D6.2 Sustainability Assessment Report

Submission date: M47

Due date: M45

DOCUMENT SUMMARY INFORMATION

Grant Agreement No	**101091575**	**Acronym**	**tExtended**
Full Title	**Knowledge Based Framework for Extended Textile Circulation**		
Start Date	**01/12/2022**	**Duration**	**48 months**
Deliverable	D6.2 Sustainability Assessment Report		
Work Package	WP6 – Benefits to sustainability and circularity		
Type	R – Document, report	**Dissemination Level**	PU - Public
Lead Beneficiary	RISE		
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DOCUMENT HISTORY

Version	Date	Changes	Contributor(s)
DRAFT	28 Aug 2026	First draft of the document	Diego Peñaloza, Celeste Lai, Yoon-Lin Chiew, Malin Brodin, Elisabeth Werrmann (RISE); Katarina Oscar, Jimmy Klintenberg (TEKO); Jānis Brizga (ZALA); Luís Ramos (CIT)
REVIEW	31 Aug 2026	Review version made, internal review started	Diego Peñaloza (RISE)
	1 Sep 2026	Review by Aravin Periyasamy	Aravin Periyasamy (VTT)
	16 Sep 2026	Review by Pirjo Heikkilä	Pirjo Heikkilä (VTT)
	18 Sept 2026	Review by Jean-Luc Derycke	Jean-Luc Derycke (UTEX)
	23 Oct 2026	Corrections based on first internal review and suggestions by VTT for Biocelsol	Diego Peñaloza, Celeste Lai (RISE)
FINAL	26-29 Oct 2026	Finalization for submission	Pirjo Heikkilä (VTT)

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LIST OF ABBREVIATIONS

Abbreviation	Definition
BHET	Bis(2-hydroxyethyl) terephthalate
CAPEX	Capital Expenditures
CLP	Classification, Labelling and Packaging
CO	Cotton
DMT	Dimethyl terephthalate
DPP	Digital Product Passport
EPR	Extended Producer Responsibility
ESPR	Ecodesign for Sustainable Products Regulation
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
NIR	Near Infra Red
NPV	Net Present Value
NYI	Not yet included
OPEX	Operational Expenditure
PEF	Product Environmental Footprint
PES	Polyester
PESCO	Polyester-Cotton blend
PSILCA	Product Social Impact Life Cycle Assessment
PUR	Polyurethane
PVC	Polyvinyl chloride
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
S-LCA	Social life cycle assessment
SoC	Substances of concern
SVHC	Substances of Very High Concern
TRL	Technology Readiness Level
UNEP	United Nations Environmental Programme

Executive Summary

The overall objective of the tExtended project is to develop a knowledge-based Blueprint, which is a master plan for a sustainable textile ecosystem where utilization of textile flows is optimized, aiming for retention of value of materials in a safe and sustainable way. Within tExtended project we will develop technological and digital solutions enabling efficient textile cycles and show potential to reduce textile waste by 80 % within Real Scale Demonstrator. More about the project in https://textended.eu/.

This study assessed the sustainability performance of innovative textile reuse, remanufacturing, and recycling solutions using a life cycle perspective, combining Life Cycle Assessment (LCA), Life Cycle Costing (LCC), Social Life Cycle Assessment (S-LCA), chemical hazard assessment, and a qualitative evaluation of the social benefits of circular textile initiatives. The aim was to identify environmental, economic, and social hotspots and support decision-making for a more circular and resilient European textile sector. The study covered both technology and product-level solutions developed within the project, including pre-treatments, sorting, reuse, fibre mechanical recycling, thermo-mechanical recycling, and chemical recycling of polyester and cellulosic fibres. Environmental impacts were assessed using the Product Environmental Footprint (PEF) framework, economic performance through LCC, and social risks using PSILCA.

Results indicate that most recycling technologies can reduce environmental impacts compared with virgin fibre production, particularly mature technologies such as mechanical recycling. Lower technology readiness level (TRL) technologies are associated with greater uncertainty due to assumptions for energy supply, chemical recovery, and future process optimization. Energy use was the main environmental hotspot across nearly all technologies, highlighting the importance of renewable electricity and low-carbon heat. Chemical use was also a hotspot, especially in chemical recycling where solvent use and recovery strongly influence environmental performance. The hazard assessment found that none of the assessed chemicals are currently listed as REACH SVHCs. Still, some substances exhibit hazardous properties according to CLP classifications or scientific literature, emphasizing the need for continuous monitoring, chemical substitution where feasible, and robust risk management.

The economic assessment identified technology scale as the main cost driver. Limited production volumes coupled with labour intensity substantially increase unit costs in several pilot-stage technologies. Results suggest that economies of scale, improved plant utilization, optimized logistics, and enhanced chemical recovery can significantly improve economic viability. Greater uncertainty was observed for technologies like Biocelsol and glycolysis due to their reliance on modelled data rather than commercial-scale experience.

The social assessment identified recurring hotspots related to energy supply and upstream value chains. Social risks were commonly linked to access to material resources, governance, and societal well-being. While overall data quality was acceptable, results should be considered indicative because they rely largely on generic databases rather than site-specific information. The qualitative analysis showed that circular textile systems can generate substantial social value. Case studies from Latvia and Finland demonstrated positive effects on employment, inclusion, skills development, wellbeing, creativity, and community engagement. These benefits depend on the organizational models and support structures that enable participation.

The study concludes that textile circularity offers significant sustainability potential, but success depends on renewable energy supply, efficient sorting, optimized chemical recovery, reduced transport requirements, and increased production scale. Although the results are generally robust, uncertainty remains higher for early-stage technologies. Future efforts should focus on scaling promising solutions, improving data quality, strengthening local circular ecosystems, and ensuring that social value is considered alongside environmental and economic performance.

