process.

Within the circular textile ecosystem, mechanical recycling represents a cascading recovery system in which textile waste streams are allocated toward different value-retention pathways according to material composition, fibre characteristics, contamination levels, and application requirements. **Depending on the recovered fibre quality, outputs may support textile-to-textile applications, nonwoven systems, or alternative industrial uses**.

The effectiveness of mechanical recycling systems relies on coordinated upstream collection, sorting, dismantling, and material identification systems capable of generating sufficiently suitable feedstock streams for fibre recovery operations.

*activities*

### 3.2.2.1.2. MAP OF THE MECHANICAL RECYCLING VALUE CHAIN: DESCRIPTION OF OPERATIONAL STEPS AND FLOWS

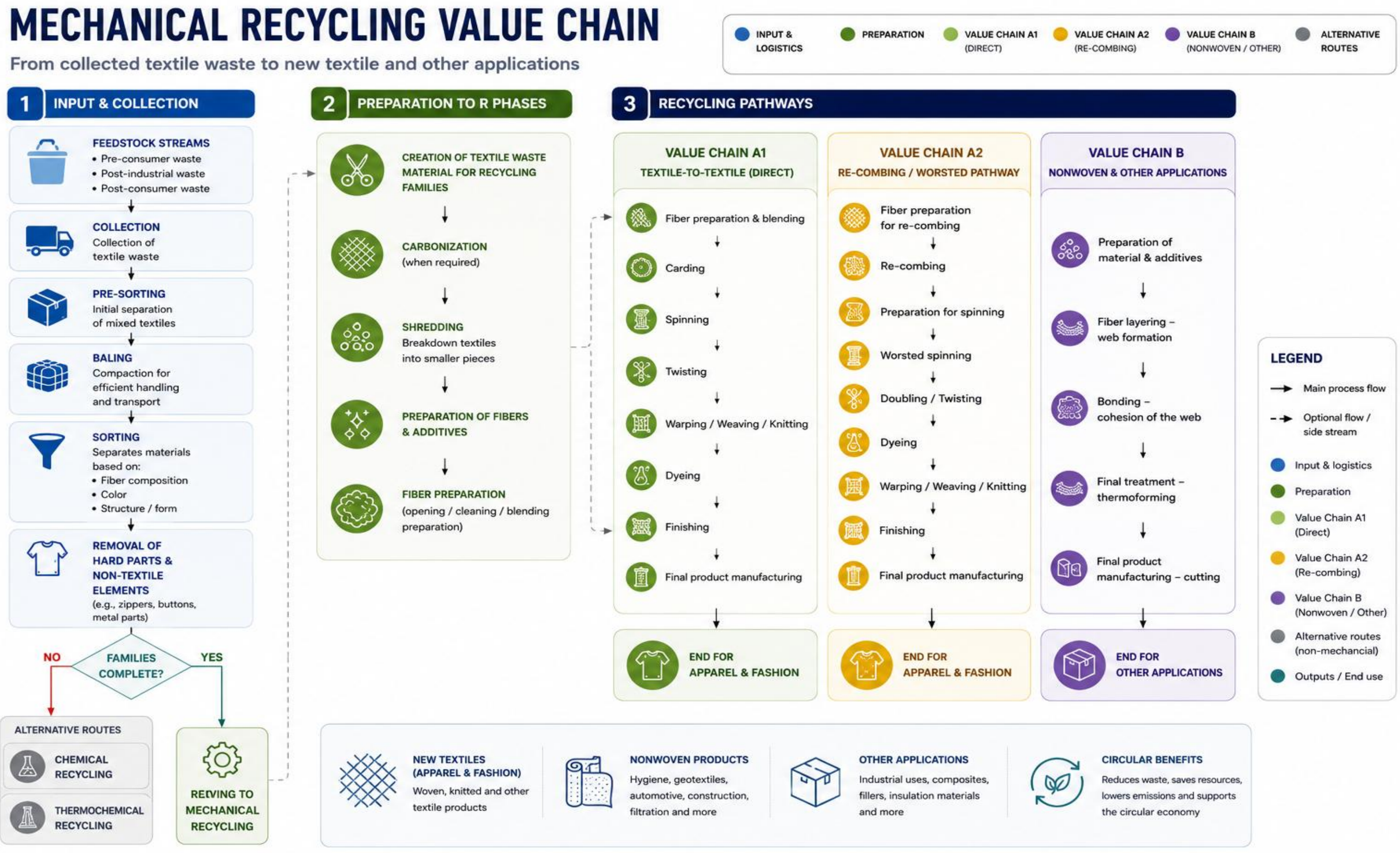



*Figure 18 - Mechanical Recycling value chain. Visual representation derived from the operational mapping activities*

The value chain starts with the input and collection phase, where textile waste originating from pre-consumer, post-industrial, and post-consumer streams is aggregated through dedicated collection systems. Pre-consumer streams generally include unused, defective, or unsold textile products, while post-industrial streams originate from manufacturing activities and post-consumer streams consist of used textiles discarded by consumers. Following collection, textile materials undergo pre-sorting operations aimed at separating mixed textile flows and removing unsuitable fractions before entering the recycling process.

After initial separation, textiles are compacted through baling operations to facilitate transportation, storage, and logistics efficiency. Materials subsequently undergo detailed sorting activities based on criteria such as fibre composition, colour, textile structure, and product form. **Since mechanical recycling performance and the final application of recycled material, strongly depends on feedstock consistency and fibre quality, sorting represents one of the most critical enabling stages of the value chain**.

Following sorting, non-textile elements and rigid components are removed from garments. At this stage, textile materials are assessed to determine whether the identified recycling "families" are sufficiently homogeneous and complete for mechanical recycling pathways. Textile fractions that cannot meet the technical requirements for mechanical recycling may instead be redirected toward alternative pathways such as chemical recycling, thermochemical recycling, non-recycling applications, or landfill disposal.

Once suitable textile fractions have been identified, materials enter the preparation stage for recycling operations. Depending on the fibre type and target application, textiles may undergo shredding, opening, blending, cleaning, and fibre preparation operations aimed at generating reusable fibrous feedstock. In specific cases, carbonization processes may also be applied to remove unwanted cellulose components from blended materials, particularly within wool-based recycling systems.

The map highlights that the mechanical recycling value chain does not follow a single linear pathway but **can diverge into multiple recycling routes depending on fibre quality, material composition and intended end use (application)**.

The first pathway, identified as *Value Chain A1 (textile-to-textile direct pathway)*, represents the highest-value mechanical recycling route. In this pathway, recovered fibres undergo preparation and blending operations followed by carding, spinning, twisting (when needed), weaving or knitting, dyeing, finishing, and final product manufacturing. The process ultimately generates new textile products intended for apparel and fashion applications. This pathway represents the closest approach to fibre-to-fibre circularity within mechanical recycling systems.

The second pathway, identified as *Value Chain A2 (re-combing pathway)*, involves additional fibre preparation and re-combing operations before spinning and textile manufacturing. This route is generally intended for fibre streams requiring more intensive fibre alignment, cleaning, or homogenization in order to achieve suitable quality for yarn production. Similar to the direct pathway, the process ultimately generates textile products for apparel and fashion applications, although often with different fibre qualities and technical characteristics.

The third pathway, identified as *Value Chain B (nonwoven and other applications)*, redirects recovered fibres toward nonwoven manufacturing systems and alternative industrial uses. In this pathway, fibres are combined with additives when necessary and transformed through web formation, bonding, thermobonding, or thermoforming operations before final cutting and product manufacturing stages. Outputs may include hygiene products, insulation materials, automotive applications, filtration systems, composites, geotextiles, construction materials, fillers, and other industrial products.

The mechanical recycling value chain map highlights several operational and systemic criticalities directly linked to the structure of the process itself. The most relevant are:

- the strong dependency on sorting and material classification. The map shows that the feasibility of the different recycling pathways depends on the ability to separate textile waste according to fibre composition, colour, structure, and product type. Multiple decision points are required before materials can enter suitable recycling routes, demonstrating the high complexity of feedstock management within mechanical recycling systems.
- The progressive fragmentation of recycling pathways. Textile waste does not follow a single linear route but is distributed across different value chains depending on fibre quality and technical suitability. Only a share of the material can remain within textile-to-textile applications, while other fractions are redirected toward nonwoven or lower-value industrial applications. This illustrates the **difficulty of maintaining closed-loop textile recycling through purely mechanical processes**.
- the dependency of mechanical recycling on fibre quality preservation. Since fibres remain the main recovered material, repeated mechanical processing operations can progressively reduce fibre length and performance, limiting the range of possible downstream applications and increasing the risk of downcycling into lower-value uses.
- Finally, the presence of alternative routes toward chemical recycling, thermochemical recycling, or landfill disposal illustrates that mechanical recycling alone cannot manage all textile waste streams.

#### 3.2.2.2. CHEMICAL RECYCLING

##### 3.2.2.3. DEFINITION

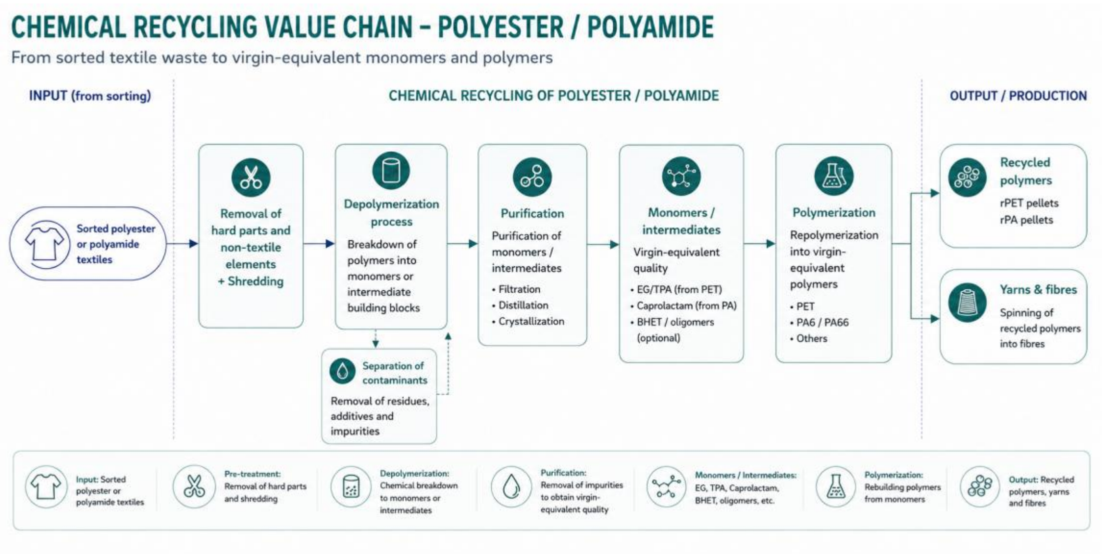
The chemical recycling value chain chemically transforms textile waste into regenerated substances, purified intermediates, monomers or rebuilt polymers that can re-enter manufacturing systems as secondary raw materials. The value chain is primarily intended for textile fractions that cannot be effectively recycled through fibre-preserving mechanical processes due to material complexity, fibre blends, additives, coatings, contamination, or degradation of fibre quality. Unlike mechanical recycling pathways, chemical recycling focuses on recovering chemical constituents of textile material through selective transformation and regeneration processes. A defining characteristic of chemical recycling is its capacity to recover material value at a level closer to the original polymer or cellulose chemistry. Depending on the feedstock composition and selected technology, **recovered outputs may approach virgin-equivalent material quality** and can potentially be reintegrated into high-performance textile or industrial applications.

The value chain is highly dependent on the compatibility between textile feedstock composition and process-specific chemical technologies. Different material families require dedicated transformation routes, purification systems, and regeneration processes, making chemical recycling strongly reliant on upstream material identification, sorting quality, and feedstock consistency.

Chemical recycling involves a **high degree of technological complexity and industrial processing intensity**.

#### 3.2.2.3.1. MAP OF THE CHEMICAL RECYCLING VALUE CHAIN: DESCRIPTION OF OPERATIONAL STEPS AND FLOWS

The maps presented in this document for the Chemical recycling value chain represent selected chemical recycling pathways. In practice, **chemical recycling systems/pathways can differ significantly depending on feedstock composition**, target outputs, process chemistry, solvent systems, polymer family, contaminant management requirements, and intended end-use applications.



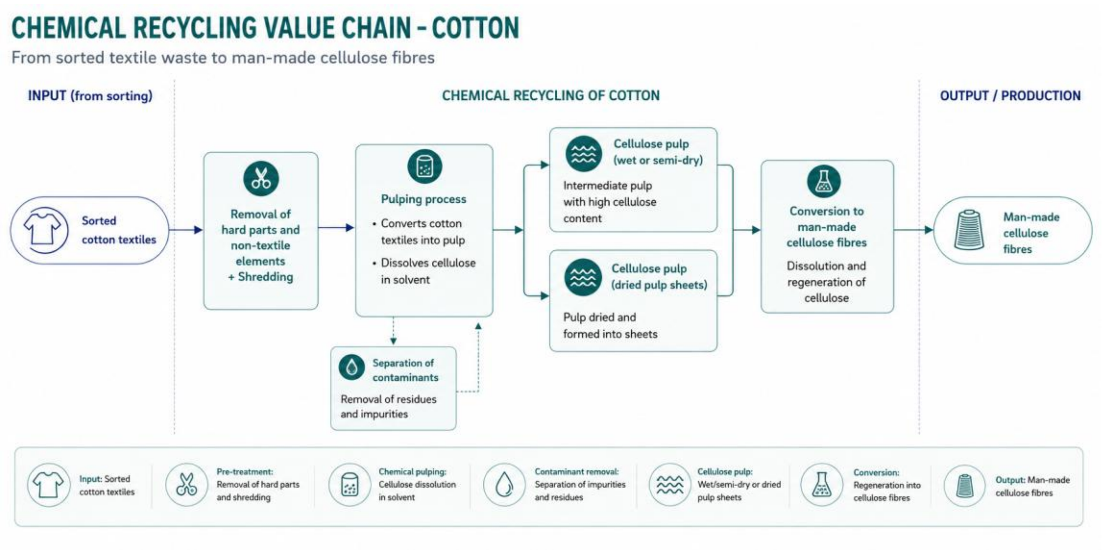




*Figure 19 - Chemical Recycling value chain. Visual representation derived from the operational mapping activities (Case studies Polyester/Polyamide - Cotton)*

The analysed maps illustrate two main chemical recycling pathways depending on the type of textile feedstock: one pathway dedicated to synthetic polymers such as polyester (PET) and polyamide (PA) and another pathway focused on cellulose-based textiles such as cotton.

The value chain starts with sorted textile input streams originating from upstream collection and sorting systems. Textile waste entering chemical recycling pathways is generally pre-classified according to material composition and polymer family in order to ensure compatibility with the selected chemical process. In both pathways, the first operational stage involves **pre-treatment and preparation activities**: textile products undergo removal of hard parts and non-textile elements. For PET and PA textile streams, the maps illustrate a depolymerization-based recycling pathway. During the **depolymerization stage**, polymers are chemically broken down into monomers or intermediate molecular building blocks. The process aims to reverse the original polymerization reaction in order to recover purified chemical constituents such as ethylene glycol (EG), terephthalic acid (TPA), caprolactam, bis(2-hydroxyethyl) terephthalate (BHET), oligomers or other intermediate substances depending on the polymer type and selected process configuration.

Following depolymerization, **purification operations** are performed to remove contaminants, additives, dyes, residues and impurities from the recovered intermediates. The maps highlight purification technologies such as filtration, distillation, crystallization, and contaminant separation systems aimed at obtaining virgin-equivalent monomer quality suitable for downstream industrial reuse.

Once purified, recovered monomers and intermediates undergo **polymerization or repolymerization processes** in which new polymers are chemically rebuilt from the recovered molecular constituents. This stage enables the production of recycled polymers such as **recycled PET (rPET)** or **recycled polyamide (rPA)** with properties approaching virgin-material performance. The resulting recycled polymers can subsequently be transformed into pellets, yarns, fibres, or other manufacturing feedstocks for textile and non-textile applications. For cotton-based textile streams, the maps illustrate a cellulose-regeneration pathway based on pulping and dissolution technologies. After pre-treatment and shredding operations, cotton textiles undergo pulping processes in which cellulose is dissolved into chemical solvents and transformed into intermediate cellulose pulp. During this stage, contaminant separation operations remove residues and impurities that could interfere with fibre regeneration quality.

The chemical recycling value chain maps highlight several criticalities directly linked to the technological structure and operational requirements of the recycling process:

- one of the most evident is the strong dependency on feedstock purity and material identification. The maps show that textile streams must already be separated according to polymer family and material type before entering the recycling process.
- High technological and infrastructural complexity of chemical recycling systems
- High number of purification and contaminant-removal stages required throughout the process. This highlights how textile products currently contain numerous substances that complicate chemical recovery processes and require extensive purification infrastructure in order to obtain virgin-equivalent outputs.
- the maps make visible the strong resource and process intensity of chemical recycling systems. The number of transformation, purification, separation and regeneration stages suggests significant dependencies on chemical inputs, solvent management, energy consumption, and industrial-scale infrastructure.

#### 3.2.2.4. THERMOCHEMICAL RECYCLING

##### 3.2.2.4.1. DEFINITION

The thermochemical recycling value chain is a resource recovery pathway within the circular textile economy in which non-reusable textile waste is converted through **controlled thermal**

**and chemical transformation processes** into **secondary chemical intermediates, syngas, fuels, or industrial feedstocks suitable for further manufacturing applications**. Rather than preserving the original textile structure or fibre integrity, thermochemical recycling recovers molecular and energetic value from textile materials that are technically difficult to reuse or recycle through fibre-preserving systems.

The value chain is primarily intended **for complex textile fractions** such as contaminated textiles, mixed-fibre materials, multi-layer products, coated fabrics, heavily degraded garments, and residual fractions generated after reuse and sorting activities. In this context, thermochemical recycling acts as a complementary circular pathway capable of processing textile streams that are often incompatible with conventional mechanical or textile-to-textile recycling technologies.

A defining characteristic of thermochemical recycling is its ability to **transform heterogeneous textile waste into standardized intermediate outputs that can re-enter industrial production systems outside their original textile application**. Depending on the selected technology and process configuration, outputs may include synthesis gas, platform chemicals, hydrocarbons, oils, or energy carriers that can subsequently support chemical manufacturing, fuel production, or industrial energy systems. The value chain therefore **contributes not only to waste reduction** but also to broader resource substitution objectives by **partially replacing virgin fossil-based feedstocks**.

The value chain is characterized by high technological complexity, strong infrastructure dependency, and significant process-control requirements. Feedstock composition, contamination levels, moisture content, additives, coatings, dyes, and non-textile components can significantly influence conversion efficiency, emissions, operational stability, and output quality. Consequently, thermochemical recycling systems require advanced pre-treatment operations, robust quality management, and stable industrial-scale feedstock supply chains.

### 3.2.2.4.2. MAP OF THE THERMOCHEMICAL RECYCLING VALUE CHAIN: DESCRIPTION OF OPERATIONAL STEPS AND FLOWS

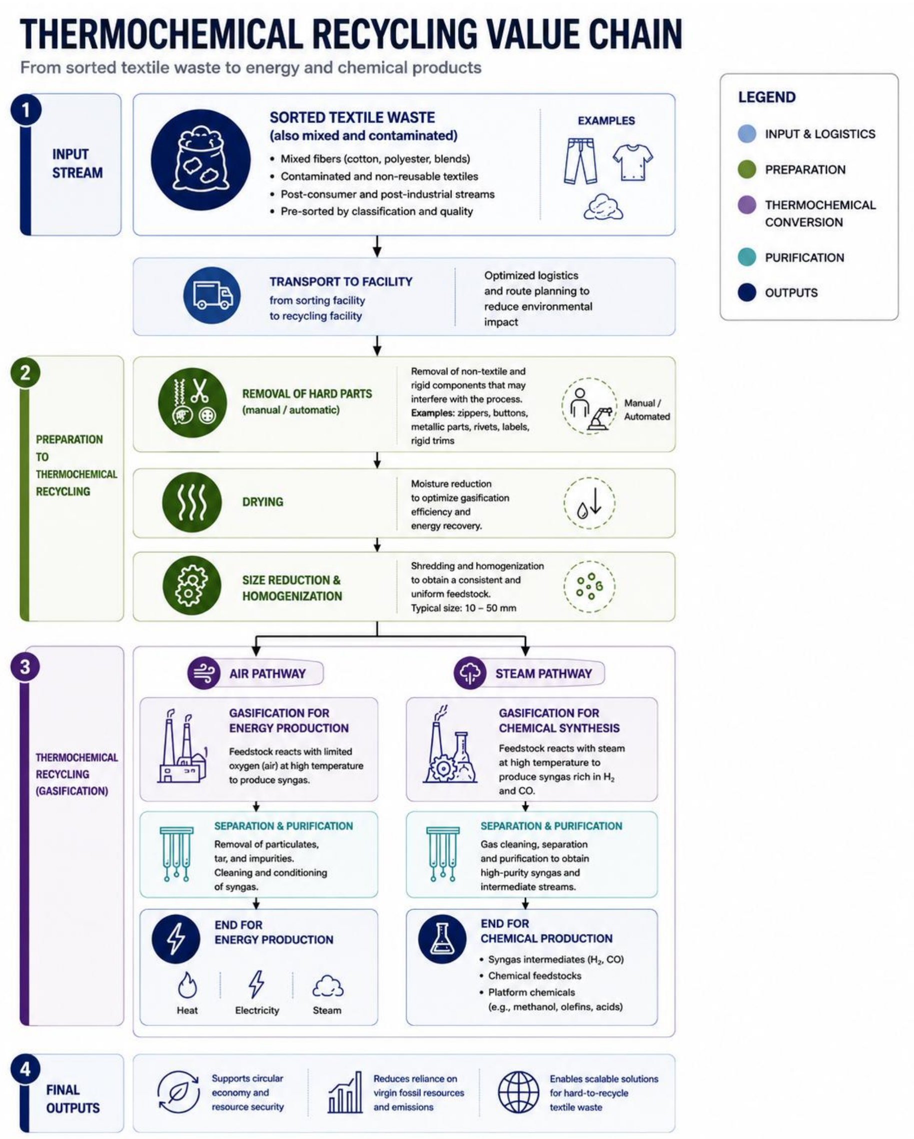



*Figure 20 - Thermochemical Recycling value chain. Visual representation derived from the operational mapping activities*

The value chain starts with the input stream phase, that includes typically mixed fibres such as cotton-polyester blends, contaminated textiles, non-reusable garments, residual fractions from sorting facilities, and textile waste streams pre-sorted according to quality and material classification. Following sorting and aggregation, textile waste is transported from collection or sorting facilities to dedicated thermochemical recycling plants. Materials undergo preparation operations required to optimize thermochemical conversion efficiency and ensure process stability: a first preparation stage involves the **removal of rigid and non-textile components**; then textile materials generally undergo **drying operations** aimed at reducing moisture content and improving thermal process efficiency, energy balance and gasification performance. Moisture reduction is particularly important because excessive water content may negatively affect thermal conversion efficiency and syngas quality. Prepared textiles subsequently undergo size reduction and homogenization processes: textile materials are shredded and transformed into smaller and more uniform particles in order to create a consistent feedstock suitable for stable thermochemical processing.

The prepared feedstock then enters the thermochemical conversion stage. In the illustrated value chain, gasification represents the selected thermochemical technology. Depending on the process objective, different gasification pathways may be implemented.

a) in ***air gasification systems***, textile feedstock reacts with limited oxygen at high temperatures **to produce syngas primarily intended for energy recovery applications**. Following gasification, separation and purification systems remove particulates, tar, and impurities from the generated gas streams. The cleaned outputs may subsequently be used for the production of heat, electricity or steam.

b) In ***steam gasification systems***, textile feedstock reacts with steam at high temperature **to generate syngas with higher hydrogen and carbon monoxide content suitable for chemical synthesis applications**. Following gasification, advanced gas cleaning, separation, and purification operations are performed in order to obtain high-purity syngas and intermediate chemical streams suitable for downstream industrial processing.

The final outputs of the thermochemical recycling value chain therefore depend on the selected process configuration. Energy-oriented pathways generate heat, electricity, and steam, while chemical-oriented pathways generate syngas-derived intermediates and chemical feedstocks that can be used for the production of platform chemicals, fuels, methanol, olefins, acids, or other industrial chemicals. In this way, thermochemical recycling contributes to reducing reliance on virgin fossil resources while supporting circular resource recovery for hard-to-recycle textile fractions.

The case study illustrates how one pair of non-reusable jeans composed of 50% (PET) and 50% cotton (COT) can move through the thermochemical recycling value chain and be transformed into chemical feedstocks through a steam gasification pathway. The jeans originate from post-consumer textile flows and are classified as suitable for thermochemical recycling due to their mixed fibre composition and limited reuse potential. Upon arrival at the facility, the jeans undergo preparation operations required for efficient thermochemical processing. A first preparation stage involves the removal of hard and non-textile components such as buttons, rivets, zippers, metallic trims, and rigid accessories that could interfere with reactor operations or contaminate downstream outputs. Following dismantling operations, the jeans undergo drying in order to reduce moisture content. The prepared garment is then shredded and uniform particles suitable for stable gasification conditions.

