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MATERIAL ANALYSIS AND SELECTION REPORT

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Authors	Karen De Clerk, Sofie Moorkens, Katarzyna Grabowska, Anna Bacciarelli-Ulacha, Michał Puchalski, Iwona Nowak, Agnieszka Cichocka, Grzegorz Szparaga
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Abstract	
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1. Introduction

The purpose of this report is to provide a comprehensive analysis of textile materials used in contemporary apparel production, with particular emphasis on their potential within circular economy (CE) loops. Within the broader project framework, the overall objective is to support the development of such loops through the application of artificial intelligence (AI) and machine learning (ML) tools.

Figure 1 illustrates the conceptual transition from a generic circular economy loop to an AI- and data-driven circular system tailored to the realities of the textile and apparel sector. While conventional circular models often assume linear and well-defined material flows, real textile systems are characterised by complex product structures, fibre blends, variable use patterns and fragmented end-of-life pathways. Integrating data, artificial intelligence and advanced analytics into the circular economy loop is therefore essential to support informed decision-making across design, production, use and recycling stages.

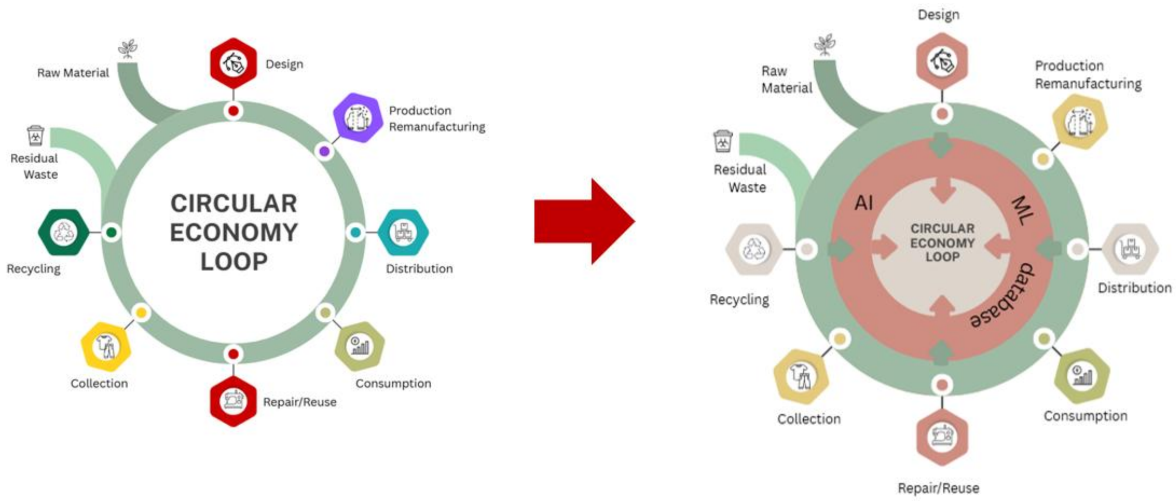

Figure 1. The conceptual transition from a generic circular economy loop to an AI- and data-driven circular system tailored to the realities of the textile and apparel sector.

However, before such AI- and ML-supported circular loops can be effectively developed, it is necessary to identify which types of loops are most relevant for textile producers and which apparel products most urgently require targeted circular solutions. This report addresses this prerequisite by focusing on material and product selection as a critical first step in the development of meaningful and scalable circular economy models.

The document serves as the methodological and analytical foundation for subsequent activities under WP4 of the AIdesignTEX project, including the selection of materials for developing circularity strategies for chosen textile products as well as the preparation of datasets and frameworks for AI/ML model development.

The scope of the report includes:

- A systematic literature review covering textile fibres and the technologies used in their production, with attention to environmental, technological, and regulatory perspectives.
- An analysis of fibre properties that are critical for product durability, recyclability, and environmental performance across the lifecycle.
- An assessment of human health impacts associated with fibre production processes, including exposure to chemicals, emissions, and other occupational or consumer-related risks.
- A comparative evaluation of production costs, considering both raw materials and manufacturing processes, to inform material selection from an economic standpoint.

- An analysis of the global market share of key textile fibres, highlighting their relevance for large-scale circularity interventions and their representation in post-consumer textile waste streams.
- An examination of the applicability of each fibre type in apparel products, considering performance requirements, user expectations, and compatibility with circular design principles.
- An evaluation of recyclability and circularity potential, including mechanical and chemical recycling options, opportunities for reuse, repairability, and pathways for second-life applications.

These components will enable the identification of priority materials for WP4 and support the development of scientifically grounded strategies for the transition towards circular textile systems within the AIdesignTEX project.

1.1. Global textile fibre market

The global textile fibre market continues to be dominated by polyester and cotton, which together account for more than three quarters of worldwide production. According to recent market analyses (Materials Market Report 2024) (1,2), polyester maintains its leading position due to its cost efficiency, versatility and scalability, while cotton remains the most important natural fibre despite fluctuations linked to climate conditions and agricultural inputs. Regenerated cellulosic fibres (MMCF), including viscose, modal and lyocell, have demonstrated stable growth and currently represent around 7% of global fibre output. This trend is supported by increasing demand for fibres with a lower environmental footprint, particularly those derived from sustainably managed forests and closed-loop processes. Meanwhile, the contribution of polyamide, acrylic and wool remains relatively small but regionally significant in specialised apparel markets. Overall, the fibre landscape is undergoing gradual diversification, yet the dominance of polyester and cotton continues to shape both the environmental burden of the sector and the opportunities for circularity interventions, making them central to the analytical scope of WP4.
The latest available market distribution is:

- Polyester (PES/PET): 54–57%
- Cotton: 22–24%
- MMCF (viscose, modal, lyocell): 6–7%
- Polyamide (nylon): ~5%
- Acrylic: 2–3%
- Wool and other natural speciality fibres: <1%
- Polypropylene ~5%
- Elastane 1-2%

These proportions have remained relatively stable in recent years, although slight increases in the MMCF segment reflect growing demand for more sustainable cellulose-based fibres.

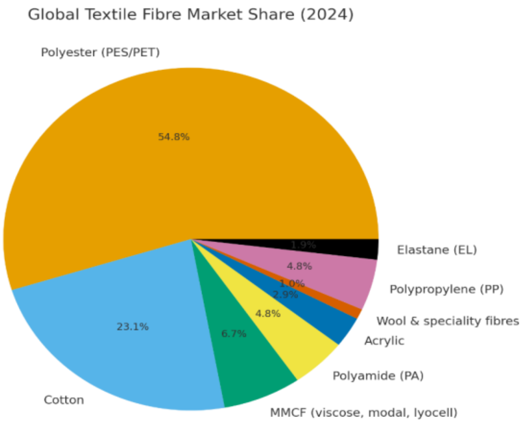

Figure 2. The global textile fibre market.

The dominance of polyester and cotton means that these fibres generate the largest absolute environmental impacts, most of the post-consumer textile waste, and the greatest challenges for sorting and recycling infrastructures. For this reason, the material scope of WP4 focuses on the fibre categories that have the highest relevance for circular transformation at scale. By analysing cotton, polyester, MMCF fibres and their common blends—especially cotton–polyester—WP4 aligns its methodology, data collection and AI-based modelling with the materials that define the global textile system and offer the largest potential for circular economy interventions.

1.2. Market Dynamics and Implications for Micro-project

Beyond the distribution of fibre types, the textile materials market in 2024 is undergoing profound structural transformation. Sustainability requirements, digitalisation trends, shifting consumer preferences and advancements in material science are reshaping both production systems and material portfolios. Industry analyses highlight that sustainability has become one of the strongest drivers influencing the sector (3). Manufacturers increasingly prioritise reductions in water and energy use, elimination of hazardous chemicals, enhanced traceability, and alignment with emerging regulatory frameworks such as the Ecodesign for Sustainable Products Regulation (ESPR) and the Digital Product Passport (DPP) (5). These developments accelerate the adoption of eco-designed materials and circular-ready fibres, which directly support the objectives of WP4.

Parallel to sustainability-driven changes, the market is seeing growing interest in innovative and high-performance materials, including bio-based synthetics, advanced MMCF fibres, chemically and mechanically recycled polyester, and specialised performance textiles. Although diversification is increasing, virgin polyester remains dominant due to its low cost and established supply chains.

Technological integration is another strong market driver. Smart textiles—based on conductive fibres, moisture-management structures, thermoregulating materials and antimicrobial finishes—are expanding across both apparel and technical sectors. However, these innovations also introduce challenges related to chemical management, sorting and recyclability, which are becoming increasingly significant under ESPR and DPP obligations.

Consumer-driven customisation and small-batch production are reshaping manufacturing, leading to more heterogeneous material compositions and finishing techniques (4). This, in turn, increases the complexity of textile waste streams and reinforces the need for robust material classification approaches and AI-supported modelling—core elements of WP4.

Regional dynamics further contribute to shaping the global fibre landscape. Asia-Pacific markets continue to drive demand for polyester and cotton due to their dominant role in global manufacturing, whereas Europe is increasingly oriented towards sustainable materials, technical textiles and regulatory-driven circularity strategies. North America shows strong growth in high-performance and smart textiles. These regional patterns influence the composition of textile waste and underscore the importance of integrating regional variability into WP4's analytical framework.

In summary, the structure of the global textile fibre market—dominated by polyester and cotton, supported by a growing but still limited share of MMCF fibres—provides a clear rationale for the material selection in WP4. The fibres chosen for detailed analysis reflect both their global significance and their strategic relevance to circular economy objectives. By focusing on high-volume materials such as cotton, polyester, viscose, and polyester–cotton blends, the AIdesignTEX project ensures that its material evaluation framework and AI-ready datasets address the most critical challenges and opportunities shaping the current and future textile system.

2. Methodological Approach

2.1. Literature Review and Data Sources

The methodological approach applied in this report is based on analytical and comparative principles, combining a systematic review of scientific literature with the analysis of industry data and statistical sources related to textile materials, their production processes, properties, market relevance, and recyclability. This multi-layered approach enables a comprehensive understanding of technological, environmental, health-related, and economic aspects of the fibre types examined.
The analysis draws on the following categories of sources:

- **Scientific publications** indexed in Scopus, Web of Science, and Google Scholar, covering fibre characteristics, manufacturing technologies, sustainability aspects, and life cycle assessment (LCA) studies.
- **Industry and market reports**, including annual publications from Textile Exchange (*Preferred Fiber & Materials Market Report*), *The Fiber Year*, Euratex, and the Ellen MacArthur Foundation, providing updated insights into global fibre production, market trends, environmental challenges, and sectoral transformations.
- **Statistical datasets** from OECD, FAO, Statista, and other recognised repositories, offering data on fibre production volumes, trade flows, consumption patterns, and long-term developments in global supply.
- **Strategic policy documents of the European Union**, such as the Ecodesign for Sustainable Products Regulation (ESPR), the Circular Economy Action Plan (CEAP), and the EU Strategy for Sustainable and Circular Textiles, which outline regulatory priorities and frameworks guiding the transition towards circular textile systems.
- **LCA-focused publications** analysing the environmental impacts of fibres and textile products, including assessments of production stages, use-phase dynamics, and identification of environmental hotspots across the value chain.
- The literature and data review considered several key thematic areas:
- **Physical, mechanical, and chemical properties of fibres**, which determine durability, performance, and suitability for different apparel applications.
- **Toxicity and chemical use** in fibre production processes, including occupational exposure and potential consumer safety risks.
- **Environmental parameters from LCA studies**, such as energy and water consumption, greenhouse gas emissions (GWP), chemical inputs, and the generation of microplastics.
- **Recycling and material recovery**, covering mechanical and chemical recycling technologies, biodegradation potential, and barriers related to fibre blends and multi-component products.
- **Global fibre consumption, supply data, and market share patterns**, enabling the identification of fibres that dominate production volumes and waste streams, and thus carry the greatest strategic importance for circular economy interventions.

This methodological framework ensures an objective, comprehensive, and cross-disciplinary evaluation of textile materials and forms a solid basis for the comparative analysis and material selection presented in subsequent sections of the report.

2.2. Rationale for Framework Design

The design of the **AIDesignTEX Material Evaluation Framework** is grounded in the need to systematically assess textile fibres in a way that is scientifically robust, aligned with emerging EU sustainability legislation, and directly applicable to the analytical and modelling tasks of WP4. The textile sector is characterised by high material diversity, complex production pathways, and rapidly evolving regulatory requirements. As a result, traditional fibre classifications are insufficient for circularity-oriented decision-making. A structured, multi-layer assessment framework enables the integration of heterogeneous data sources and provides a transparent method for prioritising materials.

A central driver for the framework design is the dominance of a small number of high-volume fibres-primarily polyester, cotton and regenerated cellulosics-which account for more than 80% of global production and make up the majority of post-consumer textile waste. Their environmental profiles, recyclability challenges, and market relevance necessitate a methodology that captures both scientific evidence (e.g., LCA parameters, durability metrics, chemical profiles) and strategic considerations (e.g., regulatory relevance, feasibility of prototyping, data availability for AI/ML modelling).

In parallel, the European regulatory landscape-including the Ecodesign for Sustainable Products Regulation (ESPR), the Digital Product Passport (DPP), the Waste Framework Directive (WFD) requirements for textile waste, and REACH chemical restrictions-places new obligations on durability, reparability, transparency and chemical safety (5). These priorities are embedded directly into the evaluation framework to ensure that selected materials reflect the regulatory realities that companies and researchers will face in coming years.

Finally, the framework responds to the technical needs of WP4, which requires standardised datasets and clear prioritisation to support machine learning model development, digital product twin creation, and circularity loop testing. By structuring the evaluation into three levels-material performance, project relevance, and final ranking-the framework ensures that only fibres with strong evidence bases, strategic market importance and realistic circularity potential are selected for deeper analysis.

2.3. AIDesignTEX Material Evaluation Framework – Introductory Summary

The AIDesignTEX Material Evaluation Framework is a three-layer evaluation system designed to support the selection of textile fibres and material structures for environmental assessments, AI/ML modelling, and circularity strategy development within WP4. It combines a scientific evaluation of material performance with a project-oriented assessment of relevance for AIDesignTEX, thereby enabling a comprehensive, multi-criteria selection methodology.

Level 1 - Material Performance Assessment

This level evaluates fibres as raw materials based solely on data from scientific literature and existing research. Seven categories are assessed: environmental impact (LCA), human health considerations, quality and durability, recyclability and circularity potential, cost, applicability in apparel, and global market share. Each criterion has defined sub-criteria, a 0–3 scoring scale, and a weighting factor.

Guiding question: "How does the material perform across its lifecycle and technical characteristics?"

Level 2 - WP4 Relevance Assessment

This level is unique to the AIDesignTEX project and evaluates how suitable each material is for WP4 research and prototyping. It considers data availability (for AI/ML), material homogeneity, EU market relevance, product complexity, prototyping feasibility, alignment with ESPR and DPP, and quality variability in waste streams.

Guiding question: "Is this material worth engaging in WP4 activities?"

Level 3 – Integration and Final Ranking

This level integrates the results from Levels 1 and 2 into a consolidated decision-making model. Weighting schemes, trade-off analysis, and relevance scoring support the identification of the most representative and valuable materials for WP4.

Guiding question: "Which materials should be prioritised for WP4?"

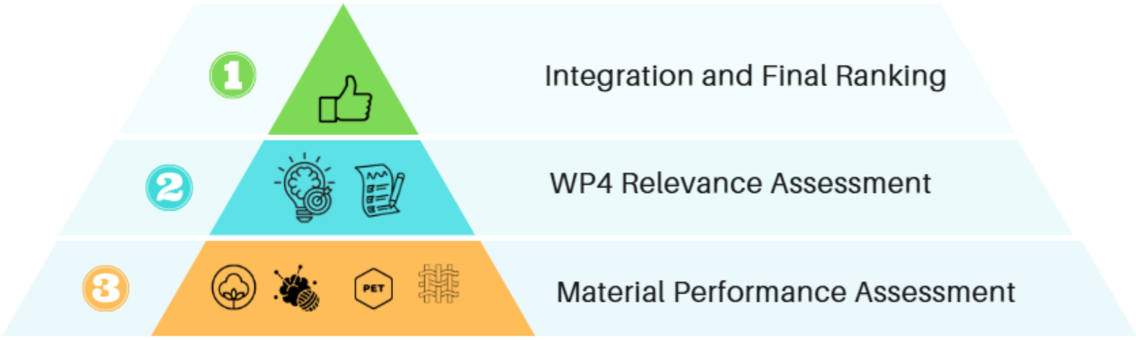

Figure 3. AIdesignTEX Material Evaluation Framework

The framework provides a coherent, scientifically grounded, and transparent foundation for material selection and serves as a cornerstone for subsequent AIDesignTEX activities.

2.4. Material Evaluation Categories and Weighting Scheme

The AIDesignTEX material evaluation follows a multi-criteria scoring system, combining qualitative and quantitative indicators across six core categories. Each category is assigned a weighting factor reflecting its relevance for circularity, environmental impact, AI/ML modelling needs, and the objectives of WP4. Scores are assigned on a 0–3 scale, where higher scores indicate more favourable performance.

Table 1: Categories and Scope of Material Evaluation

Category	Weight	Scope of Evaluation	Examples of Indicators / Specific Criteria
Environmental Impact (LCA)	20%	Evaluation of environmental burdens across the full life cycle: raw material production, fibre manufacturing, wet processing, use phase, and end-of-life.	• Water consumption (blue/green/grey) • Energy demand • GHG emissions (kg CO_2-eq) • Chemical footprint • Microplastic release (synthetics) • Eutrophication/acidification potential
Human Health Impact	20%	Risks associated with occupational exposure during manufacturing and consumer safety during use.	• Exposure to solvents (CS_2), isocyanates, dust • Toxicity of dyes and finishes • Skin irritation/allergenicity • Nanoparticle migration • Presence of restricted chemicals (REACH, ZDHC MRSL)
Product Quality , Durability & User Comfort	20%	Evaluation of material performance influencing product lifetime, maintenance needs, and functional stability.	• Mechanical durability (abrasion resistance, tensile strength, pilling behaviour) • Dimensional stability during use and care (shrinkage, shape retention) • User comfort attributes, including softness and handfeel, breathability, thermal comfort and moisture management • Comfort under repeated wear and washing (next-to-skin performance, skin compatibility) • Sensitivity to finishing and garment construction affecting wear comfort

Recyclability & Circularity Potential	20%	Assessment of suitability for circular loops: mechanical/chemical recycling, biodegradability, reuse potential, and challenges linked to blends.	• Mechanical recyclability (fibre length retention) • Chemical recyclability pathways (dissolution, depolymerisation) • Biodegradability • Repairability, reuse potential • Barriers from blends (e.g., elastane, coatings)
Cost	10%	Economic viability of using the fibre in large-scale production and circular systems.	• Raw material price • Processing costs (spinning, finishing) • Market volatility • Availability/scalability
Applicability in Apparel	10%	Suitability of the fibre for textile manufacturing technologies and its performance in garments.	• Compatibility with knits/wovens • Dyeability and finishing behaviour • Comfort, breathability, moisture management • Performance in key apparel categories (T-shirts, denim, sportswear)

Justification of the Weighting Scheme
The weighting scheme applied in the AIDesignTEX Material Evaluation Framework reflects the strategic goals of WP4, the methodological principles of circular economy assessment, and the requirements for AI/ML model development within the project. The weights were selected to balance scientific rigour, practical relevance for textile production, and alignment with EU policy frameworks such as the Ecodesign for Sustainable Products Regulation (ESPR), the Waste Framework Directive (WFD), and the forthcoming Digital Product Passport (DPP).

