# D6.7 Summary of outcome of qualitative Life cycle screening assessments of selected technologies

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| BLABAER PRODUCTION AS | Norway | Blåbær |
| NEAGU ALEXANDRU-VALENTIN | Netherlands | Bee Granted |

## LIST OF ABBREVIATIONS

| Abbreviation | Definition |
|---|---|
| DMSO | Dimethyl sulfoxide |
| DWR | Durable water repellent |
| EG | Ethylene glycol |
| EoL | End-of-life |
| FTOH | Fluorotelomer alcohol |
| F-gas | Fluorinated gas |
| GVL | γ-Valerolactone |
| KPI | Key Performance Indicators |
| LCA | Life Cycle Assessment |
| LCBROM | Life Cycle Based Risk and Opportunity Mapping |
| MET | Material, energy, and toxicity |
| PARC | European Partnership for the Assessment of Risks from Chemicals |
| PFAS | Per- and polyfluoroalkyl substances |
| PLA | Polylactic acid |
| PVC | Polyvinyl chloride |
| SSbD | Safe and Sustainable by Design |
| SuS | Sustainability screening |
| THFA | Tetrahydrofuran Alcohol |
| TRL | Technology Readiness Level |
| VOC | Volatile organic compounds |

# Executive Summary

This report presents the summary of main results of a qualitative sustainability screening conducted under Task 6.1 of the BioSusTex project. The objective was to assess selected low-TRL (Technology Readiness Level) textile technologies in their early innovation stages, focusing on environmental, economic, and social impact across their life cycles. The assessment aims to guide design decisions, prioritize promising options for further development, and align innovations with Safe and Sustainable by Design (SSbD) principles.

Two methodological approaches were used: the Life Cycle Based Risk and Opportunity Mapping (LCBROM) method and the SSbD Scoping Method. LCBROM, applied to technologies in WP1, WP2, and WP4 of BioSusTex, identifies potential sustainability trade-offs through stakeholder engagement and life cycle thinking. The SSbD Scoping Method, applied in WP3 of BioSusTex, supports structured evaluations of safety and sustainability assumptions.

In WP1, the pre-processing of textile waste focused on removing dyes and elastane from cotton-based blends using various chemical systems. Bio-based solvents such as γ-valerolactone (GVL) and dimethyl sulfoxide (DMSO) demonstrated strong performance in terms of material recovery and lower toxicity, though they face challenges in solvent recovery and energy demand. Inorganic agents, while scalable and cost-effective, present notable toxicity and environmental hazards. Overall, (GVL) and (DMSO) emerged as leading candidates for future process development.

WP2 evaluated three fibre-to-fibre recycling processes: viscose, Lyocell, and Ioncell. Ioncell stood out as the most promising option due to its use of a recyclable, non-toxic solvent and low water use, combined with potential for integration with renewable energy. While NMMO-based Lyocell is industrially established, it requires stabilizers and has higher energy demands. The viscose process remains economically viable but carries significant toxicity concerns due to the use of carbon disulphide. Ioncell's profile makes it a strong candidate for industrial scale-up and further life cycle assessment (LCA).

In WP3, the project assessed a PFAS-free, bio-based durable water repellent (DWR) for textiles, aiming to replace conventional fluorinated chemistries. The bio-based alternative showed significantly improved safety and environmental performance, particularly in reducing persistent emissions and occupational exposure. However, some uncertainties remain around the durability of the coating, emissions during large-scale application, and toxicity of minor formulation components. Further development is recommended to refine the formulation, improve performance stability, and ensure compatibility with recycling systems.

WP4 focused on a novel biobased ink for screen printing with built-in removability, intended to support textile circularity by enabling print removal prior to recycling. The formulation is largely composed of non-toxic and biodegradable materials, though the current binder is fossil-based. The ink can be used as a drop-in replacement in existing infrastructure and offers substantial environmental and social benefits. Key challenges include completing the transition to a fully biobased formulation, automating the removal process, and assessing impacts at end-of-life.

GVL and DMSO-based pre-processing systems technologies in WP1 and Ioncell technology in WP2, show strong potential for further development. It is recommended to advance these through detailed LCA, pilot-scale testing, and continued stakeholder engagement. The PFAS-free water repellent in WP3 and the biobased printable ink in WP4 present clear sustainability advantages and innovative features. However, these technologies require further refinement in formulation, durability, and end-of-life management before full-scale deployment.

Across all four work packages, the assessment identified recurring challenges such as limited data availability, solvent recovery uncertainty, scalability constraints, and the need for consistent life cycle boundaries. Social and economic dimensions, including worker safety, consumer acceptance, and job creation potential, also warrant more thorough analysis. Despite these uncertainties, the early-stage screening provided by Task 6.1 offers a baseline for prioritizing research directions, informing design improvements, and embedding sustainability at the core of future textile innovations (Table 1-1).

Table 1-1 Summary of key WP findings

| WP | Priority actions | Key uncertainties | Next step |
|---|---|---|---|
| WP1 | Advance γ-valerolactone (GVL) and dimethyl sulfoxide (DMSO) systems toward pilot-scale solvent recovery tests. (Table 3-1, Table 3-2)<br>Standardize performance testing across dye classes and elastane blends.<br>Develop protocols for ultrasound-assisted colour stripping at scale. | Solvent recovery efficiency, toxicity of dye degradation by-products, fiber quality after multiple cycles | Full LCA including upstream solvent production and end-of-life treatment (see MET+Ec+S matrices (Table 3-1, Table 3-2) |
| WP2 | Focus on Ioncell® for industrial upscaling and pilot TRL advancement (Table 3-3)<br>Benchmark energy/water use with Lyocell and viscose for cross-learning.<br>Assess occupational health risks in comparison to $CS_2$-based viscose. | Solvent stability and recovery over multiple cycles, variability of real-world feedstock, limited end-of-life recyclability data | Pilot demonstration of Ioncell® with blended waste textiles, supported by a comparative LCA |
| WP3 | Optimize formulation for durability under repeated washing and abrasion.<br>Assess emissions and wastewater fate during large-scale application.<br>Verify recyclability of coated textiles in pulping/recycling systems | Long-term coating stability, toxicity of minor additives, consumer acceptance of re-impregnation needs | SSbD-informed hazard screening and pilot durability testing of benchmark garments; refine life cycle scenarios, full LCA. |
| WP4 | Replace fossil-based binder with bio-based alternatives without loss of print quality (Table 3-4). | Binder performance and biodegradability, wastewater impacts | Pilot testing of automated ink removal and integration into textile |

| | | | |
|---|---|---|---|
| | Automate ink-removal process for recycling facilities.<br>Develop market and regulatory strategy for adoption of removable prints. | of ink removal, consumer scepticism | recycling workflows, full LCA |