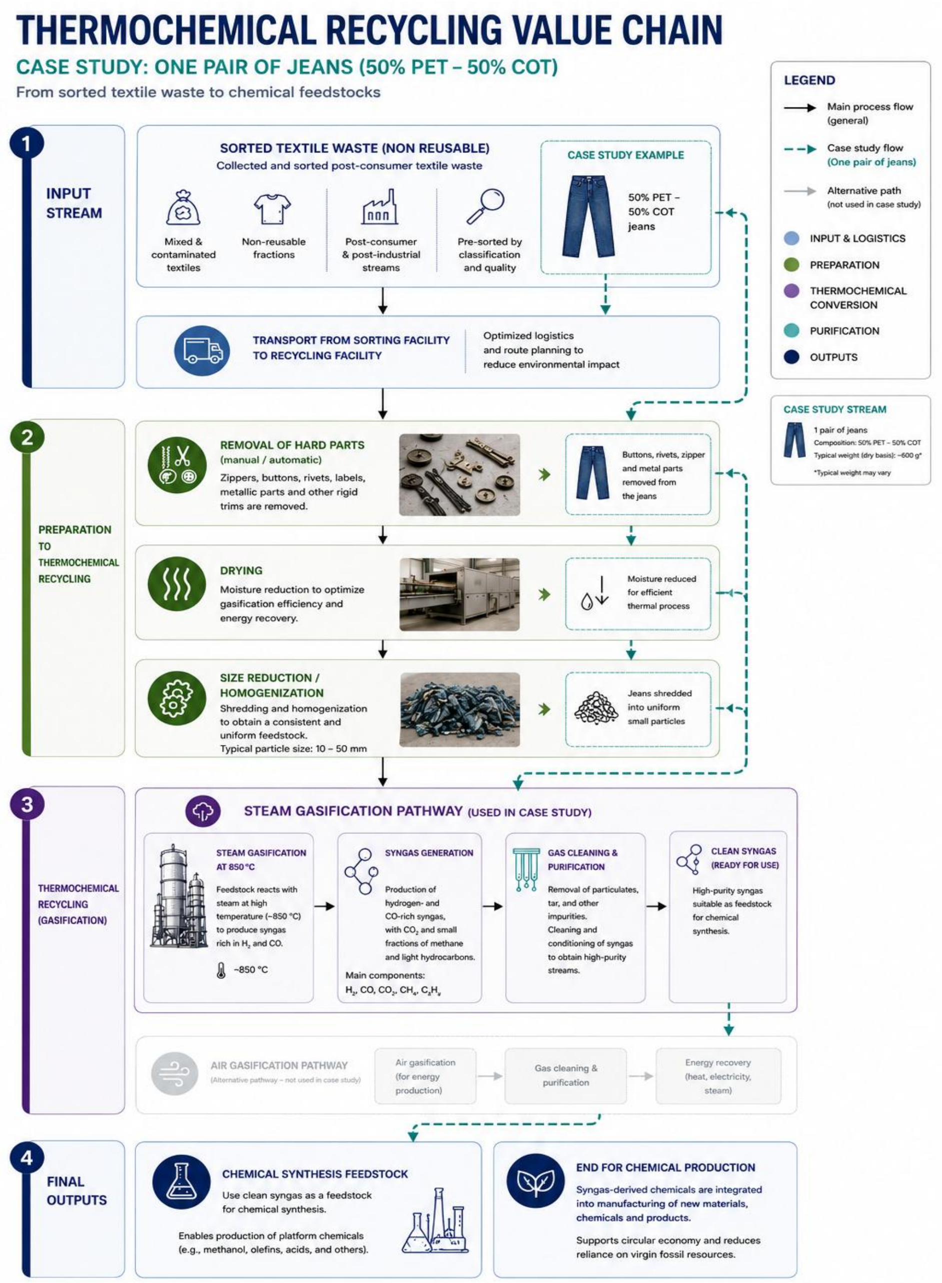



*Figure 21 - Thermochemical Recycling value chain. Visual representation derived from the operational mapping activities (Example application of Post-consumer jeans)*

After preparation, the shredded textile feedstock enters the steam gasification reactor operating at high temperature, approximately 850°C in the illustrated example. Under steam gasification conditions, the textile material reacts thermochemically to produce syngas rich in hydrogen ($H_2$) and carbon monoxide (CO), together with smaller fractions of carbon dioxide ($CO_2$), methane ($CH_4$), and light hydrocarbons. The generated gas streams subsequently undergo gas cleaning and purification operations aimed at removing particulates, tar, and impurities in order to obtain higher-purity syngas suitable for downstream industrial applications. The purified syngas can then be used as a chemical feedstock for chemical synthesis processes.

The case study demonstrates how thermochemical recycling can recover value from mixed and difficult-to-recycle textile products that are unsuitable for reuse or fibre-preserving recycling systems. It also illustrates the importance of feedstock preparation, contaminant removal, homogenization, and gas purification in achieving efficient thermochemical conversion and generating industrially usable outputs.

Although thermochemical recycling offers an important recovery pathway for hard-to-recycle textile waste fractions, the value chain faces several criticalities that emerged also from the representation in the map:

- One of the main challenges concerns process **energy demand and overall environmental performance**. Thermochemical recycling technologies operate at very high temperatures and therefore require significant energy input. Gas cleaning and purification systems represent another technically demanding and costly stage within the value chain. Thermochemical conversion generates impurities, tar, particulates, and potentially hazardous emissions.
- thermochemical recycling remains positioned relatively low within the circular value hierarchy because **the original textile structure and functionality are destroyed during processing**. Consequently, concerns persist regarding the balance between circularity objectives, energy recovery, material recovery efficiency, and the prioritization of higher-value pathways such as reuse and fibre-to-fibre recycling. Ensuring that thermochemical recycling complements rather than displaces higher circular strategies therefore remains an important systemic consideration within the textile circular economy.
- The thermochemical pathway is selected by exclusion rather than by positive material matching, as it mainly receives textile fractions that have already been excluded from reuse, refurbishment, remanufacturing, or other recycling routes. The value chain receives some of the most difficult-to-characterize textile fractions, often including mixed fibres, contaminated materials, complex products, and heterogeneous streams that could not be allocated to higher-value circular pathways.
- Thermochemical recycling operates on materials that have already lost most of their product and functional value, meaning that value creation depends almost entirely on

recovering chemical or energy value from residual textile fractions rather than preserving products, components, or fibres.

### 3.2.2.5. Thermomechanical recycling

#### 3.2.2.5.1. Definition

The thermomechanical recycling value chain is a material recovery pathway within the circular textile economy in which **thermoplastic textile waste is transformed into secondary polymer-based materials through combined mechanical and thermal reprocessing operations**. The objective of the value chain is to retain and recover the functional value of polymer materials by reintroducing them into manufacturing systems as recycled feedstocks for textile and non-textile applications. The value chain mainly addresses textile streams containing **thermoplastic polymers** such as **PET**, **PA**, **PP** and compatible synthetic blends originating from post-consumer and post-industrial sources. Unlike thermochemical recycling, the process aims to **maintain polymer functionality** and material performance rather than converting materials into chemical intermediates or energy carriers.

A defining characteristic of thermomechanical recycling is the **dependence on polymer compatibility and feedstock quality**. Since the process relies on melting and reprocessing polymer materials, textile streams generally require relatively controlled compositions, low contamination levels and sufficient material homogeneity to ensure stable processing conditions and acceptable recycled material performance. As a result, the value chain strongly depends on upstream collection, sorting, material identification and contamination management systems.

### 3.2.2.5.2. MAP OF THE THERMOMECHANICAL RECYCLING VALUE CHAIN: DESCRIPTION OF OPERATIONAL STEPS AND FLOWS

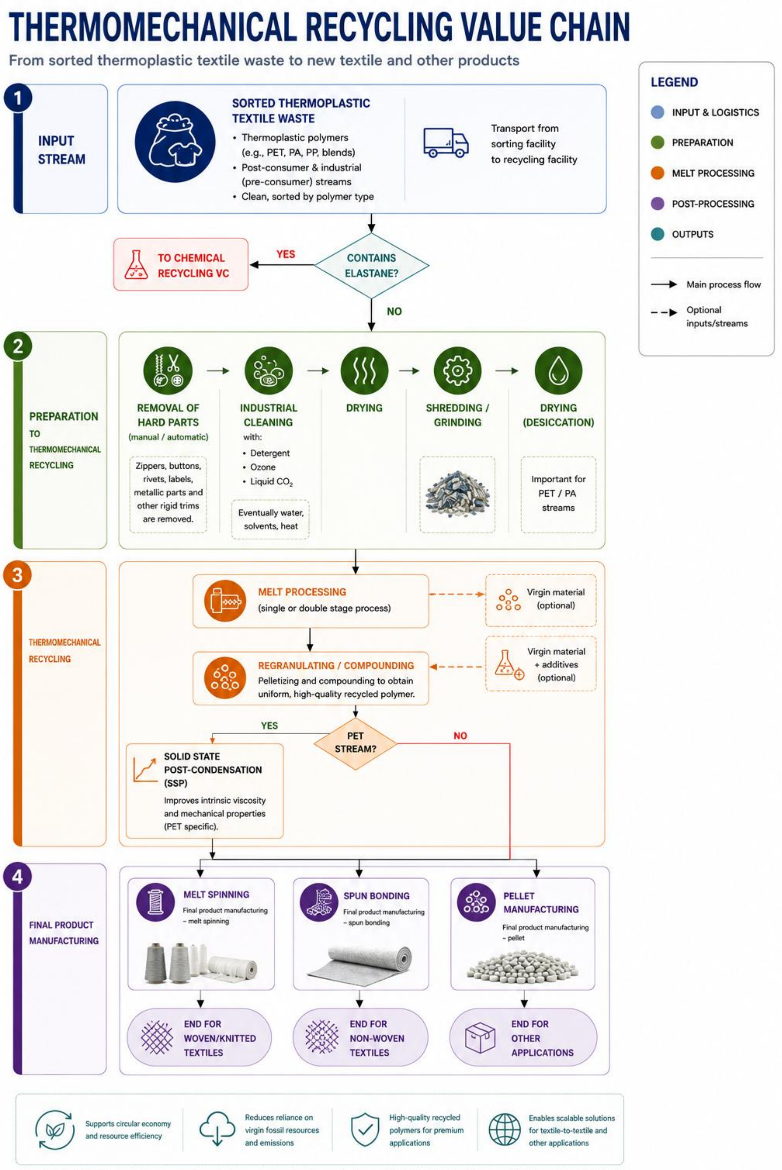



*Figure 22 - Thermomechanical Recycling value chain. Visual representation derived from the operational mapping activities*

The value chain starts with the input stream phase, where sorted thermoplastic textile waste is collected and directed toward dedicated thermomechanical recycling facilities. Since thermomechanical recycling processes are highly sensitive to material compatibility and contamination, **textile waste entering the system is generally pre-sorted according to polymer type, composition, cleanliness, and suitability for downstream melt processing operations**.

Following sorting activities, textile waste is transported from sorting facilities to recycling plants through dedicated logistics systems. Then, textile materials undergo through the traditional series of **preparation operations** aimed at generating a suitable feedstock for thermomechanical processing: removal of hard and non-textile components, industrial cleaning processes intended to remove dirt, oils, contaminants, finishing chemicals. Following, textile materials generally undergo drying operations aimed at reducing moisture content prior to thermal processing. Prepared textiles subsequently undergo shredding, grinding, cutting, or size-reduction operations in order to generate smaller and more homogeneous particles suitable for downstream thermal processing. These operations **transform garments and textile products into flakes, fibre fragments, or granulated feedstock with more consistent dimensions and bulk density**. Textile materials enter the core thermomechanical recycling stage: textile polymers undergo **melt processing through extrusion, melting, filtering, and reprocessing operations**. Depending on the selected technology, the process may involve **single-stage** or **double-stage melt processing systems**. During thermal processing, optional additions of virgin polymers or additives may be introduced to stabilize material performance, improve processing behaviour, or enhance final product properties.

Following melt processing, recycled polymers generally undergo **regranulation or compounding operations** in which molten polymer streams are transformed into pellets or compounded materials with more controlled and standardized characteristics. Pelletization enables the production of more uniform recycled polymer feedstocks suitable for downstream manufacturing applications.

The final product manufacturing stage depends on the intended downstream application. Recycled polymers and pellets may subsequently enter melt-spinning operations for the production of new yarns and fibres intended for woven or knitted textile products. Alternatively, recycled materials may be used in spun-bonding systems for nonwoven textile applications or transformed into pellets and compounds intended for industrial, packaging, automotive, construction, or other non-textile applications.

The integrated case study of a 100% PET demonstrates the importance of feedstock purity for enabling high-value thermomechanical recycling routes. Unlike mixed-fibre garments, the jeans can remain within a dedicated PET stream throughout the process, avoiding diversion to alternative recycling pathways and enabling direct conversion into recycled PET pellets suitable for fibre production. The case study also illustrates how the quality of the incoming material directly influences the achievable circular outcome. The sequence of shredding, desiccation, melt processing and polycondensation is specifically designed to preserve and restore polymer properties, allowing the recycled material to re-enter textile applications rather than being downgraded to lower-value uses. In this respect, **the example clearly shows that thermomechanical recycling is capable of supporting genuine fibre-to-fibre circularity when the feedstock is sufficiently homogeneous and compatible with the process requirements**. The case study also highlights the strategic role of advanced technologies such as the *Intarema FibrePro:IV system*, where polymer reprocessing and quality restoration are integrated within the same process chain to produce recycled pellets suitable for the manufacture of new yarns and textile products.

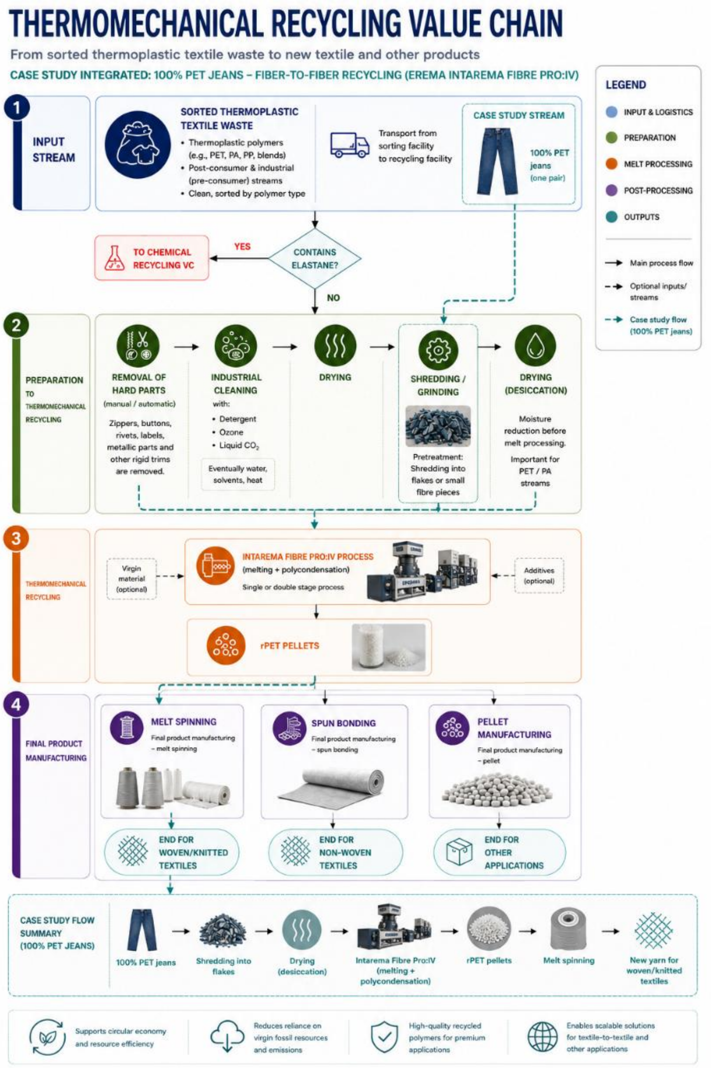



*Figure 23 - Thermomechanical Recycling value chain. Visual representation derived from the operational mapping activities (Example application of Post-consumer jeans)*

## 3.2.3. REUSE

### 3.2.3.1. DEFINITION

The textile reuse value chain is a circular value retention system aimed at extending the lifetime of textile products by maintaining garments and textile items in use for as long as possible before they are diverted to recycling, energy recovery, or disposal pathways. Reuse preserves the functional, economic, and material value embedded in textile products while reducing the need for virgin resource extraction, additional manufacturing processes, and waste generation.

The reuse value chain generally operates according to a cascading logic in which textile products are progressively directed toward the highest feasible value-retention market or application. Higher-quality garments are typically allocated to premium local resale or specialized second-hand channels, while lower-grade reusable products may be distributed through lower-cost markets, export channels, discount outlets, or alternative redistribution systems. Products may therefore move through multiple geographical and economic market tiers before ultimately exiting the reuse system.

A key characteristic of the reuse value chain is its market-driven and geographically differentiated nature. Different local, regional, and international markets absorb different product categories depending on quality expectations, consumer preferences, purchasing power, cultural acceptance of second-hand products, regulatory conditions, and logistics costs. Consequently, reuse pathways are not uniform but depend on dynamic interactions between supply quality, market demand, infrastructure availability, and operational economics.

The reuse value chain involves a broad ecosystem of actors including consumers, charities, social enterprises, collectors, sorters, repair actors, second-hand operators, online resale platforms, retailers, exporters, logistics providers, and take-back scheme operators. Consumer participation, separate collection systems, quality-preserving logistics, and effective sorting operations are fundamental enabling conditions for maintaining textile products within active use cycles and maximizing their value retention potential.

Within a circular textile economy, reuse is generally considered one of the preferred circular strategies because it preserves products in their original function with minimal material transformation and relatively low additional resource consumption compared to recycling and other downstream recovery processes.

#### 3.2.3.2. Map of the reuse value chain: description of operational steps and flows

The reuse value chain consists of a sequence of interconnected operational steps through which post-consumer and post-retail textile products are collected, assessed, graded, prepared, redistributed, and reintroduced into the market for further use cycles. The process is designed to maximize product lifetime and retain the highest possible value of textile products before they move toward lower-value circular pathways such as recycling or disposal.

The process starts with the collection and input phase, where textiles are gathered through dedicated collection systems and channels, as detailed in section 3.2.1. Collection sources may include separate household collection, take-back programmes, charities, unsold brand products, retail returns, commercial actors, and other textile streams. Depending on the collection model, products may already be partially separated or may enter the system as unsorted textile waste. Collected textiles are transported through logistics networks to sorting or processing facilities.

Once received at the facility, textiles undergo an initial pre-sorting stage aimed at identifying general product conditions and removing heavily contaminated, damaged, or clearly non-reusable items. This stage represents a first separation between reusable and non-reusable fractions. Non-reusable garments are redirected toward other circular value chains such as recycling, repurposing, or remanufacturing, while fractions with no feasible recovery potential may ultimately be directed toward energy recovery or disposal pathways.

Reusable products proceed to additional operational steps that support safe redistribution and market preparation. Basic sanitisation processes may be applied before detailed grading activities are performed. Sorting and grading operations represent a central value-creation stage within the reuse value chain. At this stage, garments are manually, digitally, or automatically assessed according to parameters such as quality, condition, durability, cleanliness, aesthetic characteristics, brand positioning, fashion relevance, functionality, and resale potential.

Based on the assessment results, garments are allocated into different quality grades corresponding to different resale opportunities and market destinations. Higher-grade products are generally directed toward premium second-hand channels with higher resale value, while lower-grade reusable products are allocated to more price-sensitive markets or longer distribution channels. This grading system enables products to be matched with the most suitable market according to their remaining functional and economic value.

Depending on the quality grade and target market requirements, garments may undergo preparation-for-reuse activities adapted to the characteristics of each fraction. These activities can include labelling, sanitisation, pressing, folding, packaging, baling, and logistics preparation. In specific cases where economically justified, products may also enter repair or refurbishment pathways before resale in order to increase product quality, extend lifetime, or improve marketability.

Following preparation activities, reusable textiles are redistributed through different resale and redistribution channels. These channels may include physical second-hand stores, vintage or specialized resale shops, online resale platforms, export markets, local redistribution systems, discount outlets, humanitarian redistribution channels, or other low-cost market segments. Different channels absorb different product qualities and categories according to local demand conditions, purchasing power, consumer preferences, and logistics economics.

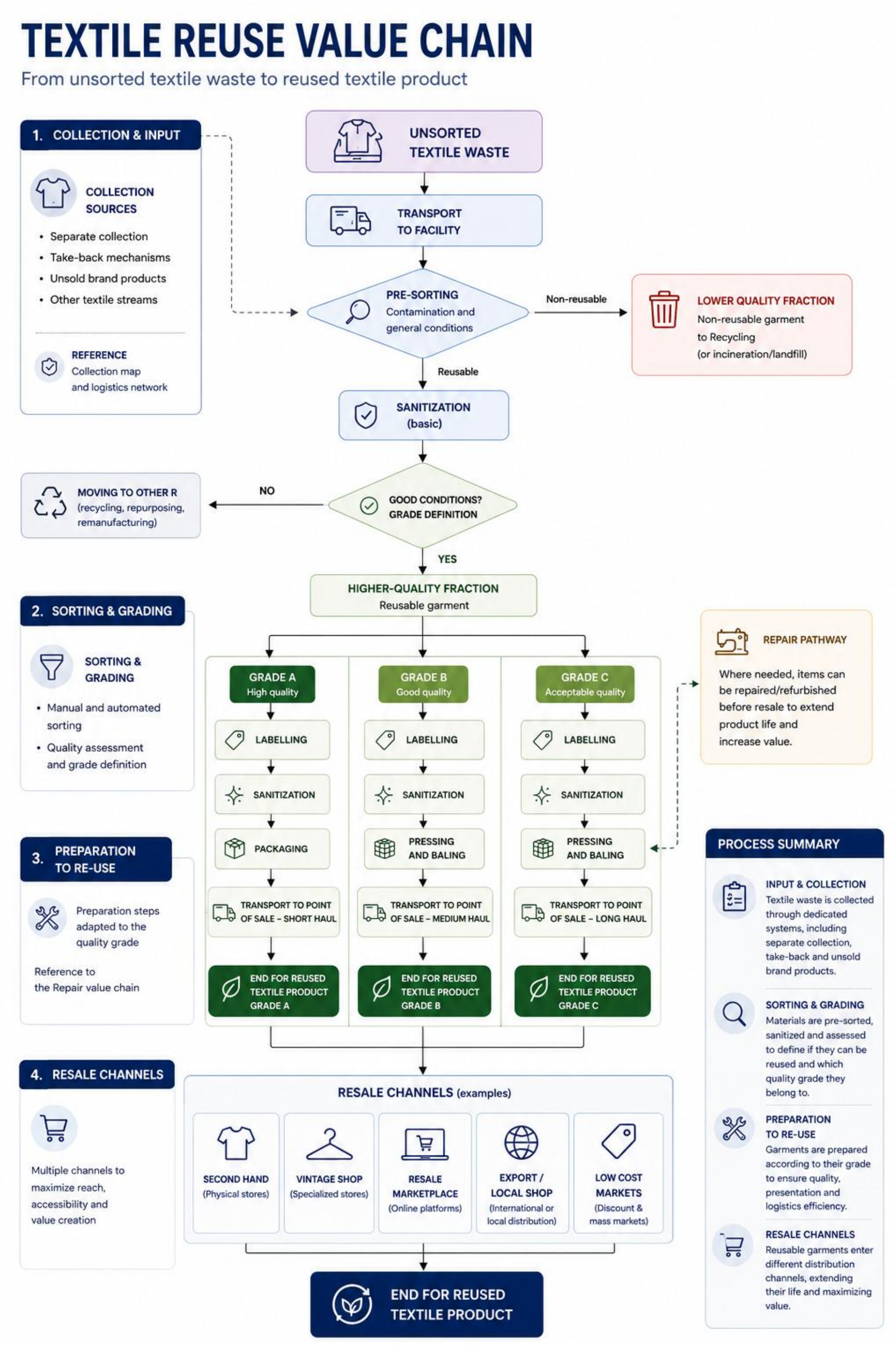



*Figure 24 - Reuse value chain. Visual representation derived from the operational mapping activities (Example application of Post-consumer jeans*

The case study of one pair of jeans for the Reuse value chain makes visible how individual products move through multiple operational decision points and how value is progressively assessed, preserved, upgraded, or redirected throughout the process. One of the main aspects highlighted by the case study is the **central role of sorting and grading activities** in determining the future pathway of a garment. The jeans only remain within the reuse pathway if they successfully pass successive evaluation stages related to contamination, hygiene, physical condition, durability, and resale potential. The case study also makes visible the **cascading structure of the reuse system**. Depending on the quality grade assigned to the garment, the jeans may enter different resale channels and geographical markets characterized by different value levels, logistics requirements, and consumer demand conditions. Higher-quality garments may remain in local or premium second-hand markets, while lower-grade reusable fractions may move toward export-oriented or low-cost redistribution systems. The example therefore demonstrates how reuse systems continuously balance technical quality, market demand, logistics costs, and economic feasibility. Another important element highlighted by the case study is that textile reuse systems are highly infrastructure-dependent and require coordinated interactions between multiple actors and operational stages.

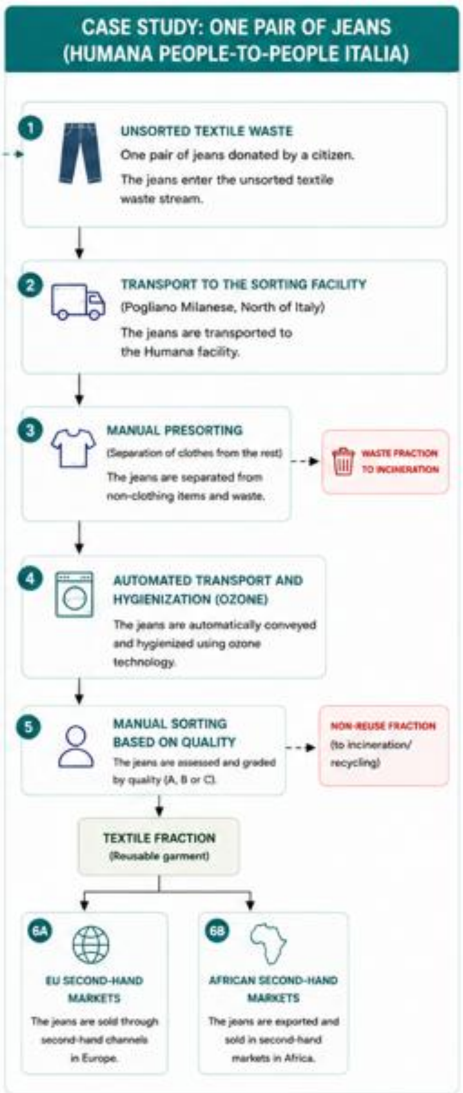



*Figure 25 - Reuse value chain. Visual representation derived from the operational mapping activities (Example application of Post-consumer jeans)*

The final part of the Reuse value chains represented above describe clearly the strong dependency of the reuse value chain on downstream market conditions. The final destination of the jeans is not determined solely by technical quality but also **by demand availability**, regional purchasing power, logistics economics, and market saturation. This demonstrates that reuse systems are not only material-management systems but also highly dynamic market-driven systems.

### 3.2.4. REPAIR

#### 3.2.4.1. DEFINITION

The repair value chain is a circular value-retention pathway focused on extending the useful life of textile products through targeted interventions that restore, maintain, or improve garment functionality, usability, and durability after damage, wear, or deterioration occurs. Repair preserves the original product, its material composition, and its embedded environmental value while minimizing additional resource consumption and material transformation. A defining characteristic of the repair value chain is its **service-based nature**. Rather than relying primarily on industrial material-processing infrastructures, repair systems are built around repair services, technical know-how, manual interventions, and customer-oriented interactions.

Repair frequently acts as an **enabling function across broader life-extension strategies** including reuse, resale, refurbishment, redistribution, take-back programmes, and remanufacturing systems. In many cases, repair interventions are necessary to maintain products within higher-value circular loops and preserve their marketability or usability over time.

Repair systems are:

- highly dependent on garment repairability and product design characteristics. Repair is closely linked to emerging design-for-repair approaches and broader circular product design strategies.
- localized and labour-intensive nature of repair systems. Repair activities are often carried out through decentralized service networks involving local repair shops, alteration services, independent tailors, social enterprises, repair centres, retailers, and digital repair platforms. As a result, repair systems are strongly influenced by local skill availability, labour costs, customer accessibility, convenience, and cultural attitudes toward garment maintenance and prolonged use.