1. **Environmental Impact (20%)** - High relevance for CE and policy alignment - Environmental performance is one of the principal drivers of material selection, as fibre manufacturing and wet processing represent major environmental hotspots in the textile lifecycle. EU legislation increasingly prioritises reducing GHG emissions, water use, chemical pollution, and microplastic release.
   Assigning a weight of 20% reflects:
   - the strategic importance of LCA indicators for circularity design,
   - strong regulatory pressure on environmental performance,
   - the need to build AI-ready datasets based on measurable environmental variables.
2. **Human Health Impact (20%)** - Essential for safe and sustainable design - Human toxicity and occupational exposure are critical factors affecting sustainability and compliance with REACH, ZDHC MRSL, and DPP requirements. Fibres that require hazardous chemicals (e.g., CS_2 in viscose) or introduce substances of concern into consumer products require careful assessment. The 20% weight reflects:
   - increasing regulatory scrutiny of toxic substances,
   - relevance for textile workers' health and consumer safety,
   - the need to identify materials compatible with future ESPR restrictions.
3. **Product Quality, Durability and User Comfort (20%) – Direct determinant of product lifetime-** Product quality, durability and user comfort jointly determine the effective service life of apparel products. Durability alone is insufficient to ensure long-term use if garments do not meet user expectations in terms of comfort, wearability and next-to-skin performance. Extending the functional and perceived lifetime of textile products often delivers greater environmental benefits than fibre-to-fibre recycling, while also reducing demand for replacement products.
   Therefore, a weight of 20% is assigned to this category to reflect:

- the importance of both durability and user comfort for circular economy loops focused on reuse, repair and rental,
- the strong correlation between product performance, user acceptance and environmental outcomes,
- the relevance of quality degradation and comfort loss for digital twin modelling of product ageing and wear behaviour (WP4).

4. **Recyclability & Circularity Potential (20%)** - Foundation of CE loops - This category evaluates whether a material can realistically participate in circular value chains. Mechanical recycling, chemical recycling, biodegradability, and ease of repair are fundamental to ESPR and industry circularity targets. The equal 20% weight reflects:
   - recyclability as a core criterion for future textile systems,
   - market relevance (PET, cotton, and MMCF have very different recyclability levels),
   - the need to identify materials that can feed high-quality circular loops.
5. **Cost (10%)** - Necessary but not decisive - Cost influences industry adoption and scalability but should not outweigh sustainability and technical performance. A moderate weight of 10% acknowledges:
   - the need for economic feasibility of material choices,
   - the risk of over-prioritising low-cost fibres (e.g., virgin polyester),
   - alignment with the project's focus on long-term sustainability over short-term savings.
6. **Applicability in Apparel (10%)** - Practical relevance for WP4 prototyping - Compatibility with apparel manufacturing (knits, wovens, dyeing, finishing) is essential for realistic prototyping within WP4. However, this criterion is constrained by the overarching environmental and circularity goals; hence, a 10% weight is appropriate. It reflects:
   - the importance of practical usability in creating AI-ready physical prototypes,
   - the need to capture the behavioral differences between fibres in T-shirts, denim, sportswear, etc
   - but without overshadowing sustainability-driven criteria.

Scoring Scale

The 0–3 scoring scale is designed to provide a transparent, comparable and reproducible method for evaluating textile fibres across multiple sustainability and performance categories. The scale captures both absolute performance (e.g., environmental impact, durability) and relative suitability for circular economy applications and WP4 requirements.

Table 2. Scoring Scale (0–3)

Score	Meaning	Interpretation
0 – Very Poor	Material performs poorly; data indicate significant negative impacts or severe limitations.	Major barriers to circularity, high impacts, unsafe, costly, or incompatible with apparel use. A score of 0 may also be assigned in cases where a material exhibits structurally high, material-level environmental impacts that cannot be fully mitigated through downstream circular strategies.
1 – Moderate	Acceptable but with notable challenges.	Material usable but with constraints (e.g., limited recyclability, inconsistent performance).
2 – Good	Favourable performance with some limitations.	Material generally aligns with CE goals; manageable constraints.

3 – Excellent	Strongly aligned with circularity and sustainability objectives.	Low impacts, high durability, excellent recyclability, strong usability and data availability.

Score 0 - Very Poor - A score of 0 is assigned when the material exhibits critical disadvantages that significantly limit its use in circular systems or apparel applications. This may include extremely high environmental impacts, hazardous chemical requirements, poor durability, absence of recycling pathways, or incompatibility with common manufacturing processes. Materials scoring 0 in multiple categories typically require exclusion from further WP4 analysis.
Score 1- Limited / Moderate- A score of 1 indicates that the material is usable, but presents substantial limitations. These may include restricted recyclability, high variability in performance, problematic additives, or insufficient data availability. Materials in this category can still be considered in WP4 but would require mitigation strategies or additional research.
Score 2- Good - A score of 2 reflects solid overall performance with only minor or manageable constraints. These materials generally align with circularity objectives, offer acceptable environmental performance, and are well-suited to apparel applications. They may not be optimal in every dimension, but they do not pose systemic barriers.
Score 3 -Excellent - A score of 3 is given to materials that show strong alignment with sustainability goals, robust technical performance, and high suitability for circular economy loops. They have low environmental and health impacts, strong durability, high-quality recycling options, and broad compatibility with textile manufacturing methods. Materials scoring 3 are ideal candidates for WP4 prototyping and AI/ML dataset development.

6.1. How Scoring Is Performed in Practice (Assessment Procedure)

The scoring procedure used in the AIDesignTEX Material Evaluation Framework follows a structured, repeatable and transparent methodology, ensuring consistency across fibres and enabling comparative analysis. Each material is evaluated using a 0–3 scoring scale, weighted according to the relevance of each category for circularity, sustainability, technological applicability, and WP4 objectives.

Step 1 - Collection of Evidence

For each fibre, available data are compiled from:

- peer-reviewed publications (LCA, toxicology, fibre science),
- industrial and market reports (Textile Exchange, The Fiber Year, Euratex),
- technical datasets from manufacturers,
- regulatory documents (ESPR, DPP, REACH),
- experimental data (if available from partners),
- known recycling performance from industrial practice.
- This ensures the scoring is evidence-based rather than subjective.

Step 2 - Category-by-Category Evaluation (0–3 score)

For every category in Table 1, assessors assign a score according to the scoring scale (0 = very poor, 3 = excellent). Examples:

- Environmental Impact: cross-compare water footprint, GHG emissions, energy demand, chemical use.
- Human Health: assess exposure risks during production and consumer safety during use.
- Durability: evaluate strength, shrinkage, colour fastness, pilling, based on literature and technical sheets.

- Circularity: determine recyclability pathways, biodegradability and barriers caused by blends or finishes.
- Cost: compare raw material and processing costs relative to alternatives.
- Apparel Applicability: consider compatibility with knits/wovens, dyeing behaviour, comfort and typical applications.

Where data is incomplete, the lowest confidence or a conservative score is used.

Step 3 - Weighting of Scores (Level 1 output)

Each category score (0–3) is multiplied by the predefined weighting factor. This step reflects AIDesignTEX priorities:

- strong emphasis on sustainability and longevity (4 categories × 20%),
- recognition of economic and industrial feasibility (2 categories × 10%).

Step 4 - WP4 Relevance Check (Level 2 assessment)

Beyond performance, each fibre is evaluated for:

- data availability for AI/ML (LCA, mechanical properties, dyeing curves),
- homogeneity or complexity (mono-material vs blends),
- EU relevance and market scale,
- waste stream characteristics (variability, contamination),
- prototyping feasibility at partner institutions,
- alignment with ESPR/DPP requirements.

Level 2 produces a Relevance Score (0-3) for each criterion, combined into a WP4 Relevance Index (0-10 or 0-100, depending on selected format).

Step 5 - Integration & Ranking (Level 3 output)

The Material Performance Score (Level 1) and the WP4 Relevance Index (Level 2) are merged using a weighted integration model (e.g., 70% Level 1 + 30% Level 2). This results in:

- Final Material Score,
- Ranking of fibres,
- Shortlist of recommended fibres for WP4 prototyping, AI/ML dataset creation, and circularity loop development.

Step 6 - Documentation and Validation

For transparency, each assessment must include:

- justification of each sub-score,
- references to evidence sources,
- notes on confidence level,
- uncertainty or data gaps.

The scoring may be validated internally across partners to ensure inter-rater consistency.

3. Material and technology characteristics

3.1. Natural fibres - Cotton

3.1.1. Cotton - generl characteristic

Cotton is the most important natural textile fibre globally and, together with polyester, one of the two dominant raw materials used in apparel production. It is characterised by a high cellulose content (approximately 88–96%), good breathability, excellent moisture absorption, and high skin comfort, which explains its widespread use in everyday clothing and underwear (6).
Depending on the variety, fibre length, and cultivation conditions, cotton can differ significantly in quality (e.g., short staple, medium staple, long staple, extra-long staple). Longer and more uniform fibres yield stronger yarns and higher-quality final products.
Cotton exhibits relatively high chemical stability but limited abrasion and pilling resistance compared to synthetic fibres, which can shorten its durability. Under composting and biodegradation conditions, cotton is capable of biological decomposition, provided it has not been treated with permanent chemical finishes that modify its surface.
From the perspective of WP4, cotton is strategically relevant due to:

- its high market share and representation in European textile waste streams,
- strong consumer acceptance and reuse potential,
- compatibility with established mechanical and emerging chemical recycling routes,
- relevance for regulatory frameworks addressing durability, recyclability and material transparency (ESPR, DPP).

At the same time, cotton exhibits moderate durability compared with synthetic fibres and shows high variability in quality depending on fibre length, yarn type, fabric construction and finishing chemistry. These characteristics directly affect product lifetime and recyclability performance and therefore require structured evaluation within circular economy models.

3.1.2. Key Production-Related Hotspots Relevant for WP4

Unlike synthetic fibres, cotton combines an agricultural production phase with industrial textile processing. From a circularity and LCA perspective, the most critical stages are not the spinning or fabric formation processes themselves, but upstream cultivation and downstream wet processing (8).

The main hotspots identified consistently in literature include:

- Agricultural phase – high freshwater consumption (particularly blue water in irrigated systems), fertiliser and pesticide use, land occupation and yield variability.
- Wet processing – scouring, bleaching, dyeing and finishing, which are among the most resource- and chemical-intensive stages of the cotton textile lifecycle.

For WP4 purposes, detailed descriptions of harvesting, ginning or spinning technologies are of secondary importance. Instead, cotton is treated as a high-impact but high-potential fibre, where relatively small design and processing changes can lead to significant environmental and circularity gains at scale.

3.1.3. Role of Wet Processing in Environmental Profile and Circularity

Wet processing represents one of the dominant environmental hotspots in cotton textiles and often equals or exceeds agricultural impacts in categories such as water use, eutrophication, ecotoxicity and energy demand. Reactive dyeing of cotton is particularly resource-intensive due to high salt loads, alkaline conditions and extensive rinsing requirements (7,8).

From a circular economy perspective, wet processing is a critical intervention point because finishing chemistry strongly determines end-of-life options. Durable crosslinking resins, pigment binders, hydrophobic coatings and certain functional finishes can:

- reduce fibre biodegradability,
- hinder chemical cellulose dissolution in MMCF-based recycling,
- contaminate mechanically recycled cotton streams,
- require additional sorting or exclusion under future DPP and ESPR criteria.

Conversely, low-impact finishes (e.g. enzymatic bio-polishing, fluorine-free systems, reduced-liquor dyeing) support longer product lifetimes and improved compatibility with recycling technologies. For this reason, wet processing parameters are treated in WP4 as key descriptors for AI-supported material classification and circularity modelling, rather than as purely aesthetic processes.

3.1.4. Functional and Technical Properties Relevant for Circular Design

Cotton exhibits excellent comfort-related properties, including high moisture absorbency, breathability and skin compatibility, which support high user acceptance and reuse rates. Mechanically, cotton offers good tensile strength, particularly in wet conditions, but moderate abrasion and pilling resistance, especially in knitted structures and fabrics made from short-staple or open-end yarns (6).

Key properties influencing circular performance include:

- Durability – moderate and highly dependent on yarn quality, fabric structure and finishing;
- Repairability – very high; cotton is easy to sew, patch and modify, supporting life-extension strategies;
- Biodegradability – high for untreated cellulose, but significantly reduced by polymeric or crosslinked finishes.

These characteristics make cotton particularly suitable for circular models prioritising reuse, repair and second-hand markets, while also enabling fibre-to-fibre recycling under controlled material and finishing conditions.

Table 3. Selected Functional and Technical Properties of Cotton

Property	Characteristics
Moisture absorbency	High; excellent vapour permeability and sweat absorption
User comfort	Very high; soft, breathable, skin-friendly
Tensile strength	Good; increases when wet, beneficial for washing durability
Abrasion resistance	Low–medium; depends on yarn quality and fabric structure (wovens > knits)
Pilling resistance	Generally low; improved with combed yarns and longer staple fibres
Dimensional stability	Moderate; prone to shrinkage, requires stabilisation (e.g., sanforisation)
Crease resistance	Low; easily wrinkles unless treated with anti-crease finishes
Dyeability	Excellent with reactive dyes; wide colour range achievable
Handle / softness	Naturally soft; easily modified through softeners or enzymatic finishing
Thermal behaviour	Moderate thermal conductivity; comfortable in temperate and warm climates
Biodegradability	High, but reduced by polymeric finishes, hydrophobic coatings or crosslinking resins

3.1.5. Environmental Impact of Cotton (LCA Perspective)

Life Cycle Assessment studies consistently identify cotton as a fibre with a substantial environmental footprint (8,9), driven primarily by:

- high water demand in cultivation (with strong regional variability),

- fertiliser- and pesticide-related emissions,
- energy- and chemical-intensive wet processing,
- significant use-phase impacts related to frequent washing, drying and ironing.

At the same time, cotton offers two major environmental advantages compared with synthetic fibres:

- absence of microplastic release during use,
- full biodegradability of the cellulose backbone.

A synthesis of selected LCA results—illustrating the variability in water consumption and carbon footprint across farming systems and methodological choices—is provided in Table 3.X. These variations underscore the need for clear justification of data sources in the subsequent stages of the WP4 evaluation.

Table 4. Example LCA Results for Cotton – Selected Studies

Study / Source	Functional Unit (FU)	System / Product	GWP (kg CO_2-eq / FU)	Water Use (blue / total)	Key Notes / Hotspots
Textile Exchange / Cotton Inc. – global average cotton (MDPI)	1 kg fibre	Conventional cotton (global average: China, India, Turkey, USA)	~1.81 kg CO_2-eq/kg fibre	~2120 m³ blue water / 1000 kg fibre (~2.1 m³/kg)	Major contributors: nitrogen fertilisers, field energy use, irrigation. High blue-water consumption in irrigated systems.
Textile Exchange – organic cotton study (MDPI)	1 kg fibre	Organic cotton (mainly India)	~0.98 kg CO_2-eq/kg fibre	~15,000 m³ total water per tonne (mostly green water)	~40–46% lower GWP vs. conventional cotton. Very high total water footprint due to lower yields and dominance of green water.
Chapagain et al. – water footprint of cotton (ResearchGate)	1 kg fibre	Global cotton (various regions and systems)	–	7000–29,000 L/kg fibre (green + blue + grey water)	Very wide range reflects climatic variation, irrigation method, and agronomic practices. Highlights high contribution to global water use.
Cotton Inc. LCA Update – Cotton Garments	1 cotton T-shirt (200 g)	Conventional cotton T-shirt, cradle-to-grave, global washing scenarios	*Ranges depending on use-phase scenario* (production + use = several kg CO_2-eq per T-shirt)	Significant water use in wet processing and washing	Wet processing + consumer-use phase often exceed agricultural impacts; washing/drying dominate energy use.
Gonçalves et al. 2024 – Portuguese white T-shirt (MDPI)	1 T-shirt (200 g; 50% recycled + 50% organic cotton)	Knitted jersey T-shirt, cradle-to-gate	0.624 kg CO_2-eq / T-shirt	~10 m³ water / T-shirt	Hotspots: fibre production (especially organic cotton), electricity in knitting, dyeing/finishing. Recycled content significantly reduces GWP compared to 100% conventional cotton.

Due to high variability in farming systems, yields and processing technologies, cotton LCA results show wide ranges. This variability underscores the need for transparent data selection and clearly defined system boundaries when cotton is used as an input for AI/ML models and comparative circularity assessments in WP4.

3.1.6. Human Health Considerations

Cotton is widely regarded as one of the most skin-friendly textile fibres. As a natural cellulose material, it does not release monomers or solvents during use and shows very low allergenic potential. Health risks for consumers are primarily linked to residual dyes or finishing agents and are largely mitigated by compliance with REACH (10), OEKO-TEX® (11) and ZDHC requirements (12).
Occupational health risks occur mainly upstream and are associated with:

- exposure to cotton dust during fibre opening and spinning,
- handling of dyes, alkalis and finishing chemicals in wet processing.

Table 5. Human Health Impact Assessment – Cotton (Standardised Indicators)

Health Impact Indicator	Cotton - Assessment	Notes / Risk Drivers
Skin compatibility / allergenicity	Very high / low risk	Natural cellulose; no monomer migration; good moisture absorption
Thermal & moisture comfort	Excellent	Breathable, absorbs sweat; extended drying time
Chemical residues in final product	Low (with certification)	Potential risks from dyes, resins, biocides if unregulated
Occupational exposure -dust	Moderate-high	Cotton dust → byssinosis risk; controlled via filtration & ventilation
Occupational exposure - chemicals	Low-medium	Depends on wet processing: reactive dyes, wrinkle-free resins, PFAS-free hydrophobics, etc.
Electrostatic behaviour	Neutral (favourable)	No static charge → lower irritation risk
Biocide/nanomaterial risk	Low, unless intentionally added	Only relevant for functional finishes
Health-related recyclability constraints	Low	Fibre itself safe; coatings/finishes may introduce risks

In regulated production environments, these risks are effectively controlled. From a WP4 perspective, cotton therefore exhibits a very favourable consumer health profile, with worker exposure risks strongly dependent on process management rather than fibre chemistry.

3.1.7. Recyclability and Circularity Potential

Cotton, as a natural cellulose-based fibre, plays a central role in circular textile systems due to its high market share, suitability for reuse, and compatibility with both mechanical and chemical recycling technologies. Its recyclability, however, is strongly influenced by fibre length, product construction, finishing chemistry and the presence of blends (13).

Mechanical recycling

Mechanical recycling is currently the dominant route for cotton waste, especially pre-consumer cutting waste. The process—shredding, opening and re-spinning—shortens fibres significantly, reducing tensile strength and yarn quality. As a result:

- mechanically recycled cotton typically requires blending with virgin fibres (commonly 20–40%),
- fabric quality decreases with each recycling cycle,
- knitted fabrics degrade faster than woven fabrics due to their lower structural stability.

Despite these limitations, mechanical recycling remains an important pathway for scaling cotton circularity, especially when feedstock is clean, homogeneous and free of elastane.