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# 1 Introduction

Task 6.1 of the BioSusTex project is dedicated to conducting a preliminary sustainability screening of selected textile technologies during their early innovation stages. The main objective is to identify potential environmental, economic, and social risks across the life cycle—from raw material extraction through production and use, to end-of-life—before engaging in more detailed quantitative assessments. This early-stage screening supports the identification and prioritization of the most promising technologies for further development under WP6 and for in-depth value chain analysis in Task 8.3.

Two methodologies are applied in Task 6.1:

Life Cycle Based Risk and Opportunity Mapping (LCBROM): A qualitative screening tool designed for assessing low Technology Readiness Level (TRL) technologies. LCBROM helps uncover critical sustainability trade-offs and supports technology developers in embedding Safe and Sustainable by Design (SSbD) principles early in the innovation process.

SSbD Scoping Method: Developed in collaboration with the European Partnership for the Assessment of Risks from Chemicals (PARC), this method enables structured mapping of key safety and sustainability issues within a system perspective. It facilitates the translation of qualitative insights from value chain actors and domain experts into inputs for future SSbD assessments.

The technologies assessed in Task 6.1 originate from WP1 through 4:

WP1 – Pre-processing of textile waste

WP2 – Dope-dyed fibre-to-fibre recycling

WP3 – PFAS-free biobased water-repellent coating

WP4 – PVC-free biobased printing with a removability feature

The LCBROM methodology was applied to WP1, WP2, and WP4, providing qualitative assessments of sustainability risks and opportunities across their respective life cycles. The SSbD Scoping Method was applied to WP3, offering a structured evaluation of assumptions, findings, and research directions relevant to safety and sustainability.

Together, these assessments support early-phase decisions regarding technology design refinement, prioritization for upscaling, and identification of critical knowledge gaps. The results from Task 6.1 contribute directly to WP6 by establishing a baseline understanding of sustainability trade-offs and informing the direction of subsequent quantitative evaluations. Furthermore, they support Task 8.3 by enhancing stakeholder engagement and transparency within the context of value chain dynamics and SSbD implementation.

# 2 Methodology Qualitative Life Cycle Risk Mapping Approach

This section describes the methodologies used to assess the sustainability and safety aspects of early-stage textile innovations. Two approaches are applied to support qualitative life cycle screening: (1) the LCBROM (Life Cycle Based Risk and Opportunity Mapping) method, and (2) a tailored SSbD (Safe and Sustainable by Design) scoping process developed in collaboration with the PARC project. Both methods combine expert and stakeholder engagement with lifecycle thinking to identify potential environmental, health, social, and economic risks and opportunities associated with novel materials and processes. These approaches are particularly suited for technologies at low to intermediate technology readiness levels, where quantitative data may be limited, but structured qualitative analysis can still inform design and prioritisation.

## 2.1 LCBROM

In this study, LCBROM (Kärnman et al. 2025) is applied as a sustainability screening (SuS) approach to identify key environmental, economic, and social risks in early-stage innovations of various processes in different WPs of BioSusTex. LCBROM follows an iterative approach, illustrated in Figure 2-1, involving continuous stakeholder engagement to uncover both potential risks and opportunities associated with these process innovations. The method is based on two questionnaires, followed by workshops with the innovators and relevant stakeholders from industry and research partners, to develop an in-depth understanding of the new technologies and life cycle-related risks and opportunities.

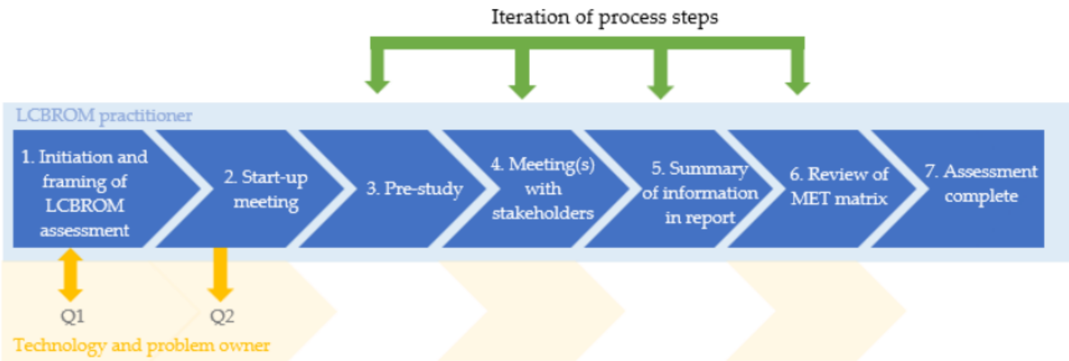


Figure 2-1 Flowchart describing the steps of the LCBROM method.

The process is initiated with stakeholder mapping, a crucial step to ensure access to relevant expertise and data. Given the diverse backgrounds and objectives of stakeholders, this mapping helps the LCBROM practitioner collect the right information for a meaningful assessment. Following this, an initial questionnaire (Q1) is distributed to stakeholders to establish a clear problem definition, document background information, identify benchmark technologies (if available), and outline the key actors involved in the case study. The purpose of this questionnaire is to guide the LCBROM practitioner in gathering essential information at the start of the assessment and to prepare the process developers for the discussion. A start-up meeting follows to formally initiate the LCBROM assessment. During this meeting, participants discuss the objectives and methodology of LCBROM, refine the problem definition, introduce the relevant technology or material, and clarify any uncertainties related to Q1. Additionally, this meeting fosters dialogue among stakeholders, encouraging knowledge-sharing and collaboration on potential risks and opportunities throughout the innovation's life cycle as well as a flowchart of the process that will be developed collaboratively to discuss the innovation and the envisioned life cycle stages. To deepen the assessment, a second questionnaire (Q2) is distributed after the start-up meeting. This questionnaire is more detailed and prompts the technology and problem owners to evaluate the innovation from a material, energy, and toxicity perspective. The questions in Q2 are briefly introduced at the end of the start-up meeting to help participants prepare for a more in-depth evaluation (Kärnman et al. 2025).