### 3.2.4.2. MAP OF THE REPAIR VALUE CHAIN: DESCRIPTION OF OPERATIONAL STEPS AND FLOWS

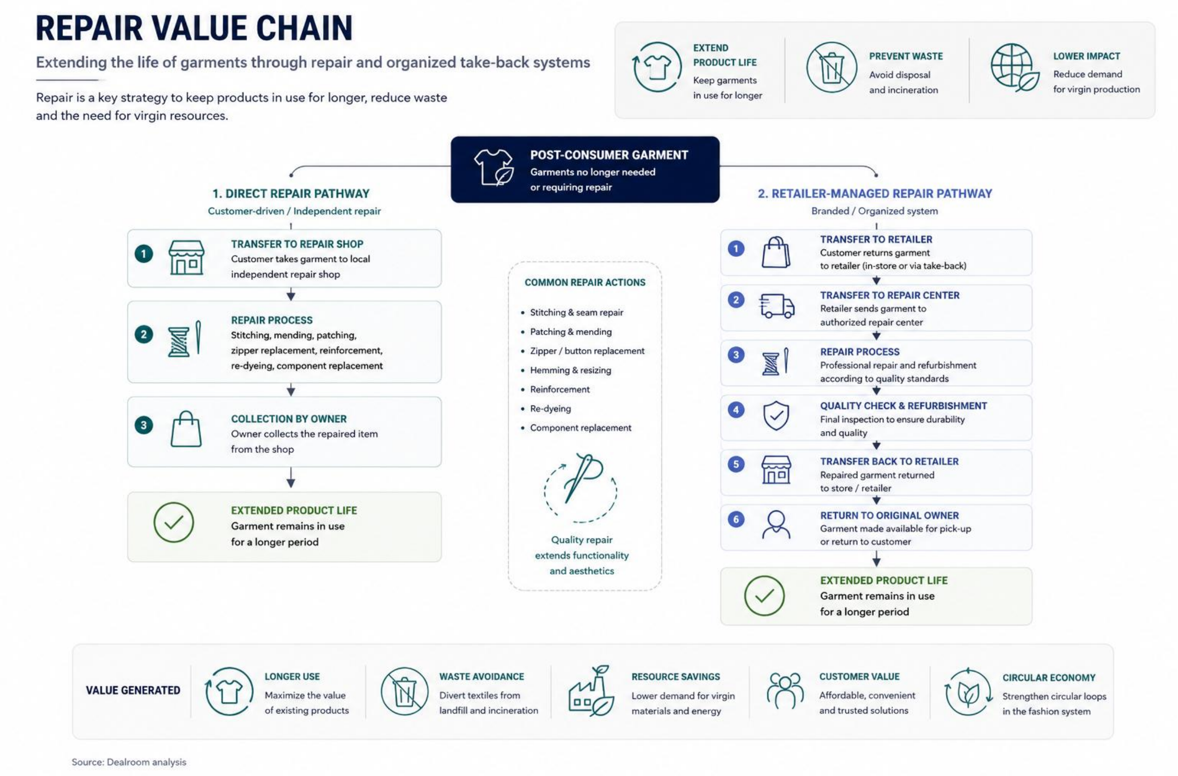



*Figure 26 - Repair value chain. Visual representation derived from the operational mapping activities*

The map illustrates that the repair value chain can follow different organizational configurations depending on the actors involved, the service model, and the level of coordination within the system. In both illustrated pathways, the process starts from a post-consumer garment that either requires repair or risks being discarded due to damage, wear, aesthetic deterioration, or functional issues.

The first pathway represented in the map is the **direct repair pathway, based on customer-driven** and decentralized repair services. In this configuration, the garment owner directly transfers the item to a local repair shop or independent repair operator. The garment subsequently undergoes repair operations which may include stitching, mending, patching, zipper replacement, reinforcement, resizing, re-dyeing, seam repair, or component substitution depending on the type and severity of the defect. Once repair activities are completed, the repaired garment is collected by the owner and returned to active use. The map highlights that this pathway is strongly localized and relies on small-scale repair infrastructures, manual skills, and direct customer interaction. The second pathway represented in the map is the **retailer-managed repair pathway**, based on more organized and coordinated repair systems operated or facilitated by brands and retailers. In this configuration, the customer returns the garment to the retailer either through in-store collection systems or take-back mechanisms. The retailer subsequently transfers the garment to a centralized or authorized repair centre where professional repair and refurbishment activities are performed according to predefined quality standards. The repaired product is then transferred back to the retailer and ultimately returned to the original owner through collection or delivery systems.

The map also highlights a set of common repair actions shared across different repair configurations. These include stitching and seam repair, patching and mending, zipper or button replacement, hemming and resizing, reinforcement operations, re-dyeing, and component replacement activities. Although technically simple in some cases, these interventions play a critical role in extending product usability, preserving garment aesthetics, and increasing residual product value.

The repair value chain map highlights several structural and operational criticalities of repair systems:

- the strong dependency on manual labour and specialized skills. The map shows that repair activities such as stitching, patching, resizing, reinforcement, or component replacement rely heavily on human intervention and technical expertise, limiting standardization and automation potential across the value chain.
- Fragmentation of repair infrastructures and logistical complexity. The coexistence of direct local repair pathways and retailer-managed systems illustrates the absence of a single dominant organizational model.
- the dependency of repair systems on customer participation and accessibility. The repair pathway is only activated if consumers decide to retain the garment, access repair services, and perceive sufficient value in extending product life.
- the strong dependency on product repairability. Garments containing complex constructions, inaccessible components, poor-quality materials, or non-replaceable elements may significantly complicate repair operations or reduce the feasibility of lifetime extension strategies.

### 3.2.4.3. REFURBISH

#### 3.2.4.4. DEFINITION

Refurbish is the process of restoring a used textile product to a functional and aesthetic condition close to new through deep cleaning, stain removal, sanitization, re-dyeing, re-newal of functional finishes, minor repairs and replacement of components, without altering the original design or intended function. Refurbishing is a proactive process, acting before the functionality of the product reaching to restore the product to like-new condition. Contrary to repair, which simply fixes a specific broken part, refurbish is a more comprehensive and proactive process that includes restoring the entire product. Both reuse and refurbish both maintain the original function, but refurbish goes further by actively returning the product to its original condition before reuse. **In contrast to remanufacturing, which involves disassembly and rebuilding to original specifications at component level**, refurbish works on the product as a whole without disassembly. Meanwhile recycling breaks down the product into raw materials; refurbish retains the product's full form, function, and value — sitting higher in the waste hierarchy. The pathway is strongly r**estoration-oriented, combining technical treatments with aesthetic interventions** to achieve a standardized near-new output.

### 3.2.4.5. MAP OF THE REFURBISH VALUE CHAIN: DESCRIPTION OF OPERATIONAL STEPS AND FLOWS

The figure below visually represents a simplified and revised version of the refurbished value chain:

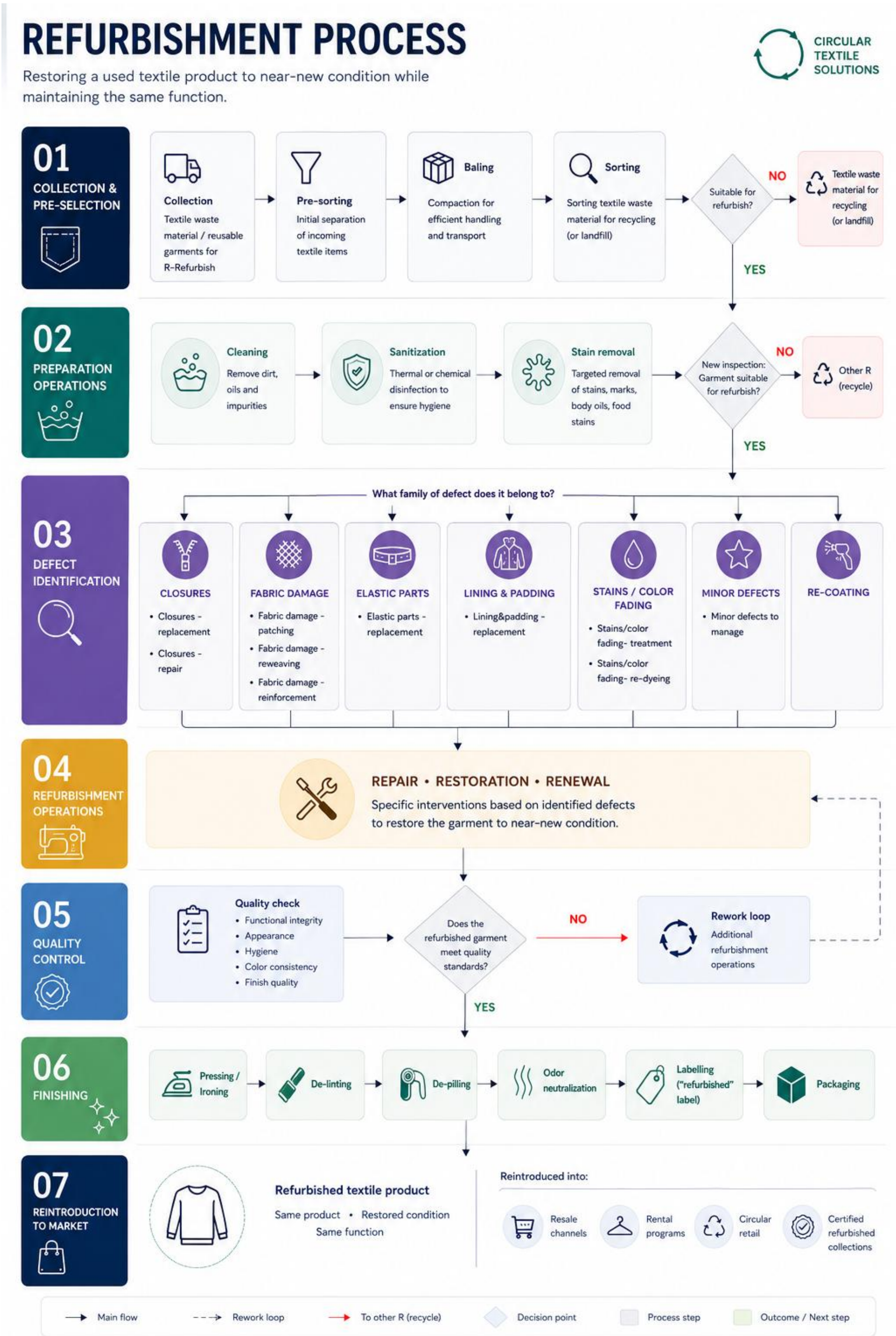



*Figure 27 - Refurbish value chain. Visual representation derived from the operational mapping activities*

The operational flow of the refurbish value chain begins with the collection and pre-sorting of post-consumer/pre-consumer/post-industrial textile products considered potentially suitable for refurbishment applications. The initial phases include baling and logistics-related activities, followed by a pre-sorting stage in which incoming garments are preliminarily assessed for their refurbishment potential. Products identified as unsuitable at this stage are redirected toward recycling pathways or landfill.

Then, garments entering the refurbish pathway undergo a sequential series of pretreatment operations. The first pretreatment stage consists of cleaning, sanitization and subsequently by stain removal, targeting localized contamination that could compromise the aesthetic quality of the final refurbished product.

The refurbish value chain is structured around three key decision points that influence the progression of garments through the operational flow and determine their pathway. The first decision point occurs at the pre-sorting stage, where incoming textile waste is assessed for its general suitability for refurbishment. The second decision point - a new inspection - occurs after the completion of the pretreatment phases, specifically following cleaning, sanitization, and stain removal: at this stage, each garment undergoes a more detailed assessment to determine whether it is genuinely suitable for refurbishment. This decision point also introduces a defect classification step: garments that pass the suitability threshold are further assessed to **identify which family of defect they present**. Each garment is directed toward one or more of these streams depending on the defect family identified, and multiple interventions may be applied in parallel or sequentially within the same product.

The third and final decision point occurs after the completion of all core treatment activities. At this stage, each treated garment is assessed against defined quality standards to determine whether the refurbishment process has successfully restored it to a near-new functional and aesthetic condition. Garments that meet the quality standard proceed to the finishing phase, which includes pressing and ironing, de-linting, de-pilling, odor neutralization, application of the refurbished product label, and packaging before reintegration into the market. Garments that do not meet the required standard are redirected accordingly.

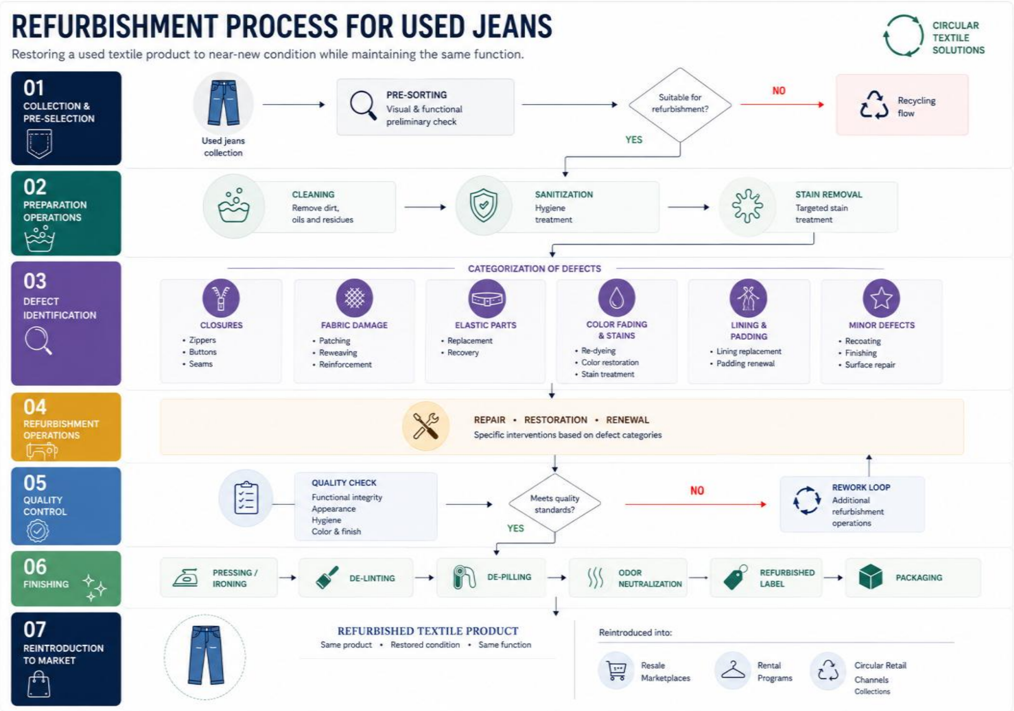



*Figure 28 - Refurbish value chain. Visual representation derived from the operational mapping activities (Example application of Post-consumer jeans)*

The jeans refurbishment case study helps make visible several operational and organizational aspects. While the general value chain explains the overall refurbishment logic, the jeans example highlights more clearly how refurbishment functions as a highly selective, condition-based, and quality-driven circular pathway aimed at restoring garments to near-new condition while preserving their original function.

One of the main elements highlighted by the case study is the high operational intensity required to restore products to "near-new" conditions. The refurbishment pathway combines multiple sequential operations including cleaning, sanitization, stain removal, repair, restoration, renewal, quality control, finishing, de-linting, de-pilling, odor neutralization, relabelling, and packaging. The map therefore demonstrates that refurbishment is positioned operationally between repair and remanufacturing, involving more extensive interventions than basic repair while still preserving the original product identity and function.

The case study further highlights the strong importance of aesthetic restoration in refurbishment systems. In addition to restoring functionality, operations such as colour restoration, stain treatment, pressing, de-pilling, and finishing are aimed at improving the visual appearance and marketability of the garment. This reflects the fact that refurbishment systems are highly dependent on consumer perception of product quality and "like-new" appearance in order to support resale, rental, or reintegration into circular retail channels.

### 3.2.5. REMANUFACTURING

#### 3.2.5.1. DEFINITION

Remanufacturing is an industrial process in which the same garment is fully disassembled into its components, cleaned, inspected, regenerated or rebuilt, and finally reassembled to achieve an as-new condition that meets the original performance specifications. Unlike other restoration pathways, remanufacturing is a **component-level process**: the product is not simply restored as a whole but systematically taken apart, evaluated at the component level, and reconstructed to original specifications. The objective is therefore not merely to achieve a near-new aesthetic standard, as in refurbishment, but to deliver a full technical restoration to original performance specifications.

Remanufacturing involves full disassembly, component-level inspection and complete reconstruction to original performance specifications.

This process requires specialized technical competences in disassembly, component identification, regeneration and precision reassembly.

### 3.2.5.2. MAP OF THE REMANUFACTURING VALUE CHAIN: DESCRIPTION OF OPERATIONAL STEPS AND FLOWS

The figure below visually represents a simplified version of the remanufacture value chain.

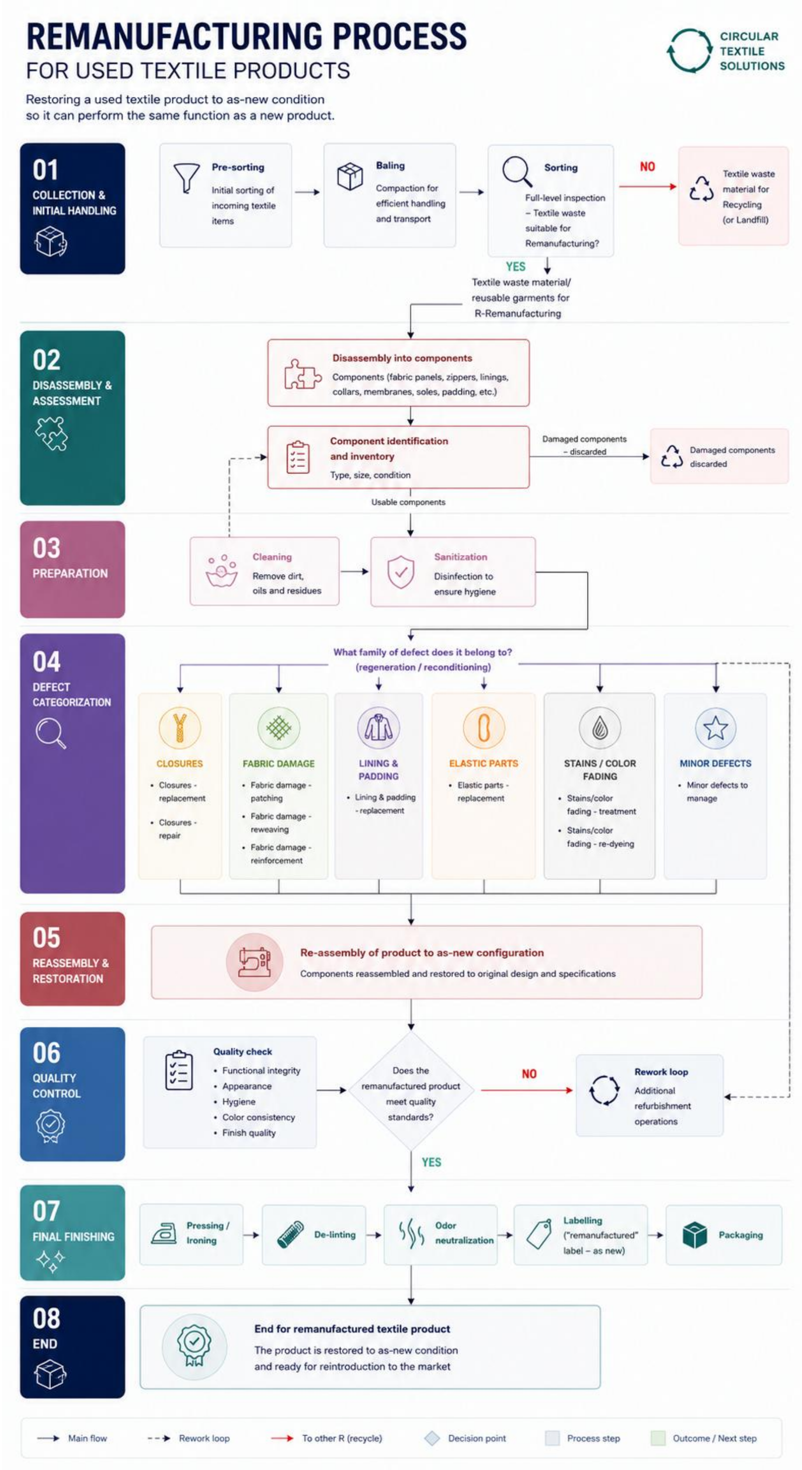



*Figure 29 - Remanufacturing value chain. Visual representation derived from the operational mapping activities (Example application of Post-consumer jeans)*

The operational flow of the remanufacturing value chain begins with a pre-sorting stage, in which garments entering through collection systems and take-back programs are preliminarily assessed for their remanufacturing potential. The first decision point occurs at the sorting stage, where a second and more detailed level of inspection determines suitability for remanufacturing against four evaluation criteria: reconstructability of the garment, structural integrity of the main fabric, feasibility of reaching as-new condition, and availability of components that can be recovered or replaced. **Garments confirmed as suitable proceed to full disassembly into their constituent components** - including fabric panels, zippers, linings, collars, membranes, soles, and padding - while those falling short are redirected toward recycling or landfill. Following disassembly, **each component is individually identified, catalogued, and assessed by type, size, and condition**. Damaged or non-recoverable components are discarded and redirected toward recycling or disposal, while recoverable components proceed to cleaning and sanitization before regeneration activities begin. The second decision point introduces a defect classification step, in which components are assessed to determine which family of defect they present and consequently which treatment stream they require. Once all regeneration and reconditioning treatments are completed, the garment undergoes re-assembly to its as-new configuration, with all components reconstructed according to original product specifications. The third and final decision point occurs here, where the reassembled product is assessed against as-new quality standards. The remanufacturing map built on the Jeans case study highlights a very high level of operational complexity: the process behaves as a reverse manufacturing system in which garments are fully deconstructed and rebuilt to achieve as-new conditions. One of the main criticalities visible in the map is the strong dependency on disassembly feasibility. The jeans must be separated into multiple individual components - such as panels, waistbands, pockets, rivets, linings, and closures - making the process highly dependent on garment construction, stitching methods, and product design. The map also emphasizes the importance of achieving "as-new" quality standards during reassembly and final quality control. Reconstructing garments according to original specifications requires high precision, component compatibility, and extensive manual intervention, while the presence of rework loops demonstrates that the process is iterative and difficult to fully standardize. Overall, the representation clearly highlights that remanufacturing is one of the most labour-intensive, quality-dependent, and technically demanding circular textile pathways.

### 3.2.6. Repurpose

#### 3.2.6.1. Definition

Repurpose is the process of transforming a used textile product or its components into a different product with a different use, without major modification of the material's intrinsic structure, through disassembly, cleaning, sorting, design-based reinterpretation and reconstruction, resulting in a new object with a new function.

Unlike remanufacturing pathways, which aim to recreate products or materials with functions and performances comparable to the original application, repurpose activities are based on the functional reinterpretation of textile products and components through redesign and reconstruction processes. In repurpose systems, the objective is not to preserve the original product identity or technical performance, but to generate a new product with a different intended use while maintaining part of the original material or component structure. Unlike reuse pathways, where the original function of the product is maintained, repurpose activities involve the functional reinterpretation of textile products and components through reconstruction and transformation processes. At the same time, differently from recycling pathways, the original textile material is generally preserved without undergoing substantial fibre-level or polymer-level transformation processes.

The repurpose pathway is therefore strongly design-oriented and component-based, relying on the identification, selection and reconfiguration of reusable textile elements into new applications and products.

The value chain typically combines operational activities related to sorting, dismantling, cleaning and material preparation with design, reconstruction and finishing processes aimed at generating new textile or non-textile products from post-consumer or post-industrial textile materials.

Within the framework developed in Task 3.1, repurpose was analysed as a specific circular pathway due to its distinct operational logic, technological requirements and strong integration between manual, semi-automated and creative transformation activities.

#### 3.2.6.2. Map of repurpose value chain. Description of operational flows, pretreatments and treatments

Figure 31 presents a simplified and visually revised representation of the repurpose value chain developed within Task 3.1. The graphical representation was redesigned to improve readability and facilitate the interpretation of the main operational stages, material flows and decision points characterising the repurpose pathway. The complete technical mappings originally developed by each partner through Draw.io are instead reported in Annex 2 as supporting material for the methodological and operational analysis.

To improve the practical understanding of the value chain, the general operational mapping is complemented by:

- a narrative operational description of the value chain, developed to support the interpretation of the mapping through a step-by-step storytelling approach describing the progression of textile materials across the different operational stages.
- a representative example illustrating the progression of a post-consumer pair of jeans through the repurpose pathway, showing how textile components can be selected, prepared and reconstructed into a new product with a different function.

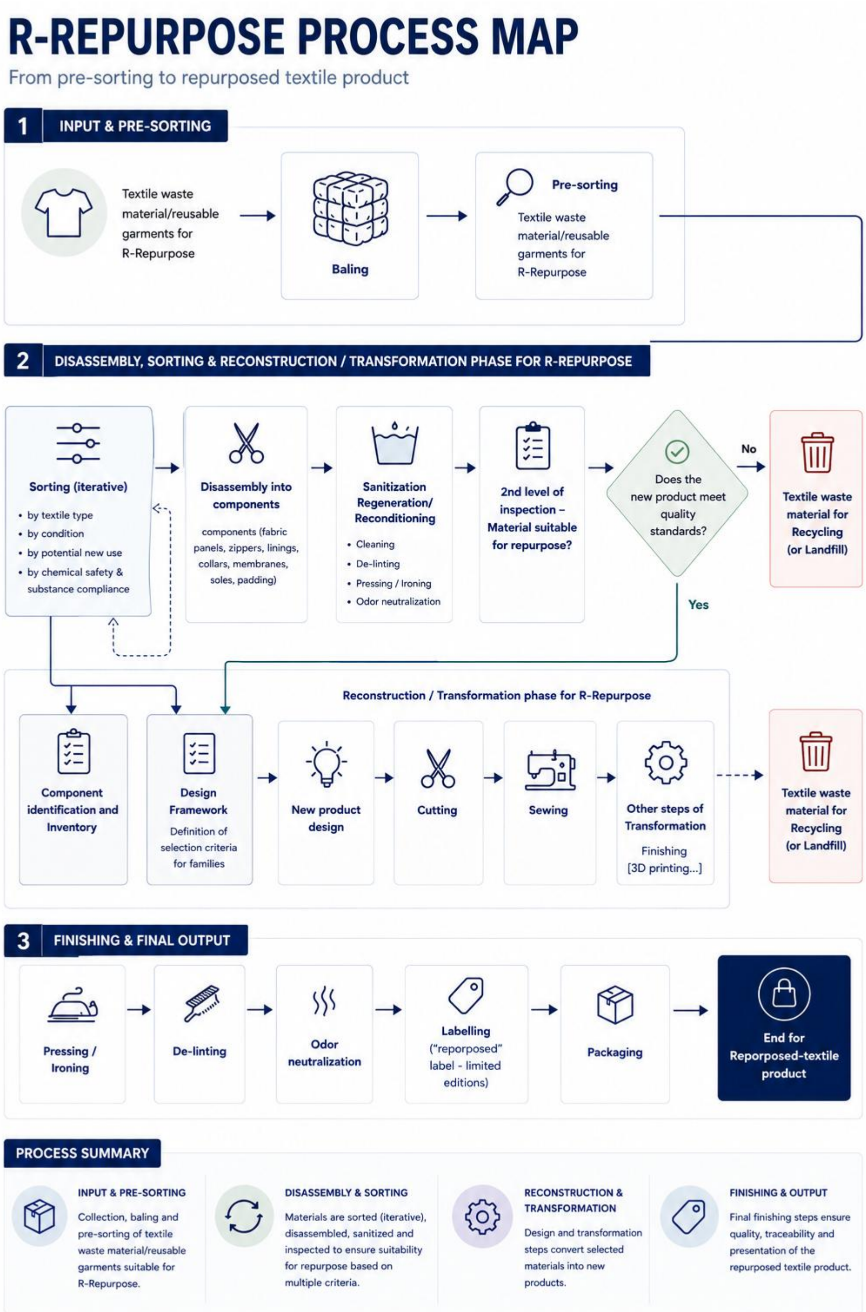



*Figure 30 - Repurpose value chain. Visual representation derived from the operational mapping activities*

The operational flow of the repurpose value chain starts from the collection and preliminary sorting of textile waste materials or reusable garments considered potentially suitable for repurpose applications. The first operational phases generally include baling and logistics-related activities, followed by pre-sorting and eligibility assessment operations aimed at identifying textile products containing reusable components, acceptable wear conditions and sufficient structural integrity for further transformation processes. After the initial selection phase, textile products undergo secondary inspection activities intended to evaluate their effective suitability for repurpose applications. Products identified as potentially suitable are subsequently disassembled into components in order to separate reusable textile panels, accessories and functional elements such as zippers, waistbands, buttons, linings, collars, membranes, soles, padding elements and other recoverable parts.