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1 Introduction

The aim of this report is to apply and develop relevant methodologies to assess the sustainability performance of the technological developments and real-scale demonstrators achieved in tExtended. The methodologies that are applied follow the three dimensions of sustainability as defined first in the Brundtland Report and developed by multiple frameworks afterwards:

- **Life Cycle Assessment (LCA) to assess environmental performance.** LCA is a standardized methodology used to quantify the potential environmental impacts associated with a product, process, or service throughout its entire life cycle, from raw material extraction and resource acquisition to manufacturing, distribution, use, and end-of-life management (ISO - International Organization for Standardization, 2006). The approach follows a systems perspective and evaluates multiple environmental impact categories, by compiling and assessing the relevant material and energy flows across all life cycle stages. LCA is widely applied in research, industry, and policymaking to identify environmental hotspots, compare alternative scenarios, and support decision-making aimed at improving environmental sustainability.
- **Life Cycle Costing (LCC) to estimate the economic costs and identify hot spots.** LCC is a systematic methodology used to assess the total costs associated with a product, process, or service throughout its entire life cycle. The approach considers costs incurred during all life cycle stages, including raw material extraction, production, transportation, operation, maintenance, and end-of-life treatment or disposal. By adopting a long-term perspective, LCC enables the identification of cost drivers and trade-offs that may not be apparent when considering only acquisition or operational expenses. The method is widely applied in research, industry, and policymaking to support decision-making, compare alternative solutions, and evaluate the economic performance of products and systems.
- **Social Life Cycle Assessment (S-LCA) to quantify the risks of negative social impacts.** S-LCA is a methodology used to evaluate the social and socio-economic impacts associated with a product, process, or service throughout its life cycle. Adopting a life cycle perspective, S-LCA examines how activities across the value chain affect different stakeholder groups, including workers, local communities, consumers, society, and value chain actors. The approach assesses a range of social issues such as labor rights, occupational health and safety, fair wages, human rights, community well-being, and governance practices. Based on the UNEP Guidelines for Social Life Cycle Assessment of Products and Organizations (UNEP, 2020), S-LCA is increasingly applied in research and industry to identify social hotspots, compare alternatives, and support decision-making aimed at improving the social sustainability of products and supply chains. The assessment of the social dimension is complemented by **qualitative assessments of health and safety hazards from chemical use** and one of the **potential societal benefits from increased textile circularity**.

The results from these assessments shall be used as input in several tasks in the project, but mainly for the impact factors in Textendifier, the task D*evelopment of the Conceptual Framework* (T4.3) and the circularity potential and symbiosis readiness assessments.

This deliverable provides an overview of the work carried out; with focus on the interpretation of results and conclusions. A full account of the study expanding on the methodology, data and results is presented in a separate document available at the RISE publication repository (Peñaloza et al., 2026). From a practical point of view, this deliverable is an executive summary while the full report works as a supplement.

2 Methodology

This section presents only a short summary of the methodology applied in this study. A full account of the methodology is available in the supplementary full report.

2.1 Goal and Scope Definition

The goal of this study is to assess different utilization options for textile waste, in order to identify negative and positive environmental, social and economic effects with a life cycle perspective. The assessments include the technologies studied in work packages of *Digital tools and technologies for textile recovery* (WP2) and *Textile recycling technologies* (WP3), the demo flows identified in *Task Development of the Conceptual Framework* (T4.3) and the real scale demonstrators developed in *Demonstrators* (WP5). A secondary goal of the work of the WP *Benefits to sustainability and circularity* (WP6) is to make comparisons between the products developed in the demonstrators and the corresponding benchmarks using virgin raw materials, more specifically for the environmental assessment. It should be noted that the fibres and garments evaluated in this study do not fulfil equivalent functions, so a direct comparison between these is not the primary aim of this study. Meanwhile, the specific goal of the economic and social assessments is to identify hotspots in the early stage of technological and value chain developments.

The target audience for the results are decision-makers from stakeholders in the textile sector, both internal and external to the tExtended consortium. The study includes some technologies that are not yet available at industrial scale, as well as product value chains that are not yet established. Therefore, the results from this study are not suited for marketing purposes and should not be used for comparative assertions with results from other studies.

2.2 System Boundaries

The assessments carried out in this study include the full life cycle of textile products, a so-called cradle-to-grave type. Nevertheless, and considering that both technologies and demonstrators in the form of products are studied, the study is performed at two levels; technology and product. The technology level presents partial results either from recycling or re-use, a so-called cradle-to-gate system. Meanwhile, the product level presents a result for the full life cycle, or the so-called cradle-to-grave stages. These two levels should not be interpreted as different systems since the technologies are an integral part of the product-level assessments. They should be rather interpreted as different perspectives to obtain results. An illustration of the system boundaries applied for this study and the two-level approach is presented in *Figure 1*.

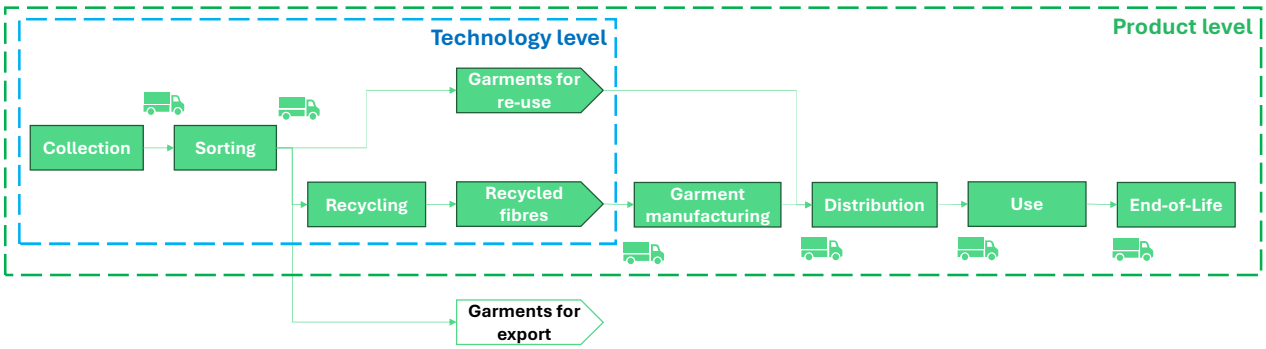


Figure 1 General setting of the system boundaries applied for the study.