Chemical recycling

Chemical recycling of cellulose-rich waste is rapidly developing and represents the highest-value circular pathway for cotton. Modern processes (e.g. Circulose®, Ioncell, Infinna™, IL-based technologies) dissolve cellulose, remove dyes, finishes and elastane, and regenerate high-quality MMCF fibres such as lyocell or modal.

Key advantages:

- restores cellulose without fibre shortening,
- enables high purity and high-performance regenerated fibres,
- tolerates certain impurities better than mechanical recycling.

Challenges:

- coatings, durable crosslinked finishes, PFAS, biocides or pigment binders may interfere with dissolution and require pre-processing,
- commercial scalability is ongoing.

Reuse, second-hand and life extension

Cotton garments have exceptionally strong reuse potential due to:

- high consumer acceptance,
- good comfort and perceived quality,
- ease of repair and modification,
- durability in shirts, denim, children's wear and home textiles.

European sorting facilities report that over 50% of cotton articles in collection streams are suitable for direct reuse after minor repairs, making cotton a cornerstone of reuse-driven circular models.

Repairability and upcycling

Cotton is easy to sew, patch, overlock, embroider and rework, which makes it highly compatible with:

- repair services,
- re-commerce platforms,
- upcycling and redesign.

Its workability significantly increases the lifespan of products — a critical aspect of circularity strategies focused on life extension, which often yield higher environmental benefits than fibre-to-fibre recycling.

Table 6. Assessment of Cotton in Circular Economy Pathways: Repairability, Reuse and Recycling

Indicator	Cotton – Assessment	Notes / Key Drivers
Mechanical recyclability	Medium	Fibre shortening; quality loss; needs virgin blend; better for wovens than knits
Chemical recyclability	High	Excellent cellulose feedstock; sensitive to finishes, pigments and elastane
Compatibility with sorting technologies	High	Easy to identify (NIR, burn test); contamination by elastane is main barrier
Impact of dyes/finishes on recycling	Medium–High (barrier)	Crosslinking, hydrophobic coatings, pigment binders, PFAS hinder chemical recycling
Reuse potential	Very high	Strong acceptance, good durability, easy repair

Repairability	Very high	Easy sewing and mending; supports GOZ life-extension strategies
Biodegradability	High	Decreases when coated with polymers or functional finishes
Downcycling risk	Medium–High	Lower fibre strength post-mechanical recycling → wipers, insulation, nonwovens
GOZ maturity level	High	Well-established reuse + advanced chemical recycling pipelines

Cotton shows one of the strongest circularity profiles among major apparel fibres. While mechanical recycling is limited by fibre damage, emerging chemical recycling technologies enable high-quality fibre-to-fibre regeneration. Cotton's exceptional reuse and repair potential significantly amplifies its contribution to circular systems, making it a high-priority fibre for GOZ strategies.

3.1.8. Implications for Recycling and Circular Economy Potential

Cotton, as a natural cellulose-rich fibre, holds significant potential within circular economy models due to its biodegradability, absence of microplastic emissions and dominant market presence. Because cotton accounts for a substantial share of global textile flows, even incremental improvements in reuse or recycling efficiency can translate into meaningful environmental benefits. (14) link

Mechanical recycling – opportunities and constraints

Mechanical recycling of cotton is widely practiced and technologically mature. It remains the primary route for both pre-consumer and post-consumer textile waste. However, the process inevitably shortens fibre length, leading to:

- reduced yarn strength and fabric durability,
- the need to blend recycled cotton with virgin fibres to maintain quality (often 20–40%),
- downcycling into lower-grade applications when fibres become too short.

The efficiency of mechanical recycling depends strongly on waste purity. Homogeneous feedstock (e.g., knit jersey without elastane, light-coloured fabrics, no pigment prints) yields substantially higher-quality recyclate. Conversely, pigment coatings, heavy finishes and elastane contamination significantly reduce process efficiency.[i]

Chemical recycling – high-value potential for closing the cellulose loop

Cotton is an excellent feedstock for emerging chemical recycling technologies that regenerate cellulose into high-quality MMCF fibres (e.g. lyocell, carbamate-based fibres, or cellulose ethers). These processes—based on solvent dissolution, purification and re-precipitation—can produce fibres comparable or superior to virgin MMCF.

Chemical recycling offers key advantages:

- no fibre shortening,
- high cellulose purity after dye/finish removal,
- compatibility with closed-loop solvent systems.

Its performance, however, depends on fibre cleanliness. Elastane, synthetic blends, crosslinked finishes, polymer coatings (e.g. PU, acrylic) and pigment binders can impede dissolution or require additional pre-treatment stages. [ii]

Blends and structural barriers

Fibre blends commonly used in apparel—particularly cotton/polyester and cotton/elastane—present one of the main obstacles to circularity:

- Cotton/Elastane blends complicate both mechanical and chemical recycling due to the presence of polyurethane elastomers.
- Cotton/Polyester requires separation technologies (mechanical-chemical hybrids, enzymatic separation, solvent-based methods), many of which are still scaling.

Therefore, monomaterial cotton or fabrics with very low elastane content currently show the highest recycling potential.

Circularity beyond recycling – reuse, repair and life extension

Cotton's high durability, ease of repair and consumer acceptance make it exceptionally suitable for circular business models based on:

- reuse and re-commerce,
- repair services,
- upcycling and redesign,
- rental models, depending on garment category.

Extending the lifetime of cotton garments often delivers greater environmental benefits than fibre-to-fibre recycling, as emphasised in circularity-focused LCA studies.

Cotton combines strong circularity potential—biodegradability, lack of microplastic emissions, suitability for mechanical and chemical recycling—with several technological challenges, including fibre shortening, chemical contamination from wet processing and the widespread use of blends.

In subsequent sections of this report (particularly those addressing recycling technologies and circular pathway design within WP4), cotton will serve as a refereence fibre, illustrating both the opportunities and systemic bottlenecks inherent in textile circularity.

3.1.9. Cost Considerations – Cotton

Cotton is generally more expensive as a raw material than virgin polyester, reflecting its dependence on agricultural production and natural resource availability. The price of cotton is characterised by high volatility, strongly influenced by climatic conditions (droughts, floods), global supply–demand dynamics, and geopolitical factors affecting major producing countries (2,15).

High-quality long-staple cotton varieties (e.g., combed or extra-long staple fibres) command significantly higher prices due to superior spinnability and performance characteristics. Consequently, yarn production costs for premium cotton are noticeably higher than for commodity-grade fibres (14).

Key cost drivers include:

- Raw material price – typically higher and more variable than synthetic fibres; sensitive to climate, yield fluctuations and global commodity markets.
- Quality-related processing costs – producing high-quality yarns (e.g., ring-spun, combed) requires additional mechanical steps (combing, cleaning, longer drafting), increasing energy use and labour costs.
- Regional variability – production costs differ substantially across countries depending on labour, irrigation requirements, agricultural inputs and infrastructure.
- Cost of sustainable certifications – organic cotton, Better Cotton or regenerative systems involve additional compliance and monitoring costs, though often offset by premium market positioning.

Overall, cotton is a medium-to-high cost fibre, especially in higher-quality grades, and its price instability poses a challenge for large-scale procurement. Nevertheless, its strong market demand and favourable consumer perception maintain its strategic importance across the apparel sector.

3.1.10. Comparison Matrix

The following comparison matrix synthesises the qualitative analysis of cotton presented in Sections 3.1.1–3.1.9 into a structured, weighted evaluation. It provides a transparent basis for assessing cotton's overall performance across environmental, technical, economic and circularity-related criteria relevant to WP4.

Table 7. AIDesignTEX Material Evaluation Matrix – Fibre: COTTON - Level 1 — Material Performance Assessment

Category	Weight (%)	Score (0–3)	Weighted Score	Evidence & References (short)	Notes for WP4
1.Environmental Impact (LCA)	20	1	0.20 × 1 = 0.20	• High blue-water footprint (3,000–10,000 L/kg) • High land use • Pesticide-intensive in conventional systems • Low energy use relative to synthetics	Score penalised mainly due to *water use* and *agrochemical load*.
2. Human Health Impact	20	2	0.20 × 2 = 0.40	• No solvent or monomer exposure for workers • Risk from pesticides in cultivation • Safe for skin; hypoallergenic	Benefits in use-phase, risks mainly upstream.
3. Product Quality, Durability & User Comfort	20	2	0.20 × 2 = 0.40	• High next-to-skin comfort due to natural fibre structure, good comfort, breathability • Moderate durability • Low abrasion and pilling resistance • Shrinkage without pre-treatment	Depends strongly on yarn type (combed, ring-spun, compact-spun).
4. Recyclability & Circularity Potential	20	2	0.20 × 2 = 0.40	• Good mechanical recyclability, but fibre shortening • Good chemical recyclability (MMCF route) • Easily reused & repaired • Elastane contamination a major barrier	Strong in reuse; medium in recycling due to fibre degradation.
5. Cost	10	2	0.10 × 2 = 0.20	• Higher cost than polyester • Sensitive to climate and market volatility • Organic cotton significantly more expensive	Stable long-term supply; price volatility affects industry.
6. Applicability in Apparel	10	3	0.10 × 3 = 0.30	• Universal applicability • Excellent comfort • Suitable for knits, wovens, denim, blends	Foundational material for nearly all apparel categories.
TOTAL LEVEL 1 SCORE	100	—	1.90 / 3.00 → 63/100	**Cotton performs moderately well with strong circularity and usability.**	

3.2. Man-Made Cellulosic Fibres (MMCF)

3.2.1. General Characteristics and Strategic Relevance

Man-made cellulosic fibres (MMCF) are regenerated fibres produced from natural cellulose sources, primarily wood pulp, and include viscose, modal, high wet modulus (HWM) fibres and lyocell. Although chemically identical to natural cellulose, MMCF differ significantly in structure, mechanical performance, durability and environmental profile depending on the production technology applied (16).
From the perspective of WP4, MMCF represent a strategically important fibre group due to:

- their growing share in global and European apparel markets,
- their positioning as comfort-oriented alternatives to cotton,
- their full biodegradability and compatibility with chemical textile-to-textile recycling,
- their strong relevance for circular economy strategies based on closed-loop cellulose systems.

MMCF are increasingly used in underwear, T-shirts, loungewear and blends with cotton or synthetics, which makes them highly relevant for AI-based material classification, circularity modelling and Digital Product Passport implementation.

3.2.2. Generations of MMCF and Key Performance Differences

MMCF can be divided into three main technological generations, each characterised by distinct performance and environmental profiles (16):

- **Viscose (I generation)** – produced via derivatisation chemistry using carbon disulphide (CS_2). Viscose fibres exhibit excellent softness and moisture absorbency but low wet strength and limited dimensional stability.
- **Modal and HWM fibres (II generation**) – improved viscose-based fibres with higher molecular orientation, enhanced wet modulus and significantly better dimensional stability and durability.
- **Lyocell (III generation)** – produced by direct dissolution of cellulose in NMMO using a closed-loop process. Lyocell combines very high dry and wet strength, excellent dimensional stability and controlled fibrillar morphology.

For WP4, these generational differences are critical, as they directly influence product lifetime, suitability for intensive use, recyclability performance and compatibility with circular business models. Modal/HWM and lyocell fibres are generally more aligned with durability-driven circular strategies than conventional viscose.

3.2.3. Production-Related Environmental Hotspots

The environmental profile of MMCF is dominated by two main stages: dissolving pulp production and fibre regeneration.

- **Feedstock production –** impacts arise from forestry practices, energy use in pulping and bleaching, and water consumption. Certified forestry (FSC/PEFC) and modern bleaching technologies (ECF/TCF) significantly reduce environmental burdens**.**
- **Fibre-forming processes –** the main differentiating factor between MMCF generations.

Viscose production is associated with:

- emissions of CS_2 and other sulphur compounds,
- sulphate- and zinc-containing wastewater,
- high chemical oxygen demand (COD/BOD),
- elevated human toxicity and ecotoxicity indicators in LCA studies.

Modal/HWM fibres show reduced emissions due to tighter process control but remain viscose-based. Lyocell production represents best available technology (BAT) within MMCF, with: solvent recovery rates exceeding 99.5%, minimal toxic emissions, substantially lower impacts in toxicity-related categories.
For WP4, these differences justify treating MMCF not as a single homogeneous group, but as a technology-dependent fibre family requiring differentiated evaluation.

3.2.4. Role of Wet Processing in Performance and Circularity

Due to their high hydrophilicity, MMCF are strongly affected by wet processing and finishing operations. Dyeing is typically carried out using reactive dyes, which ensures good colour depth but may involve high salt loads and water consumption, particularly for viscose and modal.

From a circularity perspective:

- durable crosslinking finishes, pigment printing and polymeric coatings can reduce biodegradability and complicate chemical recycling,
- enzymatic treatments and low-impact finishing improve surface quality, reduce fibrillation (especially for lyocell) and support longer product lifetimes,
- finishing chemistry directly affects the suitability of MMCF textiles as feedstock for cellulose-to-cellulose recycling processes.

In WP4, wet processing parameters are therefore considered critical descriptors for assessing MMCF circularity performance and for developing AI-supported material classification models.

3.2.5. Functional and Technical Properties Relevant for Circular Design

MMCF share several advantageous properties relevant to circular apparel systems:

- high moisture regain and breathability,
- soft handle and excellent skin comfort,
- absence of microplastic release during use,
- full biodegradability of the cellulose backbone.

However, performance varies across generations:

- viscose shows low wet strength and limited durability,
- modal/HWM fibres offer significantly improved strength and dimensional stability,
- lyocell provides the highest durability and resilience, but requires control of fibrillation during finishing.

Table 8. Functional and Technical Properties of Man-Made Cellulosic Fibres (MMCF)

Property	Viscose (I gen.)	Modal (II gen.)	HWM (II gen.)	Lyocell (III gen.)
Moisture regain	very high	high	high	high
Handle	soft, silky	smooth	soft, resilient	very smooth (“peach skin”)
Strength (dry/wet)	medium / low	high / good	high / very good	very high / very high
Wet modulus	low	medium	high	high
Dimensional stability	low	good	very good	excellent
Crease resistance	poor	better	good	moderate
Chemical resistance	weak to alkalis	improved	high	high
Fibrillation	no	minimal	minimal	characteristic (requires control)
Biodegradability	high	high	high	high

The comparison shows a clear progression in performance across generations of MMCF. First-generation viscose offers excellent softness and moisture management but suffers from weak wet strength, low wet modulus and poor dimensional stability, which limits its durability in repeated laundering cycles. Modal and HWM fibres represent a significant improvement: controlled production enables higher molecular orientation, resulting in superior wet strength, reduced swelling, improved resistance to deformation and enhanced recovery after washing. Lyocell, produced via a non-derivatising solvent route, displays the strongest overall performance, combining very high wet and dry strength, excellent dimensional stability and a smooth, high-quality handle.

From a circularity perspective, all MMCF are fully biodegradable and compatible with chemical textile-to-textile recycling routes. However, structural differences mean that modal, HWM and lyocell provide better longevity and maintain fibre integrity more effectively in recycling streams. Fibrillation, characteristic of lyocell, can be either an advantage (surface aesthetics) or a challenge (pilling, fibril shedding) depending on finishing processes (17).

Overall, MMCF combine high comfort with strong sustainability potential, making them highly relevant for the next generation of circular textile materials and a strategic material group for WP4 analyses and prototyping.

3.2.6. Environmental Impact of MMCF (LCA Perspective)

LCA studies demonstrate that MMCF generally exhibit:

- lower land use than cotton,
- significantly lower water consumption than irrigated cotton,
- lower fossil energy demand than synthetic fibres such as polyester (17).

At the same time, their environmental performance is highly technology-dependent. Viscose typically shows elevated impacts in human toxicity, freshwater ecotoxicity and acidification categories due to sulphur chemistry, while lyocell consistently ranks among the lowest-impact man-made fibres.

Use-phase impacts of MMCF are moderate and characterised by:

- no microplastic emissions,
- high moisture absorbency, which may increase washing frequency in some garment categories.

At end-of-life, MMCF are well suited for both biodegradation and chemical recycling, provided that fibre blends and finishing systems are compatible with recycling processes.

3.2.7. Human Health Considerations of MMCF

From a consumer perspective, MMCF are considered highly skin-friendly due to their cellulose chemistry, softness and excellent moisture management. They are widely used in underwear, babywear and medical textiles (10, 11,18).

Health risks are primarily associated with production stages:

- viscose manufacturing involves occupational exposure to CS_2 and sulphur compounds,
- modern modal and lyocell installations significantly reduce worker exposure through closed systems and improved process control.

For WP4, MMCF therefore represent fibres with very favourable consumer health profiles, while upstream risks depend strongly on the generation of technology applied.

3.2.8. Recyclability and Circularity Potential

MMCF are among the most promising fibres for circular textile systems based on cellulose loops (19):

- they are fully biodegradable,
- they can be chemically recycled into new MMCF fibres with high quality,
- they tolerate certain contaminants better than mechanical recycling routes.

Lyocell and modal fibres, due to higher molecular integrity, perform particularly well as feedstock for cellulose dissolution and regeneration processes. Key barriers include:

- elastane blends,

- heavy pigment printing,
- durable polymeric or crosslinking finishes.

Reuse potential of MMCF garments is generally high in comfort-driven apparel categories, although durability limitations of viscose can reduce lifetime compared with cotton or polyester.

3.2.9. Implications for Recycling and Circular Economy Potential

From a circular economy perspective, viscose represents a dual-character fibre: chemically well suited for circular cellulose loops, yet technologically constrained by durability and process-related limitations (20).
Due to its cellulose backbone, viscose is inherently compatible with chemical textile-to-textile recycling routes based on cellulose dissolution and regeneration. In principle, post-consumer viscose waste can be transformed into new MMCF fibres of comparable chemical purity. This makes viscose a relevant feedstock for emerging closed-loop cellulose systems, particularly when mono-material streams or high cellulose content fractions are available.
However, several factors limit the effective circularity of viscose textiles in practice:

- low wet strength and limited durability, leading to shorter garment lifetimes and reduced reuse potential;
- high sensitivity to mechanical stress, which negatively affects both reuse and mechanical recycling routes;
- frequent blending with elastane or polyester, significantly complicating separation and recycling;
- presence of crosslinking finishes, pigment printing and durable functional coatings, which may interfere with cellulose dissolution and reduce recycling yields.

In mechanical recycling systems, viscose fibres tend to fragment rapidly, resulting in low-quality fibre output and limited application potential. As a result, mechanical recycling of viscose is generally considered a low-value pathway, primarily suitable for insulation or nonwoven applications.
From a circular economy strategy perspective, viscose performs best in systems prioritising chemical recycling over mechanical recycling, and design-for-recycling principles are essential. These include:

- mono-material viscose constructions,
- minimisation of elastane content,
- avoidance of crosslinked or polymeric finishes,
- clear fibre identification and transparency via Digital Product Passports.

Within WP4, viscose is therefore positioned as a conditionally circular fibre, with high theoretical recyclability but strong dependence on product design, finishing chemistry and end-of-life management.

3.2.10. Cost Considerations of MMCF

Cost Considerations (Viscose)
Cost considerations play a central role in the widespread adoption of viscose fibres and strongly influence their positioning within circular textile systems. Viscose is generally less expensive than cotton of comparable quality and significantly cheaper than second- and third-generation MMCF such as modal and lyocell (2).
Key cost drivers for viscose include:

- availability and price of dissolving pulp,
- energy and chemical consumption in the viscose process,
- regulatory compliance costs related to emissions and wastewater treatment,
- scale and geographic concentration of production facilities.