Following disassembly, only the components considered suitable for repurpose applications proceed to the operational preparation phase. These selected components undergo cleaning, sanitization, regeneration and reconditioning activities aimed at restoring usability, safety, functional integrity and aesthetic quality before reconstruction. Additional preparation activities may also include de-linting, odor neutralization, pressing and ironing depending on the characteristics and intended application of the recovered elements. Components or materials assessed as unsuitable for repurpose are instead redirected towards recycling pathways or disposal streams.

Once the reusable components are identified, the process progressively shifts towards a **design-oriented operational logic**. **Components are classified** according to textile type, condition, potential future use and chemical safety compliance: parallel activities involve component identification, inventory management and the definition of selection criteria for specific product families. At this stage, the **design framework** becomes a central operational element of the value chain, guiding the reinterpretation of the recovered materials and defining the reconstruction strategy of the new repurposed product.

The reconstruction and transformation phase subsequently includes cutting, sewing, assembly and additional transformation operations aimed at generating the new product configuration. Depending on the application, complementary finishing activities may also be integrated, including decorative operations, reinforcement processes or advanced finishing technologies such as 3D printing applications. Final quality verification activities are then performed to assess structural resistance, aesthetic consistency and product conformity before packaging and reintegration of the repurposed product into the market.

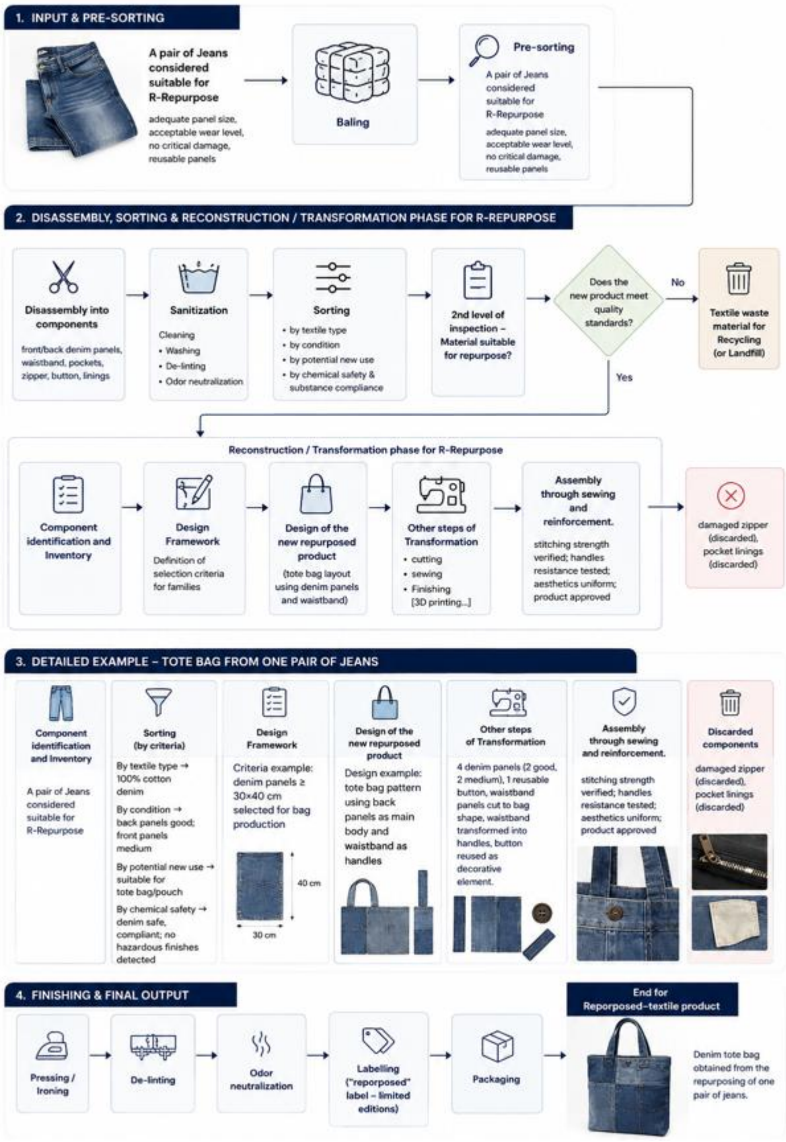



*Figure 31 - Repurpose value chain. Visual representation derived from the operational mapping activities (Example application of Post-consumer jeans)*

The representative case example based on a post-consumer pair of jeans was developed to provide a more concrete interpretation of the operational logic underlying the repurpose value chain.

The example emphasizes the component-based nature of repurpose systems, where reusable textile panels and accessories are selectively recovered, classified and transformed according to predefined design criteria. In parallel, unsuitable elements are redirected towards alternative recycling or disposal pathways, illustrating the presence of multiple decision points within the operational flow.

The case study also highlights the **intrinsic operational complexity of repurpose activities**: repurpose systems are strongly influenced by the heterogeneity of incoming textile products, the variability of recovered components and the continuous need for adaptive design decisions. The absence of homogeneous material streams makes process standardization particularly difficult and would require the integration of design-oriented competences capable of continuously identifying new reconstruction possibilities and product configurations starting from variable textile inputs.

# 4. TECHNOLOGY ASSESSMENT RESULTS

## 4.1. STRUCTURE OF THE TECHNOLOGY ASSESSMENT DATABASE (DATA FIELDS AND EVALUATION PARAMETERS)

The Technology Assessment Tool developed within the Circula-TEX project was conceived as a **structured, multidisciplinary and continuously updatable framework** designed to support the identification, classification and evaluation of technologies relevant for textile circularity and EoL textile management. From the very beginning of Task 3.1, the consortium considered the tool not as a static database, but as a "living tool", designed to evolve over time through the continuous integration of newly emerging technologies, updated technical information, additional industrial evidence and future innovation trends.

This approach was considered essential due to the rapid technological evolution characterising the textile circularity sector, where new solutions, patents and industrial applications are continuously emerging.

In general, in similar studies, one of **the main challenges was the surprising lack of comprehensive and structured sources capable of systematically collecting and organising** all the technologies and solutions currently available for textile circularity and end-of-life management.

The consortium defined **a common data structure for the Technology Assessment Tool**, designed to collect both technical and strategic information on identified technologies.

The tool was intended to integrate heterogeneous sources of evidence, including patents, scientific publications, industrial reports, project deliverables, company documentation and web-based technical sources. Particular attention was dedicated to ensuring comparability among technologies and alignment between partners.

NTT proposed from the early stages of Task 3.1 the development of a **dedicated Excel-based Technology Assessment Tool structured around a set of predefined technical, operational and strategic fields**. The objective was to create not only a repository of technologies, but also a practical assessment framework capable of supporting comparison, classification and future evaluation activities. The first structure of the tool was therefore designed by NTT based on previous technical knowledge, technology scouting experience and the operational objectives of WP3. From the operational perspective, the construction of the Technology Assessment Tool evolved progressively throughout the first months of Task 3.1

activities: since the early stages of the project, NTT proposed an initial Excel-based structure organised into multiple thematic sheets, each dedicated to a specific group of information to be collected for every identified technology. The first architecture of the tool included separate sections covering:

- General information;
- Technical features;
- Versatility and cross-applicability;
- Sources and traceability;
- Preliminary evaluation and investment-related aspects

**General Information**

| | Technology Name | Short Description | 5R Category | Stage in Value Chain | IF R-Recycling |
|---|---|---|---|---|---|
| | Name or identifier of the technology or process | Brief summary of what the technology does | Which of the 5Rs it relates to | Collection (pre-/post-consumer, post-industrial), sorting, processing, spinning, etc. | Type of Process Mechanical, chemical, enzymatic, thermal, etc |
| Technology 1 | Eeden | chemical dissolution of cotton | recycling | processing | chemical |
| Technology 2 | Induo | chemical dissolution of cotton | recycling | processing | chemical |
| Technology 3 | Infinitedfiber | chemical dissolution of cotton | recycling | processing | chemical |
| Technology 4 | Ioncell | chemical dissolution of cotton | recycling | processing | chemical |
| Technology 5 | Lenzing | chemical dissolution of cotton | recycling | processing | chemical |
| Technology 6 | Renewcell | chemical dissolution of cotton | recycling | processing | chemical |
| Technology 7 | Saxcell | chemical dissolution of cotton | recycling | processing | chemical |
| Technology 8 | Södra | chemical dissolution of cotton, chemical recyc | recycling | processing | chemical |
| Technology 9 | T-rex | chemical dissolution of cotton, depolymerisati | recycling | processing | chemical |
| Technology 10 | new cotton project | chemical dissolution of cotton | recycling | processing | chemical |
| Technology 11 | Carbios | enzymatic depolymerisation of PET | recycling | processing | chemical |
| Technology 12 | Cure | depolymerisation of PET via solvolysis | recycling | processing | chemical |
| Technology 13 | DePoly | depolymerisation of PET via solvolysis | recycling | processing | chemical |
| Technology 14 | Eastman | depolymerisation of PET via solvolysis | recycling | processing | chemical |
| Technology 15 | Gr3n | depolymerisation of PET via solvolysis | recycling | processing | chemical |

**Technology Readiness**

| | TRL | ~~Obsolescence Risk (Optional field)~~ | Deployment Status | Year of Development/New versions of the technology | Requirements for Technology Industrialization |
|---|---|---|---|---|---|
| | Standard TRL scale | ~~Low / Medium / High - subject to replacement, outdated, or emerging~~ | Lab / Pilot / Demo / Commercial / Obsolete | | If TRL < 9, what is still needed? (e.g., specialistic design support, scale-up, certification, pilot testing, funding, regulation, supply chain, etc.) |
| Technology 1 | | | | | |
| Technology 2 | | | | | |
| Technology 3 | | | | | |
| Technology 4 | | | | | |
| Technology 5 | | | | | |
| Technology 6 | | | | | |
| Technology 7 | | | | | |
| Technology 8 | | | | | |
| Technology 9 | | | | | |
| Technology 10 | | | | | |
| Technology 11 | | | | | |
| Technology 12 | 7 | | demo | 2024 | scale-up |
| Technology 13 | | | | | |
| Technology 14 | | | | | |
| Technology 15 | | | | | |

*Figure 32 - Extract of the first draft structure of the Technology Assessment Tool during the validation phase, showing examples of the Sheet "General Info" and "Technology Readiness" initially proposed for technology data collection*

During the period July - September 2025, the partners collaboratively worked on the validation and progressive refinement of the tool structure. CTB and COT contributed to reviewing the usability of the Excel structure, the clarity of the fields and the practical feasibility of data collection activities. This iterative validation phase progressively highlighted one of the main operational challenges of the assessment process: many fields were extremely difficult to populate consistently due to the fragmented and heterogeneous nature of the available information sources. In several cases, relevant data had to be reconstructed by combining patents, scientific publications, technical brochures, project deliverables and web-based industrial information, while some information - such as TRL, industrial deployment status or detailed operational specifications - was often unavailable or only partially accessible.

As a consequence, the consortium progressively simplified and reorganised the structure of the tool, removing overly complex or redundant fields and prioritising information considered more realistically retrievable and comparable across technologies. Particular attention was dedicated to **improving usability and facilitating** the practical population of the database during the scouting activities. In fact, the initial multi-sheet structure was progressively replaced by a **single-sheet logic integrating all the main technological information within one unified table**. This decision emerged from practical testing activities carried out during the first rounds of technology insertion. The consortium observed that continuously moving across different sheets complicated the identification and traceability of technologies, increased the risk of inconsistencies and reduced the overall readability of the database. The transition towards a single-sheet structure therefore significantly improved usability, visibility of information and operational efficiency during data entry and comparison activities, while also facilitating the future integration of automated or semi-automated data extraction workflows from patents and multi-source analyses.

The selected and validated fields of the final table structure aimed to capture:

- the technological identity of the solution (technology name, description, working principle);
- its position within the textile circular value chain (5R category, operational stage, pretreatment/treatment phase);
- the technical applicability (compatible fibres, input material requirements, treated textile waste types, outputs generated);
- operational and industrial aspects (processing capacity, minimum feedstock requirements, deployment status, industrial maturity, scalability);
- innovation-related indicators (TRL, year of development, technological evolution, comparative advantages);
- circularity-oriented aspects (multi-fiber adaptability, potential for low-value textiles, transferability to different contexts);
- sustainability dimensions (energy consumption)

- preliminary indications on the economic and industrial attractiveness, including aspects such as estimated price or cost-related information, scalability potential, industrial deployment perspectives, requirements for industrialisation maturity level and possible relevance for future EPR-related investments.

## 4.2. OVERVIEW OF IDENTIFIED TECHNOLOGIES

The technology scouting and monitoring activities carried out within Task 3.1 have made it possible to systematically map the global landscape of textile innovations. Through an integrated methodological pipeline - which combined the rigor of quantitative patent analysis with the semantic and qualitative exploration of multi-source data such as scientific literature, industrial reports, and technical market documentation - the consortium developed a comprehensive repository of technologies relevant to textile EoL management and circular value chains.

This knowledge repository, which flowed into the Technology Assessment Database, was subsequently subjected to a rigorous pre-filtering and cleaning phase. This operation was essential to eliminate terminological redundancies and purely incremental or marginal innovations that would not have brought real added value to the consortium's sustainability goals.

The resulting Technology Assessment Database includes 138 technologies and constitutes one of the main outputs of Task 3.1. The complete database is provided in Annex 3 of this deliverable.

To provide a clear, coherent, and easily accessible overview for stakeholders, the resulting leading technologies have been reorganized from the initial 5R categorization into four main process-based macro-domains.

This strategic shift stems from an in-depth functional analysis of the collected technologies. The analysis revealed that categorizing strictly by individual "-R strategy" did not accurately reflect the actual engineering nature of the processes. Specifically, the core modification mechanisms underlying "Repair", "Reuse", and "Repurpose" actions involve physical interventions that are intrinsically the same as, and entirely assimilable to, the operations performed in mechanical recycling (e.g., cutting, physical disassembly, material restructuring). Therefore, rather than separating them based on their circular outcome, it was decided to consolidate all these physically driven solutions into a single, comprehensive cluster named Mechanical-R.

This reorganisation also reflects what emerged from stakeholder consultations conducted in other project activities (Work Package 1): the consortium progressively realised that circular pathways and technological domains are not perceived, nor do they evolve, as completely separate systems. In practice, technologies supporting reuse, repair, refurbish, remanufacture and repurpose activities are often closely interconnected with recycling systems, either because they share common operational steps or because they ultimately interact with the same material flows. As a consequence, the boundaries between individual circular strategies become progressively less distinct when technologies are analysed from an engineering and process perspective.

This finding further confirmed that recycling should not always be interpreted as an isolated circular pathway, but rather as a technological domain that frequently embeds, supports or complements activities traditionally associated with other life-extension strategies. In many cases, technologies originally linked to reuse, repair or repurpose activities rely on the same physical transformation principles and industrial equipment found within recycling systems.

Applying the same functional rationale to the rest of the database, the remaining clusters were defined by their core operational mechanisms:

- Technologies altering the material at the molecular or polymeric level - whether via solvents, enzymatic depolymerization, or extreme heat (pyrolysis/gasification) - were grouped under Chemical and Thermochemical Recycling, as they all dismantle the fiber's chemical structure.
- Solutions relying on the melting, reactive extrusion, and phase changes of synthetic polymers were classified as Thermomechanical Recycling, representing a distinct engineering approach that bridges physical shredding and chemical synthesis.
- Finally, advanced optical, robotic, and AI-driven identification systems were isolated into the Sorting Technologies cluster. Rather than modifying the textile, these technologies act as the universal enablers and decision-making gateways that route the feedstock toward the most appropriate circular pathway.

The following sections provide a detailed and structured analysis for each of the four identified technological clusters: Chemical and Thermochemical Recycling, Mechanical-R (encompassing Mechanical Recycling, Repair, Reuse, and Repurpose), Thermomechanical Recycling, and finally Sorting Technologies, whose solutions and specificities can be fully consulted within the Technology Assessment Database. For each cluster, the discussion combines aggregate quantitative metrics—aimed at mapping the distribution of solutions by value chain phase, Technology Readiness Level (TRL), and domain specificity—with an extensive descriptive and narrative overview of the individual surveyed properties and applications.

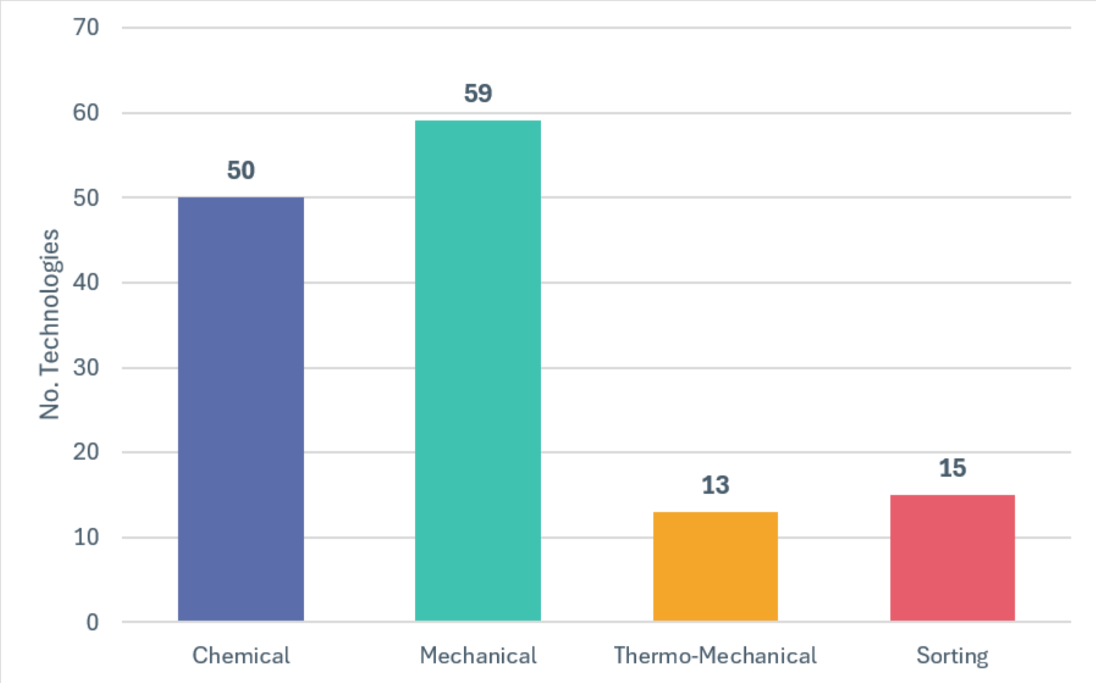



*Figure 33 - Technology Volume by Macro-Cluster*

### 4.2.1. CHEMICAL (AND THERMOCHEMICAL) RECYCLING

The macro-cluster dedicated to Chemical (and Thermochemical) Recycling comprises a subset of 50 pre-filtered technologies. The quantitative and statistical analysis of this area provides a clear snapshot of the state of the art for the molecular and thermal conversion industry:

- **Total number of technologies:** The database includes 50 unique solutions (chemical, enzymatic, thermal, and thermochemical).
- **Distribution by Value Chain:** The vast majority of innovations (45 technologies) are positioned in the *Processing* stage (the actual molecular or thermochemical transformation). Upstream of these processes are the *Pretreatment* (3 technologies) and *Disassembly* (1 technology) phases, while downstream we find advanced refining systems classified as *Processing/Refining* (1 technology).
- **Distribution by TRL (Technology Readiness Level):** The sector demonstrates a solid transition toward industrialization. There are 9 technologies at the Commercial level (TRL 9) and 2 in the pre-commercial or advanced Demo phase (TRL 8). The core consists of technologies in the Demo or Pilot phase (18 solutions at TRL 7 and 3 at TRL 6). In the laboratory validation phases, we find 1 technology at TRL 5 and 1 at TRL 4 (linked to the thermal delamination of coatings). For the remaining technologies (often stemming from very recent patents or startups in stealth mode), the TRL has not yet been formally declared, but they are estimated to be between the pilot phase and initial industrialization.

- **Distribution by 5R Category:** Given that these are intensive deconstruction processes, all 50 technologies fall under the *Recycling* macro-strategy.
- **Distribution by Technology Domain:** The technological domain is divided between purely chemical/enzymatic processes (44 technologies) and heat-driven approaches, with 6 solutions classified as *Thermal* or *Thermochemical*.

Below is a detailed and descriptive mapping of each of the 50 surveyed solutions, structured by supply chains, technical approaches and material families.

***Solutions for Cellulosic Dissolution and Cotton Valorization***

The first major pillar addresses the recovery of discarded cotton and cellulosic fibers through dissolution processes that transform the raw material into textile pulp. Within this scope, well-established commercial solutions at TRL 9 stand out, such as **Circulose** (formerly Renewcell), which dissolves cotton-rich textiles, converting them into pulp sheets suitable for the production of cellulose-based yarns, with the goal of expanding its capacity to 120,000 tonnes per year by the end of 2026. A similar level of maturity is demonstrated by **OnceMore** (developed by Södra, 6,000 tonnes per year), which dissolves the cellulosic component from poly-cotton blends, isolating PET for energy recovery. Rounding out the landscape of commercial technologies is Lenzing's **Refibra**, an established process that utilizes N-methylmorpholine N-oxide to recycle pre- and post-consumer cotton within the lyocell supply chain (LENZING™ ECOVERO™). Moving toward demo and pilot levels (TRL 7-8), **Infinited Fiber**'s highly regarded technology chemically removes dyes and polyester, subsequently activating cellulose at a molecular level to generate Infinna™ fiber. A similar engineering pathway is followed by **SaXcell**, which boasts an industrial plant nearing completion in the Netherlands (750 tonnes/year). Moving toward the pilot stage, **Ioncell** (which utilizes ionic liquids to spin post-consumer cotton) and **Refact - Induo** emerge, the latter capable of creating a bi-component fiber without requiring prior sorting by color or button removal. The exploration continues with regeneration-specialized solutions such as Nucycl (Evrnu), **Renasens, AeoniQ™**, and **Re-SanPulp™** (Re-flesh Global). Innovation then extends to hydrolytic processes like **Revalyu** and the **ShareTex** system (TRL 5), which hydrolyzes degraded cotton into sugar solutions for the chemical industry.

***The Depolymerization of Polyester (PET) and PLA***

The largest segment of the cluster is dedicated to the chemical breakdown of polyester (PET) through hydrolysis, glycolysis, and methanolysis processes. At the commercial level (TRL 9), **Carbios**'s low-temperature enzymatic hydrolysis (50,000 tonnes per year) and **Eastman**'s methanolysis in Tennessee (110,000 tonnes/year) stand out. A similar success is recorded by **Loop Industries**, whose methanolysis reduces emissions by 81% (70,000 tonnes across Canada and India), and by **HTEX** (8,000 kg per day for uniforms and workwear).

At a highly advanced demo level (TRL 8), we find **Rewind PET (Axens)**, which employs glycolysis on 30,000 tonnes annually (aiming for 80,000 in France), and **Gr3n**, which applies microwave-assisted alkaline hydrolysis. Along the pilot and demo pathway at TRL 7, the landscape is populated by numerous competing industrial solutions such as **DePoly** (room-temperature hydrolysis), **CuRe** (partial alcoholysis), **ChemPET** (Garbo/Saipem), the Dutch company **Ioniqa**, and the French company **Recyc'Elit**, which boasts the ability to keep any co-materials like elastane intact and reusable. Ambitious projects are also being driven forward by **Reju, Matterr, Poseidon Plastics,** and **Rewin**. Finally, in the polylactic acid segment, the **Noocycle** technology (TRL 7) comes into play, focusing on the selective alcoholysis of PLA.

***Treatment of Polyamides (Nylon), Acrylics, and Polycotton Blends***

The recycling of polyamides (PA6 and PA6.6) finds its commercial benchmark in Aquafil's **Econyl Regeneration System** (hydrolysis of PA6 from fishing nets and carpets) and in BASF's **Loopamid** technology, a hydrolytic depolymerization process that cuts emissions by 70% and chemically separates elastane from blends. In the pilot segment (TRL 7), standouts include **REC / écollant** for PA6/elastane blends, **Toray Europe, Epoch Biodesign** (enzymatic depolymerization of Nylon 6.6), **Solvay**'s processes (Rhodianyl), the emerging French company **Syntetica**, and the innovative **Regel**, specializing in the complex depolymerization of acrylics. On the polycotton front, pilot solutions emerge such as **Worn Again** (a 1,000-tonne demo facility), **Phoenxt**, **Dissolva** (which employs the green solvent Cyrene), and Avantium's **Dawn Technology**. Also of strategic importance are the patents integrated into the database: patent **US20230069369 A1** for separation in ionic liquids, **WO2024260883 A1** for multi-stage spectroscopic and chemical filtration, and patent **EP3835347A1** for increasing the intrinsic viscosity (IV) of PET under vacuum.

***Thermal and Thermochemical Innovations: Gasification, Pyrolysis, and Disassembly***

The most recent evolution of the cluster concerns treatments that leverage heat not only to melt but to disassemble garments or to trigger deep chemical reactions (Thermochemistry), overcoming the limitation of inseparable or highly contaminated blends.

In the field of thermal pre-treatment and disassembly, **Resortecs**' pilot technology (TRL 7) stands out. By using special heat-dissolvable sewing threads (SmartStitch), garments are passed through ovens between 150°C and 200°C: the threads melt, automatically releasing zippers and buttons at a speed 15 times faster than manual methods, ensuring a stream purity exceeding 90%.

Still in the preparatory phase (TRL 4), the **Indar** technology applies thermal action at 180°C to activate a primer capable of chemically delaminating polyurethane (PU) coatings from the textile substrate.

When textile waste reaches the limits of traditional chemical recyclability (for example, the waste residues from cellulosic dissolution itself), advanced Thermochemical Recycling takes over. The alliance between **Renewcell** and **Valmet** aims specifically to use pyrolysis to convert the unrecyclable residues of the Circulose process into bio-oil, creating a true zero-waste ecosystem. Similarly, consortia such as **Hitachi Zosen & Jeplan** utilize ultra-high-temperature pyrolytic gasification in the absence of oxygen to vaporize complex polyester blends and convert them into a combustible gas (syngas). This extreme approach is also shared by American startups such as **Tereform**, whose catalytic oxidation or gasification technology seamlessly tolerates highly mixed textile inputs, bypassing the historical limitations posed by the presence of stubborn dyes and high concentrations of spandex (elastane).