Before proceeding with the full assessment, the LCBROM practitioner conducts a pre-study, consisting of a literature review including LCAs and risks assessments of related processes that are related to the new technology if available. The responses from Q1 serve as keywords to guide this review. Additionally, the pre-study includes documentation of the problem definition using a report template, ensuring that potential applications of the material are described to facilitate a comprehensive life cycle perspective. Since LCBROM is an iterative process, multiple meetings are held throughout the assessment to discuss findings from Q2 and evaluate both risks and opportunities. As the assessment progresses, the LCBROM practitioner refines the collected information and consolidates the findings using the MET matrix (material, energy, and toxicity), and for this project economic and social aspects were also added by IVL to have more detailed result and develop MET+Ec+S (economic, and social aspects), introduced in Figure 2-2. This matrix serves as the final output of the sustainability screening, visually highlighting risks and opportunities for each alternative. Each cell of the matrix corresponds to a specific life cycle stage, such as material use in production or energy consumption during disposal. A color-coding system (e.g., green for opportunities, red for risks, and yellow for areas requiring further investigation) is recommended for clarity. Given the low technology readiness level (TRL) of many innovations, some data points carry uncertainties, and particularly uncertain information is marked in italic font for transparency (Kärnman et al. 2025).

The results from an LCBROM assessment can serve multiple purposes, depending on the scope of the evaluation. In this study, the primary objective is to guide textile waste recycling innovations toward more sustainable alternatives. Additionally, the findings can be used as a scoping method or integrated into a Safe and Sustainable by Design (SSbD) assessment. Valuable lessons from the assessment, including insights into life cycle mapping and system understanding, may inform the optimization or redesign of emerging technologies to mitigate negative environmental and social impacts.

| | Materials | Energy | Toxicity | Economic | Social |
|---|---|---|---|---|---|
| Production | Any non-renewable resources such as scarce metals? Emissions from material production? | Energy for activation and production of the products, transportation? | Are some of the ingredients toxic in production? How closed is the process, is there a risk of leakage? | Will the new material or process increase/save production costs? If so, how?<br><br>How will the materials affect supply chain dynamic and market competitiveness? | Are there any occupational health & safety risks for workers that will raise with new materials?<br><br>Are there any positive impacts (opportunities) that can be related with the new materials? E.g. technology development, local employment, decrease health and safety risk. |
| Use | Any process chemicals, cleaning? | Electricity for operation (How much or energy-intensive process?) | Any release of toxic chemicals during use or maintenance of the product? | Are there any potential economic benefits for end-users, such as lower maintenance or operational costs?<br><br>Could the new material or process enable new market opportunities or applications? | Can the use of new materials have a negative or positive impact on consumer's and/or children's health & safety? |
| Disposal | Recycling potential? | Incineration? Landfill? Recycling? Energy use or potential energy recovery? | Landfill? Toxic emissions from incineration? | Will the disposal of the new materials require additional costs? E.g new recycling infrastructure?<br><br>Could the use of the new material reduce long-term costs for waste management, such as lower emissions or improved recyclability? | Will the new materials bring risks for the workers during the waste handling?<br><br>Any opportunity during risk handling? |

Figure 2-2 MET+Ec+S matrix used in LCBROM.

## 2.2 Scoping method

This methodology presents a structured approach to identifying the Safe and Sustainable by Design (SSbD) aspects of chemical and material innovations in their early stages. It facilitates the identification of safety, sustainability and functional considerations before detailed assessment, using a combination of stakeholder engagement, lifecycle thinking and iterative analysis. In collaboration with the PARC project, the SSbD scoping method is being piloted in Work Package 3 (WP3) of the BioSusTex project, which is focused on developing a PFAS-free, bio-based, durable water-repellent textile coating. The methodology comprises five phases: framing and value proposition mapping; lifecycle scenario development; stakeholder validation; hazard screening; and research prioritisation.

**Phase 1: Framing and value proposition mapping**

The process begins with a structured stakeholder workshop to introduce participants to the SSbD concept, the scoping objectives, and the digital collaboration tools used (e.g. MURAL). Participants include developers, value chain actors, and SSbD experts. During this session, qualitative input is collected on the innovation's value proposition, including the problem it addresses, user needs, and intended performance characteristics. If a product application is not yet defined, this step also surfaces gaps in system definition that inform subsequent steps.

**Phase 2: Application definition and lifecycle data collection**

To enable meaningful lifecycle analysis, a feasible product application is defined in collaboration with stakeholders. A detailed questionnaire is then distributed to value chain actors to gather structured information on lifecycle stages and material flows, actor roles across the value chain, functional and environmental characteristics of the formulation.

Responses are analysed alongside literature sources to develop two lifecycle scenarios: a reference scenario based on a conventional benchmark and a redesign scenario reflecting the novel alternative.

Uncertain lifecycle stages (such as end-of-life) are explored with domain experts, and additional scenario variations (e.g., with higher biobased content) may be constructed to assess redesign opportunities.

All collected information is classified into three categories to guide further assessment:

Assumptions: experience-based knowledge not requiring further investigation;

Findings: information supported by peer-reviewed literature or tools;

Research directions: areas of uncertainty relevant to project goals or regulatory needs.

**Phase 3: Scenario validation and stakeholder feedback**

A second workshop is conducted to present the reference and redesign scenarios to stakeholders. The goal is to validate system boundaries, clarify lifecycle assumptions, and elicit feedback on scenario completeness and relevance. Input is integrated into the scenario models and the classification of issues into assumptions, findings, and research directions is updated accordingly.