The relatively low fibre price makes viscose attractive for mass-market apparel and fast-fashion applications. However, this cost advantage is often offset at system level by:

- shorter product lifetimes, leading to higher replacement rates,
- lower reuse value in second-hand markets,
- increased costs for wastewater treatment and emission control, particularly under stricter environmental regulations.

In circular economy scenarios, additional costs arise from:

- sorting and identification challenges in blended textile streams,
- limited suitability for mechanical recycling,
- reliance on capital-intensive chemical recycling infrastructure.

Compared with lyocell or modal, viscose often exhibits lower cost at fibre level but higher externalised environmental and end-of-life costs. For this reason, WP4 adopts a system-level cost perspective, recognising that low fibre price does not necessarily translate into lower lifecycle cost or higher circular value.

3.2.11. Comparison Matrix

The following comparison matrices synthesise the qualitative analysis of man-made cellulosic fibres (MMCF) presented in Section 3.2 into a structured, weighted evaluation. Separate matrices are provided for viscose (first generation), modal/HWM (second generation) and lyocell (third generation) in order to reflect the strong technology-dependent differences in environmental performance, durability and circularity relevance for WP4.

Table 9. AIDesignTEX Material Evaluation Matrix – Fibre: MMCF (Viscose I generation) - Level 1- Material Performance Assessment

Category	Weight (%)	Score (0–3)	Weighted Score	Evidence & References (short)	Notes for WP4
1. Environmental Impact (LCA)	20	1	0.20 × 1 = 0.20	• Wood pulp feedstock (forestry impacts) • High chemical load (CS_2, sulphur compounds) • High COD/BOD in wastewater • Moderate energy demand	Score penalised due to toxic chemicals and wastewater burden.
2. Human Health Impact	20	1	0.20 × 1 = 0.20	• Worker exposure to CS_2 and H_2S • Neurological risks documented • Final fibre safe for skin	Significant upstream occupational health risks.
3. Product Quality, Durability & User Comfort	20	2	0.20 × 2 = 0.40	• High softness and comfort • Good moisture management • Lower wet strength • Reduced abrasion resistance	Excellent comfort, limited durability.
4. Recyclability & Circularity Potential	20	2	0.20 × 2 = 0.40	• Biodegradable cellulose fibre • Limited mechanical recycling quality • Potential for chemical recycling	Circular potential exists but infrastructure is limited.
5. Cost	10	2	0.10 × 2 = 0.20	• Cost higher than cotton in some regions • Sensitive to pulp price and regulation	Moderate cost volatility.
6. Applicability in Apparel	10	2	0.10 × 2 = 0.20	• Common in T-shirts, dresses, linings • Limited use in heavy-duty garments	Mainly comfort-oriented applications.

TOTAL LEVEL 1 SCORE	100	—	**1.60 / 3.00 → 53/100**	**Viscose limited mainly by environmental and health impacts**.

Table 10. AIDesignTEX Material Evaluation Matrix - Fibre: MMCF (Modal/HWM) - Level 1 - Material Performance Assessment

Category	Weight (%)	Score (0–3)	Weighted Score	Evidence & References (short)	Notes for WP4
1. Environmental Impact (LCA)	20	2	0.20 × 2 = 0.40	• Controlled pulping processes • Lower emissions than viscose • Improved wastewater treatment	Improved environmental profile vs viscose.
2. Human Health Impact	20	2	0.20 × 2 = 0.40	• Reduced worker exposure • Final fibre skin-safe	Occupational risks reduced but not eliminated.
3. Product Quality, Durability & User Comfort	20	2	0.20 × 2 = 0.40	• Higher wet strength than viscose • Soft, breathable, stable	Balanced comfort and durability.
4. Recyclability & Circularity Potential	20	2	0.20 × 2 = 0.40	• Cellulosic structure • Potential for chemical recycling	Medium circularity readiness.
5. Cost	10	2	0.10 × 2 = 0.20	• Higher cost than viscose • Stable industrial supply	Premium MMCF segment.
6. Applicability in Apparel	10	3	0.10 × 3 = 0.30	• Widely used in knits and premium apparel	Strong comfort-driven applicability.
TOTAL LEVEL 1 SCORE	100	—	**2.10 / 3.00 → 70/100**	Modal/HWM shows balanced performance and improved sustainability.	

Table 11. AIDesignTEX Material Evaluation Matrix – Fibre: MMCF (Lyocell) - Level 1- Material Performance Assessment

Category	Weight (%)	Score (0–3)	Weighted Score	Evidence & References (short)	Notes for WP4
1. Environmental Impact (LCA)	20	3	0.20 × 3 = 0.60	• Closed-loop solvent system (NMMO) • Low emissions • Low water use	Best-in-class MMCF environmental profile.
2. Human Health Impact	20	3	0.20 × 3 = 0.60	• Minimal worker exposure • Safe solvent recovery	Very favourable health profile.
3. Product Quality, Durability & User Comfort	20	2	0.20 × 2 = 0.40	• High strength (wet & dry) • Excellent comfort	Slight fibrillation risk without finishing.
4. Recyclability & Circularity Potential	20	2	0.20 × 2 = 0.40	• Cellulosic, biodegradable • Chemical recycling possible	Circularity potential depends on infrastructure.
5. Cost	10	1	0.10 × 1 = 0.10	• High cost • Limited production capacity	Cost barrier for mass loops.
6. Applicability in Apparel	10	2	0.10 × 2 = 0.20	• Used in premium garments	Limited scalability.
TOTAL LEVEL 1 SCORE	100	—	**2.30 / 3.00 → 77/100**	**Technically strong, economically limiting for large-scale loops.**	

3.3. Synthetic Fibres – Polyester (PES/PET)

3.3.1. General Characteristics and Market Dominance

Polyester (PES), most commonly polyethylene terephthalate (PET), is the most widely used textile fibre globally and the single largest contributor to apparel production and textile waste streams. Its dominance is driven by low cost, high durability, consistent quality and compatibility with large-scale industrial manufacturing (16).

From a WP4 perspective, polyester is strategically critical because:

- it represents the largest absolute environmental burden in the textile sector,
- it dominates post-consumer textile waste flows in Europe,
- it is technically recyclable via both mechanical and chemical routes,
- it is a key focus of emerging circular economy policies and industrial investments.

Polyester therefore functions in AIDesignTEX as a system-defining fibre, where improvements in circularity can deliver the largest aggregate environmental benefits.

3.3.2. Production-Related Environmental Hotspots

Unlike natural and regenerated fibres, polyester is produced entirely from fossil-based feedstocks, primarily purified terephthalic acid (PTA) and monoethylene glycol (MEG). The environmental footprint of polyester is dominated by energy-intensive stages rather than material losses (16).

Key hotspots identified in LCA studies include:

- polymer synthesis and polycondensation, requiring high temperatures and fossil energy input,
- pellet drying, melt spinning and drawing, which together account for a substantial share of total energy demand,
- globalised supply chains, with production concentrated in Asia and long transport distances to European markets.

Typical LCA results indicate that virgin polyester fibres exhibit significantly higher greenhouse gas emissions per kilogram than cotton or MMCF, largely due to fossil energy use. However, these impacts are highly sensitive to the electricity mix and the share of recycled content (21).

3.3.3. Role of Fibre Manufacturing and Finishing in Circularity

Polyester fibre manufacturing is a critical intervention point for both performance and circularity. Polymer molecular weight, crystallinity, additives and texturing directly influence durability, dyeing behaviour and recyclability (22).

Wet processing of polyester differs fundamentally from cotton and MMCF:

- dyeing is typically performed with disperse dyes at high temperatures (~130 °C),
- processes are energy-intensive but require significantly less water,
- dope dyeing (mass pigmentation) can drastically reduce water and chemical use.

From a circularity perspective, finishing chemistry is decisive. Hydrophobic coatings, functional finishes, polymeric binders and complex additive packages can:

- hinder mechanical recycling through contamination and degradation,
- complicate chemical depolymerisation processes,
- reduce transparency and recyclability classification under DPP requirements.

In WP4, polyester finishing is therefore evaluated not only for performance enhancement, but primarily for its impact on end-of-life processability and AI-based material classification accuracy.

3.3.4. Functional and Technical Properties Relevant for Circular Design

Polyester exhibits a combination of properties that strongly influence circular performance:

- high tensile strength and abrasion resistance, supporting long product lifetimes,
- excellent dimensional stability and crease resistance, enabling repeated use and laundering,
- very low moisture regain, resulting in fast drying but reduced thermal comfort in some apparel categories.

These characteristics make polyester particularly suitable for garments designed for durability, reuse and multiple ownership cycles (e.g. workwear, sportswear, outerwear). However, comfort limitations often lead to blending with cotton, MMCF or elastane, which significantly reduces recyclability.
From a circular design perspective, polyester performs best in simple, mono-material constructions with minimal finishing complexity (16).

3.3.5. Environmental Impact of Polyester (LCA Perspective)

Life Cycle Assessment consistently identifies polyester as one of the most environmentally demanding textile fibres at the production stage (23). Key impact drivers include:

- high fossil energy demand,
- significant greenhouse gas emissions,
- reliance on non-renewable feedstocks.

In contrast to cotton and MMCF, polyester exhibits:

- negligible water use during fibre production,
- no agricultural impacts,
- high durability that can offset part of the production footprint when garments achieve long lifetimes.

A critical environmental issue unique to polyester is the release of microplastic fibres during use and laundering. Microfibre emissions represent a systemic challenge that persists even in circular systems and is increasingly addressed in EU policy discussions.
Substitution of virgin polyester with recycled polyester (rPES) can significantly reduce GHG emissions, provided that recycling processes are efficient and input streams are sufficiently clean.

3.3.6. Human Health Considerations

From a consumer perspective, polyester fibres are generally chemically inert and considered safe when produced in compliance with existing chemical regulations. Health-related issues are primarily linked to:

- limited breathability and moisture management,
- electrostatic charging,
- potential sensitivity to dyes or finishing agents.

Occupational health risks occur upstream and include exposure during:

- monomer and polymer production,
- melt spinning and texturing,
- dyeing and finishing, particularly when hazardous auxiliaries or legacy PFAS-based finishes are used.

Modern industrial installations largely mitigate these risks through closed systems and chemical management. For WP4, polyester is therefore classified as low risk for consumers but process-dependent for workers, with transparency requirements under DPP playing a central role.

3.3.7. Recyclability and Circularity Potential

Polyester has one of the highest technical recycling potentials among textile fibres due to its thermoplastic nature:

- mechanical recycling is well established but often results in downcycling and polymer degradation,
- chemical recycling (depolymerisation) enables near-virgin quality PET but remains energy- and capital-intensive (19).

The main barriers to effective polyester circularity include:

- blends with elastane or other polymers,
- complex finishing systems and coatings,
- insufficient sorting and collection quality.

Despite these challenges, polyester is a cornerstone of emerging fibre-to-fibre recycling initiatives and industrial circular economy roadmaps.

3.3.8. Implications for Recycling and Circular Economy Potential (Polyester)

From a circular economy perspective, polyester (PES/PET) is a high-impact and high-leverage fibre, whose circular performance is decisive for the overall sustainability of the textile sector. Owing to its thermoplastic nature, polyester is technically compatible with both mechanical and chemical recycling pathways, making it a cornerstone of emerging fibre-to-fibre recycling systems (24).

Mechanical recycling of polyester is technologically mature and widely implemented. It enables material recovery at scale but is associated with polymer chain degradation, contamination and progressive downcycling, particularly when feedstock quality is low or when complex blends and finishes are present. As a result, mechanically recycled polyester (rPES) often requires blending with virgin polymer to meet performance requirements.

Chemical recycling enables depolymerisation of PET into monomers or oligomers, allowing production of near-virgin-quality polyester. This route offers the highest circularity potential but remains energy-intensive, capital-intensive and highly sensitive to input purity. At present, chemical recycling is most viable for relatively clean, mono-material polyester streams.

Key barriers limiting effective polyester circularity include:

- widespread use of blends, particularly with elastane and polyamide,
- complex finishing systems, coatings and additive packages,
- insufficient sorting accuracy and contamination in post-consumer waste streams,
- lack of harmonised data on fibre composition and chemical treatments.

From a circular design perspective, polyester performs best in simple, mono-material constructions, with minimal finishing complexity and documented recycled content. Within WP4, polyester is therefore treated as a priority fibre for AI-supported sorting, quality classification and circularity modelling, due to both its scale and technical recyclability.

3.3.9. Cost Considerations (Polyester)

Polyester exhibits a wide cost range depending on feedstock origin, processing route and market conditions. Virgin polyester benefits from highly optimised global supply chains and typically offers the lowest cost per unit of durability among textile fibres. This cost advantage has been a key driver of its market dominance.

However, cost structures change significantly in circular economy scenarios:

- mechanically recycled polyester generally incurs higher costs than virgin PET due to collection, sorting and processing requirements, while also delivering variable material quality;

- chemically recycled polyester involves substantially higher capital and operational costs related to depolymerisation, purification and re-polymerisation processes.

At system level, additional cost factors include:

- investments in advanced sorting and AI-based identification technologies,
- losses due to contamination and non-recyclable blends,
- compliance with transparency, traceability and recycled content verification under DPP and ESPR frameworks,
- mitigation measures addressing microplastic emissions and environmental externalities.

While recycled polyester may currently be more expensive than virgin material, regulatory drivers, extended producer responsibility (EPR) schemes and minimum recycled content requirements are expected to progressively shift cost competitiveness in favour of circular polyester solutions.

Within the AIDesignTEX framework, polyester is therefore evaluated using a total lifecycle cost approach, recognising that low virgin fibre price does not reflect environmental externalities or long-term regulatory risks. This perspective supports strategic material selection decisions that balance cost, durability, recyclability and compliance with future circular economy requirements.

3.3.10. Comparison Matrix for PES

The following evaluation matrix summarises the performance of polyester (PES) across key environmental, technical, economic and circularity-related criteria, based on the material analysis presented in the preceding sections. The matrix provides a structured, weighted assessment to support the prioritisation of polyester for further product-level analysis within WP4, while explicitly reflecting the trade-offs between its strong durability and recyclability and its fossil-based environmental burden.

Table 12. AIDesignTEX Material Evaluation Matrix - Fibre: Polyester - Level 1 - Material Performance Assessment

Category	Weight (%)	Score (0–3)	Weighted Score	Evidence & References (short)	Notes for WP4
1. Environmental Impact (LCA)	20	0	0.20 × 0 = 0	• Fossil-based feedstock • High energy demand • GHG emissions	Penalised for fossil origin.
2. Human Health Impact	20	1	0.20 × 1 = 0.20	• Safe in use-phase • Microplastic release during wear/wash	Health-neutral for user; environmental concern.
3. Product Quality & Durability	20	2	0.20 × 2 = 0.40	•High mechanical durability and abrasion resistance •Good dimensional stability and shape retention •Low moisture absorption and limited breathability in standard fabrics •User comfort highly dependent on fabric construction and finishing •Enhanced comfort mainly in specialised sports textiles (minor market share)	Strong driver of long service life.
4. Recyclability & Circularity Potential	20	2	0.20 × 2 = 0.40	• Mature mechanical & chemical recycling	Key fibre for circular systems.

				• Fibre-to-fibre feasible	
5. Cost	10	3	0.10 × 3 = 0.30	• Low cost • Stable global supply	Highly scalable.
6. Applicability in Apparel	10	3	0.10 × 3 = 0.30	• Universal use across categories	Core synthetic apparel fibre.
TOTAL LEVEL 1 SCORE	100	—	**1.60 / 3.00 → 53/100**	**High technical performance and scalability, but penalised by material-level environmental burden.**	

3.4. Overall Ranking of Analysed Fibres Based on Level 1 Evaluation

The overall ranking highlights that no single fibre achieves optimal performance across all evaluation categories, confirming the need for a product-centred and system-level approach to circular textile design.

Table 13. AIDesignTEX Overall Material Ranking – Level 1 Performance Assessment

Rank	Fibre	Total Score (0–3)	Normalised Score (0–100)	Key Strengths	Key Limitations
1	**MMCF (Lyocell)**	2.10	70	Best-in-class environmental and health profile; high comfort; good strength	High cost; limited market scale; design-dependent durability
2	**MMCF (Modal / HWM)**	1.90	63	High comfort; improved durability vs viscose; balanced performance	Limited market scale; moderate recyclability
3	**Cotton**	1.90	63	Excellent user comfort; strong reuse and repair potential; wide applicability	High water and land use; moderate durability
4	**Polyester (PES)**	1.60	53	Very high durability; dimensional stability; low cost	Fossil-based feedstock; low comfort in mainstream apparel; microplastics
5	**MMCF (Viscose, I gen.)**	1.50	50	High softness and drape; good moisture absorption	High environmental and occupational health burden; low durability

The Level 1 performance ranking provides a comparative overview of intrinsic material characteristics across environmental impact, human health, product quality, durability, user comfort, recyclability and applicability in apparel. The results highlight that materials with favourable environmental profiles, such as advanced MMCF (e.g. lyocell), achieve higher performance scores, while high-volume fibres such as polyester and cotton exhibit significant trade-offs related to environmental burden or user comfort.

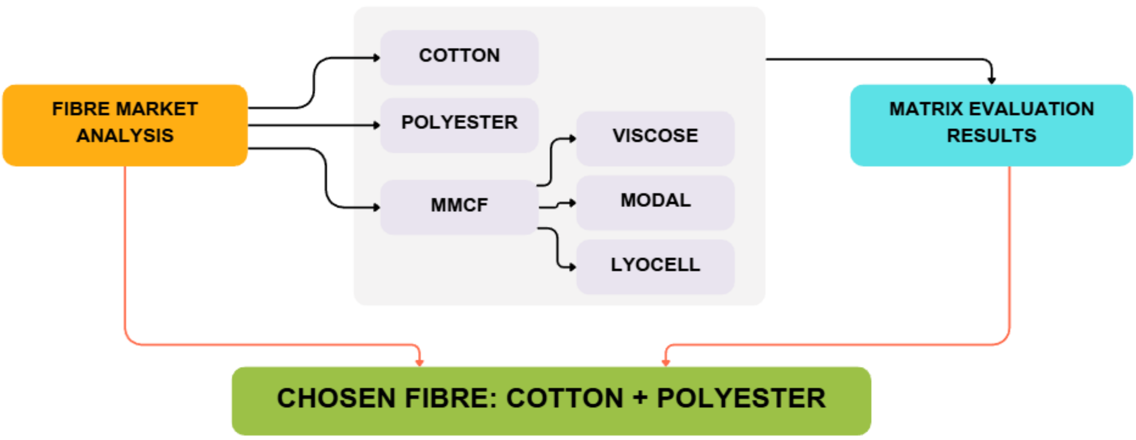

Figure 4. Summary of the fibre selection pathway based on market analysis and matrix evaluation.

Market analysis clearly indicates that polyester and cotton dominate global apparel production, together accounting for the vast majority of fibres used in contemporary clothing systems (1). The combined production volumes of these two fibres are several times higher than those of all other textile fibres, including advanced man-made cellulosic fibres and specialty materials. **As a result, their presence in both apparel markets and post-consumer textile waste streams is structurally unavoidable.**
The material-level assessment presented in this report demonstrates that the production of polyester and cotton is associated with significant environmental and sustainability challenges when compared to alternative fibres. Polyester exhibits high environmental burdens linked to fossil-based feedstock, energy demand and microplastic emissions, while cotton is characterised by intensive water use, land occupation and agrochemical inputs. Despite these limitations, the sheer scale of production means that even incremental improvements in the circularity of polyester- and cotton-based products can deliver disproportionately large environmental benefits at system level.