### 4.2.2. MECHANICAL RECYCLING

The macro-cluster dedicated to Mechanical Recycling and Pre-treatments comprises a subset of 59 pre-filtered technologies. The quantitative and statistical analysis of this area provides a broad overview of a traditional sector that is reinventing itself through engineering and digital hybridization:

- **Total number of technologies:** The database includes 59 solutions and patents related to mechanical methodologies.
- **Distribution by Value Chain:** As evidence of the extreme fragmentation of mechanical recycling, the technologies cover a wide spectrum of operational stages. Among the densest clusters are the primary and secondary transformation phases, namely *Processing / Crushing / Spinning* (14 technologies), the *Manufacturing and end-of-life* phase (10 technologies), the crucial *Pre-treatment and Disassembly* (11 technologies), and the combined phases of *Sorting, Collection, and Channelling* (9 technologies). Rounding out the picture are innovations aimed at *Finishing and Dyeing* (4) and further *hybrid preparatory stages* (11).
- **Distribution by TRL (Technology Readiness Level):** Since a large portion of the database consists of recent engineering patents whose commercial deployment status has not been publicly declared (53 entries with no explicit TRL), 6 technologies with verified TRLs distinctly emerge, ranging from validation in a relevant environment (TRL 5) to established commercial solutions (TRL 9).
- **Distribution by 5R Category:** The primary purpose is undoubtedly Recycling (40 technologies), followed by approaches aimed at Remanufacturing (7) and Repurpose (6). Finally, we find cross-cutting tools suitable for Reuse / Reduce / Sorting frameworks (6).
- **Distribution by Technology Domain:** The technological domain is heterogeneous but firmly rooted in physical principles: 50 technologies are classified as purely mechanical, while 9 patents rely on hybrid processes to optimize yield (*Mechanical / Thermal*, *Mechanical / Chemical*, *Mechanical / Cryogenic*, and *Hydroentanglement*).

The mechanical cluster is no longer limited merely to textile shredding; instead, it describes an industry undergoing a profound transformation, where Artificial Intelligence, advanced robotics, and materials science step in to digitalize production lines, improve fiber purity, and generate novel composite products.

***Automation, Computer Vision, and Intelligent Sorting***

The integration of advanced software and robotic hardware is redefining the pre-recycling phases. In this field, algorithms such as **GSL-YOLOv8n** stand out—a lightweight deep learning model capable of visually inspecting fabrics in real time with an accuracy of 98.29% to discard defects or anomalies. This predictive logic merges with cutting machinery in the patent **Integrated fabric defect detection and cutting system (CN 113403831 B)**, which leverages robotic arms and algorithmic computations to bypass defects, thereby minimizing waste.

Downstream, the challenge of handling limp fabrics (a historical barrier in robotics) is addressed by **Soft Robotic Grippers**—electro-adhesive grippers capable of moving deformable garments without damaging them, enabling sorting tasks that were once exclusively manual. On the pure sorting front, the **Cloth waste sorting machine** (with color sensors) (**CN205042764U**) emerges, and most notably, the open-source solution by **CISUTAC**—a strategic decision-making tool to channel waste toward reuse, repair, or recycling pathways, laying the groundwork for the Digital Product Passport (DPP).

For advanced inspection (specifically for carpets and complex plastic polymers), the **Method for the automatic analysis of polymer-containing waste** (**EP1522851_A1**) utilizes mass spectrometry on laser-vaporized samples to distinguish chemically similar polymers such as PA6 and PA66.

***Pre-treatment, Innovative Disassembly, and Extraction***

Garment preparation is the key to preserving mechanical fiber length. **Laser shredding** deconstructs fabrics using air jets and laser beams without the use of water. A paradigm shift is represented by thermo-mechanical disassembly (*Design for Disassembly*) using engineered yarns or zippers: **Wear2** disintegrates stitched threads via microwaves, while the technology titled **Biomedical applications of thermally activated shape memory polymers** leverages Shape Memory Alloys (SMA) to unseam or detach buttons from the garment simply by altering its temperature, ensuring the perfect recovery of hardware components.

Regarding pre-recycling cleaning, notable developments include the removal of coatings (e.g., PU or PVC) using localized solvents (**CreaSolv** and **PolySep** technologies) and the technology **A novel approach for textile cleaning based on supercritical CO2 and Pickering**

**emulsions**, which eliminates both hydrophilic and hydrophobic dirt without water. For the management of depleted bobbins in the spinning industry, the patent **Cutting device for cleaning waste yarn (CN221756117U)** employs "floating" rotary blades to remove residues without damaging the cores.

***Innovations in Shredding and Spinning Machinery***

On the core shredding front, compact and multi-functional engineering systems are emerging, such as the **Textile waste recycling machine with reciprocating opening function**, which combines beating, pulling, and magnetic screening for felts and non-wovens. For tough and ultra-high-density fabrics (e.g., automotive airbags and seat belts), the **Method for producing a thread from textile waste from motor vehicles** adopts sequential pulling phases using lubricants to produce high-tenacity yarns. Other innovations aim to preserve fiber length (such as the **Method for producing spinnable fibers using high-count and high-density fabric waste**, which uses fluids to facilitate opening), while the **ADuro Shredder** ensures shredding and the removal of hard parts in a single pass.

Noteworthy is the cryogenic approach of the **Oscillating follow-up processing device for textile waste**: by freezing the fabric in liquid nitrogen, the material becomes a brittle polymer and shatters easily without tangling in the blades. In the spinning segment, innovations focus on waterless and chemical-free processes (e.g., **Yarn manufactured from recycled clothing fibers**, where the blend reaches up to 95% pulled fiber), or on the optimization of legacy machinery, such as the **Card with Fixed Carding Flats**, equipped with inclined-blade flats to discard less "good" material and eject impurities.

***Manufacturing Processes for Upcycling and Non-Wovens***

When fibers are too short or blended, mechanical recycling consolidates them into new composites and felts (Manufacturing). Needle-punching techniques combine waste and dead stock to create insulating non-wovens (as described in the **Process to regenerate woven and knit fabric (US 2024/0351304 A1)**). Several patents transform textile waste into panels and components for the construction and automotive sectors: **Composite Building Materials, Carpet Waste Composite,** and **the Method for producing a honeycomb core** form layered thermo-acoustic structures; the **Integrated Insulation Finishing Material** hot-presses polyester to create an insulating formwork to be covered directly with concrete, while the patent for **Multi-Functional Automotive Flooring** hot-presses residues to generate flooring without additional aesthetic layers.

Also utilizing thermomechanical presses and polymeric binders, the methods within **Method of producing rigid package material and rigid box** transform shredded cotton blends into thin **1–3 mm** panels to replace packaging cardboard and MDF furniture. Finally, also noteworthy is the processing of leather waste via ultra-high-pressure jets (Hydroentanglement, typical of non-wovens) described in **Waste Material Processing**.

***Hybrid Processes: Mechanics, Chemistry, and Enzymes***

The mechanical domain expands, extending into auxiliary chemical and thermal treatments. For complex polycotton and mixed blends, alkaline hydrolysis methods stand out (such as the **Method for the recovery of starting materials from blended textile wastes** and the use of subcritical water in **Methods for recycling cotton and polyester**). These processes successfully deconstruct the polyester by precipitating TPA while leaving the cellulose intact, enabling the recovery of both material streams.

Specific thermal solvents are employed in the **Elastane Separation Method** to extract elastane from sportswear, in the **Recycled Polyester Production Method (Teijin)**, and in the **Process and plant for removing dyes from waste textiles** to return garments to the **greige** (neutral white) stage. Furthermore, innovative wet systems regenerate high-value carbon and PAN (polyacrylonitrile) fibers from aerospace waste, utilizing organic solvents and vacuum filtration to form spinnable dopes or conductive electrothermal sheets.

Finally, the cluster includes biotechnologies for finishing: the **Eco friendly Textile Finish** (cellulase enzymes) and **Glucanases** *(*endoglucanases*)* hydrolytically break down pilling, soften the cotton, and fade garments without aggressive chemicals (e.g., ecological stonewashing), prolonging the fabric's life without compromising its mechanical strength. Concurrently, innovative processes like **Textile Color Retention** leverage powerful compressed air jets instead of water to transport dyes into the synthetic fiber, closing the loop of *Remanufacturing* with zero wastewater discharge.

### 4.2.3. THERMOMECHANICAL RECYCLING

The macro-cluster focused on Thermomechanical Recycling isolates a subset of 13 pre-filtered technologies. The statistical analysis of this cluster highlights a highly vertical sector, dominated by large-scale plant engineering firms and industrial machinery manufacturers:

- **Total number of technologies:** The database includes 13 solutions and thermomechanical extrusion systems.
- **Distribution by Value Chain:** Consistent with the nature of these technologies, almost all are positioned in the central Processing phase (11 technologies), namely the actual melting and extrusion processes. Only 2 solutions have been classified as spanning across Pre-treatment/Processing, indicating an integrated approach right from the waste preparation stage.

- **Distribution by TRL (Technology Readiness Level):** Being a sector populated by established manufacturers, the technologies with a publicly declared maturity demonstrate high industrial readiness: there are 2 technologies at TRL 9 (Commercial) and 1 technology at TRL 8 (Demo). The remaining 10 solutions do not declare a specific TRL in the database, despite being predominantly commercially available industrial machinery or proven supply-chain take-back projects.
- **Distribution by 5R Category:** All 13 technologies converge exclusively on the single category of *Recycling*.
- **Distribution by Technology Domain:** The entire cluster (13 out of 13) is uniquely identified under the *Thermo-mechanical* domain.

Below is a descriptive mapping of the surveyed solutions, structured by industrial trajectories: from closed-loop (fiber-to-fiber) recycling to the cross-sectoral valorization of blends toward the plastics industry.

***Integrated Industrial Systems for Closed-Loop (Fiber-to-Fiber) Recycling***

The core of thermomechanical recycling is represented by the transformation of thermoplastic textile waste (polyester, polyamide, polypropylene) into new filaments or pellets through the combined action of heat and mechanical stress. The primary objective of this segment is to keep the macromolecular structure and the viscosity of the polymer intact, enabling high-performance re-spinning.

In this field, the market is driven by large industrial plant suppliers. The **OMNI recycling line** by Gneuss stands out—a highly versatile system (capable of processing PET, PA, PP, PS, LDPE, and HDPE at volumes ranging from 25 to 2,000 kg/h) that integrates a rotary feeder, an MRS multi-screw extruder, and the RSFgenius automated melt filtration system. Echoing this in the ultra-high-performance arena is Erema, with its **INTAREMA® FibrePro:IV** technology, capable of processing up to 1,300 kg/h of PET while ensuring the controlled restoration of its intrinsic viscosity—a critical step for obtaining spinnable recycled fibers. The FibrePro:IV family itself finds further technological expression in the shredder-extruder machine **ISEC evo FibrePro:IV** by Pure Loop (an Erema Group company), already certified at TRL 9.

Remaining in the field of polyester and PET regeneration, the landscape offers robust commercial technologies such as **Muovi**, which ensures a throughput of 500 kg/h of post-consumer pellets (TRL 9, introduced in 2023), and widely recognized extrusion systems on the market like the **Vacufil** line by BB Engineering GmbH. The systemic approach to the supply chain is instead championed by major players in fiber production: **Antex** manages a 2,400-tonne-per-year extrusion and filament system (associated with the ATEVAL initiative in home textiles); **DS Fibres** focuses on thermomechanical lines capable of processing both polyester and bioplastics like PLA; and the renowned **UNIFI REPREVE® Takeback** program integrates mechanical and thermomechanical methodologies to maximize the reuse of recovered polyester.

***Reactive Extrusion, Compounding, and Downcycling (Open-Loop)***

An inherent limitation of thermomechanical extrusion is its sensitivity to mixed materials: elastane, cotton, or other contaminating fibers can drastically alter the quality of the melt. However, the database shows how several companies are overcoming this obstacle by developing processes to create plastic compounds intended for the molding industry, foregoing textile spinning in favor of open-loop recycling.

The most prominent example in this direction is provided by Mapea (also present in the database as **Textium® Mapea**). This technology (TRL 8, 2024) employs a reactive extrusion and compatibilization approach to process heterogeneous waste and fiber blends containing cotton, polyester, polyamide, and elastane, thereby supplying new materials directly to the plastics industry. Operating along the same strategic line is **Cycl-add** (introduced in 2022), which specifically addresses the challenge of recovering stretch nylon by melting and extruding PA/elastane blends to transform them into industrial plastic compounds as well. The importance of this polymer hybridization phase is further confirmed by the technologies of **Binova**, which develops and supplies complete lines for compounding and recycling.

Finally, to manage the purely physical challenges of the waste—such as shredded materials with extremely low bulk density, which struggle to consistently feed extruders—Davis-Standard's **Scrapper** technology comes into play. Thanks to a dual-diameter extruder and grooved feed technology, this machine is specifically designed to ingest voluminous, low-density feedstock, directing the recycled raw materials toward bulk manufacturing or downcycling applications.

### 4.2.4. SORTING

The macro-cluster dedicated to Sorting Technologies (Automated Sorting and Pre-treatment) gathers a subset of 15 pre-filtered technologies. The statistical analysis highlights a highly homogeneous yet essential ecosystem, acting as a universal enabler for the entire value chain:

- **Total number of technologies:** The database includes 15 unique solutions, comprising industrial machinery, process patents, and intelligent software.
- **Distribution by Value Chain:** The vast majority (13 technologies) are concentrated exclusively in the primary *Sorting* stage. These are accompanied by 1 technology classified under *Pre-treatment* (hardware removal) and 1 interface solution classified as *Sorting/Pre-treatment*.
- **Distribution by TRL (Technology Readiness Level):** The ecosystem is driven by major players in the waste management sector. We explicitly find 2 established

commercial technologies (TRL 9), while the remaining 13 entries (lacking a declared TRL in the datasheet) predominantly belong to companies already operating on the market with automated lines, recent patents, or optical sensors borrowed from plastic recycling and repurposed for the textile sector.

- **Distribution by 5R Category:** All 15 solutions are transversally classified as *ALL potentially*. Indeed, sorting does not belong to a single "R," but rather represents a preliminary decision-making hub (*enabler*) that is vital for any subsequent phase of reuse or chemical and mechanical recycling.
- **Distribution by Technology Domain:** The entire cluster (15 out of 15) falls uniquely under the specific functional domain of *Sorting*.

Below is a descriptive mapping of the surveyed innovations, exploring the evolution of optical sorting machines, the integration of AI, and hybrid and pre-treatment systems.

***Advanced Optical Systems and Hyperspectral Imaging (HSI)***

Sorting technologies act as the entry filter to enable subsequent chemical or thermomechanical recycling processes, which require raw materials of the highest purity. To overcome the inefficiency and slowness of manual sorting, the industry has rapidly adopted high-speed automated solutions. Two of the main commercial players (TRL 9) stand out in this area: **PICVISA ECOSORT** and TOMRA's **AUTOSORT**. The ECOSORT system processes between 2.5 and 3 tonnes of dry garments per hour, leveraging RGB cameras paired with robust near-infrared hyperspectral technology (NIR at 1000–1700 nm) to analyze fiber composition on the fly and sort garments into their respective streams. Similarly, TOMRA's AUTOSORT solution (capable of 4.5 tonnes per hour) relies on ultra-high-precision visual and NIR spectrometry, with a special focus not only on fibers but also on identifying impurities, plastics, and metals that are harmful to the shredding process.

A similar approach is adopted by the established **Fibersort** machinery (by Valvan Baling Systems), which, thanks to hyperspectral camera tracking, scans materials at a speed of approximately 1 garment per second (up to 900 kg/h), separating them by combinations of composition and color. The same framework underpins massive, fully automated facilities like the **Siptex sorting facility** (estimated at 24,000 tonnes per year, at 4.5 t/h) and highly modular solutions designed for already shredded fabrics, such as the **REDWAVE TEX** systems (over 3 t/h). Beyond large European facilities, Northern European joint ventures such as the integrated optical system by **Norsk Tekstilsortering (NTS) + HySpex** also propose the large-scale industrial application of hyperspectral imaging.

***The Evolution Toward AI and the Management of Heterogeneous Waste***

While optical technology enables excellent processing speeds, it also exhibits clear physical limitations: NIR sensors can barely detect marginal fiber percentages (such as elastane at less than 5%), struggle to penetrate multi-layered garments, and are literally "blinded" by black or very dark fabrics. To overcome these obstacles, predictive logic and algorithmic automation step in. Solutions like **Databeyond Technology** fuse HSI and Artificial Intelligence to process 2 tonnes per hour, allowing the machine to progressively learn and predict blend ratios even in edge cases.

Systems based on recent patents (e.g., the *Photoelectric sorting machine for sorting of homogenized waste*, originally designed for low-value plastics) and the patent for an *Automated sorting system* (for the optical and pneumatic separation of heterogeneous 2D and 3D mixes) further confirm the growing integration between deep learning and optical sensors. In the field of applied robotics, the company **NewRetex** goes beyond simple visual classification, promising fully autonomous robotic sorting based on material, composition, and color (currently operating at around 200 tonnes per month).

***Deep Contaminant Analysis and Pre-treatment (Hardware Removal)***

Beyond fiber sorting, a recycler's true nightmare is the presence of "hard" contaminants (metal zippers, buttons, rigid trim) or toxic residues that can damage chemical reactors and break thermomechanical extruders. This challenge is addressed by technologies focused on metal detection and early-stage processing, such as machinery by **Loptex** (specialized in optical inspection and inlet contaminant removal) and, for heavy-duty industrial applications, X-ray systems (**XRF/XRT**) by **SGM Magnetics**, which are capable of revealing heavy metals and deeply embedded hardware "in transparency" where NIR fails.

To facilitate post-scanning disassembly, machinery such as **Trimclean** emerges, moving from the sorting hub to the pre-treatment stage by automating the cutting and physical removal of zippers and decorations (a TRL 7 installation is currently in operation at Brightfiber/Wieland). Finally, fully coupled industrial systems serve as a solid bridge between these two phases, such as the integrated NIR and pre-treatment lines jointly developed by **ANDRITZ & Pellenc ST**, which close the loop by delivering a raw material that is not only well-sorted but also partially decontaminated for its subsequent circular journey.

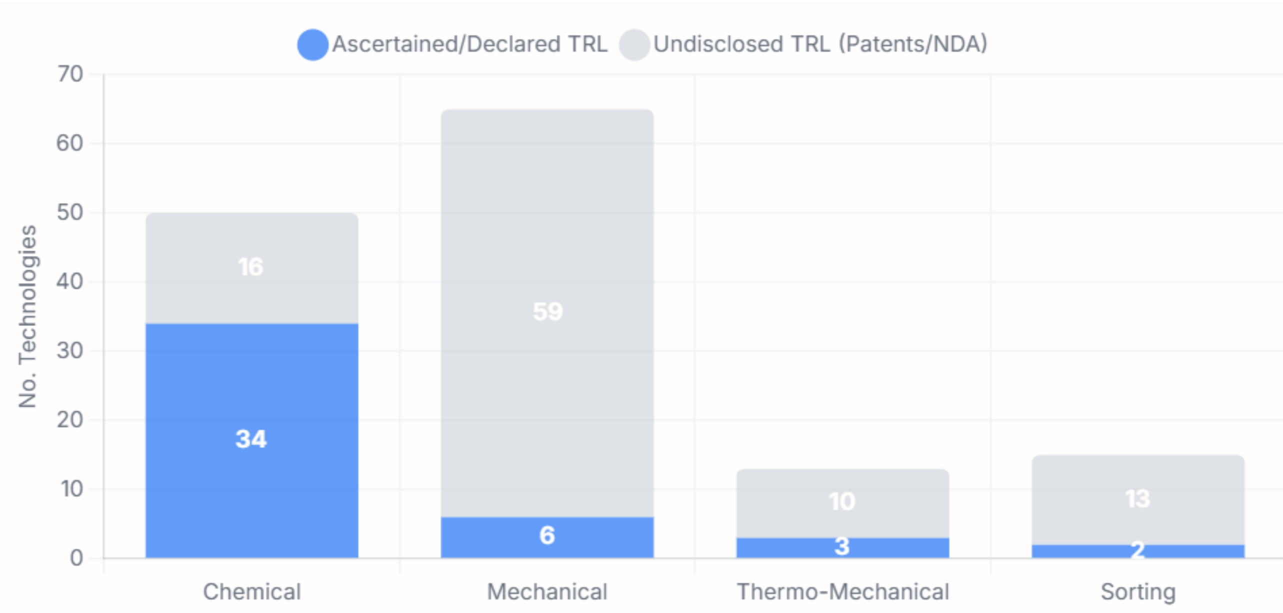



*Figure 34 - TRL Transparency (Maturity). Comparison between technologies with an established public TRL and patents/technologies with undisclosed TRL*

## 4.3. OVERALL ANALYSIS OF THE IDENTIFIED TECHNOLOGIES (TECHNOLOGY MATURITY AND INNOVATION TRENDS, KEY TECHNOLOGICAL DOMAINS EMERGING FROM THE ANALYSIS)

The analysis of the technologies identified within the Technology Assessment Database provides a snapshot of a sector in profound transition. The textile recycling and recovery industry is leaving behind the pure academic research phase (TRL 1-4) to focus on a massive industrial scale-up and validation in an operational environment.

Observing the distribution of Technology Readiness Levels (TRL), where available, a clear polarization emerges:

- ➔ On the one hand, mechanical and thermomechanical recycling rests on mature plant engineering foundations (often at TRL 9), but the true innovation in these fields is incremental in nature and is focusing on efficiency optimization and the integration of smart sensors to minimize fiber loss.
- ➔ On the other hand, chemical and thermochemical recycling is experiencing a technological boom: the majority of solutions are concentrated in the TRL 6-8 range (pilot and demo phases). This indicates that the next 3-5 years will be crucial for the commercial consolidation of technologies capable of handling complex blends (such as polycotton or elastane mixes), historically considered the main hurdle toward full circularity.
- ➔ A further macro-trend is the strong hybridization of processes: the industry is no longer speaking of solely mechanical or chemical solutions, but rather of integrated approaches where, for example, mechanical action is supported by ionic liquids, thermal solvents, or cryogenic systems.

From the categorization of 138 pre-filtered technologies analyzed across the four main clusters, several key technological domains have emerged. These will act as catalysts for the implementation of the 5R framework and future European regulations on Ecodesign and Extended Producer Responsibility (EPR):

- **Automated sorting:** Manual sorting currently represents the main economic and logistical bottleneck of the supply chain. Emerging technologies are automating this phase through the massive use of robotics and pneumatic ejection systems capable of processing several tonnes per hour. Automation concerns not only whole-garment sorting but also pre-treatment phases, such as the automated removal of hardware (zippers, buttons) or smart cutting based on the preventive identification of defects.
- **AI-assisted sorting:** Closely linked to automation, the use of Artificial AI and deep learning is revolutionizing sorting precision. Algorithms no longer merely recognize a color; they cross-reference visual and chemical data to predict blend ratios even in partially overlapping or deformed garments, minimizing sorting errors that would contaminate downstream chemical reactors or extruders.
- **Fiber identification:** Accurate fiber identification is the prerequisite for any fiber-to-fiber recycling. Beyond traditional NIR technology, the domain is evolving toward Hyperspectral Imaging (HSI), X-rays (XRF/XRT) for detecting deep contaminants, and mass spectrometry. These evolutions are crucial to overcoming the historical limitations of optical sensors, such as the inability to penetrate multi-layered garments or correctly read black-dyed fabrics.
- **Solvent-based recycling:** Within chemical recycling, solvent-based processes (solvolysis, glycolysis, methanolysis, and cellulosic dissolution) represent the most promising frontier. This domain is strongly emerging due to its capacity to act selectively: for example, it allows cotton to be dissolved while leaving polyester intact, or elastane to be broken down without damaging polyamides. Solvent-based processes (*mild processes*) are also evolving to operate at low temperatures and atmospheric pressure, drastically reducing the energy footprint compared to virgin yarn production.
- **Melt processing:** The extrusion and melting of thermoplastics (PET, PA, PP) are making enormous strides. Emerging domains in thermomechanical recycling focus on controlling and increasing the intrinsic viscosity (IV) of the melt through solid-state or vacuum polycondensation, which is essential for ensuring high-tenacity yarns. In parallel, reactive extrusion is establishing itself as a bridging solution to convert unspinnable textile blends into plastic compounds for industrial molding.
- **Tracking systems & Digital Product Passport (DPP) integration:** The circular transition cannot occur without traceability. The technological infrastructure is shifting from solely physical hardware to data architecture, developing IoT systems, cloud platforms, and interchange protocols. These systems are preparatory to the adoption of the DPP: embedding data on chemical composition, origin, and use history within the

garment will allow future sorters to completely bypass the fiber identification phase, making End-of-Life (EoL) operations incredibly faster, more reliable, and economically sustainable.

To support this overarching vision and provide empirical evidence of the dynamics just described, the analysis of patent literature represents an indispensable investigative tool. While the technological assessment outlines theoretical development trajectories, the Patent Trend Analysis objectively certifies where the industry is concentrating its capital for scale-up. As an example, a specific case study on the Mechanical Recycling domain is presented below: the examination of patent filings will demonstrate, backed by data, how the macro-trend of physico-chemical hybridization is already operationally transforming industrial processes to overcome the historical limitations of fiber-to-fiber recovery.

### 4.3.1. CASE STUDY OF THE TREND ANALYSIS ACTIVITY WITHIN THE TASK 3.1: MECHANICAL RECYCLING

As highlighted in the general analysis, mechanical recycling is addressing optimization challenges to overcome its historical limitation: the breakage and shortening of fibers during the processing phase (pulling/garnetting). Since the quality of the regenerated yarn depends directly on the length of the extracted fibers, today's engineering goal is no longer merely to "open" the fabric, but to do so in a non-destructive manner. The analysis of the patent landscape in this specific domain reveals a radical paradigm shift that confirms the macro-trend of technological hybridization.