**Phase 4: Hazard screening of input chemicals**

A hazard screening is performed for the input chemicals in the novel formulation. Publicly available sources (e.g., EC classification databases) are used to assess potential intrinsic hazards. To facilitate open discussion while protecting confidential information, chemicals are grouped into functional categories (e.g., waxes, emulsifiers, cross-linkers) and anonymised (e.g., "Chemical 1").

Hazard data are used to extract relevant research directions, particularly in relation to SSbD substitution, worker safety, and downstream use phase risks. The results inform further risk-based scoping or regulatory engagement.

**Phase 5: Final research direction prioritisation**

A final workshop is conducted to review the hazard screening and redesign scenarios. Participants confirm or refine the list of research directions by assessing their relevance, uncertainty, and feasibility. The resulting prioritised list forms the basis for subsequent technical assessments, redesign activities, or regulatory submissions.

# 3 Results and Findings

This section presents the summary of the main outcomes of the qualitative life cycle risk assessments carried out using the LCBROM method and the SSbD scoping approach. The findings are organised according to the work packages (WPs) under evaluation, with each subsection highlighting key sustainability and safety insights across the life cycle stages—from raw material sourcing to end-of-life. The results synthesize stakeholder inputs, expert analysis, and literature review.

## 3.1 WP1 – Pre-processing

### 3.1.1 Technology description

The pre-processing described in this section is a critical innovation in textile recycling, specifically focused on removing dyes and elastane from cotton-rich, post-consumer textiles. The process enhances the recyclability of mixed-fiber fabrics by applying optimized chemical and physical treatments while aiming to minimize environmental impacts and maximize solvent reuse. The system is designed to maximize fiber recovery while minimizing environmental harm, making it a foundational step toward more sustainable textile circularity.

Key components of the technology (Figure 3-1):

Preparation of dyed textiles: Post-consumer textile conditions are simulated by dyeing cotton fabrics with various dye types and subjecting them to repeated wash-dry cycles to replicate real-world wear.

Color removal unit: The dyed fabrics undergo stripping treatments using bio-based solvents (e.g., γ-valerolactone, THFA), inorganic agents (e.g., $H_2O_2$, NaOCl, NaOH), and organic solvents (e.g., DMSO, ethylene glycol). A significant innovation is the application of ultrasound to improve dye removal efficiency and reduce energy use. Treatment parameters like pH, temperature, chemical dosage, and ultrasound settings are systematically optimized.

Elastane removal system: Elastane is separated from cotton blends using two methods:

Dissolution: Selective solvents dissolve elastane while preserving cotton fibers.

Degradation: Chemical agents break down elastane polymers.

Solvent recovery systems such as distillation or membrane separation are integrated to reduce waste and costs.

Outcome and limitations:

The treated fabrics are nearly free of dyes and elastane and are suitable for fiber recycling. However, the process can cause fiber damage, particularly with repeated cycles, limiting its reuse potential in multiple recycling rounds.

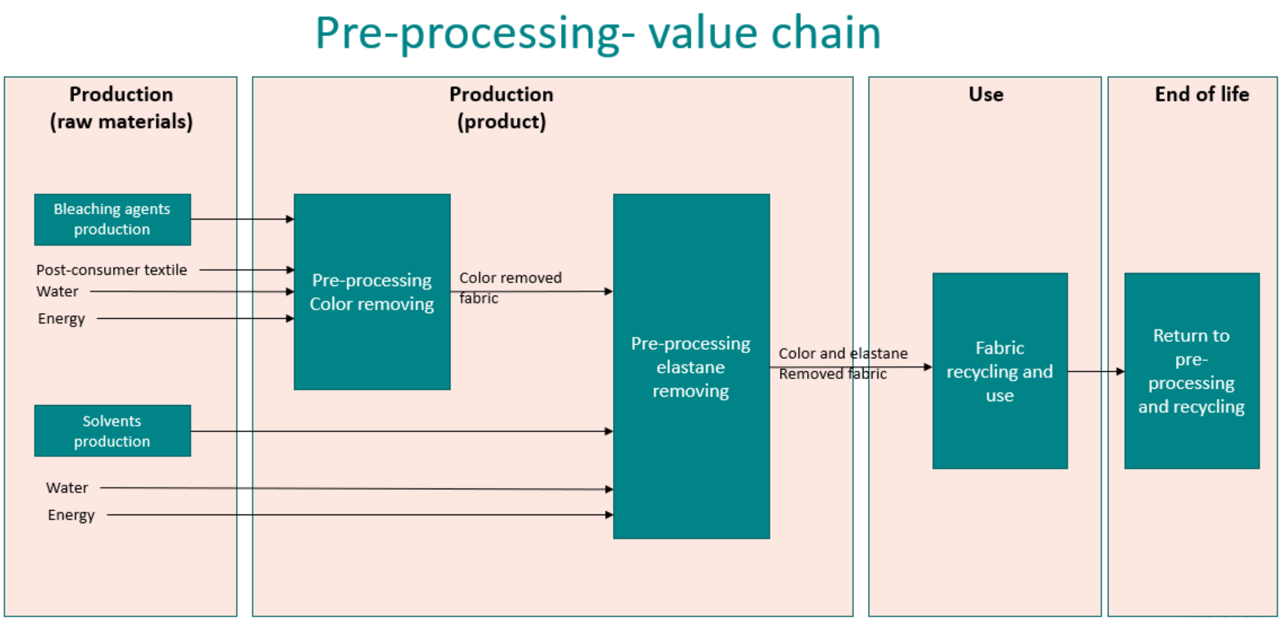


Figure 3-1 Value chain flow chart of WP1- pre-processing.

### 3.1.2 Sustainability screening results

Using the LCBROM approach, a comprehensive assessment was conducted through two rounds of questionnaires, two stakeholder workshops, and an extensive literature review. Based on these inputs, two MET+Ec+S matrix were developed and are presented in Table 3-1 and

Table 3-2 for color and elastane removal, respectively. These matrices highlights the opportunities and risks associated with each system, across environmental, economic, and social dimensions. The evaluation spans the key life cycle stages of production, use, and disposal.