The sustainability assessment adopts European geographical boundaries to reflect the tExtended project's objective of strengthening the resilience and circularity of the European textile sector. Data collected for foreground processes represents European practices during the period 2024–2026, while background datasets are no more than five years old and are selected to be representative of Europe or specific European countries where relevant. Economic assessments use 2025 as the reference year, apply adjustments for inventories based on different years, and evaluate costs over a 10-year period (2025–2034), assuming a 20-year lifetime for manufacturing plants and equipment. Technological boundaries encompass both industrial-scale processes currently representative of the European textile sector, such as fibre mechanical recycling and textile manufacturing operations, and emerging laboratory- and pilot-scale technologies. These pilot-scaled technologies were in selected cases modelled at full scale using specialised software, acknowledging that these represent approximations rather than fully commercial-scale systems.

2.3 Studied Technologies and Products

A description of the innovations that have been developed within tExtended and are analysed in this deliverable at the technology level can be found in Table 1. Some of the pre-treatments developed in *Digital Tools and Technologies for Textile Recovery* (WP2) have been excluded: the use of specific equipment such as near-infrared hyperspectral imaging, the sorting machine development and the polyester colour removal. Some of the technologies in Table 1 have not yet been included due to delays in data collection but will be included in future updates of this deliverable.

Table 1 Summary of the technologies included in this study. NYI: Not yet included.

Technology	Fibre	Partner, location	TRL achieved	Scale	Short description
Sensor analytics and sorting	All	AIM, Spain	7	1 kg/ min	Application of NIR spectroscopy to identify textile waste. NYI
Hygienization	All	CIT, Portugal	5	NA	Ozone disinfection using experimental equipment, chemical and water free. NYI
Colour removal	CO	CIT, Portugal	4-5	16 kg	Decolorization of 100% cotton textile samples using water-based solutions.
Elastane removal	CO	CIT, Portugal	3-4	1 kg	Elastane removal from blends using microwave, enzymatic and chemical strategies. NYI
PVC removal - solvent	PUR	AIM, Spain	4-5	1 litre	Recovering PVC from textile waste using solvents, for use in upholstery. NYI
Fibre mechanical recycling pilot line	CO	CIT, Portugal	9	80- 100 kg/h	Focusing on optimizing the quality of recycled fibres and their spinnability. Only for the LCA in Textendifier.
Fibre mechanical recycling - RES	PESCO	RES, Finland	9	Industrial	Automated feeding, cutting and tearing to produce pressed fibre bales.
Soft mechanical recycling	CO	PURF, Belgium	9	Industrial	Two-step tearing and reverse spinning at very slow pace to produce high-quality recycled fibres.

Technology	Fibre	Partner, location	TRL achieved	Scale	Short description
Thermo-mechanical recycling	PES	CTB, Belgium	8-9	Semi-industrial	Includes Vacurema compounding, MODIX compacting and melt-spinning.
Chemical recycling of cellulosics (Biocelsol)	PESCO, CO	VTT, Finland	7	15-30 kg fibres produced	Separation of PESCO blends via dissolution of CO, filtration of PES and spinning of CO fraction into regenerated cellulose fibres. However, for tExtended, only 100% CO textile waste was used as feedstock, and no separation of blends was performed.
Chemical recycling of PES	PES	RISE, Sweden	7	6 kg/ batch	Depolymerisation of PES via glycolysis into a monomer, and re-polymerisation.
Chemical recovery of polyols	PUR	AIM, Spain	7	100 litre reactor batches	Recovery of polyols, to reintegrate them into the chemical recycling via glycolysis. NYI

The real scale demonstrators developed by all partners within the work package *Demonstrators* (WP5) are one of the most significant outcomes in tExtended, as they show that real scale products can be achieved via re-use, remanufacturing and recycling. A wide range of activities have been performed for the demonstrators, resulting in several different products. Given the constantly changing nature of these activities and the limited time window available, only a selected group of products were selected for this sustainability assessment, summarised in Table 2. Some of the demonstrators in the table have not been included yet due to delays in data collection but will be included in future updates of this deliverable.

Table 2 Summary of the demonstrators included in this study. NYI: Not yet included

Demonstrator	Technology (ies) featured	Partners involved
1 – Re-use and remanufacturing	Sorting	KLW, ZALA
2 – Denim workwear	Fibre mechanical recycling	RES, UTEX, external partner for confectioning
3 – Polo, t-shirt, hoodie, NYI	Soft-mechanical recycling	KLW, PURF, external partner for manufacturing
4 – Fleece jacket, NYI	Soft-mechanical recycling	RES, JFA, TAW
5 – Towel, NYI	Soft-mechanical recycling	RES, TAW
6 – Polyurethane foam, NYI	Solvolysis, only LCA	ERT, AIM, SOP
7 – Garment, NYI	Biocelsol	RES, VTT, CIT
8 – PES dress and hoodie, NYI	Glycolysis	RES, RISE, External partner for repolymerization

2.4 Functional Units

Multiple functional units are applied in this study:

- **Technology level:** The functional unit depends on the technology studied (see Table 1):
  - For the LCA of re-use, the functional unit is one use of a t-shirt. Other garments are studied in the sensitivity analysis.
  - For the LCA of fibre mechanical recycling and chemical recycling of cellulosics, the functional unit is one kilogram (kg) of staple fibres.
  - For the LCA of thermo-mechanical and chemical recycling of PES, the functional unit is one kilogram of multifilament PES yarn.
- **Product level:** One use of a specific garment (see Table 2).
  - The specifics about the garment vary for each demonstrator.
  - With the exception of the Polyurethane foam (demonstrator 6), where 1 kilogram of polyurethane (PUR) foam is the functional unit.