***Patent Evidence and Chemical-Mechanical Hybridization***

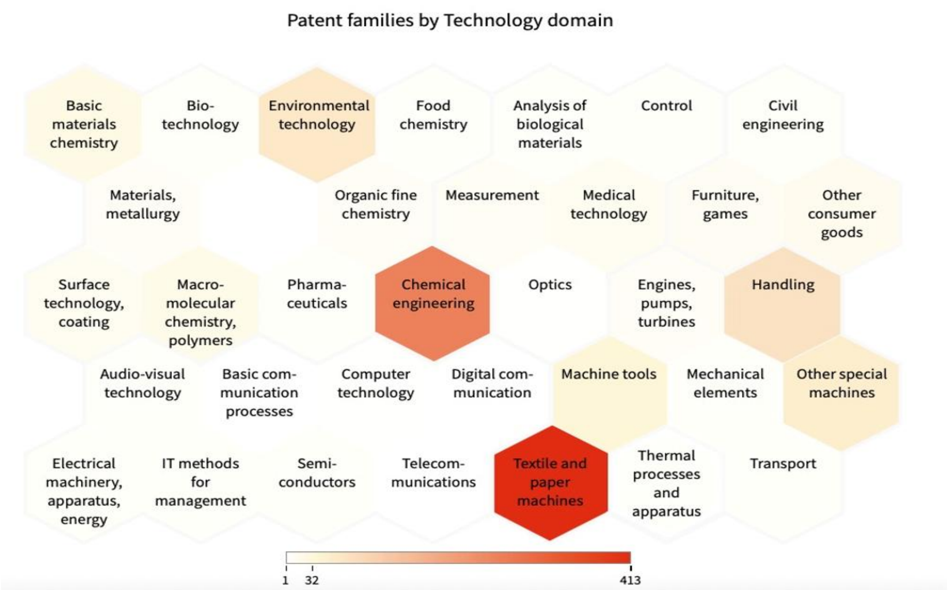



*Figure 35 - Heatmap of patent distribution for specific technology domains (IPC/CPC) in mechanical recycling*

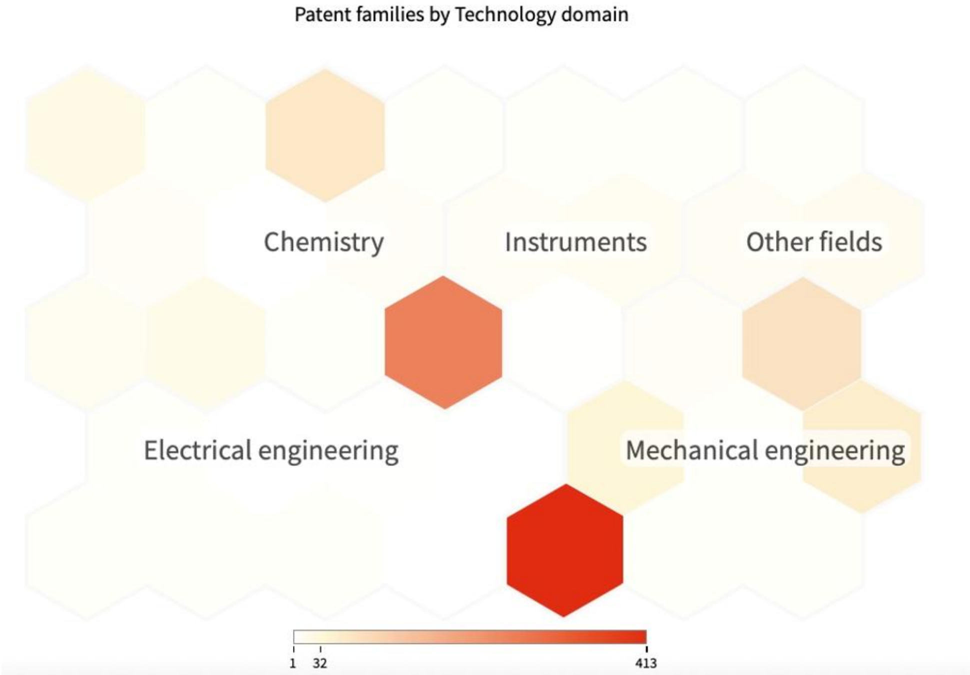



*Figure 36 - Aggregation of patent families by technological macro-areas*

Although the recycling is defined as "mechanical," the analysis of technological domains (IPC/CPC) shows that the pure geometric optimization of textile machinery (e.g. pins and metallic clothing) has reached a plateau. Innovation has shifted toward hybrid solutions: a striking finding reveals that as much as 23.15% of the patent families related to this process fall within the domain of Chemical Engineering.

This marks the emergence of the trend defined as Chemically-Aided Mechanical Recycling. The industry is heavily patenting pre-treatments for textile waste that utilize tribological auxiliaries, such as lubricants, softeners, or enzymatic agents. These chemical agents temporarily reduce inter-fibrillar cohesion and fiber-metal friction, allowing the fiber to "slip" out of its original weave during the action of the drum, thereby minimizing tensile stress and consequent breakage.

### *Competitive Landscape and Downstream Integration*

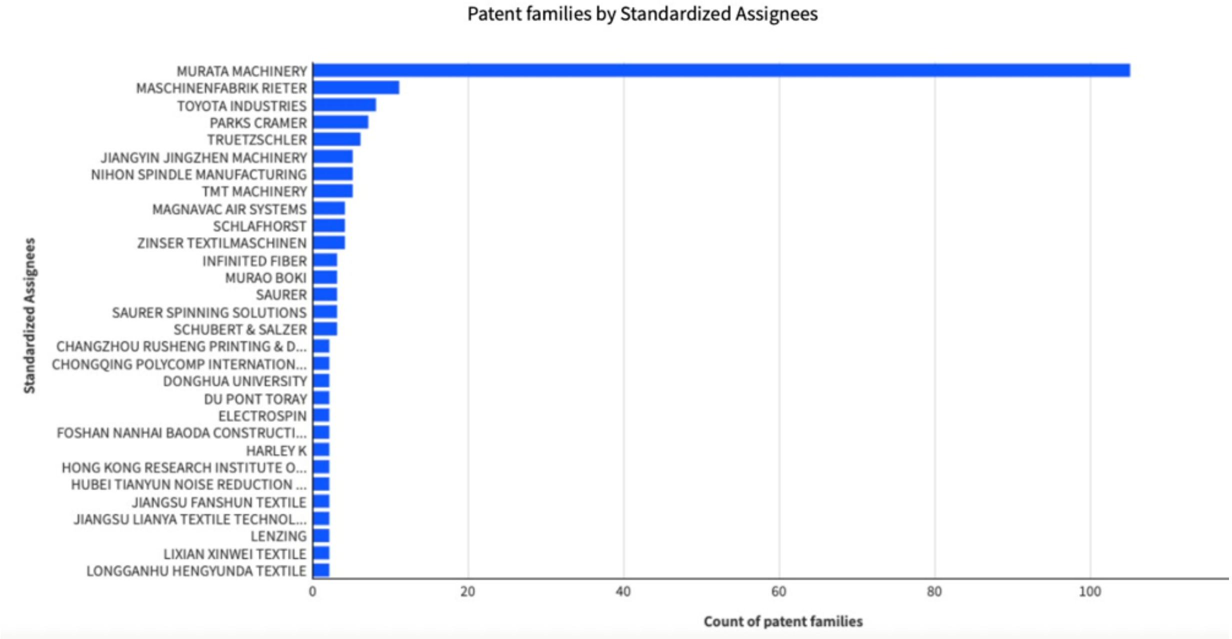



*Figure 37 - Ranking of top original assignees by number of patent families*

The evolution of the sector is confirmed by the analysis of the main patent assignees (Top Assignees). Dominating the Intellectual Property landscape are not the traditional manufacturers of recycling machinery for insulation or padding, but rather the global leaders in high-quality yarn preparation and spinning, including Murata Machinery, Maschinenfabrik Rieter, and Truetzschler.

This strategic positioning of major market players outlines two clear and closely interconnected Research and Development trajectories. On the one hand, the industry is focusing on an adaptive opening, progressively abandoning "brute" and destructive pulling in favor of technologies derived from fine carding, historically used for processing virgin cotton. The goal is to apply a mechanical action that is energetic yet meticulously controlled by sensors, capable of calibrating pressure in real time to avoid breaking the material.

On the other hand, there emerges a need for deep downstream integration between the pulling process and the spinning itself. Instead of merely seeking the perfect fiber upstream, innovation focuses on the development of advanced spinning systems—such as air-jet or vortex technologies—designed to compensate for recycling defects downstream. In fact, these machines are custom-modified to successfully capture, integrate, and valorize even sub-optimal length fibers, hiding their imperfections while still ensuring the maximum tenacity of the final yarn.

From a geographical perspective, the analysis highlights a massive concentration of patents in China, followed by Japan, India, and, to a lesser extent, Europe and the United States. This distribution demonstrates that China is evolving from a purely manufacturing hub into a primary innovation center, driven in part by state regulations on circularity. Simultaneously, Japan maintains a leadership role in high technology, propelled by historical players such as Murata and Toyota. The overall Asian predominance clearly indicates that the technologies required for large-scale processing and massive volume management are being developed and consolidated in that region.

It is essential, however, to decode the qualitative nature of these innovations: Chinese patents frequently focus on incremental process improvements, whereas Japanese and European filings tend to cover radical and architectural innovations in machinery. Consequently, an effective technological monitoring strategy must be bifocal: on one side, tracking Chinese patents to capture process optimizations (such as workflows and auxiliary chemistry), and on the other, monitoring Japanese and European players to anticipate the adoption of next-generation hardware.

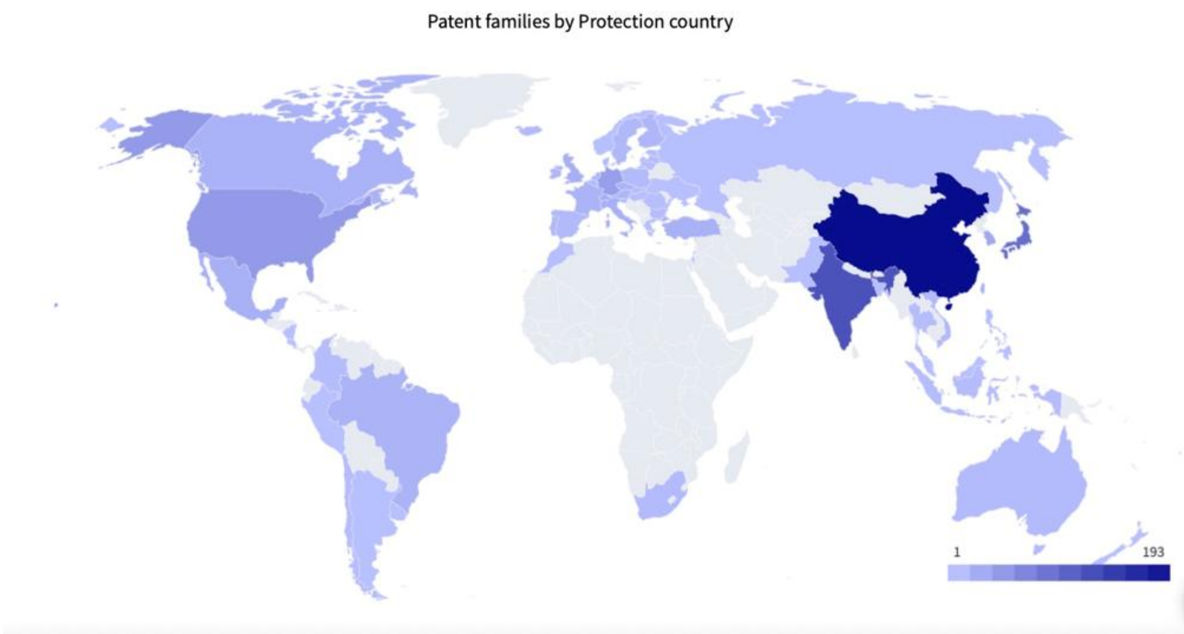



*Figure 38 - Choropleth map of the territorial extent of patent protection*

In summary, the case study on mechanical recycling empirically demonstrates how the traditional boundaries between mechanical and chemical approaches are progressively dissolving, revealing a profound and unprecedented technological convergence. The winning technology for fiber-to-fiber circularity, in fact, no longer resides in a single, isolated piece of machinery, but rather in a systemic approach that integrates a physico-chemical conditioning module followed by a digitally controlled fine mechanical opening unit.

# 5. IDENTIFICATION OF PROMISING TECHNOLOGIES

## 5.1. PROCESS AND CRITERIA FOR IDENTIFYING RELEVANT TECHNOLOGIES

As in the main scope of the task 3.1, the technology scouting and ranking activity developed were designed to identify the most relevant and promising technologies supporting circular textile systems, with a particular focus on EoL textile management and the implementation of the 5R framework (Reuse, Repair, Refurbish, Remanufacture/Repurpose and Recycling).

Thus, following the technology scouting activities carried out through patent analysis and multi-source research, the consortium collected, in January 2026, a database of 138 candidate technologies related to circular textile systems. This initial database is a broad and heterogeneous set of solutions covering different operational stages of the textile circular value chains, including collection, sorting, pretreatments, recycling processes, reuse, repair, refurbish, remanufacture and repurpose activities.

At this final stage, **the objective of the work shifted from the simple identification of technologies to a more structured process of technology selection, prioritisation and ranking**. The purpose of this activity was not to identify a single "best technology", but rather to distinguish the most relevant, promising and representative solutions for the objectives of the project and for the subsequent sustainability assessment activities developed within WP3.

The ranking activity was therefore designed as a progressive filtering and prioritisation process combining technical relevance, circularity contribution, innovation potential and feasibility considerations.

### 5.1.1. FROM TECHNOLOGY COLLECTION TO TECHNOLOGY PRIORITISATION

The consortium recognised from the beginning that the technologies collected through patents and multi-source analysis presented very different levels of:

- technical maturity;
- detail of available information;
- industrial applicability;
- innovation relevance;
- scalability potential.

In many cases, patent analysis generated large volumes of documents associated with technologies that were not sufficiently relevant for the project objectives. Several patents referred only to incremental improvements of already existing machinery or processes and did not represent meaningful advancements for textile circularity. Similarly, multi-source analysis frequently produced overlapping technologies, duplicated concepts or technologies lacking enough technical evidence to support further assessment activities.

For this reason, a ranking methodology, including cleaning activities, became necessary in order to:

- **reduce redundancy within the database**;
- identify the technologies most aligned with circular textile objectives;
- support the selection of technologies suitable for deeper technical investigation;
- prioritise solutions potentially relevant for sustainability assessment, industrial uptake and future investment considerations.

### 5.1.2. MAIN RANKING CRITERIA ADOPTED AND WORKFLOW FOR EVALUATION

The ranking process combined structured comparison criteria developed internally by the consortium and qualitative expert evaluation.

The definition of the technology ranking framework was itself developed through an iterative process involving validation rounds and methodological refinements. In the first phase, NTT proposed an initial set of evaluation criteria intended to support the prioritisation of the technologies included in the Technology Database. At the same time, operational instructions were provided to CTB and COT in order to perform offline database cleaning and preliminary harmonisation activities, aimed at reducing redundancies and improving the consistency of the collected technology profiles.

A first simplified scoring structure was then introduced based on a three-level scale:

1 = low relevance/performance;

3 = medium relevance/performance;

9 = high relevance/performance.

The adoption of a non-linear scale was intended to better highlight substantial differences between technologies and avoid excessively homogeneous evaluations.

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WP3

TASK 3.1: Technologies scouting and definition of the best available solutions

## Technology Evaluation and Prioritisation Framework

**1st suggested step**

**DATABASE CLEANING**

*Objective: define a shared approach for refining the technology database before evaluation.*

Partners @CTB, @COT are invited to work offline by:

proposing additional criteria for database cleaning, and/or

adding comments and suggestions to the criteria already listed

All inputs will be collected and discussed during the next dedicated working meeting, with the aim of reaching a shared approach.

| | Criteria |
|---|---|
| 1 | It is a duplicate (same technology already included) |
| 2 | It lacks minimum information to allow evaluation |
| 3 | ... |

**2nd step**

**SCORING OF THE TECHNOLOGIES LISTED**

*Objective: define a shared evaluation framework for comparing and prioritising technologies.*

Partners @CTB, @COT are invited to work offline by:

suggesting additional criteria where relevant.

providing comments or reflections on the existing criteria, and

proposing how the scoring scale (1–3–9) should be interpreted for each criterion

All inputs will be collected and discussed during the next working meeting, with the aim of ensuring a consistent and shared evaluation approach.

| | Criteria | Description | Note |
|---|---|---|---|
| 1 | Year | The year of development or patent publication, used as a proxy indicator of how recent the technology is. | |
| 2 | Geographic position | The geographical relevance and accessibility of the technology, particularly in relation to the European context (e.g. availability of operators, ease of contact, deployment feasibility). | |
| 3 | Cross-functionality | The ability of a technology to be applied across multiple value chain stages or for different functions (e.g. sorting, recycling, reuse). | |
| 4 | Recycling potential | Define the potential of a specific recycling solution | |
| 5 | Multimaterial | The ability of the technology to process different types of textile materials, including blends and mixed fibres. | |
| 6 | Industrial potential | The potential of the technology to be scaled up and implemented at industrial level, considering maturity, scalability, and operational feasibility. | |
| 7 | Comparative advantage | The extent to which the technology provides improvements compared to current standard solutions in terms of efficiency, cost, performance, or environmental impact. | |
| 8 | *Link with EPR requests* | The degree to which the technology aligns with the needs and objectives of Extended Producer Responsibility (EPR) schemes, including its potential to be supported, funded, or incentivised within such frameworks. | |
| 9 | ... | ... | |

Each criterion is scored using the following scale:

1 = Low

3 = Medium

9 = High

*Figure 39 - Extract of the first version of the technology evaluation and ranking framework*

This first methodological phase led to the selection of **five preliminary evaluation criteria** and enabled the consortium to launch an initial round of scoring activities.

An operational rule, introduced since the first round of evaluation, concerned the possibility for evaluators to leave specific technologies *unscored* whenever the available technical information was considered too limited or ambiguous to ensure a sufficiently objective evaluation. The workflow also included the possibility for evaluators to flag technologies *for potential exclusion from the database* in cases where the available information was too limited or where the technology was considered not sufficiently relevant for the project objectives. This criterion became particularly important because, on average, only a limited portion of the fields included in the Technology Assessment Tool could initially be filled directly through patent data alone. The integration of multi-source information therefore became essential for improving the robustness of the technology profiles.

This approach was adopted to reduce the risk of forced or poorly grounded scoring and to improve the overall robustness and reliability of the prioritisation process.

The following extract illustrates how the preliminary evaluation criteria were initially integrated into the Technology Database in order to support the first technology scoring and prioritisation activities.

| Technology number | Contributor / Partner | Technology Name | Cross-functionality | R - potential | Multimaterial | Industrial potential | Comparative advantage | Remove? | Not evaluable | Notes | 5R Catego |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *Name or identifier of the technology or process* | *The ability of a technology to be applied across multiple value chain stages or for different functions (e.g. sorting, recycling, reuse)* | *The potential of a technology to enable, improve, scale circular strategies across the 5R framework (Recycling, Reuse, Repair, Repurpose, Remanufacture), by improving material recovery, preserving or enhancing material value, or increasing the efficiency,* | *The ability of a technology to process different types of textile materials, including blends and mixed fibres, without requiring strict pre-sorting.* | *The potential of a technology to be deployed at industrial scale, considering the robustness and clarity of the needed process, its scalability in terms of capacity and the technical and operational conditions required for real-world* | *The extent to which the technology provides improvements compared to current standard solutions in terms of efficiency, cost, performance, or environmental impact.* | *Yes for suggesting to exlude technology from further evaluation (e.g. duplicates, out of scope).”* | *Yes, if there are insufficient information for evaluation* | | *Which of the relates to* |
| | | | | | | | | | | | |
| 44 | NTT | Textile waste recovery device on embroidery machine | | | | | | | | | |

*Figure 40 - Preliminary definition of the evaluation criteria included in the Database*

Following this first test phase, **NTT organised an internal evaluation workshop** (April, 17, 2026) involving nine experts with complementary technical backgrounds and competences related to textile recycling, chemical processes, circular systems and industrial innovation assessment. The meeting represented an important validation step for the technology graduation process and highlighted several methodological challenges. In particular, the participants observed that some criteria could be interpreted differently depending on the technical background of the evaluators, potentially generating inconsistencies in the scoring process. For this reason, the consortium progressively recognised the need to introduce:

- clearer evaluation guidelines for each criterion;
- weighting factors associated with the evaluation criteria themselves;
- differentiated weighting factors associated with the evaluators.

Particular attention was dedicated to the strategic importance of the criteria in relation not only to technological innovation, but also to future industrial implementation and potential investment relevance. During the internal discussions organised by NTT, “Industrial Potential” progressively emerged as one of the most important criteria and was therefore assigned a higher weighting factor within the overall framework.

At the same time, the consortium recognised that the **technical background of evaluators** could significantly influence the robustness and outcome of the assessment: nine technical experts participated in the evaluation process for NTT. The panel included two experts with strong backgrounds in chemical recycling and chemical processes, five experts specialised in mechanical recycling and industrial equipment, and two experts with broader textile-sector expertise. For chemical technologies, the assessments provided by chemical experts were assigned full weight, while the evaluations of the remaining experts received a reduced weighting factor. For sorting technologies, the highest weighting was assigned to experts with mechanical and equipment-related competences. For the technologies primarily assessed by NTT, full weighting was assigned to both mechanical and textile experts, while chemical experts contributed with a lower weighting factor where appropriate.

Following this extensive internal validation and discussion process, the task leader consolidated the final evaluation framework, including:

- **refined evaluation criteria**;
- detailed scoring guidance;
- weighting mechanisms for both criteria and evaluators;
- structured comparison logic for technology prioritisation.

This framework subsequently became the methodological basis for the ranking and prioritisation activities carried out within Task 3.1.

In the following page, the Evaluation framework defined and shared among the three partners involved for the evaluation:

*Table 2 - Final and validated Framework for the Technology Evaluation and Prioritisation*

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WP3

TASK 3.1: Technologies scouting and definition of the best available solutions

## Technology Evaluation and Prioritisation Framework

| | Criteria | Description | Assessment Questions | Use "1" when | Use "3" when | Use "9" when |
|---|---|---|---|---|---|---|
| 1 | **Cross-functionality** | The ability of a technology to be applied across multiple value chain stages or for different functions (e.g. sorting, recycling, reuse). | - Can the technology be applied in more than one value chain stage or process?<br>- Can it serve different functions (e.g. sorting, recycling, reuse)?<br>- Does it have potential applications across different contexts or use cases? | 1 = LOW cross-functionality<br><br>- The technology is limited to a single function or stage<br>- No clear adaptability to other applications<br>- Highly specific or niche use | 3 = MEDIUM cross-functionality<br><br>- The technology can be applied to more than one stage or function<br>- Some flexibility is evident, but within a limited scope<br>- Potential for extension exists but is not fully demonstrated | 9 = HIGH cross-functionality<br><br>- The technology can be applied across multiple stages and/or functions<br>- High adaptability to different use cases or processes<br>- Clear potential to create synergies across the value chain |
| 2 | **R- potential** | The potential of a technology to enable, improve, scale circular strategies across the 5R framework (Recycling, Reuse, Repair, Repurpose, Remanufacture), by improving material recovery, preserving or enhancing material value, or increasing the efficiency, throughput, and feasibility of circular processes. | Does the technology enable or significantly support one or more circular strategies (e.g. recycling, reuse, repair, repurpose, remanufacture)?<br>Does it improve material recovery or help preserve/enhance the value of the material?<br>Does it increase the efficiency, throughput (e.g. amount of material processed), or feasibility of circular processes? | 1 = LOW R-potential<br><br>- Does not significantly improve material recovery or value retention<br>- Marginal impact on circularity or process efficiency or throughput | 3 = MEDIUM R-potential<br><br>- Provides some improvement in material recovery, value, throughput, or process efficiency<br>- Contributes to at least one circular strategy | 9 = HIGH R-potential<br><br>- Strongly enables or improves one or more circular strategies<br>- Clearly improves material recovery, throughput, and/or preserves or enhances material value |
| 3 | **Multimaterial** | The ability of a technology to process different types of textile materials, including blends and mixed fibres, without requiring strict pre-sorting. | - Can the technology process different fibre types?<br>- Can it handle blended or mixed textile materials?<br>- Does it require highly pure or pre-sorted input? | 1 = LOW multimaterial capability<br><br>- Works only with single fibre types<br>- Requires highly pure or pre-sorted input<br>- Not suitable for mixed or complex waste streams | 3 = MEDIUM multimaterial capability<br><br>- Can process limited combinations of materials<br>- Requires some level of pre-sorting or input control<br>- Partial flexibility with blends | 9 = HIGH multimaterial capability<br><br>- Can process multiple fibre types and blends<br>- Handles mixed or unsorted textile waste streams<br>- High flexibility in input materials |
| 4 | **Industrial potential** | The potential of a technology to be deployed at industrial scale, considering the robustness and clarity of the needed process, its scalability in terms of capacity and the technical and operational conditions required for real-world implementation.<br>The assessment takes into account the current level of development, but also recognises technologies that, although not yet mature, show credible and well-defined pathways toward industrialisation | - Is there evidence of real-world use (pilot, demo, industrial)?<br>- Even if not yet mature, is there a clear and realistic path to industrial scale (e.g. mainly requiring investment and scale-up), or are there still fundamental technological uncertainties?<br>- Can the process realistically be scaled to industrial volumes? | 1 = LOW industrial potential<br><br>There are significant technological uncertainties<br>There is no evidence of real-world application (no pilot, no demo, only concept or patent)<br>The pathway to industrial scale is unclear or uncertain<br>The process appears difficult or unrealistic to scale | 3 = MEDIUM industrial potential<br><br>The pathway to industrialisation is plausible (mainly requiring scale-up and/or investment)<br>No major technological barriers are evident<br>There is some evidence of real-world application<br>(pilot, demo, or small-scale testing) | 9 = HIGH industrial potential<br><br>The technology is already, or very close to, industrial deployment<br>No significant technological uncertainties remain<br>There is clear evidence of industrial or near-industrial application<br>(operational plant or significant production capacity) |
| 5 | **Comparative advantage** | The extent to which the technology provides improvements compared to current standard solutions in terms of efficiency, cost, performance, or environmental impact. | - Does the technology offer clear improvements compared to existing solutions?<br>- Are there identifiable benefits (e.g. lower energy use, higher efficiency, better output quality)?<br>- Does it solve a known limitation or bottleneck in current processes? | 1 = LOW comparative advantage<br><br>- No clear improvement compared to existing solutions<br>- Similar or lower performance<br>- marginal benefit only | 3 = MEDIUM comparative advantage<br><br>- Some improvements compared to standard solutions<br>- May improve one aspect (e.g. cost or efficiency) but not significantly overall | 9 = HIGH comparative advantage<br><br>- Clear and significant improvements over existing solutions<br>- Addresses key limitations or bottlenecks<br>- Strong advantages in one or more areas (e.g. cost, performance, sustainability)<br>- Potential to change current practices |

Important !!! Scores should be assigned based only on the available information. If information is insufficient, use a conservative score or mark as "Not evaluable".

The five final evaluation criteria were weighted as follows:

*Table 3 - Weights assigned to the technology assessment criteria used in the technology ranking framework*

| **Criterion** | Cross-functionality | R-Potential | Multi-material capability | Industrial Potential | Comparative Advantage |
|---|---|---|---|---|---|
| **Weight** | 0.05 | 0.10 | 0.35 | 0.45 | 0.05 |

Industrial Potential received the highest weighting because the consortium considered industrial feasibility, scalability and deployment potential to be critical factors for the future adoption of circular textile technologies. The consortium considered this aspect particularly important because the project aimed not only to analyse theoretical innovations, but also to identify solutions potentially transferable into real circular textile systems.

Multi-material capability was assigned the second-highest weighting due to the recognised importance of managing heterogeneous textile waste streams, one of the major barriers to textile circularity identified throughout the project activities.

The consortium observed that many retrieved patents described only marginal improvements of already existing technologies rather than genuine innovation.

Consequently, higher priority was assigned to technologies showing: novel process approaches; innovative material separation capabilities; advanced automation; digitalisation or AI integration; enhanced recovery performances; potential to significantly improve circular textile operations.

One important methodological consideration emerging from the ranking activities concerned the **balance between objectivity and expert-based interpretation within the evaluation process**. The consortium recognised from the beginning that the assessment of emerging circular textile technologies could not be considered fully objective, mainly due to:

- heterogeneous levels of available information;
- different maturity stages of the technologies;
- limited industrial evidence for several solutions;
- strong variability in the quality and completeness of patent documentation;
- different technological domains involved (mechanical, chemical, digital, automated systems, etc.).

For this reason, the evaluation framework was not designed as a purely quantitative scoring exercise, but rather as a structured expert-based assessment process aimed at improving consistency, comparability and robustness while acknowledging the unavoidable presence of interpretative elements.

Several methodological measures were progressively introduced to reduce excessive subjectivity, including:

- shared evaluation criteria;
- scoring guidelines;
- weighted criteria;
- differentiated evaluator weights based on technical expertise;
- cross-review discussions among partners;
- possibility to abstain from scoring technologies characterised by insufficient information;
- possibility to suggest the exclusion of weakly documented or insufficiently relevant technologies.