Table 3-1 MET+Ec+S matrix for sustainability screening of color removal unit.

| | | Material (M) | Energy (E) | Toxicity (T) | Economic (Ec) | Social (S) |
|---|---|---|---|---|---|---|
| **Production** | **Bio-based agents (THFA and GVL)** | THFA derived from furfural (biomass-based, corn cobs or wood waste) | THFA is based on hydrogenation of furfural; moderate energy use and high pressure | Moderate carbon footprint for THFA production | Both are solvent-based, removes both dyes and elastane | THFA has a high risk to worker safety due to its flammability and reproductive toxicity |
| | | GVL derived from lignocellulosic biomass (plant waste, wood) | GVL production is an energy-efficient process | THFA can cause irritation and burns upon contact with skin and eyes, requiring careful handling and use of PPE | THFA is more expensive than H2O2 and NaOCl | Less social risk due to less raw material impact for recycling (for both) |
| | | Need metal catalysts (e.g., nickel, ruthenium, palladium) for production of both | | THFA is flammable and volatile | Raw material cost for both THFA and GVL is moderate | GVL has low risk for worker safety, non-toxic |
| | | Recycling could be challenging due to high boiling points | | Low carbon footprint for GVL production | High production cost for THFA due to hydrogenation of biomass | GVL industry is growing, potential for job creation |
| | | | | Low toxicity for GVL | Limited commercial availability for both | |
| | | | | GVL has very low health risks, and is a mild irritant to skin and eyes | Low disposal cost for GVL, fully biodegradable, minimal wastewater treatment | |
| | | | | GVL is fully biodegradable | GVL is an emerging technology for which the production cost could be moderate | |
| | | | | Reaction of these solvents with dye can produce toxic/hazardous by-products | | |
| | | | | The degraded dyes remain in water and generate polluted wastewater | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | Using renewable electricity reduce carbon footprint | | |
| | **Inorganic agents (H2O2, NaOCl and NaOH)** | H2O2 can be produced via biocatalytic process using enzymes or green H2 | H2O2 is based on oxidation; energy-intensive | Carbon footprint for H2O2 production is high if H2 is derived by natural gas reforming | H2O2 is scalable | H2O2 has low risk for worker safety |
| | | Less NaOCl is required for color removal (at least compared to H2O2) | Replacing anthraquinone with electrochemical process (for H2O2 production) at lower temperature and less energy | Using renewable electricity reduce carbon footprint | Raw material cost is low for all | NaOCl has high risk for worker safety, caustic and corrosive |
| | | | NaOCl production has very high energy-intensity since it is based on electrolysis and chlorination | NaOCl is corrosive, strong irritant and releases toxic chlorine fumes | High availability, well-established global (for all) | NaOH has high risk for worker safety, caustic, corrosive, can cause severe burns |
| | | | NaOCl production is highly dependent on electricity | NaOH is corrosive and reactive | Low production cost for all | High job creation, well-established industry (for all) |
| | | | Less energy is required for color removal by using NaOCl (since it works at low temperature) | NaOH is strong skin and eye irritant | Low disposal cost for H2O2, decomposes into water and oxygen, minimal waste | |
| | | | NaOH is based on electrolysis of brine; and has high energy-intensity | Reaction of these with dye can produce toxic/hazardous by-products | High disposal cost for NaOCl, toxic byproducts require neutralization and treatment | |
| | | | NaOH production is highly dependant on electricity | The degraded dyes remain in water and generate polluted wastewater | NaOH is cheaper than H2O2 and NaOCl | |
| | **Organic agents (dimethyl sulfoxide and ethylene glycol)** | DMSO can be derived from lignin | EG is based on oxidation of ethylene; high energy use | The carbon footprint of DMSO can be moderate if it is. based on biomass | High production cost for DS productiondue to synthesis process | DMSO has low risk for worker safety |
| | | Ethylene can be produced from biomass via bioethanol dehydration | Color removing using these chemicals should be conducted at elevated temperature (high energy consumption) | Carbon footprint for EG is high since ethylene is based on fossil fuels | Raw material cost for EG is moderate-derived from petrochemical ethylene | High job creation, well-established industry for EG and DMSO |
| | | | DMSO has high boiling point (189 C) so demands high energy for distillation | Replacing EG with bio-EG can significantly reduce carbon emission | High production cost for EG | |
| | | | | Ethylene oxide is highly toxic and carcinogenic, both to workers and to the environment | EG is produced a lot and is available globally in large quantities | |
| | | | | Release of large air pollution in the refining process for EG production | DMSO is well established globally | |
| | | | | Reaction of these agents with dye can produce | Both are solvent-based, removes both dyes and elastane | |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | toxic/hazardous by-products | | |
| | | | | The degraded dyes remain in water and generate polluted wastewater | | |
| | | | | Using renewable electricity reduce carbon footprint | | |
| | Color stripping via ultrasound | Decreases the need for harsh chemicals in textile treatments | Ultrasound-assisted colour stripping works in low temperature so low energy use | Using renewable electricity reduces carbon footprint | Low operational cost for ultrasound-assisted colour stripping due to lower energy use | |
| | | Less chance to damage the fabric | Ultrasound-assisted process is highly dependent electricity consumption | | Higher initial investment for ultrasound-assisted unit | |
| | | | Ultrasound-assisted works fast andefficient (67-93%) | | Lower cost for post-treatment of ultrasound-assisted process | |
| | | | | | Ultrasonic equipment needs regular maintenance | |
| Use | Color-stripped fabric | The fabric can be reused, reducing demand for virgin textile production | | Avoids the environmental impact of producing new textiles from raw materials | Using pre-processed fabric can be cheaper than virgin materials | Sorting, reprocessing, and resale create employment opportunities |
| | | The color stripped fabric is a white feed stock for further mechnaical recycling | | | Additional treatments like elastane removal add production expenses | |
| Disposal | Color-stripped fabric | Fibers can be damaged through several times of color removed | | | Re-using fabrics reduces the financial burden of landfill disposal | |

Table 3-2 MET+Ec+S matrix for sustainability screening of elastane removal unit.