2.5 Allocation

Allocation procedures across the environmental, economic, and social assessments were primarily based on physical relationships, with mass used as the default allocation method for multi-output systems. Sensitivity analyses were conducted using economic allocation where relevant to evaluate the influence of allocation choices on the results. For post-consumer textile waste used as a feedstock, upstream environmental burdens were assigned to the original product life cycle, consistent with the cut-off allocation approach applied in the Ecoinvent database. In the environmental assessment, the Circular Footprint Formula developed within the Product Environmental Footprint (PEF) framework was also explored as an alternative allocation method in sensitivity analyses. For the life cycle costing (LCC) and social LCA assessments, post-consumer and post-industrial textile waste was generally assumed to be available at no cost, based on information provided by project partners, and therefore no material costs were allocated to textile waste inputs, except in the case of soft mechanical recycling.

2.6 Impact Assessment Methods

The environmental impact categories and assessment methods are based on the PEF framework (European Commission, 2021), which lists 16 life cycle impact categories. For this, the method called Environmental Footprint 3.1 (adapted) version 1.04 from SimaPro was applied. It should be mentioned that even if all the impact categories have been calculated and analysed, a special emphasis is given to climate change and water use for contribution analysis.

The aggregated economic indicator used is Net Present Value (NPV), which accounts for the present time cost per kilogram (kg) of material or per use of the textile product, depending on the system boundaries adopted. The calculations are performed utilizing an LCC model developed in the Python programming language. A baseline discounting rate of 6.8% and an inflation rate of 2% are applied.

For the social LCA, the methodology framework proposed by the PSILCA (Green Delta, 2022) version 4.0.1 database has been applied. All the indicators available in PSILCA have been assessed. For each technology and demonstrator analysed, the indicators with the highest risk of negative social impact are identified, as well as the most contributing processes to these high scores. This way, social risk hotspots are identified.

2.7 Intrinsic Hazard Assessment

The LCA conducted within tExtended accounts for the environmental impacts associated with chemical use in the evaluated processes; however, it does not capture intrinsic chemical hazards such as carcinogenicity, reproductive toxicity, or environmental persistence. To address this limitation, a complementary three-step assessment was performed to identify substances of concern (SoC) in accordance with Article 2(27)(a) and (b) of the Ecodesign for Sustainable Products Regulation (Regulation (EU) 2024/1781, 2024).

First, chemicals were screened against the REACH Candidate List of Substances of Very High Concern (SVHCs). Second, their harmonized hazard classifications under the Classification, Labelling and Packaging (CLP) Regulation (Classification, Labelling and Packaging of Chemicals (CLP Regulation), 2024) were evaluated to identify relevant SoC hazard classes and categories. Finally, industry CLP classifications and scientific literature were reviewed to identify additional evidence of potential SoC-related hazards for substances lacking harmonized classifications, providing a broader assessment while acknowledging a lower level of certainty in the underlying data.

2.8 Social Benefits of Circularity

This qualitative assessment evaluates the social impacts of two social innovation spin-offs developed in tExtended (by CARR, ZALA, LSJH, CTB, KLW, CIT, AIM)[1]: Visi Var in Latvia, a work-integration social enterprise combining circular material use with employment opportunities for people with disabilities and mental health-related support needs, and a garment remaking workshop in Finland that engages citizens in participatory clothing remanufacturing to promote circular consumption practices. Recognizing that different circular textile activities generate distinct forms of social value, the assessment examines the mechanisms through which social impacts are created, for whom they occur, and under what conditions.

Drawing on social impact assessment and social life cycle assessment (S-LCA) perspectives, the analysis considers key dimensions including employment, inclusion, skills development, wellbeing, agency, community effects, economic and organizational trade-offs, risks and constraints, scalability, and the availability of monitoring indicators. It also explores how different circular strategies, such as reuse, repair and remaking, remanufacturing, and recycling, influence the nature and magnitude of social impacts generated.

2.9 Data and Data Quality

A large majority of the data used to model the foreground systems in the LCA, LCC and S-LCA was collected directly from the project partners involved in the technologies and demonstrators. In selected cases where data collected was from lab or pilot scales, the processes were modelled using specialised software (WinGEMS and Aspen Plus) to simulate the conditions at industrial scale, including also chemical recovery processes and auxiliaries. The study also includes data quality assessments, sensitivity analyses and uncertainty analyses, to enhance the robustness of the results. A full account of the inventory data, sensitivity analyses, uncertainty analyses and data quality assessments is presented in the supplementary report (Peñaloza et al., 2026) .

[1] Set of consumer engagement activities with the aim of raising awareness among consumers about sustainability and circularity of textiles. More information can be found in https://textended.eu/2025/11/28/textended-starts-consumer-engagement-activities/.