Consequently, this analysis supports the conclusion that polyester and cotton represent priority fibres for circular economy intervention. The development of dedicated circular economy loops for products made from these fibres is not driven by their material superiority, but by their overwhelming market dominance, persistent use in staple apparel categories and critical contribution to textile waste generation. Addressing circularity for these fibres is therefore essential for achieving meaningful impact within realistic industrial and policy contexts.

While Table 13 compares fibres based on intrinsic (mono-material) performance, real apparel products rarely consist of a single fibre. In practice, cotton and polyester are frequently combined within blends (e.g., cotton/PES) and are often used together with elastane or incorporated into coated and laminated structures. These design choices significantly affect end-of-life outcomes by reducing sorting accuracy, lowering recycling yields and limiting the feasibility of high-value fibre-to-fibre pathways.

Therefore, fibre blends and composite constructions are treated as a key cross-cutting factor in WP4. They do not change the material-level ranking itself, but they directly influence which product archetypes should be prioritised, which loop designs are realistically feasible, and which design-for-recycling constraints must be imposed already at the product development stage. The implications of blends and composites are addressed in Section 3.4 and are carried forward into the garment-centred analysis in Chapter 4.

3.5. Fibre Blends and Composite Materials: Barriers and Design Implications for Circularity

3.5.1. Role of Fibre Blends in Contemporary Apparel

Fibre blends and composite textile structures are widely used in contemporary apparel to enhance comfort, fit, durability and functional performance. By combining fibres with complementary properties, manufacturers can optimise garments for specific use scenarios, cost targets and aesthetic requirements.
However, from a circular economy perspective, fibre blends represent one of the most significant structural barriers to effective textile recycling. While blends often improve short-term product performance, they systematically reduce end-of-life processability and complicate material recovery at scale.
Within WP4, fibre blends are therefore analysed not as isolated material solutions, but as design decisions with long-term system consequences, directly affecting sorting accuracy, recycling yields and the feasibility of closed-loop systems (25).

3.5.2. Cotton/Polyester Blends: Performance Versus Circularity Trade-offs

Cotton/polyester blends are among the most common fibre combinations in apparel, combining the comfort and breathability of cotton with the durability and dimensional stability of polyester. From a user perspective, these blends often deliver balanced performance and are perceived as versatile and practical.

From a circularity perspective, however, cotton/PES blends pose major challenges:

- mechanical recycling leads to mixed fibre fractions with reduced quality and limited reuse potential,
- fibre separation is technically complex and economically demanding,
- chemical recycling requires selective dissolution or depolymerisation processes that are not yet widely available at industrial scale.

As a result, cotton/PES blends frequently fall into low-value recycling routes or energy recovery, despite being composed of two individually recyclable fibres. This paradox highlights a key insight for circular design: blend-level optimisation for use-phase performance often conflicts with system-level circularity goals (25).

3.5.3. Elastane-Containing Blends as a Systemic Circularity Disruptor

Blends containing elastane (e.g. PES/EL, cotton/EL) represent a particularly critical barrier to textile circularity. Although elastane typically constitutes only a small mass fraction (often 1–5%), its presence disproportionately affects recycling outcomes.
Key challenges associated with elastane include:

- disruption of mechanical recycling processes due to elastic filament behaviour,
- incompatibility with most chemical recycling technologies,
- reduced accuracy in automated sorting and fibre identification systems,
- contamination of otherwise recyclable mono-material streams.

Despite its functional importance for fit and comfort, elastane currently lacks scalable fibre-to-fibre recycling solutions. Within circular economy frameworks, elastane is therefore treated as a performance-critical but circularity-limiting fibre, requiring careful consideration and minimisation at the design stage.

3.5.4. Laminated, Coated and Composite Textile Structures

Laminated and coated textiles, including multi-layer fabrics, membrane-backed materials and heavily coated surfaces, are increasingly used to provide functional properties such as water resistance, wind protection and durability. These structures are particularly prevalent in outerwear, sportswear and technical garments (26).
From a circularity perspective, such composite constructions present severe challenges:

- inseparable material layers prevent fibre-level recycling,
- coatings and membranes contaminate recycling streams,
- material composition is often opaque, complicating sorting and DPP documentation.

While these materials may be justified for high-performance applications, they are fundamentally incompatible with most closed-loop textile recycling systems. Their analysis in WP4 serves primarily to illustrate design-for-performance versus design-for-circularity trade-offs, rather than to identify candidates for circular loops.

3.5.5. Implications for Sorting, AI-Based Classification and DPP

Fibre blends and composite materials significantly increase the complexity of automated sorting and AI-based material classification systems. Heterogeneous compositions:

- reduce spectral clarity in NIR-based identification,
- require more complex training datasets for AI models,
- increase uncertainty in material labelling and quality grading.

Furthermore, blends complicate the implementation of Digital Product Passports by increasing the amount of material and chemical information required to enable informed end-of-life decisions. In the absence of clear documentation, blended products are more likely to be excluded from high-value recycling pathways.

3.5.6. Design Implications and Transition Strategies

The analysis of fibre blends and composite materials highlights a fundamental principle of circular textile design: performance gains achieved through material complexity often come at the expense of recyclability. For WP4 and subsequent experimental work, this leads to the following design implications:

- prioritisation of mono-material or near-mono-material constructions,
- minimisation of elastane content where functionally feasible,
- preference for mechanical design solutions over chemical finishes,
- clear documentation of material composition to support DPP and sorting systems.

Rather than advocating the elimination of all blends, this approach supports a strategic and selective use of material complexity, aligned with clearly defined product lifetimes, reuse strategies and end-of-life pathways.

3.5.7. Transition Towards Product-Based Circular Loops

The challenges associated with fibre blends and composite materials provide a strong rationale for shifting the analytical focus from fibre-level properties to product-level circularity performance. In the following chapter, fibres are therefore evaluated within specific garment archetypes, allowing comfort, functionality and circularity to be assessed in an integrated manner.
This transition enables the identification of product categories where circular loops are both technically feasible and systemically meaningful, forming the basis for the experimental design and loop development presented in subsequent sections.

4. Overview of recycling techniques

This chapter provides an overview of textile recycling techniques relevant for interpreting the material- and product-level analyses presented in Chapters 3 and 5. The overview is not intended as an exhaustive technical review, but as a contextual reference for assessing the feasibility and limitations of circular loops developed within WP4.

The generation of textile waste is problematic. Most of this waste -both inside and outside Europe – ends in inceniration and landfills. In addition to reducing the total comsumption and refurbishing or remanufacturing textile products, a part of the solution for the textile waste lies in recycling. (4)
Recycling is an activity to obtain recovered resources for use in a product (excluding energy recovery). (5)
The recycling processes as described by the ISO 5157:2023 are mechanical, thermo-mechanical and chemical reycling. These recycling processes also include more specific techniques as thermo-chemical recycling, recycling by dissolution and biological recyling. (4; 6)
When textile products are used and then recovered and turned into new textile products indefinitely, without losing their inherent properties, this is called a **closed loop recycling process**. For textile products, it can be expected that there will be some materials loss in the recycling process. (5)

4.1. Mechanical recycling

A mechanical recycling process is a way of recycling based on physical forces. Specifically for fibre mechanical recyling, this means that the used textile products are dissassembled in a mechanical process and that the fibres are extracted to incorporate them into a new textiel product or other application (27)

Basically, all kinds of textile waste, material type (natural, man-made or blends), types of textile products (yarns, fabrics, used garments, carpets) and structures (knitted, woven or non-woven) can be processed via mechanical recycling. Depending on the type of fibres or structures, different machinery is being used.

In general, the more uniform, untreated, undamaged, and uncontaminated the input is, the higher the amount and quality of the fibre output from the mechanical recycling process will be.(28) Mechanical recycling leads to the progressive degradation of the fibre quality with each recycling cycle. (29)

Two common problems in mechanical recycling of textiles are (28,29)

- Blends of different fibre e.g. presence of elastane (especially when >10%). (see §**Błąd! Nie można odnaleźć źródła odwołania.**)
- Poor quality of post-consumer fabric waste. When a fabric is too weak to resist the mechanical recycling process, a lot of material will turn into waste in the form of small particles or dust.

Mechanical recycling is an established technology in the market. Developments in this technology mainly focus on adjustments to the machinery or recycling line set-up. Furthermore, there is looked at additional (chemical) treatments and better sorting of the input material.

The main advantages of mechanical recycling (27):

- Practically any textile waste stream can be processed
- Relatively small quantities of waste material can be handled
- Requires a relatively low level of investment and space
- Less highly skilled personnel required compared to e.g. chemical recycling

(Hazardous) chemicals such as additives, dyes and finishes can not be removed in a mechanical recycling process. Therefor, they stay in the output product. This can be as well advantageous as disadvantageous.
Mechanical recycling is currently the most mature and widely used method for fibre material recovery. (30).

4.2. Thermo-mechanical recycling

Thermo-mechanical recycling uses a combination of pressure and heat to melt synthetic textile materials and recover the polymers into granulates and/or new fibres. This recycling process can be used for termoplastic textiles as polyester, polyamide and polypropylene, but can't be used for natural fibres such as cotton or wool or for regenerated fibres as lyocell and viscose. With thermo-mechanical recycling, the quality of the polymer will reduce (slightly) with every recycling step. (31)

The thermo-mechanical process is similar to the melt processing of virgin materials. This makes thermo-mechanical recycling a cost-effective, efficient and well-known process. Though the production process for the virgin materials should be adapted to include suitable shredding, cleaning, feeding and degassing steps to make it suitable for processing waste materials (27).The process is used on a commercial level for non-textile waste like PET bottles. For textile materials, it's mainly used at smaller scales since there are still specific technical challenges like for example a limited feedstock availability due to the very strict feedstock requirements. (31)

4.3. Chemical recycling

Chemical recycling is also known as feedstock recycling. In this process, waste materials are converted into feedstock by changing the chemical structure of waste materials to be used in the production of new polymers, monomers, intermediates or other materials. Examples of chemical recycling processes are: pyrolysis, gasification, depolymerization, solvolysis, catalysis, reforming, purification, hydrogenation, dissolutione and dehydrochlorination. (27)
In the textile industry, there are several examples of chemical recycling (30):

- Monomer recycling of PA6 or PET via (partial) degradation into oligomers or monomers. These oligomers or monomers are seperated and purified before entering the polymerization process again to produce new virgin-quality polymers.
- Recovery of both cellulose and PET from polycotton blends. This can be done in different ways. A first option is a solvent-based dissolution and filtration process te seperate the different materials and extract the desired components (e.g. dissolving the cellulose and use it in a pulping and wet-spinning procces, while remaining the PET polymers). A second option is a hydrothermal option in which either the cotton or the PET or both are (partially) degraded. A third option degrades the cotton via an enzymatic route, resulting in glucose, cellulose powder and PET fibres (see also §4.5).
- Recycling of cellulosic-based fibres like cotton and man-made cellulosic fibres (MMCF) by a pulping process. The obtained pulp can be used to make new MMCF. (see also §**Błąd! Nie można odnaleźć źródła odwołania.**)

In general, chemical recycling processes require more energy compared to mechanical recycling. A core advantage of chemical recycling is that it can produce (almost) virgin-quality polymers and/or fibres. (4)

4.4. Thermo-chemical recycling

Thermo-chemical recycling uses processes as pyrolysis and gasification. It are both thermal decomposition processes. Pyrolysis generates products like gas, tar, and char, while gasification converts carboncontaing materials (e.g. the outputs from pyrolysis) into a maily gaseous output (e.g. syngas).
Thermo-chemical recyling can be used for all type of fibres. The output products can be used for heat and power purposes, but after separation/purification it can also be used as feedstock. (30, 31).

4.5. Dissolution recycling

The recycling via dissolution process involves the liquification of waste fibres by dissolving them in a suitable solvent. In practice, this recycling method is currently applied at a commercial scale only to cotton and sometimes polyester waste. Cotton consists of cellulose, which can be suspended in a liquid and then re-extruded into man-made cellulose fibres by means of wet spinning (30).
In recent years, there has been a significant focus on the process of dissolution for the removal of impurities with inorganic or organic origins from polymeric textile waste. This allows the separated polymer to be recycled more efficiently. Moreover, dissolution recycling can help eliminate contaminants such as dyes and additives.
Some advantages of dissolution recycling (30):

- Doesn't require plenty pretreatment. Fabrics with different structures (woven, knitted, nonwoven, etc.) can be processed without cutting it to size. The process is often tolerant of dyed textiles because the colors can be removed or bleached during the recycling process, as long as it is known which dyes were used.
- It can deal with fibre blends without making the process too complex. This requires the use of a solvent that selectively dissolves one fibre without dissolving the others.
- Ability to produce pure polymers of virgin-like quality (to a limited extend).

Dissolution recycling requires more water and energy than a process such as mechanical fibre recycling. To make this process economic viable, large scale recycling is needed. (11) Dissolution recycling still requires the removal of hard parts (buttons, zippers, etc.). The process yield is highly dependent on the purity of the input material, so sorting is still very important. Furthermore, dissolution can make the polymers to degrade. Therefor, the process can't be continued infinitely. (6)

4.6. Biological recycling

Biological recycling uses specific enzymes or microorganisms to break down the polymers in the waste, converting them into monomers or other vaualbe products like cellulose or bioethanol. Biological recycling typically operates under gentler conditions than chemcial recycling. (32)
Biological recycling is primarily applied to natural fibres. Cellulases are typically used for cellulose-based materials like cotton and linen, while proteases are used to degrade protein-based materials such as wool and silk. In recent years, there's progress in research on the biodegradation of man-made fibres. (30)There are for example multiple studies on the biodegradation of synthetic polymers like poly ethylene terephtalate. (13) (14) The biotech company Carbios even launched a first enzymatically recycled polyester garment made from 100% textile waste in October 2024. (33)
Biological recycling is seen as an environmentally friendly process with a low energy consumption. It has a high selectivity, which makes it interesting for separating textile mixtures. Dispite these advantageous, to date, it is a process with a low efficiency, high cost and a long response time. (30)

5. The Role of Fibres in Apparel: From User Comfort to Circular Performance

The selection of fibres in apparel production plays a decisive role not only in determining the material properties of textiles, but also in shaping garment performance in use, user experience, product lifetime and end-of-life outcomes. While Section 3 focused on the intrinsic characteristics of fibres and their environmental and circularity profiles, this chapter shifts the analytical perspective towards **garments as user-facing systems**.
In contemporary apparel, fibres are rarely selected in isolation. Instead, they are combined with specific fabric structures, garment constructions and finishing technologies to meet functional, aesthetic and economic requirements. These design decisions directly influence thermal comfort, moisture management, fit, durability and maintenance behaviour, which in turn affect user satisfaction, wearing frequency and product lifetime.
From a circular economy perspective, the use phase is a critical determinant of environmental performance. Garments that provide high comfort and functional reliability are worn longer, repaired more often and more readily reused, reducing the demand for virgin materials. Conversely, products that fail to meet user expectations tend to be discarded prematurely, regardless of their theoretical recyclability.
This chapter therefore examines the role of fibres within key apparel categories, linking fibre properties to **user-centred performance**, **functional durability** and **market permanence**. By analysing how fibres perform in real garment applications, it becomes possible to identify product types that simultaneously pose significant circularity challenges and offer high recovery potential due to their widespread use and long-term relevance in the market.
On this basis, a set of representative garment archetypes is selected to serve as the foundation for circular loop design and experimental work in subsequent sections. Rather than defining loops at the fibre level alone, the analysis prioritises **product-based circular loops**, reflecting the realities of textile use, collection and recycling systems.

5.1. User-Centred Performance: Comfort, Health and Wear Experience

User-centred performance is a primary determinant of garment acceptance, frequency of use and product lifetime. Comfort, skin compatibility and physiological response during wear directly influence whether a garment remains in active use or is prematurely discarded. From a circular economy perspective, these factors are therefore critical, as prolonged use and reuse represent the most effective strategies for reducing environmental impact.

In apparel worn close to the skin or during everyday activities, fibre selection plays a decisive role in shaping the user experience. Key performance dimensions include tactile comfort, moisture management, thermal regulation and interaction with the human skin.

5.1.1. Next-to-Skin Comfort in Everyday Garments

Garments such as T-shirts are typically worn directly on the skin and often for extended periods. In this context, fibres with high moisture absorbency, good air permeability and a soft surface feel are strongly preferred by users.

Cotton is widely valued for its high hygroscopicity, breathability and natural hand feel, which together support thermal comfort and reduce skin irritation. These properties contribute to high user acceptance across diverse demographic groups and climatic conditions.

Man-made cellulosic fibres, such as viscose, modal and lyocell, offer similar or enhanced softness and moisture management, making them attractive alternatives in premium or comfort-focused applications.

Polyester, while less absorbent, is often used in T-shirts designed for active or athletic use due to its quick-drying behaviour, although it may provide lower comfort in static, everyday wear (16).

User perception of comfort in next-to-skin garments is therefore strongly linked to fibre moisture behaviour and surface characteristics, which influence wearing time and washing frequency (15).

5.1.2. Comfort under Dynamic Use: Sweatpants and Casual Wear

In garments designed for movement and prolonged daily use, such as sweatpants, user comfort depends not only on fibre properties but also on fabric elasticity, breathability and thermal balance. These garments are expected to perform under varying levels of physical activity while maintaining comfort during rest.

Cotton-based sweatpants provide good thermal comfort and moisture absorption but may exhibit slower drying times and reduced shape retention over extended use. Polyester-based sweatpants offer improved dimensional stability, faster drying and resistance to deformation, which can enhance perceived durability and functional comfort during dynamic activities (6).

The frequent inclusion of elastane in such garments improves fit and freedom of movement but introduces trade-offs related to skin comfort for some users and, importantly, to circularity at end-of-life. From a user-centred perspective, elastane enhances wearability; from a system perspective, it represents a critical design compromise.

5.1.3. Skin Compatibility and Health Considerations

Fibre–skin interaction is a key factor in user satisfaction and health, particularly in garments worn close to the body. Cotton and other cellulose-based fibres are generally considered skin-friendly and are widely used in products for sensitive skin, children’s wear and medical textiles. They do not release microplastics during wear and have a long history of safe use (11).

Synthetic fibres such as polyester are typically chemically inert in use, but lower breathability and moisture absorption may contribute to discomfort or skin irritation in certain conditions, particularly when combined with occlusive fabric structures or finishes.

In most cases, health-related issues are not inherent to the fibre itself but are associated with residual chemicals, dyes or finishing agents. Compliance with chemical safety standards and transparent documentation of finishing processes are therefore essential to maintaining user trust and supporting prolonged garment use (12).

5.1.4. User Behaviour and Implications for Circularity

User behaviour is strongly influenced by comfort and wear experience. Garments that are perceived as comfortable and skin-friendly are worn more frequently, kept for longer periods and are more likely to be reused or passed on to secondary users. This behavioural dimension significantly affects circular economy outcomes.