| | | Material (M) | Energy (E) | Toxicity (T) | Economic (Ec) | Social (S) |
|---|---|---|---|---|---|---|
| Production | Elastane removal-dissolution | Most industrial DMSO is petroleum derived. (Methanol is from natural gas. Hydrogen sulphide from natural gas or petroleum refining by-products) | Dissolution with DMSO works under moderate temperature (100 C) | MeTHF can be produced from agricultural waste, reducing environmental footprint | NBP has high solvency power, effectively dissolves elastane | DMSO is safe to workers since it has low toxicity |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | One part of DMSO is derived from lignin (a renewable source) | NBP has the highest boiling point (256 C) resulting in a high energy demand for distillation | MeTHF is flammable, requiring careful storage and handling | DMSO is well-established industrial product. | NBP has high risk for workers, causing skin and respiratory irritation |
| | | MeTHF can be bio-based | DMSO has a high boiling point (189 C) so needs high energy for distillation | MeTHF is volatile | Moderate production cost for DMSO | Potential for green jobs in bio-based MeTHF production |
| | | NBP is fully petroleum-derived | MeTHF has a lower boiling point (80 C) resulting in smaller energy demand for distillation | DMSO has low toxicity, is biodegradable and easy to handle | NBP is well-established industrial product, widely available | For NBP, requires strict handling procedures, increasing labor training costs |
| | | NBP is recoverable and recyclable in closed-loop systems | Using vacuum distillation or cooling the solute to cause “precipitation” of elastane crumbles, or at least an aggregation so they can be filtered out? Or adding a flocculant instead of using distillation | | Production of NBP involves toxic intermediates | MeTHF is under regulation due to flammability |
| | | Elastane removal by dissolution need higher amount of solvent compared to degradation | Elastane removal by dissolution is faster and at lower temperature and needs less energy (compared to degradation) | | High production cost for NBP | DMSO generally well-accepted with fewer restrictions |
| | | | | | Elastane removal by dissolution is faster and at less temperature reducing energy cost | |
| | | | | | Elastane removal by dissolution needs more solvent, resulting in higher cost for chemicals (compared to degradation) | |
| | **Elastane removal- degradation** | Ethylene glycol can be bio-based (from sugar-based feedstocks) | Ethylene glycol+pentylamine is effective for breaking down elastane at high temperatures | Pentylamine production is corrosive and toxic and involves hazardous intermediates | Ethylene glycol well established in large scale | Ethylene glycol is relatively safe, but pentylamine is a health hazard |
| | | Pentylamine is petroleum-derived | Methanol has a low boiling point (64 C) and has lower energy demand for distillation, very easy to distill | Ethylene glycol is biodegradable | Pentylamine is expensive | Pentylamine handling requires special training |
| | | Methanol can be produced from biomass or $CO_2$ conversion | Tert-amyl alcohol has a moderate boiling point (102 C) and has moderate energy demand for distillation but forms azeotropes | Pentylamine is persistent in the environment | Methanol scalable, widely available, and cost-effective | Pentylamine is under chemical safety regulations due to toxicity |
| | | Tert-amyl alcohol relies mostly on petroleum sources | Pentylamin has a moderate boiling point (104 C) but reacts with other substances, complicating separation | Methanol production releases $CO_2$ if not derived from biomass | Tert-amyl alcohol requires multi-step synthesis, increasing production costs | Tert-amyl alcohol is limited industrial use, reducing job growth potential |
| | | Elastane removal by degradation needs less amount of solvent | Ethylene glycol has a high boiling point and high energy for distillation | Methanol is toxic and highly flammable | Methanol is the easiest and cheapest to produce | There is risk of leakage of degradation products to the local environment |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | Using vacum distillation or cooling the solute to cause “precipitation” of elastane crumbles, or at least an aggregation so they can be filtered out? Or adding a flocculant instead of using distillation | Methanol is easily biodegradable | Tert-amyl alcohol requires a more complex synthesis process | |
| | | | Elastane removal by degradation is longer and at higher temperature so it needs more energy | Tert-amyl alcohol is resistant to biodegradation | Elastane removal by degradation is longer and at higher temperature so the energy cost is higher | |
| | | | | Tert-amyl alcohol can be recovered and reused | Elastane removal by degradation needs less amount of solvent so less cost for chemicals | |
| | | | | Tert-amyl alcohol has lower volatility but toxic | | |
| | | | | Toxic degradation products of elastane are formed | | |
| Use | | The fabric can be reused, reducing demand for virgin textile production | | Avoids the environmental impact of producing new textiles from raw materials | Using pre-processed fabric can be cheaper than virgin materials | Sorting, reprocessing, and resale create employment opportunities |
| | | | | Pre-processed fabric can have lower emission than virgin materials | | Pre-processed fabric can have less social impacts than virgin materials |
| Disposal | | Fibers can be damaged through several times of elastane removal | | | Re-using fabrics reduces the financial burden of landfill disposal | |

- **Color removal**

The study evaluated three systems for removing color from textiles: bio-based, inorganic, and organic agents, against five sustainability criteria: material use, energy demand, toxicity, economic feasibility, and social impact.

Bio-based agents, especially γ-valerolactone (GVL), emerged as the most balanced option. GVL is biodegradable, non-toxic, and safe for workers, though energy-intensive to produce. THFA also showed potential but poses higher toxicity and flammability risks, making it less favorable.

Inorganic agents ($H_2O_2$, NaOCl, NaOH) are cost-effective and widely used but raise significant concerns due to their corrosive nature, toxic by-products, and risks to worker safety and wastewater quality.

Organic agents, such as DMSO and ethylene glycol (EG), offer good dye removal efficiency and are compatible with existing processes. DMSO is relatively safe and renewable, while EG has higher carbon and energy costs but is recyclable.

- **Elastane removal**

Two approaches: dissolution and degradation, were assessed using similar sustainability criteria.

Dissolution methods favor DMSO, which is safe, effective at moderate temperatures, and partially bio-based. It is industrially viable and has low toxicity. DMSO + MeTHF offers energy efficiency but carries flammability and regulatory concerns. NBP is effective and recyclable but very energy-intensive due to its high boiling point.