2.10 Key Assumptions and Limitations

This section summarizes the most important assumptions and limitations for the study:

- No life cycle stages have been excluded knowingly from the study, and the general cut-off is set as less than 2%. In cases where data is lacking for a specific process, literature values or proxies are prioritised before exclusion.
- Infrastructure was not included (e.g. production of factory, roads or equipment). However, for Ecoinvent transport datasets, road construction and vehicle manufacturing are included.
- Packaging for the products was included, but not for raw materials or intermediate products.
- No impact from retail was considered, i.e. no electricity use, distribution loss nor product waste during retail.
- When modelling the collection and sorting processes, the impacts from the waste stream going to export are not accounted for in any of the technologies or demonstrators studied. They are considered outside the system boundaries.
- No e-commerce was considered.
- Only one user per garment was considered, i.e. no transport between different users.
- The residual electricity mix relevant for the specific location was used as the base case scenario for all production processes, as it is the PEF guideline when proof of origin is missing. Other electricity mixes were applied for the sensitivity analyses.
- Some Ecoinvent datasets were modified and adjusted to the reflect the conditions for the specific country where the process occurs. These adjustments are mainly electricity mixes, heat supply, regionalisation of water flows and supply of materials from European market when available. Those adapted are background processes including heat production, water supply, waste management and wastewater treatment.
- Even using specialised software, the simulations generated for the upscaled process are still theoretical and do not capture all the complexities of a full-scale process. This is why the LCI model used in this study to model laboratory and pilot scale processes should not be considered as representative of the process at full scale and comparisons to other fibres should be drawn with caution.
- While the simulation program WinGEMS (see section 5.3.1) provides exact mass balances for the Biocelsol process, it does not provide data for energy use. The energy use in all processes was estimated and thus not exact, adding uncertainty to the results.
- For the reference or baseline scenarios assessed in the LCC, a constant inflation is applied to project OPEX costs over a 10-year period. In other words, factors such as learning and experience curves are not considered, assuming output capacity, labour hours, maintenance, and overhead for each technology to remain constant over this period.
- In the LCC, it is assumed that the relationship between the costs of the input parameters and the calculated LCC is linear. Based on this assumption, global sensitivity analysis methods such as tornado analysis and Spearman rank correlation are applied using the Monte Carlo simulation results. However, it should be noted that these methods have limitations in capturing more complex non-linear or non-monotonic relationships within the LCC model.

3 Summary of the Results – Technologies

This section presents a summary of the main findings from the assessment. For more detailed results including quantities and figures, the reader is referred to the supplementary full report (Peñaloza et al., 2026) .

3.1 Environmental Assessment

The overall results of the environmental assessment at the technology level indicate that most of the recycling technologies analysed have the potential to reduce the environmental impacts of garments by substituting virgin fibres partially in a yarn. Nevertheless, a correlation can be observed between the TRL of the technologies and the extent of the impact mitigation potential, as technologies with higher TRL typically produce higher quality output, have lower uncertainty and operate at realistic industrial conditions. While the potential is very clear for established technologies such as fibre mechanical recycling and melt spinning, it is not for the chemical recycling technologies which are both at lower scale and not ready for the market.

The energy demand is across the board a hot spot for all the recycling technologies analysed. The electricity supply contributes significantly to all the assessments, and a switch to renewable energy sources results always in environmental impact reductions. This can also be observed for heat generation, although it is not required in all processes. Access to clean energy seems to be a key issue that will define the environmental profile of any recycling technology in further developments and applications.

Another commonly found type of hot spot is the use of chemicals, especially for the two chemical recycling technologies studied. The use of chemicals such as ethylene glycol, sulfuric acid or sodium hydroxide becomes a potential source of environmental impact not only because of the impacts from production of the raw materials, but also the impacts from the emission or disposal of the substances as they exit the processes. This is very clearly illustrated by the substantial influence of the ethylene glycol in the chemical recycling of polyester. Consequently, it is key to figure out a way to efficiently recover and recirculate any chemical used for this type of process. Such processes however can become hot spot and significant source of uncertainty themselves when not fully developed nor understood, as is the case of the Biocelsol process and the electrodialysis.

Methodological assumptions do not seem to have a significant influence on the results, with the exception of the choice of allocation approach for the Biocelsol process, which in any of the settings analysed has multiple co-products. Another example is the sorting step, which has typically several different sorted fractions that are handled as co-products. Still concerning sorting, the disposal of unsorted waste can also have significant contribution to the environmental impact of the process and the technologies. This may be appreciated better in the assessment of the demonstrators, more specifically if the circular footprint formula is applied where some of these impacts will be allocated to the previous life cycle.

The results of the uncertainty analysis and the data quality assessment suggest that most conclusions drawn from the results of this assessment are robust, and that the data quality is in general very good. Some exceptions are worth mentioning though. For the fibre mechanical recycling technologies, uncertainties can be traced back to the datasets chosen to model electricity generation. Meanwhile, for the glycolysis of polyester the datasets related to ethylene glycol production and disposal are the main source. Otherwise, it is worth mentioning the somewhat higher uncertainty and lower data quality for the Biocelsol process. Just for this technology, any observations should be taken with caution, because of the high uncertainty related to the main hot spot identified, the electrodialysis for chemical recovery.

3.2 Economic Assessment

The economic assessment shows that the life cycle costs (LCC) of the tExtended technologies are strongly influenced by production volume, labour requirements and key consumables, although the importance of these factors varies across technologies. For emerging technologies, such as thermo-mechanical recycling, increased production capacity, longer operating hours, and learning-related reductions in labour requirements were identified as opportunities for improving economic performance. The Biocelsol process shown to be highly sensitive to technological and methodological assumptions, including electrodialysis operation and the choice of allocation method, resulting in large variations in life cycle costs. In particular, the exclusion of electrodialysis and economic allocation reduced calculated unit costs. For de- and re-polymerization, improved methanol recovery considerably improved economic viability. Overall, the analysis highlights that increasing scale and operational efficiency, improving material recovery, and allocation choices are influential factors for enhancing the economic performance of textile recycling technologies.