The consortium therefore adopted a *hybrid approach* combining structured scoring logic with expert interpretation and collective validation activities. Rather than eliminating subjectivity entirely, the methodology aimed to manage and balance it through transparency, iterative discussion and competence-based evaluation mechanisms. The consortium also recognises that the proposed ranking framework should not be considered a fixed methodology, but rather an *adaptable decision-support approach* that can be refined according to the objectives of future applications. Additional evaluation criteria may be incorporated where relevant. For example, future prioritisation exercises could explicitly consider the global distribution of textile fibre types processed by each technology, assigning greater strategic relevance to solutions addressing the most widely used fibres (e.g. polyester, cotton and polyester–cotton blends) or particularly challenging materials such as elastane. Such adaptations would allow the ranking methodology to remain aligned with evolving market needs, industrial priorities and sustainability objectives.

### 5.1.3. SELECTION OF TECHNOLOGIES FOR DEEPER INVESTIGATION

The ranking activity ultimately came to the identification of a subset of technologies considered the most promising for deeper investigation activities.

The overall ranking was generated by combining the evaluations and scores assigned by the partners (referring to the partner organisation, not to individuals ) involved in the assessment process, allowing the consortium to build a consolidated prioritisation of the technologies collected in the database.

The consortium decided not to simply select the top-ranked technologies across the entire database. Such an approach would have risked over-representing specific technological domains while neglecting other relevant operational stages of the circular textile value chains.

For this reason, the technologies were first clustered according to the different value chains and operational domains previously defined within the Task 3.1 framework. **A dedicated ranking was then produced for each value chain, and the top-ranked technologies within each cluster were identified**. Section 5.2 reports the resulting "Top 10 technologies" for each analysed value chain. This methodological choice was considered more coherent with the systemic approach adopted by the project, ensuring that all major circular pathways and operational stages remained represented within the assessment process, independently from the uneven maturity or visibility of the associated technologies.

Following this first prioritisation phase, the consortium performed an additional selection step aimed at identifying a smaller subset of technologies for deeper investigation and technical refinement activities. This further selection was not based exclusively on the ranking score itself, but also on strategic considerations related to:

- technological attractiveness and innovation potential;
- relevance for future industrial implementation;
- availability or lack of technical information;
- opportunity to collect additional primary data directly from technology providers or operators.

Consequently, the selected technologies included both:

- technologies already recognised as highly promising and therefore suitable for detailed cross-analysis activities;
- less documented or emerging technologies considered strategically interesting for further investigation.

For example, within the thermomechanical recycling value chain, two technologies among the top-ranked solutions were selected because they were already considered highly promising and suitable for extensive cross-analysis activities aimed at filling the majority of the fields included in the Technology Assessment database. In parallel, one specific technology developed by MAPEA was selected despite the more limited availability of information, precisely because it represented an interesting and relatively less explored solution for which the consortium considered valuable to directly engage with the technology provider.

This led to the organisation of targeted interviews and direct information collection activities aimed at refining technical specifications, operational characteristics and implementation conditions. Details regarding these interviews and the associated data collection activities are presented in the following section.

The consortium considered this deep-dive phase essential because technologies identified through patents and literature alone rarely provided sufficient technical detail for advanced assessment activities such as sustainability analysis (LCA, LCC and S-LCA), industrial applicability assessment or investment-oriented evaluation.

In general the deep-dive phase has included:

- cross-analysis of additional technical sources;
- collection of industrial documentation and technical datasheets;
- targeted interviews with technology providers and industrial operators;
- refinement of technical specifications;

In addition to the complete Technology Assessment Database provided in Annex 3, Annex 4 presents the results of the prioritisation and deeper investigation activities carried out on the technologies identified as the most promising within each technological cluster. The annex 4 first reports the Top 10 ranked technologies for each cluster emerging from the evaluation and ranking process. Subsequently, it provides a detailed assessment of the technologies selected for further investigation, including the three highest-priority technologies within each cluster.

For these technologies, additional information was collected through targeted desk research, expert assessment activities and direct interactions with technology developers and providers. As a result, Annex 4 contains substantially enriched technology profiles, allowing a more detailed understanding of their technical characteristics, maturity, applicability, strengths, limitations and potential role within future circular textile systems.

Despite these efforts, some parameters - particularly those related to technology costs, operational expenditures, energy consumption, economic value and other commercially sensitive indicators - remain only partially available. Such information is frequently proprietary, context-dependent or not publicly disclosed, making its collection challenging even through direct engagement with technology manufacturers. Nevertheless, the deeper investigation phase significantly increased the level of detail, reliability and comparability of the information available for the selected technologies.

## 5.2. LIST OF REPRESENTATIVE TECHNOLOGIES

This section presents the outcome of the final technology selection and prioritisation activities carried out within Task 3.1. Building on the ranking methodology previously described, the objective of this section is to report the highest-ranked technologies and provide an overview of the technological landscape emerging across the analysed circular textile value chains.

For each value chain, a selection of the top-ranked technologies is presented, together with a concise overview of the "Top 10" technologies, Following this first overview, a synthesis of the smaller subset of technologies selected for deeper investigation activities is provided (details in Annex 4), with particular attention dedicated to the identification of their comparative advantages within the context of circular textile systems. The analysis therefore highlights the specific characteristics that potentially differentiate the technologies from conventional or competing solutions.

### 5.2.1. SORTING TECHNOLOGIES

*Table 4 - "Top 10 Sorting technologies". Extract of the Technology Database showing the Top 10 highest-ranked technologies associated with sorting activities, ordered according to the final technology assessment score*

| Sorting | | | | 0,05 | 0,1 | 0,35 | 0,45 | 0,05 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Name or identifier of the technology or process | Brief summary of what the technology does | Ability of the technology to be applied across multiple stages of the value chain, across different value chains, or for multiple functions | Ability of the technology to enable or improve recycling, reuse, and repair processes (efficiency, output quality, etc.) | Ability to process different or mixed textile materials | Level of maturity and potential to scale at industrial level | Advantage compared with current solutions (costs, performance, impact) | | Which of the 5Rs it relates to | Collection (pre-/post-consumer, post-industrial), sorting, processing, spinning, etc. |
| Technology number | Partner | Technology Name | Short Description | Cross-functionality | R - potential | Multimaterial | Inustrial potential | Comparative advantage | Final Score Weight | 5R Category | Stage in Value Chain |
| 85 | COT | PICVISA ECOSORT | automated sorting machine for composition identification and | 13,00 | 49,00 | 81,00 | 81,00 | 43,00 | 72,50 | ALL potentially | sorting |
| 57 | COT | Fibersort by Valvan Baling Systems | sorting machine based on hyperspectral imaging and automatic separation | 19,50 | 62,50 | 76,50 | 67,50 | 46,50 | 66,70 | ALL potentially | sorting |
| 61 | COT | NewRetex | fully automated robotic sorting | 24,00 | 49,00 | 78,00 | 60,00 | 42,00 | 62,50 | ALL potentially | sorting |
| 62 | COT | Trimclean | automatic cutting of trims for disassembly | 20,00 | 45,00 | 81,00 | 57,00 | 48,00 | 61,90 | ALL potentially | pretreatment |
| 59 | COT | AUTOSORT by TOMRA | sorting machine based on NIR and VIS sensors and automatic separation | 21,00 | 43,00 | 75,00 | 63,00 | 22,00 | 61,05 | ALL potentially | sorting |
| 63 | COT | ANDRITZ & Pellenc ST | Integrated NIR and Pre-treatment Systems | 14,00 | 43,00 | 72,00 | 62,00 | 18,00 | 59,00 | ALL potentially | sorting/pretreatment |
| 65 | COT | REDWAVE | Sensor-based Sorting Systems (REDWAVE TEX) | 14,00 | 49,00 | 78,00 | 48,00 | 18,00 | 55,40 | ALL potentially | sorting |
| 76 | COT | Siptex sorting sysyem | fully aytomated sorting facility | 14,00 | 43,00 | 81,00 | 42,00 | 25,00 | 53,50 | ALL potentially | sorting |
| 58 | COT | Norsk Tekstilsortering (NTS) + HySpex | fully integrated oprical sorter based on | 20,00 | 45,00 | 54,00 | 45,00 | 30,00 | 46,15 | ALL potentially | sorting |
| 71 | COT | Databeyond Technology | fully automated sorting lines integrating AI and HSI | 41,00 | 58,00 | 54,00 | 36,00 | 46,00 | 45,25 | ALL potentially | sorting |

The cluster dedicated to Sorting technologies represents the crucial operational hub for enabling the entire value chain of the textile circular economy. Without proper identification and separation of inbound flows, all recycling phases and 5R value chains/phases in general could not operate efficiently. Innovations in this area have heavily focused on process automation through the integration of AI systems and advanced optical technologies (such as NIR and VIS/RGB spectroscopy), with the goal of overcoming the slowness and physical limitations of manual sorting.

One of the most established technological trajectories is the use of hyperspectral imaging combined with pneumatic or mechanical separation systems. Among the market leaders is PICVISA ECOSORT, a fully automated machine that uses near-infrared (1000-1700nm) hyperspectral imaging alongside VIS/RGB cameras to sort dry, previously separated post-consumer garments. The system has reached commercial scale (TRL 9) and can process between 2.5 and 3 tons per hour, offering integration with artificial intelligence algorithms for more refined predictions and separating batches based on composition. Another key system in this segment is Fibersort (Valvan Baling Systems), which combines NIR cameras, RGB sensors, and 3D tracking. With a throughput of approximately 900 kg per hour (processing one garment per second), the technology separates textile fractions by composition and color, preparing them directly for baling. Valvan is also studying the integration of robotic systems to automate the "singulation" of garments on the conveyor belt, thus overcoming one of the main bottlenecks in the process. For even higher volumes, technologies like AUTOSORT by TOMRA and the Siptex sorting system stand out. TOMRA's system, operating at a commercial level (TRL 9), uses high-precision NIR and visual sensors, achieving throughputs of up to 4.5 tons per hour; its main advantage lies not only in fiber and color recognition but also in the identification of plastic and metallic impurities within the stream. Equivalent productivity levels (4.5 tons/hour, equal to about 24,000 tons annually) are also guaranteed by the Siptex plant, which leverages a fully automated setup based on NIR/VIS sensors and air jets. To handle already shredded textile flows in a modular way, the market offers solutions like REDWAVE TEX, capable of processing over 3 tons per hour, and the integrated systems by ANDRITZ & Pellenc ST, which combine pre-treatment with NIR recognition technologies. The precision of Artificial Intelligence also plays an increasingly central role: Databeyond Technology (around 2 tons/hour) and Norsk Tekstilsortering (NTS) + HySpex merge AI and hyperspectral imaging to continuously refine accuracy in the automatic recognition of blends and specific fiber ratios.

In addition to optical sorting, a fundamental part of pre-treatment involves the mechanical preparation and dismantling of garments before they enter the recycling lines. For this purpose, innovations like Trimclean offer automatic cutting and the removal of zippers, buttons, or inserts (trim removal), automating an essential phase of pre-recycling disassembly. Regarding robotics-based physical handling, technologies like NewRetex aim for automated sorting by composition and color with the aid of robotics, currently processing about 200 tons per month.

In conclusion, the evolution of the sector demonstrates an increasing integration of advanced recognition systems, process automation, and algorithm-based support, with the aim of improving throughput capacity, classification accuracy, and operational continuity compared with conventional manual sorting practices. Currently available solutions are capable of processing industrial-scale volumes in the range of several tonnes per hour, with technological maturity levels that, in many cases, are close to full commercial deployment. These systems enable material discrimination according to composition, colour, and the presence of impurities, while also supporting the management of heterogeneous streams originating from post-consumer sources or from mechanical pre-treatment stages. In parallel, preparation and disassembly operations are becoming increasingly relevant, as they facilitate the removal of incompatible components and the conditioning of materials for subsequent recovery processes. Overall, the sector shows a high degree of technical maturity and a progressive transition towards scalable industrial configurations. Nevertheless, several structural and operational challenges remain, particularly those associated with the complexity of multi-material textile products, the presence of minor fractions that are difficult to detect, the variability of feeding conditions, and the need to ensure reliable, repeatable, and economically sustainable performance at industrial scale.

Despite enormous progress, several engineering and application challenges remain for the entire cluster. Traditional NIR systems, for instance, only read the surface fabric, failing to identify potential polyester linings placed underneath multi-layer garments. Furthermore, they usually struggle to recognize black/dark fabrics and marginal fiber percentages, such as elastane below 5%.

*Table 5 - "Top 3 Sorting technologies" emerging from the last ranking exercise*

| Technology Name | Working Principle | Key Benefits |
|---|---|---|
| **PicVisa ECOSORT** | Sorting system based on NIR hyperspectral imaging (1000-1700nm) and VIS (RGB) cameras and other optional detectors or AI for separation of garment waste | The system guarantees total automation guided by artificial intelligence for real-time garment ejection. It combines highly accurate molecular identification with visual pattern recognition and objective color clustering, eliminating human error and generating extremely pure fractions that do not require redyeing. This optimizes fiber-to-fiber recycling, maximizing environmental benefits and significantly reducing labor costs. The platform is also easily scalable through remote updates of machine learning models, requiring no structural modifications to the machinery. |
| **NewRetex** | The system processes and separates textiles based on material, composition, color | Overcoming the physical limits of manual sorting, the system processes large volumes of material with extremely high speed and efficiency through an automated matrix that simultaneously separates by composition and color. This approach eliminates human error and provides mechanical recyclers with blends of guaranteed purity. By removing the need for subsequent dyeing processes, the technology ensures significant water and energy savings and a clear reduction in polluting emissions in downstream processing phases. |
| **Valvan Fibersort** | NIR/Hyperspectral camera for detection of composition and color | The technology stands out for its extreme operational speed and accuracy, guaranteed by simultaneous garment classification for both polymer type and color, a process that significantly streamlines subsequent processing stages. On a strategic level, it also offers an ecosystem characterized by total commercial transparency, facilitating investor decisions through open and clear sharing of cost dynamics, operational challenges, and financial returns linked to the plant's adoption. |

### 5.2.2. MECHANICAL-R

*Table 6 - "Top 10 Mechanical Recycling technologies". Extract of the Technology Database showing the Top 10 highest-ranked technologies associated with Mechanical Recycling activities, ordered according to the final technology assessment score*

| Mechanical | | | | 0,05 | 0,1 | 0,35 | 0,45 | 0,05 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Name or identifier of the technology or process | Brief summary of what the technology does | Ability of the technology to be applied across multiple stages of the value chain, across different value chains, or for multiple functions | Ability of the technology to enable or improve recycling, reuse, and repair processes (efficiency, output quality, etc.) | Ability to process different or mixed textile materials | Level of maturity and potential to scale at industrial level | Advantage compared with current solutions (costs, performance, impact) | | Which of the 5Rs it relates to | Collection (pre-/post-consumer, post-industrial), sorting, processing, spinning, etc. |
| Technology number | Partner | Technology Name | Short Description | Cross-functionality | R - potential | Multimaterial | Inustrial potential | Comparative advantage | Final Score Weight | 5R Category | Stage in Value Chain |
| 88 | NTT | **CISUTAC's solution for post-consumer textile waste management** | Open-source tool (based on decision logic) that identifies and prioritizes | 69,50 | 77,50 | 85,50 | 59,50 | 53,50 | 70,60 | Recycling / Reuse (Sorting Enabler) | Sorting / Channelling |
| 92 | NTT | **Card with Fixed Carding Flats (Cleaning Members)** | Carda con cappelli fissi dotati di lame inclinate (circa 45°) che fungono da | 58,50 | 38,50 | 74,50 | 71,50 | 59,50 | 68,00 | Recycling | Spinning / Preparation (Carding) |
| 128 | NTT | **Method for recovering textile fibers from discarded textile** | This is a complete industrial plant and | 34,50 | 69,50 | 71,50 | 41,50 | 29,50 | 53,85 | Recycling | Pretreatment |
| 103 | NTT | **Soft Robotic Grippers** | Robotic gripping systems based on soft materials | 55,50 | 68,50 | 79,50 | 32,50 | 27,50 | 53,45 | Repurpose (Automation) | Sorting |
| 105 | NTT | **GSL-YOLOv8n (Improved Lightweight YOLOv8n)** | Lightweight, optimized deep learning artificial | 55,50 | 62,50 | 73,50 | 32,50 | 56,50 | 52,20 | Remanufacturing | Sorting |
| 117 | NTT | **Method of producing rigid package material and rigid box** | A method to produce a thin, sustainable, and rigid | 50,50 | 47,50 | 61,50 | 46,00 | 49,00 | 51,95 | Recycle | Manufacturing |
| 109 | NTT | **IoT-based Cloth Stacking Machine Control System** | Control system for cloth stacking using sensors to | 44,50 | 51,50 | 76,50 | 33,50 | 37,50 | 51,10 | Reduce (Quality control) | Processing (Stacking) |
| 142 | NTT | **Yarn manufactured from recycled clothing fibers and** | Process to create upcycled yarn from used clothes | 33,50 | 53,50 | 60,00 | 45,00 | 37,50 | 50,15 | Recycling | Processing / Spinning |
| 91 | NTT | **PROCESS TO REGENERATE WOVEN AND KNIT FABRIC AND** | Mechanical upcycling process using needle | 18,50 | 36,50 | 85,50 | 32,50 | 17,50 | 50,00 | Recycling | Processing |
| 101 | NTT | **Textile Color Retention** | Dyeing technology that uses air instead of water to | 20,50 | 20,50 | 52,50 | 56,50 | 59,50 | 49,85 | Remanufacturing / Refurbishing | Dyeing / Re-dyeing |

The cluster dedicated to Mechanical Recycling brings together a series of heterogeneous solutions aimed at maximizing the physical recovery and use of fibers without altering their chemical structure. This grouping is not limited to traditional shredding and spinning machinery, but ranges from robotic automation and the digitalization of quality control to the development of new composite materials. The overarching goal is to optimize yields, reduce the loss of "good" fibers, cut down on resource consumption (water and chemicals), and find innovative application outlets for lower-quality waste. The main use of mechanical recycling is still centered on fibre-to-fibre recycling.

A strong trend of innovation in this category concerns the intelligent handling and inspection of fabrics, which are fundamental steps in preparing the material for recycling. Technologies such as Soft Robotic Grippers overcome the limitations of rigid mechanical arms: by using flexible materials and electroadhesion, they can handle individual, deformable, and porous garments without damaging the fibers, enabling the full automation of material handling. On the quality control front, artificial intelligence plays a key role with algorithms like **GSL-YOLOv8n**, a lightweight, ultra-high-speed visual model (ideal for edge computing) capable of detecting stains, holes, or pulled threads in real-time with an accuracy of 98.29%, drastically reducing waste and manual inspection costs. Digital integration also extends downstream, with systems such as the **IoT-based Cloth Stacking Machine Control System**, which uses sensors to monitor fabric tension, folds, and alignment during stacking, self-correcting the machine in real time. At the decision-making and logistical level, the open-source tool by **CISUTAC** stands out: a logic platform that analyzes the critical data points of the garment (condition, composition) to standardize and route the waste towards the most suitable path (reuse or recycling), paving the way for future integration with the Digital Product Passport (DPP). Regarding pure mechanical regeneration, innovations aim to improve the efficiency of historic machines. The patent (albeit historical) for the **Card with Fixed Carding Flats (Cleaning Members)** introduces a system of fixed flats with inclined blades which, combined with a suction and cooling system, significantly reduces the breakage and loss of useful fibers compared to traditional carding machines.

At a systemic level, recent patents propose entire sensor-driven industrial plants to categorize, sanitize, and process flows based on their composition. From these processes, highly sustainable yarns are born, such as those described in the patent *Yarn manufactured from recycled clothing fibers*. This is a completely dry process (zero water, zero chemicals, zero dyeing) that, by combining shredded fibers with a small percentage of reinforcing fibers, generates a new yarn composed of 70-95% recycled material. An interesting branch of mechanical recycling concerns the exploration of alternative industrial and material applications for lower-value flows. The patent *Method of producing rigid package material and rigid box from textile waste* describes a process where mixed textile waste (with at least 40% synthetic content) is shredded and mixed with a polymeric binder to create rigid and lightweight sheets (1-3 mm thick) that are thermo-mechanically pressed. This solution transforms waste into durable, foldable boxes that can replace traditional packaging cardboard.

For the valorization of unsold stock (dead stock) and regenerated fibers (shoddy), the *Process to regenerate woven and kint fabric* exploits needle-punching technology: barbed needles mechanically interlock layers of fabric without the use of chemical binders (or by using bio-based nanocellulose gel), creating new felts or completely recyclable composite fabrics. Finally, for color restoration or finishing, **Textile Color Retention (Air-dyeing)** technology is gaining ground. This process uses air, rather than water, to transport and uniformly diffuse pigments within the fibers (especially synthetic ones), ensuring enormous water and energy savings.

In conclusion, in this context, a strong integration of automation, intelligent control systems, and advanced industrial processes emerges as a key enabling factor for reducing the loss of valuable material, improving recovery quality, and optimising resource use. In parallel, additional solutions are being explored to extend the potential applications of textile waste, converting it into new materials or semi-finished products for alternative high-value uses. Overall, the landscape highlights a transition towards more efficient, digitalised, and sustainable recycling models, capable of combining material recovery, environmental impact reduction, and the development of new application opportunities within a circular economy framework.

*Table 7 - - "Top 3 Mechanical Recycling technologies" emerging from the last ranking exercise*

| Technology Name | Working Principle | Key Benefits |
|---|---|---|
| **CISUTAC's solution for post-consumer textile waste management** | Open-source tool (based on decision logic) that identifies and prioritizes the data points needed to correctly route textile waste towards reuse or recycling. The tool combines information from multiple sources, including DPP data, RFID identification, NIR fibre recognition, AI-based garment analysis, and manual condition assessment. These inputs are processed through a decision-support framework that recommends whether a textile item should be directed towards reuse, repair, recycling, or disposal | Addresses one of the major bottlenecks in textile circularity by improving sorting accuracy through the integration of multiple data sources. By combining product information, fibre identification, condition assessment, and digital traceability, the **tool enables more informed and differentiated routing decisions**, helping maximize value retention through reuse, repair, and recycling pathways. |
| **Card with Fixed Carding Flats (Cleaning Members)** | Carding machine with stationary flats equipped with carding strips featuring an adjustable point density per cm², which act as carding, cleaning, and fiber parallelization elements, facilitating the extraction of impurities and improving the carding process. The strip system allows the carding action to be graduated progressively. These features make this type of carding machine highly flexible, capable of quickly and effectively processing different types of fibers, both recycled and virgin. | This technology integrates the carding and cleaning phases, minimizing the loss of intact fibers while allowing for effective active cooling of the system. These distinctive elements translate into direct benefits such as reduced fiber breakage, a significantly higher level of cleanliness, and precise, constant control of the process temperature |
| **Method for recovering textile fibers from discarded textile articles and related plant** | This is a complete industrial plant and method for recovering textile fibers from post-consumer or industrial waste. | The method offers the strategic advantage of a complete industrial plant that uses advanced sensors and data analysis to categorize, sanitize, and process textile waste streams based on their specific composition. This targeted approach ensures highly optimized material recovery, maximizing efficiency, safety, and overall recycling quality |

### 5.2.3. CHEMICAL RECYCLING

*Table 8 - "Top 10 Chemical Recycling technologies". Extract of the Technology Database showing the Top 10 highest-ranked technologies associated with Chemical Recycling activities, ordered according to the final technology assessment score*

| Chemical | | | | 0,05 | 0,1 | 0,35 | 0,45 | 0,05 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Name or identifier of the technology or process | Brief summary of what the technology does | Ability of the technology to be applied across multiple stages of the value chain, across different value chains, or for multiple functions | Ability of the technology to enable or improve recycling, reuse, and repair processes (efficiency, output quality, etc.) | Ability to process different or mixed textile materials | Level of maturity and potential to scale at industrial level | Advantage compared with current solutions (costs, performance, impact) | | Which of the 5Rs it relates to | Collection (pre-/post-consumer, post-industrial), sorting, processing, spinning, etc. |
| Technology number | Partner | Technology Name | Short Description | Cross-functionality | R - potential | Multimaterial | Inustrial potential | Comparative advantage | Final Score Weight | 5R Category | Stage in Value Chain |
| 13 | CTB | **Carbios** | enzymatic depolymerisation of PET | 25,50 | 59,50 | 55,50 | 67,50 | 56,50 | 59,85 | recycling | processing |
| 31 | CTB | **Loopamid (Basf)** | depolymerisation of PA6 via solvolysis; Separation of elastic fibers in textile materials | 25,50 | 51,50 | 55,50 | 67,50 | 59,50 | 59,20 | recycling | processing |
| 14 | CTB | **HTEX** | depolymerisation of PET via solvolysis | 24,50 | 56,50 | 55,50 | 64,50 | 50,50 | 57,85 | recycling | processing |
| 24 | CTB | **Loop industries** | depolymerisation of PET via solvolysis | 25,50 | 47,50 | 56,50 | 64,50 | 47,50 | 57,20 | recycling | processing |
| 10 | CTB | **Rewind PET (Axens)** | depolymerisation of PET via solvolysis (glycolysis) | 23,50 | 47,50 | 55,50 | 64,50 | 37,50 | 56,25 | recycling | processing |
| 17 | CTB | **Eastman** | depolymerisation of PET via solvolysis | 25,50 | 44,50 | 55,50 | 64,50 | 41,50 | 56,25 | recycling | processing |
| 29 | CTB | **REC / écollant** | chemical recycling of polyamide blends | 25,50 | 51,50 | 53,50 | 61,50 | 56,50 | 55,65 | recycling | processing |
| 3 | CTB | **Infinitedfiber** | chemical dissolution of cotton | 25,50 | 53,50 | 54,50 | 61,50 | 43,50 | 55,55 | recycling | processing |
| 35 | CTB | **Worn again** | chemical recycling of polycotton | 25,50 | 44,50 | 60,50 | 58,50 | 41,50 | 55,30 | recycling | processing |
| 6 | CTB | **Circulose** | dissolution of cotton | 24,50 | 50,50 | 50,50 | 64,50 | 43,50 | 55,15 | recycling | processing |

The cluster dedicated to Chemical Recycling represents a highly innovative technological area, oriented toward molecular recovery and fiber dissolution. This stage of the value chain is a fundamental piece for managing fabrics that are mixed, contaminated, or too worn out to be processed through mechanical recycling. The solutions mapped in this group aim to yield a virgin-equivalent quality output and are mainly divided into two broad trajectories: the depolymerization of synthetic yarns to extract their base monomers, and chemical dissolution for the regeneration of new man-made cellulosic fibers.