Degradation methods use solvents like ethylene glycol + pentylamine, methanol, and tert-amyl alcohol. Methanol is cost-effective and biodegradable but toxic and flammable. EG + pentylamine is effective but raises serious safety and environmental concerns. Tert-amyl alcohol is safer but costly and less scalable.

### 3.1.3 Key challenges in more detailed sustainability screening

**General challenges**

- Color and elastane removal processes in textile recycling face several overarching obstacles:
- Data limitations: There is a lack of consistent, quantitative data on energy use, emissions, toxicity, solvent recovery, and scalability. This hinders accurate comparisons and assessments.
- Early-stage technologies: Many techniques (e.g., ultrasound-assisted treatments, bio-based solvents) are still experimental and untested at industrial scale, making their feasibility and long-term impacts uncertain.
- Life cycle uncertainty: Defining comprehensive life cycle boundaries is difficult, especially when accounting for upstream (e.g., solvent production) and downstream (e.g., waste treatment) impacts.
- Sustainability trade-offs: Gains in one area (e.g., energy efficiency) may lead to drawbacks in others (e.g., increased chemical hazards), and trade-offs are rarely analyzed in depth.
- Social impact gaps: Information on worker safety and job creation is sparse, limiting understanding of the broader social implications of these technologies.

**Specific challenges**

- **Color removal:**
  - Performance varies by dye type, fabric, and condition, complicating standardization.
  - Limited knowledge exists about the toxicity and fate of dye degradation by-products.
  - Solvent recovery is poorly documented, particularly in terms of energy costs and effectiveness.
  - Lab conditions may not reflect real-world performance, especially on aged or blended textiles.
  - Potential fiber damage and uncertain compatibility with downstream recycling steps are concerns.
- **Elastane removal:**
  - No standard tests exist to confirm complete elastane removal.
  - Degradation products are not fully studied for their environmental or health effects.
  - Processes are chemically complex and variable, making comparisons difficult.
  - Most technologies remain at lab-scale, with limited data on their practical, economic, or ecological viability.

### 3.1.4 Conclusions

This sustainability screening compares color and elastane removal technologies used in textile waste pre-processing across five key dimensions: material, energy, toxicity, economic, and social impact.

**Color removal:**

γ-Valerolactone (GVL) is identified as the most sustainable solvent due to its low toxicity, biodegradability, and renewable sourcing, despite high energy requirements. Hydrogen peroxide ($H_2O_2$) is cost-effective and widely used but raises safety and environmental concerns. Dimethyl sulfoxide (DMSO) provides a good balance of performance and reusability but requires improvements in energy efficiency during recovery.

**Elastane removal:**

DMSO-based dissolution leads in terms of sustainability, offering safe, efficient, and scalable processing. Methanol-based degradation is low-cost and simple but presents high safety risks due to toxicity and flammability. Other options—DMSO + MeTHF, NBP, and EG + pentylamine—show promise but require further research on energy use, toxicity, and solvent recovery.

**Cross-cutting challenges:**

Common barriers across all systems include data gaps, lack of industrial-scale testing, difficulties in solvent recovery, and unclear life cycle boundaries. Additional complexity arises from variations in textile materials, dye types, and elastane content, as well as limited understanding of degradation by-products.

## 3.2 WP2 – Dope-dyed fibre to fibre recycling

### 3.2.1 Technologies description

Work Package 2 (WP2) examines three textile recycling processes—viscose, Lyocell, and Ioncell®—with a focus on their production methods, solvent use, and potential for circularity.

Viscose process (Figure 3-2):

This method uses post-consumer textiles combined with chemicals like sodium hydroxide (NaOH) , and carbon disulfide to convert fabric into a viscose dope, which is then spun into regenerated cellulose fibers. The process is chemically intensive and ends with the fibers being used in new textiles, which can later be recycled, incinerated, or landfilled.

Lyocell process (Figure 3-3):

Using *N*-methylmorpholine *N*-oxide (NMMO) as a solvent, Lyocell dissolves cellulose from waste textiles or wood pulp. The cellulose is regenerated into fibers in a water-based coagulation bath. The process is considered more sustainable than viscose due to the recyclability of NMMO and the absence of derivatization chemicals, though it requires significant energy for solvent recovery and purification (Haule 2013).

Ioncell® process (Figure 3-3):

Ioncell® uses an ionic liquid - 1,5-diazabicyclo[4.3.0]non-5-enium acetate ([DBNH]OAc) to dissolve cellulose. Similar to Lyocell, fibers are regenerated in a coagulation bath, and the solvent can be recycled. However, challenges remain in maintaining solvent purity and stability over multiple cycles, which may affect fiber quality (Hart 2024).

All three systems are assessed within a closed-loop value chain, where recycled fabrics are ideally returned to the recycling stream at end-of-life. The processes differ mainly in solvent type, environmental impact, and technical challenges associated with solvent recovery.