Conversely, garments that cause discomfort, poor thermal regulation or irritation tend to be underutilised and discarded earlier, even if their material composition is theoretically recyclable. As a result, user-centred performance must be considered an integral component of circular design strategies.
Within the AIDesignTEX framework, comfort and health-related performance are therefore treated not as secondary qualities, but as key enablers of circularity, directly influencing product lifetime, reuse potential and material recovery rates (29).

5.2. Functional Performance: Durability, Wear Resistance and Service Life

Functional performance determines whether a garment can withstand repeated use, laundering and mechanical stress without significant loss of form or function. From both a user and circular economy perspective, durability and service life are critical parameters, as they directly influence product lifetime, repairability and the timing of entry into end-of-life pathways.
In everyday apparel, functional performance results from the interaction between fibre properties, fabric structure and garment construction. These elements collectively determine resistance to abrasion, dimensional stability and the garment's ability to maintain acceptable appearance and fit over time (28).

5.2.1. Durability and Wear Resistance in Common Garment Types

Resistance to mechanical wear is particularly important in garments subjected to frequent movement and friction, such as sweatpants and jeans. In such products, abrasion resistance, seam strength and fabric density strongly influence perceived quality and longevity.

- **Cotton-based garments** provide satisfactory durability in many applications but are more susceptible to abrasion and surface wear, especially in lightweight knitted structures. Over time, this may result in thinning, pilling or tearing, which often triggers disposal rather than repair.
- **Polyester-based garments** generally exhibit higher abrasion resistance and better retention of mechanical properties under repeated stress. This contributes to longer service life and a perception of robustness, particularly in casual and sportswear applications.
- **Jeans represent** a distinct durability archetype. Although typically made from cotton, denim fabrics are woven in dense structures and often use heavier yarns, resulting in high resistance to tearing and extended wear life. However, this durability is achieved through structural complexity and heavy finishing, which later influences recyclability.

5.2.2. Dimensional Stability and Shape Retention

Dimensional stability is a key functional requirement affecting user satisfaction and garment longevity. Loss of shape, shrinkage or deformation can significantly reduce a garment's usability, even if the material remains mechanically intact.
Cotton garments, particularly in knitted constructions, may experience shrinkage and deformation if not properly finished or cared for. Polyester offers superior dimensional stability and crease resistance, maintaining garment shape over repeated washing cycles.
In sweatpants and other relaxed-fit garments, dimensional stability is often enhanced through the inclusion of elastane. While this improves fit and comfort, it introduces additional complexity at end-of-life and must be considered a trade-off between use-phase performance and recyclability.

5.2.3. Failure Modes and Repairability

Understanding common failure modes is essential for assessing circular performance. Typical failure mechanisms include:

- surface abrasion and pilling,
- seam failure in high-stress areas,
- loss of elasticity in waistbands and cuffs,

- colour fading or uneven wear.

Simple garments such as T-shirts are often discarded due to aesthetic degradation rather than structural failure. Sweatpants may remain structurally intact but lose elasticity or shape, reducing their perceived value. Jeans, despite their durability, are frequently repaired, reflecting higher user willingness to invest in maintenance due to cultural acceptance and perceived value.
From a circular design perspective, garments with clearly identifiable and repairable failure modes offer higher potential for extended use and delayed entry into recycling streams.

5.2.4. Functional Performance and Circularity Trade-offs

High functional performance does not automatically translate into high circularity. Design strategies aimed at enhancing durability, such as complex constructions, heavy reinforcements or multi-material components, can improve service life while simultaneously reducing recyclability.

This trade-off is particularly evident when comparing:

- simple cotton T-shirts with complex, reinforced sweatpants,
- mono-material cotton sweatpants with multi-component jeans,
- durable polyester garments with elastane-enhanced comfort features.

Functional performance must therefore be evaluated in relation to both use-phase benefits and end-of-life implications. Within the AIDesignTEX framework, durability is treated as a necessary but not sufficient condition for circularity.

5.2.5. Implications for Product Selection

The analysis of functional performance highlights why certain garment types are particularly suitable for circular loop development. Products that combine acceptable durability with relatively simple construction and high market volume offer the best balance between long service life and recyclability.
These insights directly inform the selection of garment archetypes in the following sections, where product categories are evaluated not only for their functional performance, but also for their capacity to support effective material recovery and circular loop implementation.

5.3. Sustainable Fashion and Market Permanence: Identifying Circular-Relevant Garments

Sustainable fashion strategies increasingly recognise that material and design choices must be aligned not only with environmental objectives, but also with long-term market relevance and user behaviour (1,2,3).
From a circular economy perspective, the effectiveness of recycling and reuse systems depends strongly on the selection of garment types that are consistently present on the market and available in sufficient volumes.
Garments that are highly trend-driven or niche-oriented may exhibit favourable material properties, yet their limited circulation reduces the overall impact of circular interventions. In contrast, timeless, high-volume apparel staples offer stable and predictable material flows, making them particularly suitable for the development and testing of circular loops.

5.3.1. “Never Out of Fashion” Staples as Circular Opportunity

Certain apparel categories remain largely unchanged across fashion cycles and generations. Products such as T-shirts, sweatpants and jeans fulfil fundamental functional and cultural roles and are consistently demanded regardless of seasonal trends.
These garments are characterised by:

- long-term presence in global and European markets,
- high production and consumption volumes,
- broad demographic acceptance,
- standardised forms that evolve incrementally rather than radically.

Their permanence ensures a continuous supply of post-consumer textiles, which is a prerequisite for scalable sorting, recycling and reuse systems.

5.3.2. Volume, Availability and Collection Potential

High-volume garments are more likely to enter organised collection systems and municipal textile waste streams. T-shirts, sweatpants and jeans are widely owned, frequently replaced and commonly discarded through both formal and informal channels.
From a system perspective, these product types offer:

- high statistical relevance in waste composition analyses,
- predictable material composition patterns,
- suitability for standardised sorting and classification approaches,
- sufficient quantities to justify investment in recycling infrastructure.

This makes them ideal candidates for experimental circular loops aimed at generating transferable insights and scalable solutions.

5.3.3. User Acceptance and Second-Life Potential

Market permanence is closely linked to user acceptance and cultural norms. Garments that are familiar and trusted are more readily reused, repaired and passed on to secondary users. T-shirts and sweatpants are commonly reused within households, while jeans benefit from strong cultural acceptance of wear, ageing and repair.
This behavioural dimension enhances the circular potential of these products by extending their use phase and delaying entry into recycling streams. High reuse potential also reduces pressure on recycling systems and supports value retention at higher levels of the waste hierarchy.

5.3.4. Strategic Relevance for Circular Loop Design

The combination of stable demand, high volume and user acceptance positions T-shirts, sweatpants and jeans as strategically relevant product archetypes for circular economy experimentation. These garments simultaneously present:

- significant environmental and circularity challenges due to scale,
- substantial opportunities for material recovery and system optimisation.

Focusing on such products enables a realistic assessment of how fibre selection, garment construction and user behaviour interact to influence circular outcomes. This product-centred approach forms the basis for the selection of garment archetypes and circular loops developed in the following section.

5.4. Product Archetypes Selected for Circular Loop Design

Based on the analysis of user-centred performance, functional durability and market permanence, a set of representative garment archetypes was selected to serve as the foundation for circular loop design and experimental activities. The selection prioritises products that are simultaneously problematic from a circularity perspective and highly relevant in terms of market presence and recovery potential.

Rather than focusing on idealised or niche products, the chosen archetypes reflect everyday apparel items that are consistently available on the market, widely used across demographic groups and present in significant volumes within post-consumer textile waste streams.

5.4.1. Selection Criteria

The product archetypes were selected based on the following criteria:

- High market volume and permanence, ensuring continuous availability in collection and recycling systems.
- Timeless design and functional relevance, independent of short-term fashion trends.
- Significant circularity challenges, arising from material choice, garment construction or use-phase behaviour.
- High recovery potential, enabling meaningful investigation of reuse and recycling pathways.
- Comparability, allowing controlled analysis of material effects and design effects.
- Data readiness, supporting material identification, Digital Product Passport implementation and AI-based sorting within WP4.

These criteria ensure that the selected products are both scientifically relevant and systemically representative.

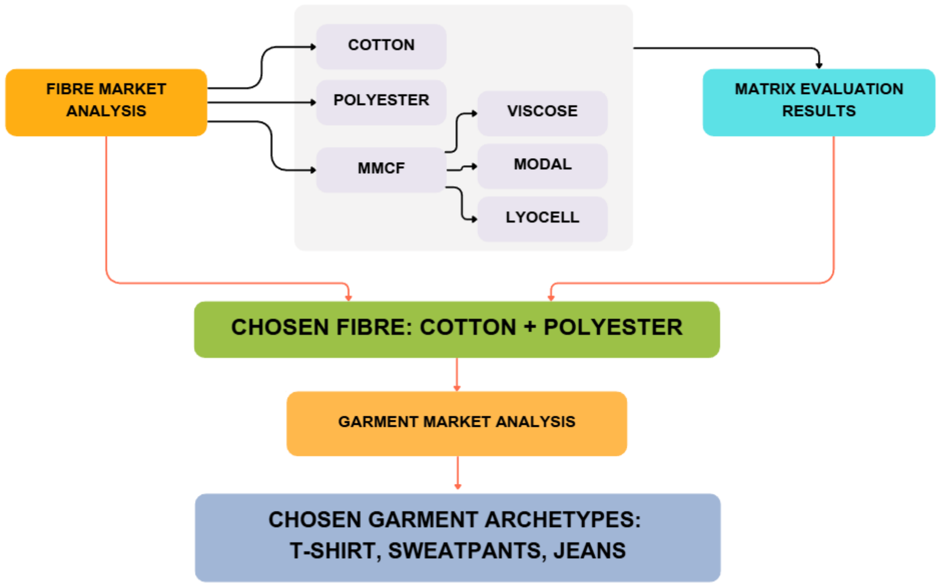

Figure 5. Decision pathway for material and garment archetype selection.
Red arrows indicate decision points and narrowing of scope.

The figure illustrates the multi-stage selection process applied in the Material Analysis and Selection Report. Starting from a fibre market analysis covering natural, synthetic and man-made cellulosic fibres, a matrix-based evaluation was used to assess material relevance from a circular economy perspective. Based on market scale, performance trade-offs and end-of-life challenges, cotton and polyester were selected as the focus fibre system. Subsequently, garment market analysis led to the selection of three representative garment archetypes—T-shirt, sweatpants and jeans—for further experimental and recycling performance assessment.

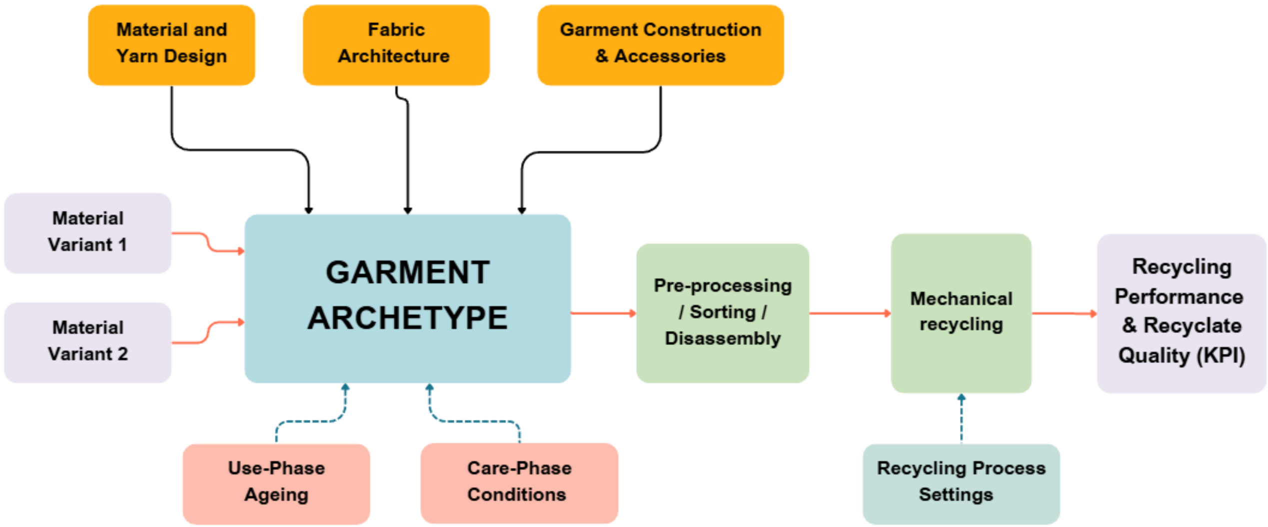

Figure 6. Conceptual framework linking garment archetype design, use-phase behaviour and mechanical recycling performance.

Figure X presents the conceptual framework used to operationalise the selected product archetypes within the circular loop design and experimental methodology of WP4. The diagram illustrates how material- and design-related variables are systematically linked with use-phase behaviour, pre-processing steps and mechanical recycling outcomes.

At the core of the framework is the Garment Archetype, defined as a standardised reference product with fixed construction parameters. This approach ensures comparability between material variants and allows controlled assessment of fibre- and design-driven effects on recycling performance. Material variants (e.g. cotton- and polyester-based systems) are introduced at this level to isolate the influence of fibre composition under otherwise comparable product conditions.

Upstream, three design-related parameter groups—Material and Yarn Design, Fabric Architecture, and Garment Construction & Accessories—define the intrinsic properties of the archetype and establish its baseline performance and structural complexity. These parameters determine not only functional behaviour during use but also the degree of fragmentation, contamination and fibre damage during end-of-life processing.

Downstream influences from Use-Phase Ageing and Care-Phase Conditions represent cumulative and indirect effects associated with real-life consumer behaviour, including wear, washing and maintenance. These factors modify material integrity prior to recycling and are therefore explicitly considered as contextual variables affecting recyclability.

Before recycling, garments undergo Pre-processing, Sorting and Disassembly, reflecting realistic industrial preparation steps such as removal of non-textile components, size reduction and feedstock homogenisation. The prepared material is then subjected to Mechanical Recycling, operated under controlled Recycling Process Settings, which enable reproducible comparison of outcomes across material variants and archetypes.

The framework culminates in a set of Key Performance Indicators (KPI) describing recycling performance and recyclate quality, including material yield, fibre length distribution, contamination levels and reuse potential. By linking design decisions, use-phase effects and process parameters to measurable recycling outcomes, the framework provides a transparent and reproducible basis for circular loop design and experimental evaluation.

5.4.2. Material Effect: Cotton versus Polyester

T-shirts (Cotton vs Polyester)

To assess the influence of fibre selection on circularity performance, two garment types were selected in both cotton- and polyester-based variants:

- T-shirts (Cotton vs Polyester)
- T-shirts represent a simple, next-to-skin garment with minimal structural complexity.

By comparing cotton and polyester T-shirts, it becomes possible to isolate the impact of fibre properties on:

- user comfort and wear behaviour,
- washing and maintenance patterns,
- material identification and sorting,
- recyclability and quality of recovered material.

This comparison provides a clear case for evaluating fibre-driven differences under otherwise similar product conditions.

Sweatpants (Cotton vs Polyester)

Sweatpants introduce greater structural and functional complexity, including waistbands, cuffs and, in many cases, drawstrings or elastic components. Comparing cotton and polyester sweatpants allows assessment of:

- fibre performance under dynamic use,
- the role of dimensional stability and durability,
- the impact of trims and elastane on end-of-life processing,
- trade-offs between comfort, performance and recyclability.

5.4.3. Design Effect: Influence of Garment Construction

To evaluate the impact of garment design and construction independently of fibre type, cotton jeans were selected as a third archetype.

Cotton Jeans

Jeans are typically manufactured from 100% cotton denim but exhibit high constructional complexity, including multiple panels, heavy seams, metal components and intensive finishing processes. Despite these challenges, jeans are culturally valued, durable and frequently repaired, resulting in long service life.

By comparing cotton jeans with cotton sweatpants, it becomes possible to assess:

- the influence of garment construction on recyclability,
- the role of trims and hardware in material recovery,
- differences in reuse and repair behaviour,
- how design complexity affects circular loop feasibility even within mono-material systems.

This comparison highlights the importance of design-for-recycling principles alongside material selection.

5.4.4. Overview of Selected Product Archetypes

The final set of product archetypes selected for circular loop development includes:

1. Cotton T-shirt

2. Polyester T-shirt
3. Cotton sweatpants
4. Polyester sweatpants
5. Cotton jeans

Together, these products form a coherent experimental framework enabling:

- direct comparison of fibre effects,
- assessment of design and construction impacts,
- evaluation of user behaviour and market dynamics,
- development of realistic, scalable circular loops.

5.4.5. Implications for Circular Loop Design and Experimental Work

The selected product archetypes provide a structured basis for designing and testing circular loops that reflect real-world conditions. They allow exploration of:

- how fibre selection influences recycling pathways and material quality,
- how garment design and trims affect disassembly and processing,
- where design interventions can most effectively improve circular outcomes.

By grounding loop design in widely used and well-understood products, the experimental work can generate insights that are transferable to broader segments of the apparel market. This product-centred approach ensures that the resulting circular loop models are both technically relevant and systemically meaningful.

6. Material analysis

The parameters described in this chapter are applied both as baseline descriptors of fibres, fabrics and garment archetypes prior to recycling, and as comparative indicators used to evaluate changes induced by mechanical recycling and care-phase processes. This dual use enables a consistent assessment framework, in which initial material properties serve as reference values for interpreting recycling performance and material degradation. As the project is ongoing, selected results are reported as preliminary screening outcomes supporting material and archetype selection within WP4.

6.1. Input parameters – Material & Garment Archetype

Baseline material characterisation was performed to define the initial state of fibres, fabrics and garment archetypes prior to recycling and ageing. These parameters serve two functions within WP4:

- they enable a controlled comparison between different fibre systems and garment constructions, and
- they provide reference values against which material changes induced by mechanical recycling and care-phase processes can be evaluated.

The selected input parameters reflect properties that are known to strongly influence recyclability, fibre damage, process efficiency and the quality of recovered fibres.

6.1.1. Fibre composition

Accurate identification of fibre composition is a prerequisite for interpreting recycling performance, fibre degradation behaviour and variability in recycled material quality. In this study, fibre identification and blend verification were performed using a combination of classical and instrumental techniques, selected for their relevance to textile recycling contexts rather than to provide an exhaustive analytical comparison.

Quantitative determination of fibre blends can be performed using chemical analysis methods described in the EN ISO 1833 series. These methods are based on either manual separation or selective chemical dissolution of individual fibre components.

Qualitative fibre identification follows the guidance of CEN ISO/TR 11827 and includes the techniques outlined below.

Microscopy

Optical microscopy and scanning electron microscopy (SEM) were used to identify characteristic longitudinal and cross-sectional features of fibres. This method is particularly effective for distinguishing natural, regenerated and synthetic fibres and for detecting elastane cores or wrapping structures in blended yarns.

Figure shows for example the very typical longitudinal view of a cotton fibre.

Figure 7. Longitudinal view of cotton fibres

Flame test

Flame testing is a classical identification method based on combustion behaviour, flame appearance and odour of generated fumes. It is particularly useful for distinguishing between cellulosic, protein-based and synthetic fibres. Additional flame-based tests include chlorine and nitrogen detection for specific polymer classes.

Staining tests

Some type of fibres interact with certain solutions. Protein components in a fibre can for example be visualised by applying a drop of nitric acid onto the fibre. If the fibre appears yellow and changes to orange when neutralizing it with ammonium, the fibres is composed of proteins.