Global sensitivity analyses show that production volume, for all technologies assessed, consistently ranks among the three most influential parameters affecting the corresponding unit life cycle cost. For several pilot-stage technologies, limited production volumes contribute significantly to increased unit costs. The current low production volumes, particularly concerning the technology pilots, are directly connected to technological immaturity in which efficiency gains from experiences, learning, and operational optimization are not yet realized.

The data quality assessment identified several important uncertainty hotspots in the LCC analysis. Across all technologies, the highest levels of uncertainty were associated with environmental externalities, transport costs, and research costs, primarily due to limitations in data reliability, completeness, and temporal representativeness. Estimating the monetary value of environmental impacts remains challenging because of limited and often outdated data sources, while transport costs are subject to significant variability and future market fluctuations that are not fully captured in the assessment.

Research costs also present considerable uncertainty, as they were estimated based on project work allocations rather than actual technology development expenditures. At the technology level, the Biocelsol and de-/re-polymerization processes exhibited the greatest uncertainty in capital expenditure (CAPEX), overhead, and maintenance costs. This is largely because these technologies are not yet commercially established and therefore rely on engineering estimates, process simulations, and rule-of-thumb cost models rather than primary industrial data. Overall, the results indicate that while the assessment provides valuable insights into economic performance, greater uncertainty remains for emerging technologies and cost categories that depend heavily on assumptions and modelled data.

3.3 Social Life Cycle Assessment

Despite the remarkable differences among the technologies studied, some common aspects can be spotted. The hotspot that appeared most often was the local supply of electricity and heat. For the soft mechanical recycling by PURF and the thermo-mechanical recycling of PES, this hotspot was exclusively for the local supply of energy for the process itself. Finally, another hotspot that appeared in some cases and in specific impact subcategories is mining activities upstream, in Russia. This is in all cases connected to the supply of energy goods for energy generation, in Belgium, Sweden and Finland for the cases located in those countries. The chemical recycling of PES via glycolysis was the only one where the upstream production of a specific chemical was the main hot spot, more specifically the catalyser.

With regard to the most affected stakeholders, the impact subcategory that appeared most often topping the risk scores was the access to material resources affecting the local communities. These risks are caused by the

extraction of raw materials and resources like water, ores, biomass and quarries, but also the competition for the service of waste management. These impacts appeared most often in upstream processes, mainly in China and Russia. Society is another stakeholder that appears in most of the cases among the most affected, with risks in varying subcategories such as nature, governance, health and safety and migration. Finally, in some cases workers were also at risk of negative impacts concerning fair salary, but never among the top scores.

When social risks are analysed for the whole life cycle, the contribution from the recycling processes becomes less noticeable, as other processes are of more significance. Still, the production of the fabrics is the main hot spot in most of the indicators with the highest risk scores, but the main source of impact varies among the weft yarn, the liner fabric and the production of chemicals for finishing. The transports and the use phase are the other two processes with the highest contribution. These findings shed light into what parts of the life cycle need to be monitored the most regarding social risks. However, it is difficult to assess the difference that the use of recycled fibres makes for the social risks of the garment without a comparison to a garment made of virgin fibres.

These observations should however be interpreted with caution considering the level of uncertainty and data quality. The overall data quality is good, but since a significant share of the data used comes from generic databases, the results from this assessment should be interpreted as indicative and should not be used to make any comparisons. The observations drawn from the study could be used to guide efforts towards monitoring the social performance of suppliers and business partners in future implementation of the technologies. It should be noted that improving the data quality in the social LCA would require the collection of specific data, and this can only be achieved by reaching out directly to specific companies in the value chain. Such effort would then shift the focus from the technology to specific organisations, and it would not fit anymore the goal of this study.

3.4 Qualitative Analysis of Social Benefits

The qualitative analysis of social benefits highlights that circular textile systems do not generate a single, uniform type of social benefit; rather, the nature and magnitude of impacts depend on how circular activities are organised and how people engage with them. The two tExtended case studies demonstrate that social value can be created through diverse pathways, including employment, inclusion, skills development, wellbeing, agency, and behavioural change.

The findings show that positive social outcomes arise not from circularity itself but from the enabling conditions that support participation, such as tailored organisational arrangements, access to resources, training, and social support. Higher-value circular strategies, particularly reuse, repair, remaking, and remanufacturing, were found to offer significant opportunities for direct participation, creativity, learning, and inclusion. The assessment also indicates that conventional productivity and efficiency metrics may overlook important social benefits, suggesting the need for broader evaluation approaches that capture social additionality and impact intensity. Finally, the results reveal important synergies between social and environmental performance, with enhanced skills, confidence, and inclusion fostering greater engagement in circular practices and thereby contributing to improved environmental outcomes.

3.5 Intrinsic Hazard Assessment

Overall, the results indicate that while none of the assessed chemicals are currently listed as SVHCs under REACH, several chemicals show evidence of hazardous properties according to CLP classifications and scientific literature. Especially hazardous properties identified in scientific literature are often not yet reflected in regulatory classifications, despite their potential relevance for human health and environmental protection. As chemical regulations and classifications are continuously evolving, the chemicals identified in the third

assessment step may become subject to future regulatory restrictions or exposure limit values. Consequently, changes in chemical classifications and regulations should be monitored. The chemicals used in textile recycling processes should always be handled with appropriate risk management measures to ensure high safety for workers and environment.