In the field of polyester recycling, the landscape shows technologies that are now mature and close to large-scale implementation. A particularly distinctive approach is that of **Carbios**, which utilizes an enzymatic hydrolysis process operating at low temperatures to break down PET into its constituent elements (PTA and MEG). This technology has reached a commercial level (TRL 9) with a capacity of 50,000 tons per year, offering the advantage of being able to process colored garments and yielding virgin-equivalent monomers. In parallel, several companies have consolidated technologies based on solvolysis, methanolysis, and glycolysis processes. **Loop Industries**, for example, uses atmospheric-pressure methanolysis capable of guaranteeing an 81% greenhouse gas saving compared to virgin production, operating commercial plants of 70,000 tons in Canada and India. Operating on an even larger scale is **Eastman** (up to 110,000 tons per year at its Tennessee plant), which converts PET into DMT and EG, cutting emissions by 20-30%, although its European expansion project in France is currently stalled due to regulatory issues. For lower but highly specialized capacities, we find **HTEX**, ideal for PET-rich flows such as workwear or uniforms (8,000 kg per day), and **Rewind PET (Axens)**. The latter employs glycolysis to obtain BHET and is in a highly advanced demonstration phase (TRL 8 for

30,000 tons per year), with solid prospects for industrial scale-up thanks to strategic partnerships with companies like Jeplan and Toray. Moving on to polyamides, the industry is developing chemical solutions aimed at separating complex blends, which are historically difficult to recycle. **Loopamid** (supported by BASF) uses solvolysis focusing on PA6 waste and elastane-containing mixtures; the technology, already commercial (TRL 9), allows for the effective separation of elastic fibers, regenerating very high-quality PA6 and reducing the climate impact by up to 70%. In a complementary manner, **REC / écollant** tackles the challenge of mixed PA6/elastane fabrics (requiring at least 70% input PA6) with a treatment that chemically destroys the elastane to preserve the intact structure of the polyamide. Currently in the demo phase (100 tons per year), the company's goal is to scale to 20,000 tons by 2030.

The second major branch of chemical recycling addresses the treatment of cotton-based fibers and complex polyester/cotton mixes (polycotton). In this segment, **Worn Again** offers a targeted solution for blends: the process selectively dissolves the cellulose while leaving the polyester intact, thus allowing the recovery of both cellulosic pulp and PET pellets from the same garment (technology in the demo phase for 1,000 tons/year). For flows with a very high concentration of cotton (>88%), **Infinited Fiber** stands out with a process that first eliminates dyes and PET residues, then breaks down the cellulose at the molecular level to recreate a new liquid cellulose carbamate fiber (Infinna™). Already used in European projects such as New Cotton, the technology is transitioning from the demo phase (150 tons/year) toward a future 30,000-ton commercial plant. Finally, **Circulose** (formerly Renewcell) represents one of the most commercially structured players (TRL 9): it dissolves cotton fabrics, transforming them into pulp sheets ideal for producing viscose, lyocell, modal, and acetate. With production estimates between 60,000 and 120,000 tons per year expected by the end of 2026, the company is moving to progressively replace wood cellulose (currently used at 70% in a mix with textile waste) to eventually produce 100% circular sheets.

In conclusion, the primary objective of these systems is to generate secondary raw materials with quality characteristics comparable to those of virgin inputs, thereby enabling their reintegration into new high-value industrial value chains. Overall, the current landscape points to a rapidly evolving technological ecosystem, encompassing solutions aimed both at the recovery of synthetic fractions and at the regeneration of cellulosic components. A key strength of these solutions is their ability to handle complex blends and composite materials, which have historically represented a major challenge in terms of valorisation, through selective separation and transformation processes. From an industrial perspective, the sector demonstrates an increasing level of maturity, with several initiatives already close to, or having reached, commercial deployment and showing tangible prospects for scale-up. From a strategic standpoint, these solutions constitute a key enabling factor for the transition towards more circular production systems, contributing to the reduction of dependence on virgin raw materials and to the improvement of the environmental performance of the overall value chain

*Table 9 - "Top 3 Chemical Recycling technologies" emerging from the last ranking exercise*

| Technology Name | Working Principle | Key Benefits |
|---|---|---|
| **Carbios** | French biotechnology company developing enzymatic PET recycling: enzymes degrade PET into monomers to recreate new virgin-quality PET, reducing the quality loss typical of traditional recycling. | It ensures efficient PET depolymerization, yielding a final quality equivalent to virgin material with less degradation compared to mechanical recycling. It promotes a closed-loop model with high circularity and a potential reduction in carbon dioxide emissions, operating under milder conditions and successfully processing even complex or contaminated materials. Optimization and costs remain the main factors to be perfected. |
| **Loopamid (Basf)** | Polyamide 6 recycled from textile waste through chemical recycling: BASF converts nylon 6-containing waste into a raw material almost identical to virgin nylon for fashion, sportswear, and industrial textile applications. | It enables fiber-to-fiber recycling of the highest quality, capable of generating nylon that is almost identical to virgin material, while simultaneously offering a drastic reduction in global warming potential. Priority areas for further development and improvement remain efficiency, process speed, cost management, and scalability. |
| **Rewind PET (Axens)** | Continuous PET chemical recycling technology via glycolysis: PET reacts with ethylene glycol to produce BHET, which is then purified and repolymerized into new PET equivalent to virgin material. | It offers a continuous process with good industrial scalability for molecular recycling, generating high-purity PET that is equivalent to virgin material and potentially suitable for food-contact use. It guarantees greater circularity and high flexibility in treating contaminated feedstocks compared to mechanical methods, reducing material losses thanks to the direct integration between the reaction and purification phases. |

### 5.2.4. THERMOMECHANICAL RECYCLING

*Table 10 - "Top 10 Thermomechanical Recycling technologies". Extract of the Technology Database showing the Top 10 highest-ranked technologies associated with Chemical Recycling activities, ordered according to the final technology assessment score*

| Thermo - mechanical | | | | 0,05 | 0,1 | 0,35 | 0,45 | 0,05 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Name or identifier of the technology or process | Brief summary of what the technology does | Ability of the technology to be applied across multiple stages of the value chain, across different value chains, or for multiple functions | Ability of the technology to enable or improve recycling, reuse, and repair processes (efficiency, output quality, etc.) | Ability to process different or mixed textile materials | Level of maturity and potential to scale at industrial level | Advantage compared with current solutions (costs, performance, impact) | | Which of the 5Rs it relates to | Collection (pre-/post-consumer, post-industrial), sorting, processing, spinning, etc. |
| Technology number | Partner | Technology Name | Short Description | Cross-functionality | R - potential | Multimaterial | Inustrial potential | Comparative advantage | Final Score Weight | 5R Category | Stage in Value Chain |
| 80 | COT | OMNI recycling line - Gneuss | integrated thermomechanical recycling system | 13,00 | 41,00 | 75,00 | 81,00 | 67,00 | 70,80 | Recycling | Processing |
| 81 | COT | Binova compounding & recycling | | 19,00 | 29,00 | 65,00 | 73,00 | 48,00 | 61,85 | Recycling | Processing |
| 43 | CTB | Muovi | thermo-mechanical recycling of PET | 25,50 | 56,50 | 55,50 | 64,50 | 49,50 | 57,85 | recycling | processing |
| 73 | COT | UNIFI REPREVE® Takeback | integrated mechanical-thermomechanical | 14,00 | 50,00 | 56,00 | 57,00 | 25,00 | 52,20 | Recycling | Pretreatment/Processing |
| 46 | CTB | Resortecs | desintegration of sew threat via heating | 24,50 | 61,50 | 50,50 | 52,50 | 52,50 | 51,30 | recycling | disassembly |
| 77 | COT | Antex | thermomechanical recycling system | 9,00 | 42,00 | 29,00 | 72,00 | 30,00 | 48,70 | Recycling | Processing |
| 79 | COT | Erema | integrated thermomechanical | 11,00 | 41,00 | 25,00 | 72,00 | 37,00 | 47,65 | Recycling | Processing |
| 44 | CTB | Mapea | thermo-mechanical recycling of mixtures via | 17,50 | 50,50 | 52,50 | 46,50 | 47,50 | 47,60 | recycling | processing |
| 45 | CTB | Cycl-add | thermo-mechanical recycling of PA/elastane | 17,50 | 47,50 | 46,50 | 46,50 | 44,50 | 45,05 | recycling | processing |
| 78 | COT | DS Fibres | thermomecanical recycling system | 10,00 | 36,00 | 40,00 | 49,00 | 25,00 | 41,40 | Recycling | Processing |

The cluster dedicated to Thermomechanical Recycling and supporting thermal technologies focuses on the treatment of thermoplastic polymers, such as PET, PA, and PP. Unlike chemical recycling, thermomechanical processes maintain the macromolecular structure of the original polymer intact through the combined action of heat and mechanical stress, melting and extruding the material to reintroduce it into the production cycle in the form of pellets or new filaments. Because this methodology is highly sensitive to contamination, which can cause drastic drops in intrinsic viscosity or fiber degradation, it requires highly selected and pure upstream feed streams. Analyzing the technology database, three main operational trajectories emerge:

- **Closed-Loop Trajectory (Fiber-to-Fiber):** Concerns industrial systems designed for the closed-loop fiber-to-fiber:
  - **Gneuss (OMNI Recycling Line):** see the table below for more information
  - **Erema (INTAREMA® FibrePro:IV):** see the table below for more information
  - **Muovi:** Alongside these giants are established commercial solutions that process approximately **500 kg/h** of post-consumer PET to produce pellets ready for textile use.
  - Other supply chain initiatives: There are also solid collaborative efforts led by players like **Antex**, **DS Fibres**, and the **UNIFI REPREVE® Takeback** project.
- **Open-Loop Trajectory (Plastic Compounds):** When direct fiber-to-fiber spinning is not feasible, often due to intimate blends that are difficult to separate or the presence of contaminants, the material is diverted toward an open-loop model, namely the production of plastic compounds for the plastics industry.

- ○ **Mapea (Textium):** In this segment, this technology (currently at the demo stage, TRL 8) offers an engineering response to the complexity of waste. By exploiting reactive extrusion, it can process heterogeneous blends based on cotton, polyester, polyamide, and elastane.
- ○ **Cycl-add:** This company adopts a similar approach, specifically focusing on the recovery of critical polyamide and elastane mixes.
- ○ **Binova:** Offers industrial lines capable of coupling thermomechanical recycling and compounding to effectively add additives to and stabilize waste polymers.
- ○ **Thermal Pre-treatment & Design for Disassembly:** Thermal pre-treatment technologies designed to facilitate Design for Disassembly take on strategic importance.

In the case of termomechanical recycling, an emblematic and revolutionary example is represented by **Resortecs** (currently in a 150-ton/year pilot phase):

- SmartStitch Technology: By replacing traditional seams with special heat-dissolvable threads, the company makes it possible to place end-of-life garments into designated industrial ovens.
- Thermal Detachment: At calibrated temperatures (between 150°C and 200°C), the thread melts, causing the automatic detachment of zippers, buttons, and labels.
- Efficiency and Purity: This approach is not only 15 times faster than manual disassembly, but it also doubles the portion of recoverable fabric from a single garment and, above all, guarantees input purity rates of over 90%, eliminating at the root the contaminants that would otherwise end up hindering the thermomechanical recycling machinery.

In conclusion, the analysis highlights that the effectiveness of material recovery and valorisation processes depends on a balanced combination of input stream quality, the adequacy of the treatment stages, and the integration of solutions across the value chain. From this perspective, enhancing selection, preparation, and transformation operations represents a key enabling factor for increasing recovery yields, ensuring the quality of the resulting material, and supporting the broader industrial uptake of these processes within a circular and sustainable framework.

*Table 11 - "Top 3 Thermomechanical Recycling technologies" emerging from the last ranking exercise*

| Technology Name | Working Principle | Key Benefits |
|---|---|---|
| **OMNI recycling line - Gneuss** | Advanced thermomechanical textile recycling system designed for direct fiber-to-fiber recycling of PET textile waste through a single extrusion step integrating degassing, melt filtration, viscosity stabilization, and inline quality monitoring (Developer GNEUSS). The system processes shredded textile waste through a 3C Rotary Feeder for cutting, compaction, preheating, and initial degassing. The material is then processed in an MRS extruder equipped with an extended multi-rotation section operating under high vacuum (~1 mbar), enabling efficient removal of moisture, volatile contaminants, and spin finish oils while stabilizing or increasing intrinsic viscosity. Melt filtration and inline viscometry ensure melt purity and process control. | The OMNImax system stands out among thermomechanical recycling technologies due to its capability to achieve fibre-to-fibre polyester recycling within a compact **single-step process**. By integrating advanced vacuum degassing, melt purification and inline viscosity stabilization, the technology reduces the need for additional upgrading steps while maintaining high recycled material quality. Its **ability to process challenging textile feedstocks with high moisture content and residual finishing agents**, together with **lower energy requirements** and easier integration into existing fibre production lines, represents a significant advantage over conventional PET recycling systems. |
| **Erema** | Advanced thermomechanical PET recycling technology designed for producing high-quality recycled polyester through extrusion, decontamination, and intrinsic viscosity enhancement. PET waste is processed through extrusion combined with vacuum degassing, decontamination, melt filtration, and intrinsic viscosity enhancement technologies to produce high-quality recycled PET suitable for textile and packaging applications. | EREMA stands out for its industrial robustness, large-scale deployment and ability to produce **high-quality recycled polyester** through integrated decontamination and viscosity enhancement processes. Compared to less mature recycling solutions, its key advantages include **proven industrial performance, high throughput capacities** and the capability to generate recycled PET suitable for demanding textile applications. These characteristics make EREMA one of the most commercially mature and scalable options currently available for polyester circularity, supporting the transition towards increased use of recycled content in textile production. |

| | | |
|---|---|---|
| **Mapea** | A two-step thermomechanical recycling process. Sorted and composition-controlled textile waste is first mechanically prepared and densified into **textile capsules** through a **proprietary densification process (patent)**. These capsules can either be supplied as feedstock for chemical recyclers or processed through extrusion and compounding to produce recycled plastic compounds for injection moulding applications. The process is designed to handle both mono-material and selected multi-material textile streams with known compositions. | MAPEA primarily addresses one of the most critical bottlenecks in textile circularity: **feedstock preparation**. The technology improves the quality, consistency, and handling of textile waste streams through densification and standardization processes, enabling more efficient integration with downstream recycling operations. By **reducing material volume**, facilitating storage and transportation, and providing a more **homogeneous input for recyclers, MAPEA contributes to improvin**g the overall efficiency and scalability of textile recycling value chains. An additional advantage is its flexibility, as the prepared **feedstock can be directed towards both thermomechanical and chemical recycling pathways**, supporting a wider range of circular applications. |

# 6. CONCLUSIONS

Task 3.1 progressively evolved from what initially appeared to be a "technology collection activity" into a much broader reflection on how circular textile innovation can actually be identified, interpreted and assessed in a sector characterised by fragmentation, heterogeneous information and rapidly evolving technological pathways.

One of the strongest reflections emerging from the work concerns the intrinsic complexity of defining what a "relevant technology" really is in the context of textile circularity. During the activity, the consortium realised that the concept of innovation itself is often ambiguous. Many technologies presented as innovative are, in reality, incremental optimisations of already existing industrial equipment, while other potentially transformative solutions remain weakly visible because they are poorly documented, not patented, still at pilot scale or dispersed across disconnected technical sources. This became particularly evident during the patent analysis activities. Patent databases initially appeared as a promising entry point for technology scouting because of the large quantity of available information and their ability to highlight innovation trends. However, the work progressively showed that patents alone are not able to represent the real technological landscape of textile circularity. In many cases:

- patents are intentionally broad and non-transparent. But patents are intentionally broad and non-transparent by nature;
- the actual industrial applicability is difficult to understand;
- technical feasibility and scalability are unclear.

The consortium also observed that the abundance of information does not necessarily correspond to clarity or usefulness. On the contrary, one of the main challenges of the task was precisely the opposite: **filtering enormous quantities of fragmented, inconsistent or redundant information to identify technologies** that were genuinely meaningful for circular textile systems.

A further important reflection concerns the current state of the textile circularity sector itself. The analysis highlighted that several operational stages of textile circularity - particularly in recycle, reuse, repair, refurbish and remanufacturing systems - are still characterised more by organisational, logistical and operational practices than by strongly patent-driven technological innovation. In contrast, other domains, such as sorting automation, chemical recycling or thermomechanical processing, show much stronger technological acceleration and industrial experimentation.

To be noted that the CIRCULAT-TEX stakeholders' engagement and their feedback gathered through the field analysis proved that recycling is still the major area of interest among industrial actors, despite the growing importance of other Rs, mainly Reuse and Repair. The industrialists are still mainly focused on technology based solutions, i.e. recycling plants; other Rs are mainly managed by less-industrialised actors, like artisans or social ventures, dedicated to reuse and resell waste material or repair it. A long road is in front of the other Rs like repurpose and remanufacturing. This also lead to the consideration that most of the technology development, at least in the short term, is focused on recycling rather than the other Rs.

The work also generated an important methodological reflection regarding **the role of AI-supported tools in research and technology scouting**. AI tools significantly accelerated several activities, particularly large-scale document screening, summarisation, keyword extraction, clustering and classification of information.

However, Human expertise remained indispensable for understanding: whether a technology was truly innovative; whether it was applicable to circular textile systems; whether it represented a scalable solution or merely a theoretical concept; whether the retrieved information was technically coherent.

The importance of human intervention is confirmed also in specific operational steps, crucial for the circularity transition of the textile sector, like sorting. Sorting for reuse is still in need of human evaluation, even if deep learning is starting to grow in this domain; nonetheless, operators still have to rely on the high level of skilled workforce to perform good quality sorting.

Another significant reflection emerging from the activity concerns the dynamic nature of circular textile technologies. During the work, the consortium realised that creating a "final" and static database of technologies would have been conceptually wrong. The technological landscape is evolving too rapidly, driven by regulatory pressure, industrial experimentation, investments and emerging sustainability requirements. For this reason, the Technology Assessment Tool was intentionally conceived as a living and continuously updateable system rather than as a closed inventory. This aspect is particularly relevant because several technologies identified during the task are still evolving, while entirely new solutions are continuously emerging. In the longer term, the establishment of a dedicated governance mechanism could ensure the continuous management, validation and updating of the Technology Assessment Tool.

To this extent, the structuring and the design of the data base has been one of the most relevant phases of the technology assessment exercise, and the data base itself probably represent the most valuable outcome of the exercise. If it will be kept updated, it represents a milestone in the progress of the sector and in the circularity advancement in the coming years. It is a tool featuring versatility, adaptability and ease of use. It can be adapted to meet specific needs of the user, i.e. finding the technology that better meet the desired research criterion.

The ranking and prioritisation phase also led to an important awareness: **technologies cannot be selected only on the basis of novelty**. Some highly sophisticated technologies may remain economically unrealistic, difficult to scale or poorly adaptable to real textile waste streams. Conversely, some less “disruptive” technologies may have stronger short-term implementation potential because they are already compatible with existing infrastructures and industrial practices.

Beyond the methodological lessons learned, the technology assessment activities also generated a number of strategic insights regarding the future evolution of textile circularity systems.

- the central role of collection and sorting activities within the overall circular textile ecosystem. Although often considered preliminary operational stages, the analysis demonstrated that the effectiveness of almost all pathways - including reuse, repair, refurbish, remanufacturing, repurposing and recycling - depends heavily on the quality of material identification, classification and separation processes. As a consequence, advanced sorting technologies, automated material recognition systems, sensor-based solutions and AI-supported classification tools emerged as some of the most strategic enabling technologies identified during the assessment activities. **Investments in these areas have the potential to generate benefits across multiple circular pathways simultaneously**.
- Among the most relevant significant technological challenges remains the **management of heterogeneous textile waste streams**. Mixed fibres, blended materials and complex textile products continue to represent major barriers to circularity across several value chains. Technologies capable of managing such complexity consistently emerged among the most promising solutions identified within the database. This finding suggests that future innovation efforts should focus not only on improving individual recycling or recovery processes, but also on increasing the capability of circular systems to handle real-world textile waste streams rather than idealised and homogeneous materials.
- **different levels of technological intensity characterising the analysed circular pathways**. While recycling pathways are increasingly driven by technological innovation, automation and process engineering, other pathways such as reuse, repair, refurbish and repurpose remain strongly dependent on organisational models, logistics, human skills, design capabilities and market dynamics. Recycling pathways, particularly mechanical and chemical recycling, emerged as the most technology-intensive segments of the circular textile ecosystem. Mechanical recycling appears as a relatively mature technological domain, where innovation is primarily driven by process optimisation, equipment improvements, fibre quality preservation and increasing levels of automation. Patent and technology analyses highlighted a strong focus on improving process efficiency, reducing fibre degradation and integrating advanced monitoring and control

systems within established industrial infrastructures. Chemical recycling is currently experiencing a phase of rapid technological expansion and industrial scaling (plans). The analysis revealed a broader diversity of technological approaches, a higher level of patenting activity and significant efforts directed towards the treatment of blended fibres and complex textile materials. While many chemical recycling solutions are still progressing through pilot and scale-up phases, the sector is characterised by intense innovation activity and growing industrial interest. At the same time, the analysis highlighted the progressive convergence between mechanical, chemical and digital technologies. Emerging solutions increasingly combine physical processing, chemical treatments, sensor-based monitoring, automation and data-driven optimisation systems, suggesting that future recycling infrastructures will likely rely on integrated technological architectures rather than on isolated process technologies.

A different situation was observed for reuse, repair, refurbish, remanufacturing and repurpose pathways. Although technologies certainly play a role in supporting these activities, the analysis showed that their performance often depends more strongly on organisational models, logistics systems, collection infrastructures, product traceability, workforce skills, design capabilities and market conditions than on breakthrough technological innovation alone. In particular, repair, refurbish and repurpose activities frequently require human intervention, product-specific decision making and creative adaptation processes that are difficult to fully standardise or automate. An important observation emerging from the technology assessment activities is that many technologies supporting reuse, repair and repurpose activities rely on the same physical transformation mechanisms used in mechanical recycling processes. As a result, these technologies were progressively consolidated within the broader Mechanical-R cluster, highlighting **how recycling technologies often embed and integrate technological solutions originally associated with other circular pathways**.

- The technology scouting activities further revealed **a growing convergence between technological domains that have traditionally been considered separate**. In particular, the distinction between mechanical, chemical and digital solutions appears progressively less defined. Several emerging technologies increasingly combine physical processing, chemical treatments, advanced sensing systems, process automation and digital intelligence within integrated solutions. This suggests that future technological breakthroughs in textile circularity are likely to emerge from the integration of complementary technologies rather than from isolated innovations.

In general, the task therefore provided not only a technical output, but also a broader methodological contribution for future circular textile innovation assessment activities, demonstrating the necessity of combining different dimensions:

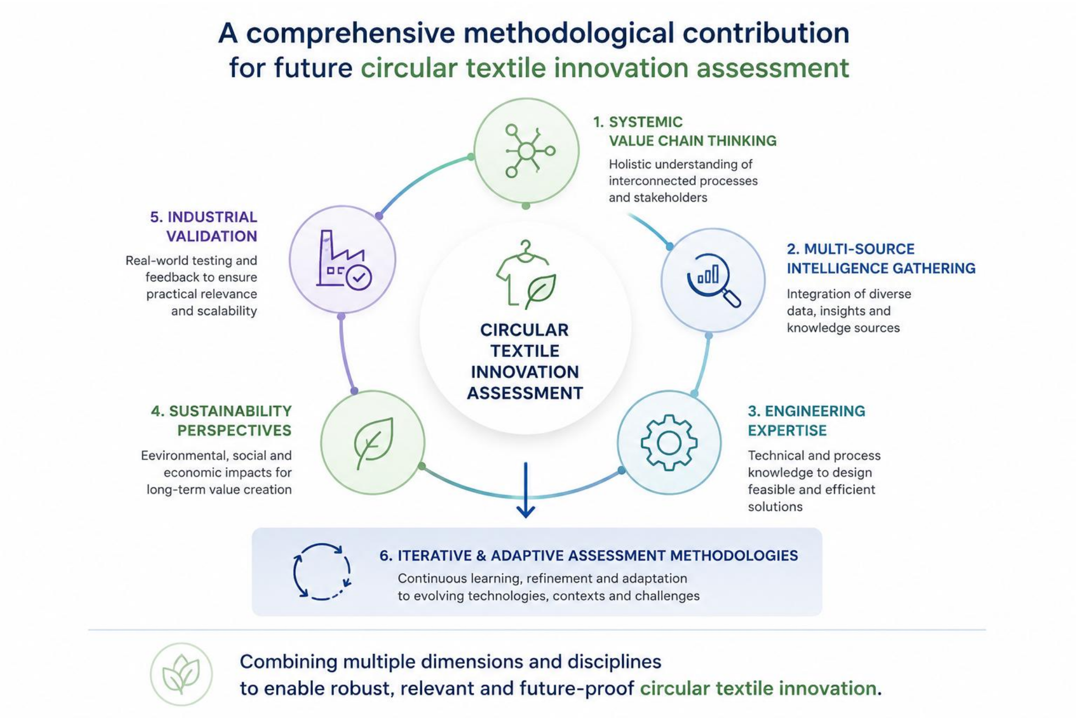


*Figure 41 -Framework for assessing circular textile innovation*

| Short term solutions | Medium-long term solutions |
|---|---|
| Automatic sorting for recycling | New compact carding solutions |
| Intelligent sorting for reuse | Innovative depolymerisation for high volumes |
| Thermo-mechanical treatment of textile waste (synthetic and cellulosic) | AI empowers repair and repurpose |
| Thermo-chemical treatment of textile waste | Integrated sorting and material preparation for recycling |
| AI for ecodesign and repair | Extensive repair and repurpose through automatic processes |
| Repurpose design assisted by AI | |

From the outcomes of the analysis general considerations about the timing of technologies development can be extracted

The technologies that show in the short term the highest potential for development and diffusion relate mainly to the preliminary phases of the 5Rs value chains. Sorting is undoubtfully the area where R&D and industrial development are mainly focusing at the moment. It emerged that technologies in the domain of other Rs, like reuse, repair, repurpose are progressing at a slower pace, or are more managed and diffused at social level through civil initiatives. Therefore, the technological development still present barriers today: in the **short term** the main progresses are expected on sorting solutions, for the high quality identification of textile EoL material, but also in sorting for reuse, to support the human workforce and boost the volumes of post-consumer textiles to be evaluated. The short term will see less technology in repair and repurpose, currently focused on the handwork of small shops, artisans and designers. These last paths are a growing trend though; research is moving towards finding solutions (mainly in the robotics domain), but they will likely be ready in more than 3 years outlook. Finally, recycling technologies will progress fast in the short term: thermomechanical is surely a potentially large growing area, as well as chemical solutions. Both of them are going to be the focus for grow-ups, start-ups and SMEs in Europe in the next-coming years, starting to provide recycling services on a large scale. A growth in the number of businesses in this area is easily predictable.

As regards the **medium-long term**, mechanical recycling will have more chances. The investigation of novel and more flexible technologies will progress (at low pace) but will allow for more options in applications and volume of products based on recycled fibres. The patented carding with fixed carding flats and the textile colour retention are good examples in this respect. Chemical recycling will see a large growth, provided that economic barriers will be removed or softened, thanks, among the others, to EPR schemes. Actually, chemical recycling is the most relevant development needed to shift from a recycled fibres small-scale production worldwide to an extensive use of synthetic regenerated material for many diverse applications (from clothing to furniture, from technical textiles to medical and packaging).

Approximately the same considerations can be repeated for thermomechanical recycling, where an exponential growth can be foreseen in the long term, at a higher speed of chemical recycling, if possible. This is because thermomechanical solutions are often technically and economically more viable than chemical recycling itself.

Task 3.1 demonstrated that the future of textile circularity will depend on the ability to combine technological innovation, operational efficiency, industrial scalability and systemic integration across the entire end-of-life value chain. The resulting Technology Assessment Database, value chain maps and evaluation framework therefore represent not only a snapshot of the current technological landscape, but also a foundation for future monitoring, assessment and investment-oriented decision-making activities within the textile circularity sector.

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