Solubility tests

Different materials dissolve in different solvents. Cellulosic fibres are dissolved by adding a copper(II)ethylenediamine reagent to the fibres.

Infrared spectroscopy

Infrared spectroscopy is an instrumental technique which is an alternative for the above described classical tests. Spectroscopy studies the interaction of a sample with irradiation. An infrared examination results in a spectrum which is mainly determined by the chemical constitution of the fibre. It is less dependent on the physical structure. Only a few miligrams are needed to perform a measurement.
A specific form of infrared spectroscopy is **the attenuated total reflection** (ATR). It's a simple, quick technique that doesn't need any preparation of the sample. ATR is a surface technique that passes infrared radiation through an infrared transmitting crystal to obtain a spectrum.
The peaks shown in an infrared spectrum are linked to chemical bonds. It gives a fingerprint of the material (example in *Figure*). A broad peak centered around 3300cm^{-1} indicates for example the presence of CH-bonds.

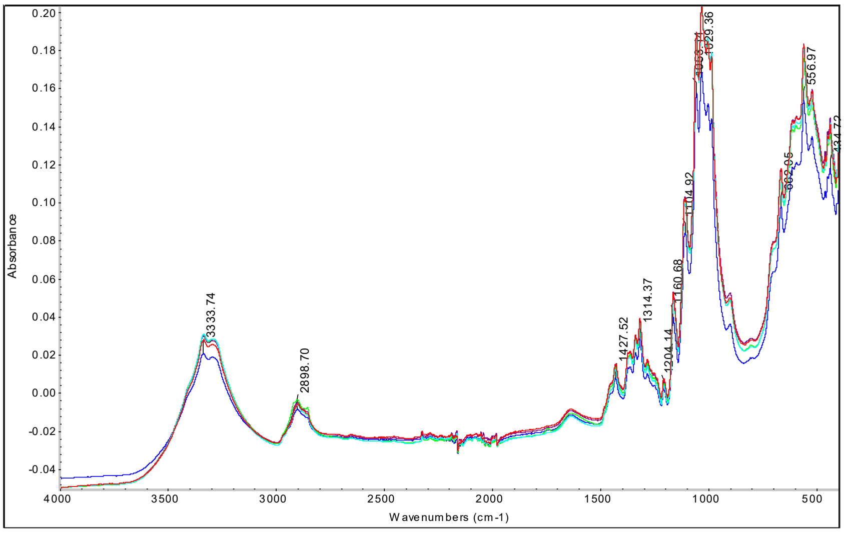

Figure 8. ATR spectra of cotton samples

Thermal analysis

Fibres made of thermoplastic polymers will have a melting point (except when they are 100% amorphous). The melting point can be defined as the temperature (or temperature range) at which crystalline regions melt or the point at which the solid fibres become liquid.

An instrumental technique to measure the melting point is **differential scanning calorimetry** (DSC). Apart from the melting point other phase transitions (e.g. glass transition) or chemical reactions can be studied with DSC. The measurement is based on the difference in heat flow (power) into a test specimen and that into a reference specimen. The result is a curve or thermogram in which the heat flow is plotted in fuction of temperature or time (example in *Figure*). Endothermic changes like e.g. melting and exothermic changes like e.g. crystalisation can be distinguished in the DSC-curve.

DSC gives the possibility to distinguish fibres classified within the same fibre class e.g. different types of polyamides like polyamide 6 and 6.6. The melting point of PA6 is around 223°C, while PA6.6 melts around 255°C. (19)

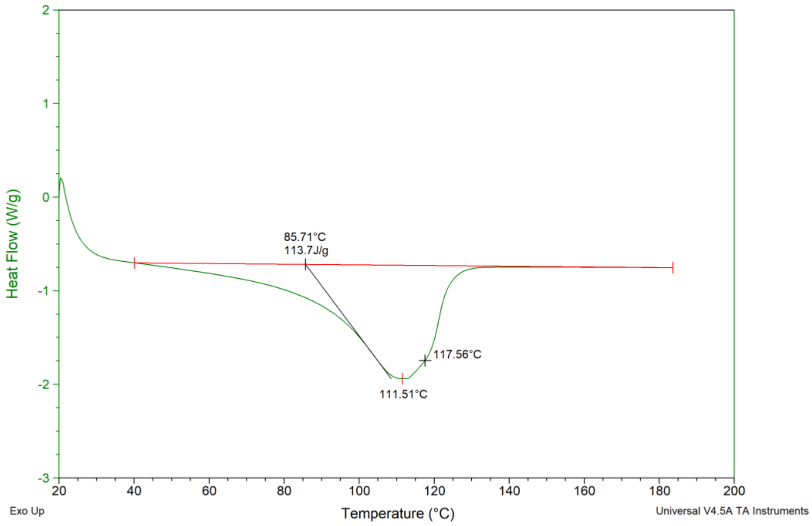

Figure 9: DSC-analysis of PE filament with indication of melting temperature

Another thermal analysis technique is **thermal gravimetric analysis** (TGA). With TGA, a sample is heated and weight changes are measured. This gives information on thermal stability and decompostion of the sample.

In subsequent case studies, fibre composition and chemical signatures are re-evaluated after recycling and ageing processes to assess material stability, contamination effects and suitability for circular recovery pathways.

6.1.2. Fibre fineness

The fibre fineness or linear density determines the fibre thickness. This property is crucial for the quality of the end product (e.g. a yarn).

To measure fibre fineness, serveral test methods and devices exist. A few examples:

- Gravimetric method (e.g. EN ISO 1973): specimens of a given length are weighed on a balance
- Vibroscope method (e.g. EN ISO 1973): individual fibres of a given length are put under a specified tensioning force and are subjected to vibration at resonance fequency. The linear density is determined from the conditions of the resonance state (i.e. resonance frequency, vibrating length of the fibre, tensioning force).
- Optical method: laser diffraction or polarized light microscopy (like OFDA/Cottonscope) is used to analyze light patterns or images of dispersed fibres, rapidly determining diameter/linear density from diffraction angles or pixel analysis,
- Airflow method (Micronaire): Air is pressed through a fibre plug. The air pressure indicates fineness. The finer the fibres, the less the airflow is restricted. This method is most common for cotton.

6.1.3. Fibre length and length distribution

To measure the fibre length and length distribution several test methods and devices exist. A few examples:

- Direct/manual measurement (e.g. ASTM D5103 and the BISFA methodes „Recommended test methods for testing staple fibres"): the fibres are gripped at the tips with pincers or forceps. The fibre is than fully extended without stretching and than measured with a ruler. Depending on the type of fibre, 50 or more fibres are measured.

- High Volume Instrument (HVI): a standard, automated system using optical methods typically used for cotton. A bundle or „beard" is made from a small sample of fibres. This fibre bunlde passes through an optical system which detects the fibre lenghts.
- Photoelectric method (e.g. Fibrograph): uses photocells to measure light blockage as a fibre bundle passes.
- Manual comb sorter method (e.g. Suter-Webb array method): fibres are aligned with parallel combs and manually sorted into length groups, weighed, and analyzed for length distribution.

The manual methods are seen as more accurate, but the automated test methods are way faster.
The results of the fibre length measurement can be plotted into a histogram or fibrogram to get de fibre length distribution.
In the case studies presented in this report, fibre length and length distribution are re-measured after mechanical recycling and compared against these baseline values to quantify fibre damage and recovery potential.

6.1.4. Fibre strength

Fibre strength can be measured with a tensile testing machine which measures force as a function of displacement (elongation) (see *Figure*).
Several machines exist, but the most widely used machines are constant-rate-of-extesion (CRE) testing machines (e.g. Favimat from Textechno). The measured fibre strength and elongation at break can be influenced by the machine settings (i.e. gauge length, test speed, pretension, envrionmental conditions). For that reason, the use of standard test methodes, like ISO 5079, is recommended.

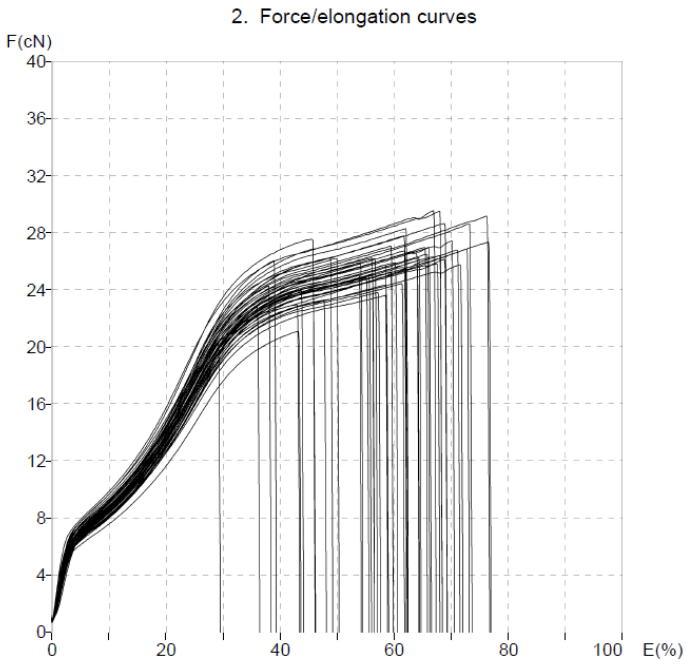

Figure 10: Force/elongation curves of 50 PET fibres tested according to ISO 5079

Fibre tensile properties are re-assessed after mechanical recycling in order to evaluate strength retention and mechanical performance losses relative to the baseline state.

6.1.5. Visual evaluation

Visually evaluating mechanically recycled fibres quickly reveals quality issues like (17)

- Shortened fibre length
- Color inconsistencies

- Contamination/impurities (e.g. foreign materials)
- Neps/entangled clusters (small, tightly wound balls of cotton that refuse to separate during processing)
- Fibre damage (e.g. fibrillation, frayed ends)
- Problems with fibre opening (see *Figure*).
-

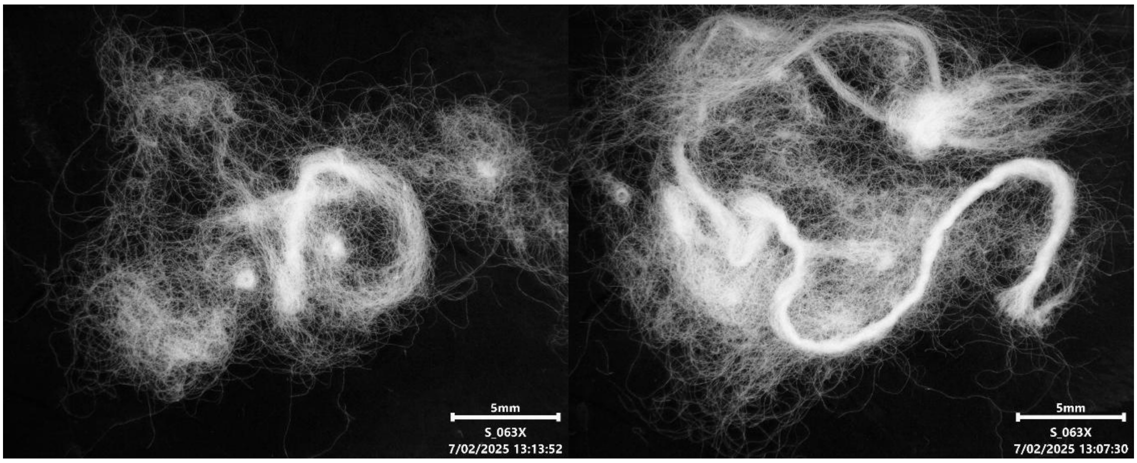

Figure11. Improper fibre opening of fibre after mechanical recycling of cotton

Visual evaluation can be done by using a microscope but also automated systems exist like a Micro-Dust and Trash Analyser (MDTA) (18). Also digital imaging with AI/machine learing can be used for the visual evaluation.

6.2. Output parameters and expected results

The experimental activities described in Part B generate a set of output parameters that support material and garment archetype selection for circular textile design. These outputs are used to evaluate recyclability performance, material degradation and suitability for further processing within WP4 and subsequent project phases.
The key output parameters include:
Material identification and integrity

- verified fibre composition and blend structure (microscopy, FTIR, DSC),
- detection of contamination, finishes and non-target components.

Structural and morphological performance

- changes in fibre morphology and surface condition (SEM, visual evaluation),
- degree of fibre opening and presence of neps or dust after mechanical processing.

Mechanical performance indicators

- fibre tensile strength and elongation at break after recycling,
- retention of mechanical properties relative to baseline values.

Recyclate quality indicators

- fibre length and length distribution after mechanical recycling,
- **variability (CV) of key fibre properties as an indicator of process stability.**

Ageing and care-related effects (planned)

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the European Union

- evolution of chemical, thermal and structural properties after controlled laundering cycles (0, 1, 5, 10, 50, 100),
- impact of use-phase ageing on recyclability and fibre recovery potential.

Together, these output parameters provide an evidence-based foundation for validating selected material variants and garment archetypes and refining recycling process settings.

6.3. Planned care-phase and ageing experiments

In addition to recycling-related testing, controlled care-phase ageing scenarios are planned for selected garment archetypes. The experimental plan includes defined laundering cycles (0, 1, 5, 10, 50 and 100 washes), with intermediate drying steps applied where feasible. The same analytical parameters described in this chapter (FTIR, DSC, fibre morphology, fibre length and tensile strength) will be used to assess ageing-induced changes prior to recycling. These activities will be completed and reported in subsequent project deliverables.

7. 1rst Case study: Recycling of jeans into yarns

The objective of this case study is to evaluate the feasibility of recycling cotton-based denim garments through mechanical fibre recovery and reintroduction of recycled fibres into yarn manufacturing. The study serves as an applied validation of the selected garment archetype and the material selection logic defined in this deliverable.
The experimental work presented represents preliminary screening results generated within the ongoing AIdesignTEX project. Its primary purpose is to assess material behaviour, recyclability and fibre quality under representative mechanical recycling conditions, and to verify the applicability of the selected characterisation methods.
The experimental activities were carried out at Lodz University of Technology, with selected analyses and process trials performed in collaboration with Ghent University. Further optimisation of recycling parameters, extended ageing studies and upscaling activities are planned for subsequent phases of WP4.

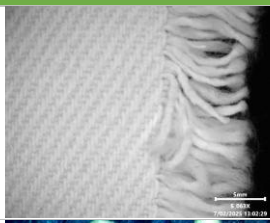
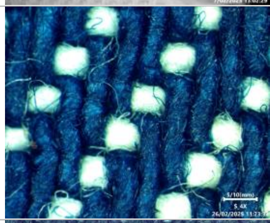
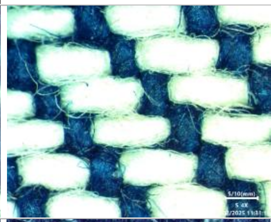
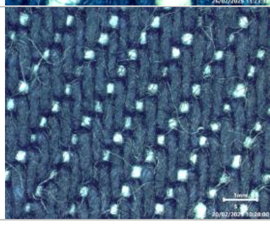
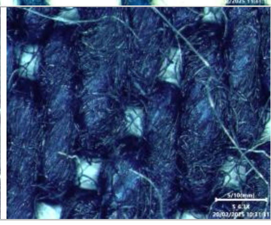
Figure12. Schematic overview of case study: recycling of jeans into yarns

7.1. Sample selectionand material description

Three types of cotton-based denim fabrics were selected to represent typical jeans constructions with varying fibre compositions relevant for recycling assessment. The materials were provided by the Polish jeans manufacturer Viking and include both mono-material and elastane-containing variants.
The selected materials represent common industrial denim constructions and were chosen to enable comparison between mono-material cotton systems and elastane-containing variants, which are known to pose additional challenges in textile recycling.

Figure 13. Viking jeans – cooperation with polish company

Table 14. 3 different types of cotton fabrics from Turkey and Brasil were provided by the Polish jeans manufacturere Viking

Name	Description	Microscopic image
ASTRA	100% white cotton	
ZAT	Denim, 100% cotton	 
ANSIN PACITO COMFORT	Denim, cotton + elastand	 

The selected materials enable comparative assessment of recycling performance in relation to fibre composition, fabric structure and the presence of elastane.

7.2. Mechanical recycling

Mechanical recycling was selected as the primary recycling route for the denim samples due to its relatively low energy demand, technological maturity and industrial availability. This choice aligns with the objectives of evaluating scalable and practically applicable recycling solutions.
The initial step of the process involved manual disassembly and unravelling of the garments to remove non-textile components and facilitate controlled fibre recovery. Subsequently, shredding and carding operations were applied to convert the fabric into fibrous material suitable for further analysis.
The mechanical recycling process was conducted using the technological system available at Lodz University of Technology, following the configuration illustrated in Figure 8.

Figure 14. Technological system of TUL for mechanical recycling of cotton

The applied mechanical recycling route reflects a scalable and industry-relevant approach and was used to generate comparable recyclate samples for quality assessment rather than to achieve process optimisation

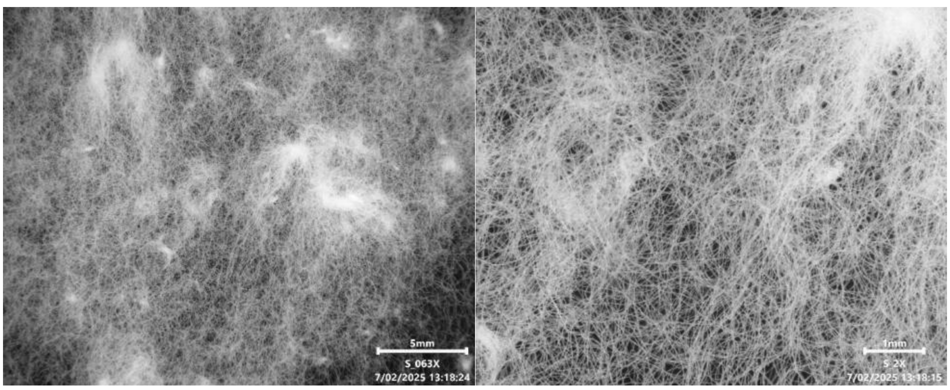
7.3. Quality control recycled fibres

The The quality control results presented in this section should be interpreted as relative indicators of recyclability and fibre degradation, benchmarked against baseline values defined in Chapter 6, rather than as absolute performance limits. The analyses focus on comparing virgin and mechanically recycled fibres in order to assess the impact of the recycling process on fibre integrity, variability and suitability for further processing.
Recycled fibres were subjected to visual evaluation and mechanical characterisation, including measurements of linear density, tensile strength and elongation at break. These parameters were selected to capture both qualitative effects (such as fibre opening and damage) and quantitative changes in mechanical performance resulting from mechanical recycling.

7.3.1. ASTRA 100% Cotton

Visual evaluation and composition of recycled fibres

Microscopic examination confirmed that the recycled fibres consist of cotton, with no evidence of foreign fibre contamination. However, visual analysis revealed the presence of partially opened fibre bundles and locally entangled fibre clusters, indicating incomplete fibre opening during mechanical processing.