4 Conclusions

With the goal in mind, the following conclusions can be drawn from the study:

- **Potential environmental impact reductions**

Most of the recycling technologies have the potential to offer environmental impact reductions with reference to benchmark virgin fibres. However, in the technologies with lower TRL and therefore higher uncertainty, these potential reductions are only observed under certain assumptions regarding energy mix and chemical recovery efficiency. In addition, currently immature technologies may have potential to reduce their LCC through economies of scale as they progress to higher TRLs.

- **Energy supply is critical**

Energy supply is the most commonly found hot-spot and the result in all technologies is sensitive to the assumed electricity mix. Having access to renewable electricity is therefore a key aspect in the environmental impact mitigation that is expected from increased use of recycled fibres. The same can be said about heat generation for those technologies where it is required, but to a lesser extent. Energy supply is also a significant contributor to the social risks in the S-LCA of some technologies such as soft mechanical recycling and chemical recycling of cellulosic.

- **Chemical use should be optimised**

Recovery and recirculation of chemicals and solvents is a key aspect for chemical recycling technologies. Such mechanisms need to be considered from early stages in the technology development, as the robustness of the data for their inclusion in simulation models can be a definitive factor in any sustainability assessment. The loses of these chemicals or solvents have a three-way negative effect for costs, environmental impacts and social risks; they increase the amount of make-up substance, potentially release the substance directly to the environment and require hazardous waste disposal. Even in other non-chemical technologies, the use of any chemical substance usually appears as a hot spot in some categories. Nevertheless, it is worth noting that recovery and recirculation of chemical may result in trade-offs in energy use, which needs to be considered early in the model design as well. Although none of the chemicals currently used in the technologies are listed as SVHC under REACH, some of them show evidence of hazardous properties according to other sources and may be subjected to regulation in the future.

- **The importance of sorting**

Sorting of the textile waste after collection is a process that is required for all the technologies and demonstrators studied. For this step, the most relevant parameters are labour intensity, transport (for economic and social assessment) and the production volume of the sorting facility (for environmental and economic assessment), which in turn affect the unit CAPEX cost and the amount of residual waste going to disposal after sorting. Reducing the unit transport cost and transport distance would drive down the costs and the risks of social impacts, while reducing the amount of residual waste disposal after sorting would mitigate the environmental impacts and costs.

- **The influence of allocation**

The influence of methodological assumptions in the results is low, with the exception of the allocation approach in the assessment of Biocelsol. The choice of allocation has a significant effect in the environmental and economic assessment, which suggests that it would also affect the social risk assessment via S-LCA since the

data used for this is the same as the others. A shift to economic allocation is affected by a difference in the market value of the co-products, and this market value also changes depending on the location and time.

- **Production volume is a defining variable**

Production volumes are found to be negatively correlated with the unit LCC across all technologies assessed, indicating that larger-scale production can substantially improve economic performance. This finding is particularly relevant for technologies such as thermo-mechanical recycling and soft mechanical recycling, which are currently at the pilot stage (TRL 5 – 6) and therefore operate at relatively small production volumes. Increasing production capacity is expected to reduce unit costs economies of scale. Furthermore, although technologies such as Biocelsol and de-/re-polymerization have been evaluated at larger scales through process simulations, the assumed production capacity of 1 tonne per hour is modest compared with commercial fibre production plants, which typically operate at capacities of 30 to 50 tonnes per hour. This suggests that additional cost reductions may be achievable for all assessed technologies as they develop into industrial-scale operations.

- **Transports: highly uncertain**

Although transport has not been identified as a dominant hotspot in the current assessments, it should be mentioned that transport unit costs are highly uncertain. In this assessment, costs are adapted from the logistic scenarios and standardized linehaul benchmarks provided by TEKO. However, one may also derive the average country-based unit transport cost for international trade from the (UN Trade & Development, 2026), presenting a wide variation of unit costs. The assumption of a constant transport rate over the next 10 years is a major limitation. In reality, transport costs are volatile as they are closely tied to demand and fuel prices. These, in turn, are affected by external factors such as geopolitical instability, conflicts, energy crises, outbreak of disease, etc. Such disruptions can drive inflation and increase fuel prices, ultimately dampening demand for goods and services.

Although transport distance is not a direct contributor to the LCC at technology level, it can be an indirect contributor from a functional perspective when environmental costs are included. In such cases, long transport distances, amid uncertain, can contribute to particulate matter emissions due to tyre wear, which affect human health negatively and increase environmental costs, thereby contributing to a higher LCC. This effect is not apparent at the technology level since environmental costs are not considered. In the current project, long-distance travel was attributed to cross-border movement of materials and products among consortium partners distributed across Europe. In contrast, industrial ecosystems are often geographically clustered, allowing for shorter transport routes and more efficient exchanges between related industries.

- **Uncertainty and data quality**

The uncertainty and data quality overall should not influence the robustness of the conclusions from this study, but in some cases the conclusions should be interpreted with caution. Concerning the environmental assessment, the results are mostly robust, but more uncertain for Biocelsol and glycolysis, as well as all toxicity impacts. Data quality for the LCA is good for most technologies, but only fair for Biocelsol. The uncertainty in Biocelsol results is due to the low quality of the data used to model the electrodialysis, which at the same time is the highest contributor in all categories.

For the LCC, production volume has the highest influence on uncertainty. Data for environmental externalities (reliability, completeness, temporal representativeness), transport cost (reliability, temporal representativeness), as well as the CAPEX data for Biocelsol and glycolysis have the lowest data quality. Finally, uncertainty assessment and data quality of the S-LCA are deemed good enough, but turning to more specific data would shift the focus away from the technologies into specific organisations and their practices.