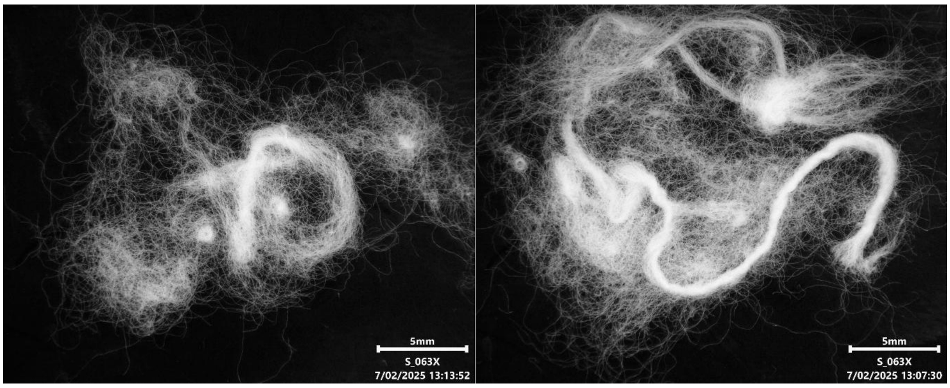


Figure 15 Images of recycled cotton fibres.

The mechanical recycling process therefore requires further optimisation to improve fibre opening. The observed presence of partially opened fibre bundles and increased variability in fibre properties indicates that the applied shredding and carding settings are sufficient to enable fibre recovery, but not yet optimised for achieving consistent recyclate quality.

Fibre fineness and tensile properties

Table 15 presents the linear density and tensile properties of virgin and recycled ASTRA cotton fibres. The average linear density remains unchanged after recycling, while tensile strength and elongation at break show only minor differences between virgin and recycled fibres.

Table15. Fibre fineness and tensile properties

Parameter		**Unit**	**ASTRA 100% cotton**	
			Virgin fibres 	**Recycled fibres** 
Linear density	Average	dtex	2.0	2.0
	CV	*%*	*22.8*	*46.1*
Tenacity	Average	cN/dtex	2.55	2.67
	CV	%	31.11	32.76
Elongation at break	Average	%	7.0	7.4
	CV	%	56.7	35.5

Despite the comparable average values, the coefficient of variation increases notably after recycling, reflecting increased heterogeneity in fibre properties. This variability is consistent with the visual observations and highlights fibre opening and process control as key optimisation targets in subsequent recycling trials.

7.3.2. ZAT 100% cotton

Visual evaluation and composition of recycled fibres

Microscopic images of the recycled yarns and fibres confirm the presence of cotton fibres without detectable contamination from non-cellulosic materials. Similar to the ASTRA sample, visual evaluation indicates incomplete fibre opening, manifested by residual fibre bundles and uneven fibre separation.

The mechanical recycling process therefore requires optimisation to improve fibre opening and to reduce variability in fibre morphology.

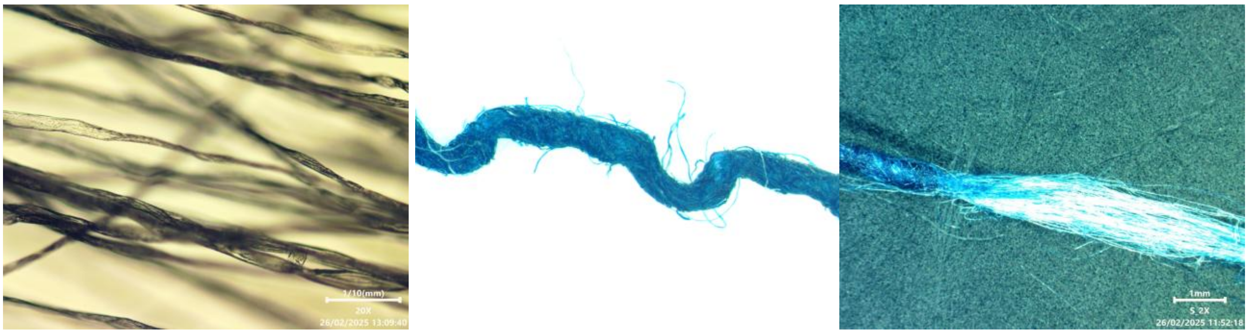


Figure 16. Microscopic images of recycled cotton fibres showing partially opened fibre bundles and uneven fibre separation after mechanical recycling.

The mechanical recycling needs to be optimised because of problems with fibre opening.

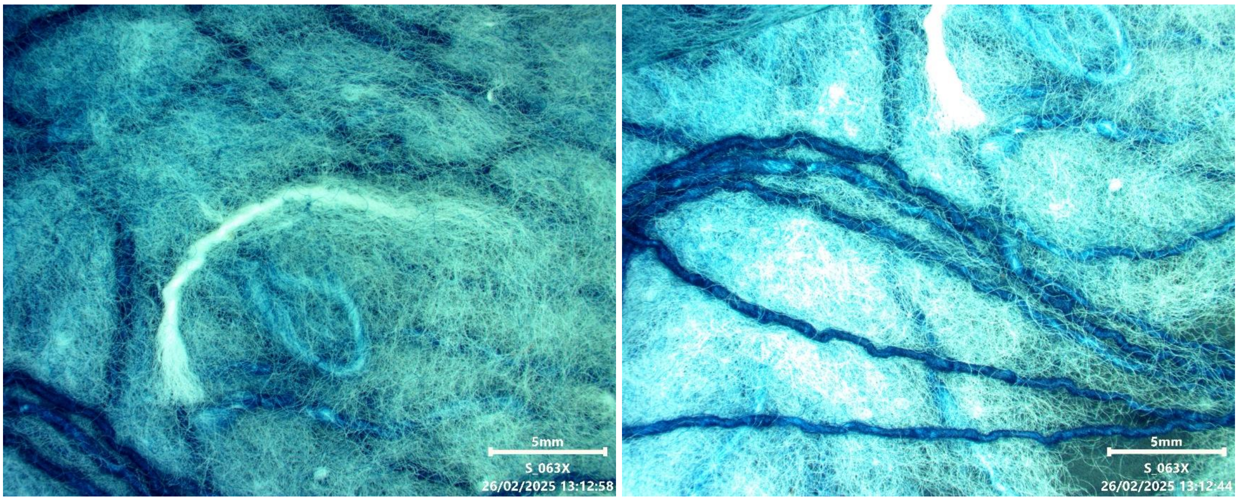


Figure 17. Problems with fibre opening.

Fibre fineness and tensile properties

Table 16 summarises the mechanical properties of virgin and recycled ZAT cotton fibres. The average linear density and tensile strength of the recycled fibres remain comparable to those of the virgin material, indicating that the mechanical recycling process does not result in significant fibre weakening.

The elongation at break is slightly higher for the recycled fibres, which may be attributed to structural changes introduced during mechanical processing. As observed for the ASTRA sample, the variability of fibre properties increases after recycling, reinforcing the need for further optimisation of shredding and carding parameters to improve process consistency.

Table16. Fibre fineness and tensile properties

Parameter		**Unit**	**ZAT 100% cotton**	
			Virgin fibres 	**Recycled fibres** 
Linear density	Average	dtex	2.2	2.0
	CV	*%*	*33.2*	*23.0*
Tenacity	Average	cN/dtex	2.26	2.21
	CV	%	31.20	29.58
Elongation at break	Average	%	4.7	6.8
	CV	%	31.6	35.1

For the ZAT sample, the average linear density and tensile strength of recycled fibres are comparable to those of the virgin material, indicating that mechanical recycling does not result in significant fibre weakening. The slight increase in elongation at break observed after recycling may be attributed to structural rearrangements introduced during fibre opening and carding.
As for the ASTRA sample, an increase in variability of fibre properties is observed after recycling. This trend highlights the influence of fibre separation efficiency and supports the need for further optimisation of mechanical recycling settings to reduce heterogeneity in the recycled fibre fraction.

7.3.3. Ansin Pacito comfort cotton + elastane

Visual evaluation and composition of recycled fibres

Microscopic analysis of the recycled material confirms a composite fibre structure, with an elastane core wrapped by cotton fibres, characteristic for stretch denim yarns. Visual evaluation further reveals the coexistence of white and indigo-dyed fibres, reflecting the original yarn and fabric construction.
The presence of elastane significantly affects fibre behaviour during mechanical recycling. In contrast to mono-material cotton samples, elastane filaments remain largely intact during shredding and carding, leading to incomplete fibre separation, local fibre entanglement and the formation of heterogeneous fibre bundles.

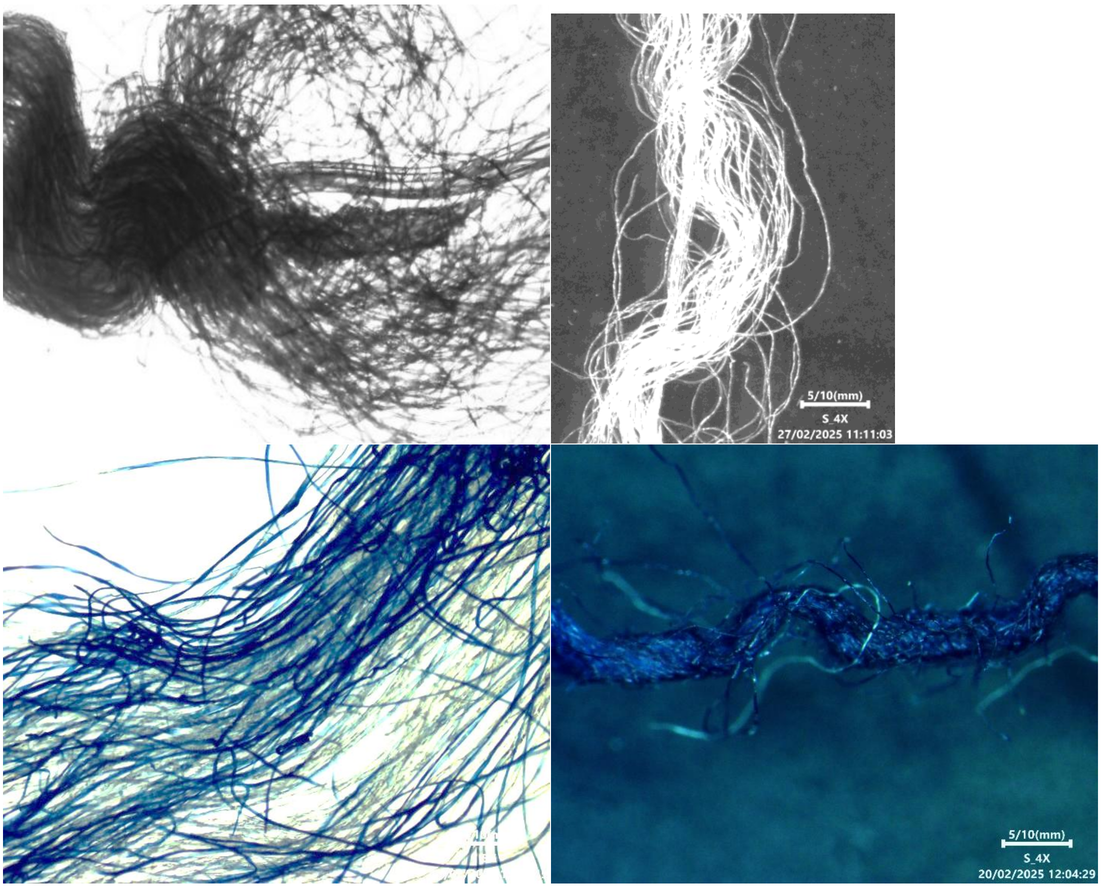


Figure 18: Microscopic images of recycled cotton–elastane fibres showing elastane cores and incomplete fibre separation

Fibre fineness and tensile properties

Table 17 summarises the linear density and tensile properties of virgin and recycled fibres obtained from the ANSIN PACITO COMFORT fabric. In comparison with the mono-material cotton samples, the recycled fibres exhibit a clear increase in average linear density and a reduction in tensile strength.

The increase in linear density and the higher variability of fibre properties indicate insufficient separation of cotton fibres from the elastane component during mechanical processing. The reduction in tensile strength suggests additional fibre damage and structural heterogeneity introduced by the presence of elastane.

These results confirm that elastane-containing denim represents a more challenging recycling scenario under purely mechanical processing conditions. While fibre recovery is technically feasible, the quality and consistency of the recyclate are reduced compared to mono-material cotton systems.

Table 17: Fibre fineness and tensile properties of virgin and recycled ASTRA cotton fibres.

Parameter		Unit	ANSIN PACITO COMFORT cotton	
			Virgin fibres	Recycled fibres
				
Linear density	Average	dtex	2.1	3.1

	CV	*%*	*24.8*	*46.1*
Tenacity	Average	cN/dtex	2.56	1.95
	CV	%	31.28	52.76
Elongation at break	Average	%	4.9	5.6
	CV	%	40.3	36.9

The results demonstrate a clear impact of elastane on the properties of mechanically recycled fibres. In comparison to the mono-material cotton samples, the recycled fibres exhibit an increased average linear density and a reduction in tensile strength, accompanied by a marked increase in variability.

These trends indicate insufficient separation of cotton fibres from the elastane component during mechanical processing, leading to heterogeneous fibre bundles and reduced mechanical performance. The data confirm that elastane-containing denim represents a more challenging material system for mechanical recycling and requires alternative or complementary recycling strategies to achieve higher-quality recyclates.

7.4. Remarks on preliminary results „recycling of jeans"

The observations from this case study confirm the relevance of denim jeans as a representative garment archetype and highlight the influence of yarn structure, dyeing and elastane content on mechanical recycling performance. These findings directly inform the selection logic applied in this deliverable and define priority areas for further experimental work.

- **Influence of yarn structure**. - The disintegration behaviour of woven denim during shredding is strongly dependent on yarn construction. Highly twisted yarns, such as warp yarns in the ASTRA fabric, exhibit more resistance to fibre separation, indicating that yarn twist and fabric architecture are important parameters influencing mechanical recyclability and require further investigation.
- **Influence of dyeing. -** The presence of indigo-dyed warp yarns in the ZAT and ANSIN fabrics adversely affects fibre separation during mechanical recycling. Indigo impregnation contributes to increased fibre cohesion and hampers efficient fibre opening, suggesting that dye-related effects should be explicitly considered in recycling-oriented material selection and, where feasible, addressed through dedicated pre-treatment or dye-removal strategies.
- **Influence of elastane.** - In elastane-containing fabrics, the persistence of non-cellulosic fibres after unravelling and shredding significantly complicates mechanical recycling. The results indicate that while fibre recovery remains technically feasible, elastane reduces fibre separation efficiency and recyclate consistency. For such material systems, selective removal of elastane and dyes—potentially through complementary chemical recycling routes—may be required to achieve higher-quality recycled fibres.
- **Mechanical performance of recycled fibres -** The mechanical characterisation results show that the average tensile strength, elongation at break and linear density of recycled cotton fibres remain comparable to those of virgin fibres. However, the reusability of the recycled fibres is expected to be primarily constrained by fibre length reduction and increased variability, underscoring the importance of optimising mechanical recycling parameters and further assessing fibre length distribution.

8. Conclusions and next steps

This deliverable establishes a structured and evidence-based foundation for material and garment archetype selection within WP4 of the AIdesignTEX project. The report consolidates market relevance, material characteristics and recyclability considerations into a coherent selection logic, supported by a clearly defined experimental and analytical framework.

The analysis confirms that cotton-based garments, particularly denim jeans, constitute a highly relevant and representative archetype for circular textile research due to their market prevalence, material complexity and recycling challenges. The selected analytical parameters—covering fibre composition, morphology, mechanical performance and recyclate quality—are shown to be suitable for both baseline material characterisation and post-processing assessment.

Figure X summarises the conceptual circular lifecycle context in which the material and garment archetype selection, analytical framework and planned recycling activities presented in this deliverable are positioned.

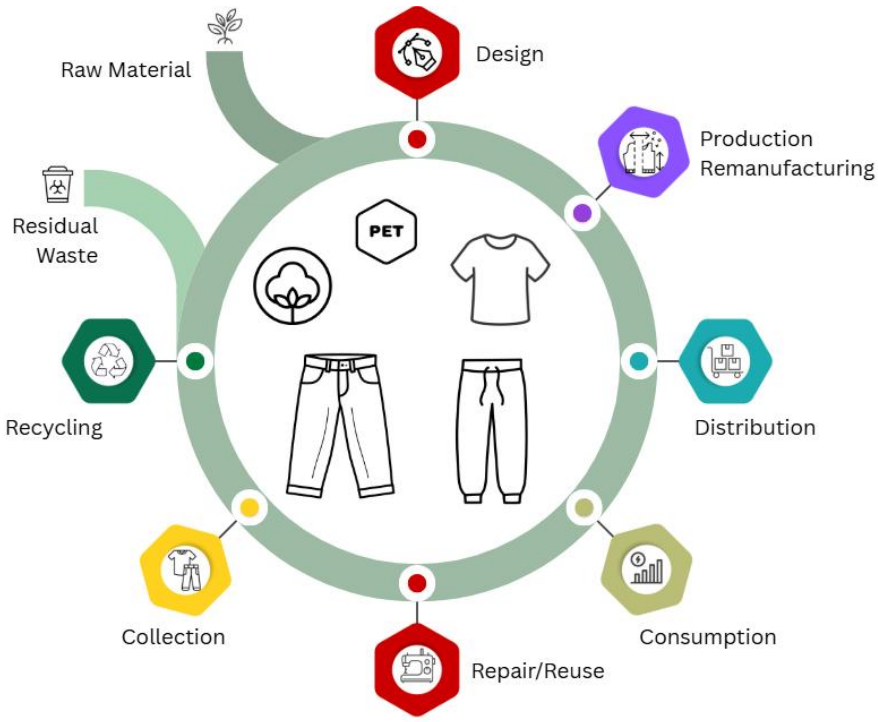


Figure 19. Conceptual circular lifecycle framework for textile products, illustrating the role of material and garment archetype selection, recycling pathways and future circular loop development within the AIdesignTEX project.

Figure 19 summarises the conceptual circular lifecycle context in which the material and garment archetype selection, analytical framework and planned recycling activities presented in this deliverable are positioned.

The presented case study on mechanical recycling of denim jeans demonstrates the practical applicability of the defined methodology and provides preliminary validation of the selection approach. The results indicate that mechanical recycling enables fibre recovery with largely preserved average mechanical properties; however, fibre length reduction, increased variability and the presence of dyes and elastane remain critical factors influencing recyclate quality and process consistency. These observations confirm that optimisation of recycling parameters and targeted treatment strategies will be required in subsequent project phases.

Importantly, this deliverable does not aim to present fully optimised recycling loops. Instead, it defines what materials and product archetypes are prioritised, why they are relevant, and how their circular performance will be assessed. Experimental validation and loop development activities—including extended ageing and laundering studies, optimisation of recycling routes, and the investigation of complementary recycling strategies for complex material systems—are ongoing and will be reported in subsequent WP4 deliverables and in the mid-term project report.

Next steps

Based on the outcomes of this deliverable, the following next steps are defined within WP4:

- further experimental validation of the selected analytical framework across additional material variants and controlled ageing scenarios;
- optimisation of mechanical recycling parameters to improve fibre opening, reduce fibre length degradation and limit dust formation;
- investigation of alternative or complementary recycling strategies for elastane-containing and dyed textiles;
- generation of structured experimental datasets to support AI/ML-based modelling of material degradation, recyclability and circular loop performance.

These activities will support the transition from material and archetype selection toward data-driven circular loop design and decision-support tools developed in later phases of the AIdesignTEX project.

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