- **The hidden social value of circular textile models**

The two social innovation spin-offs demonstrate that circular textile development can generate substantial social value, but the type and magnitude of that value depend on the organisational model, circular strategy and role of participants. The Visi Var model demonstrates the potential of reuse and remanufacturing to support labour-market inclusion, meaningful participation, skills and wellbeing among vulnerable groups. Its defining characteristic is the adaptation of production to human capabilities, even where this limits productivity and conventional business scaling. The Finnish spin-off demonstrates a different pathway, where designer-facilitated remaking strengthens citizen competencies, creativity, confidence, social interaction and agency. Preliminary follow-up evidence indicates that these capabilities can translate into subsequent garment-remaking behaviour, although longer-term persistence remains uncertain.

5 Recommendations

The following are recommendations based on the results from the sustainability assessment, with future developments of the technologies in mind:

- **Sorting**

Results indicate that to approach cost breakeven at the sorting stage requires consideration of multiple factors. Lower transport costs and shorter distance between sorting facility and collection point, or waste treatment facility could minimize LCC costs and risks of negative social impacts. For future planning of a sorting facility, waste treatment facility, and the placement of textile collection points, it is worth considering the proximation of the three connecting points consistently. A reduction in residual sorting waste including non-textile materials, can lead to higher yield of reusable and recyclable textiles, and less materials being sent to incineration, which would both reduce costs and environmental impact. This finding highlights the need for further fine tuning of sorting line accuracy, as well as enhanced public awareness concerning correct disposal of non-textile waste. As the sorting further develops, the operation is expected to become less labour-intensive and at the same time increasing its output capacity, lowering the unit capital cost and the overall life cycle cost.

- **Soft mechanical recycling**

Securing renewable energy sources for electricity and heat would reduce the environmental impacts significantly, similarly to the social risks. This could be achieved via local generation or certificates of origin, as larger scale change cannot be achieved by a single organisation. In addition, the increasing share of renewable energy may lead to lower per kilowatt hours cost for electricity. The scale of technology also contributes to lowering the LCC. Whether upscaling is feasible depends on product demand. Given that the EU regulations, such as ESPR, DPP, EPR, Green Claims Directive, etc. are expected to materialize in the coming years, there is potential for recycled fibre to become a mainstream input material. This could, in turn, create demand and pave ways for a competitive market environment for the recycling business to grow, as well as keeping the input material cost affordable.

- **Fibre Mechanical recycling**

For the traditional fibre mechanical recycling case (RES), switching to renewable electricity (via local generation or certificates of origin) or increasing material efficiency would be the most effective measures to mitigate the environmental impacts. The production volumes and labour requirements have the highest influences on the LCC, suggesting that as technologies progress along the learning curve, production capacity may increase and labour may become less intensive, potentially resulting in lower overall LCC.

- **Thermo-mechanical recycling**

Production volume and labour requirements are both coupled to learning effects in production and can therefore significantly influence the cost of spun yarn. As demonstrated in the sensitivity analyses, these parameters exert comparable impacts on the LCC, indicating that improvements in both are necessary if the goal is to reduce the cost of spun yarn production. Concerning the environmental impacts, switching to renewable energy sources (via local generation or certificates of origin) and minimizing the use of virgin polyester for purges and reference would be the most efficient mitigation strategies. These measures would also reduce the risks of negative social impacts.

- **Chemical recycling of cellulosic via Biocelsol**

The high cost associated with electricity consumption suggests that internal recycling of Na_2SO_4 through electrodialysis may be economically infeasible, rendering the cost of producing cellulosic fibre far from parity with its virgin counterpart. It is worth noting that similar observations about electrodialysis can be made for the environmental profile and social impacts. The Biocelsol process may benefit from synergies with other local industries, such as the battery sector. The development of such industries may lead to large-scale local production of deionized water, potentially reducing costs, social risks and environmental impacts or creating opportunities for co-investment in deionized water production facilities. Amid relatively high data uncertainty, this assessment indicates that technological optimization alone may not necessarily result in environmentally, economically, and socially sustainable processes. For future implementation of Biocelsol pilots with chemicals recovery and recirculation, it is recommended to weigh in the trade-offs for optimized sustainable solutions.

- **Chemical recycling of PES via glycolysis**

Under the premises of low quality and highly uncertain data, recycling of methanol may be considered as economically beneficial despite the increased consumption of electricity and heat, both for minimizing purchase of fresh methanol and for reducing costs associated with wastewater treatment. For future large-scale optimized processes, it is advisable to explore opportunities to achieve higher recycling rates for ethylene glycol and methanol, which would also reduce the environmental impact of the technology. In addition, using electricity produced from renewable sources via local generation or certificates of origin may improve the technology's environmental performances.

- **Enhancing social impact assessment of circular textile models**

This research highlights the need for a pathway-based approach to social impact assessment in circular initiatives, where indicators are selected according to the specific mechanisms through which social value is created. Assessments should differentiate between circular strategies and value-chain stages, recognising that labour- and participation-intensive activities such as reuse, repair and remanufacturing often generate greater direct social benefits than lower-value retention strategies. A robust framework should combine quantitative indicators, such as participation, employment and skills development, with qualitative evidence on wellbeing, agency and social inclusion, while clearly distinguishing immediate outputs, short- to medium-term outcomes and longer-term impacts. The assessment should also account for enabling conditions that influence success, including access to resources, facilities and support, and report both the intensity of impacts and their reach across different populations. Socially oriented initiatives should be evaluated against their intended social objectives rather than conventional productivity metrics alone, and stronger longitudinal monitoring is needed to understand sustained effects over time. Finally, practical implementation requires a core set of feasible indicators for resource-constrained organisations, while approaches to scaling should encompass not only growth in participation but also replication, institutionalisation and broader shifts in behaviours, skills and social norms that support circular practices.

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