**For Viscose process**

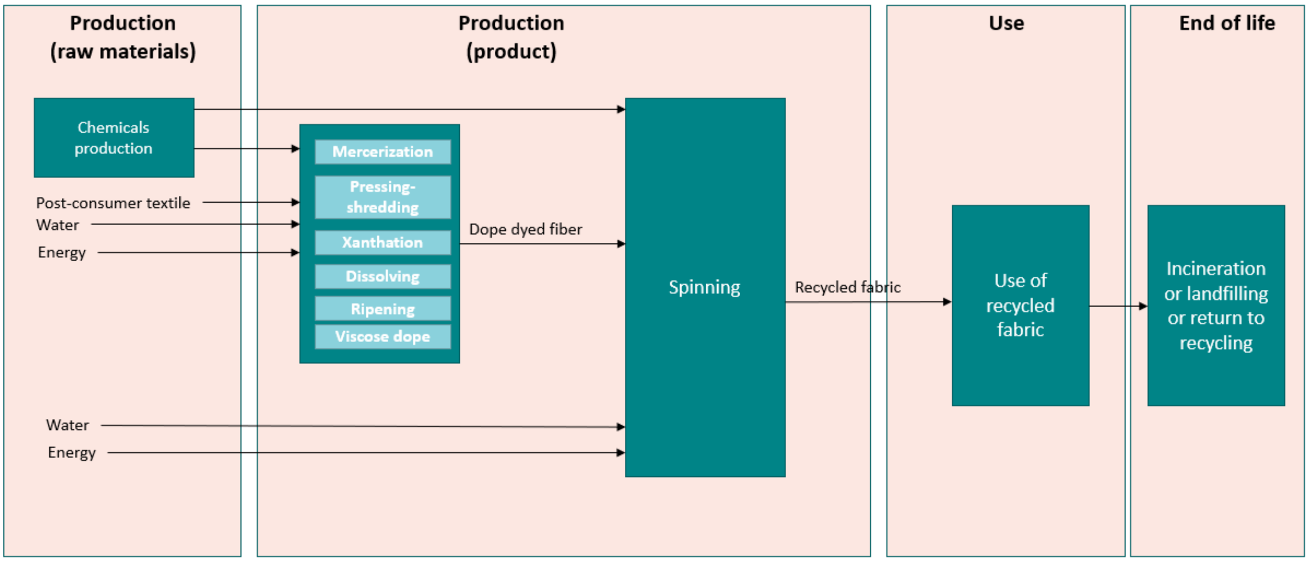


Figure 3-2 Value chain flow chart of WP2 - viscose process.

**For Ioncell and Lyocell**

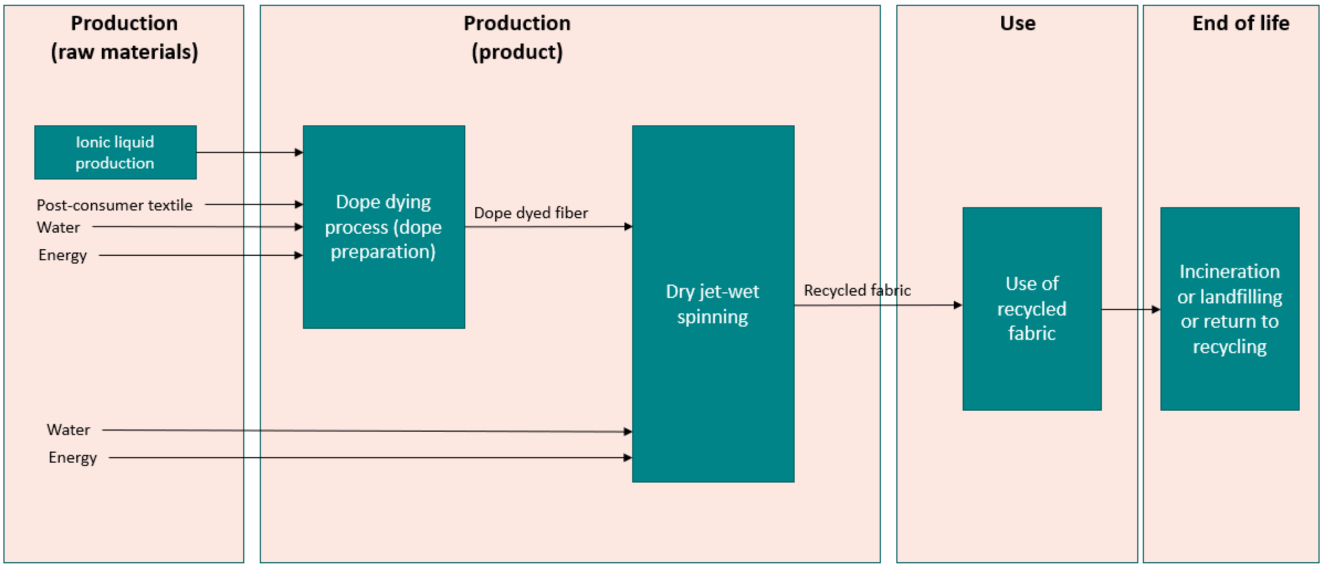


Figure 3-3 Value chain flow chart of WP2 - Lyocell and Ioncell® processes.

### 3.2.2 Sustainability screening results

Using the LCBROM approach, a comprehensive assessment was conducted through two rounds of questionnaires, two stakeholder workshops, and an extensive literature review. Based on these inputs, the MET+Ec+S matrix was developed and is presented in Table 3-3. This matrix highlights the opportunities and risks associated with three fabric recycling technologies- Ioncell, Lyocell, and viscose process, across environmental, economic, and social dimensions. The evaluation spans the key life cycle stages of production, use, and disposal.

- The production phase refers to the manufacturing of recycled fabric using the selected recycling technology.
- The use phase refers the fabric's performance during washing, wearing, and its application in various textile products.
- The disposal phase considers the end-of-life pathways, including recycling and reuse, incineration, or landfilling.

Table 3-3 MET+Ec+S matrix for sustainability screening of fabric recycling technologies.

| | | Material (M) | Energy (E) | Toxicity (T) | Economic (Ec) | Social (S) |
|---|---|---|---|---|---|---|
| Production | Ioncell process | Less water is used in the dope dying process | High dissolution efficiency at lower temperatures, reducing energy use | The used ionic liquid is non-toxic | There is no large-scale implementation, but it could be scalable | Many textile industry players depend on traditional dyeing and risk losses if dope dyeing becomes the standard |
| | | Little water is used in spinning | Process requires high-yield solvent recycling, so it is energy-intensive | Using renewable electricity for spinning can reduce carbon emission; spinning operations can be integrated into pulp mill operations to utilize its surplus energy | On large scale, the spinning line would be running continuously with a recovery process of the ionic liquid available in place which will decrease cost of the overall process | [DBNH]OAc is safe for workers and is non-toxic |
| | | Solvent can/must be recycled (100%) | | Contaminants and dyes can leach into the bath, affecting the entire recycling process | Fibers with higher durability | New industry potential, can create other market opportunities |
| | | Water from dope dyeing wastewater can be separated and reused in the process or for post-spinning washing | | Need to develop strategies to separate and remove contaminants | Expensive solvent, still in limited commercial use | Raw materials (e.g., solvents) can be sourced from companies that aren't transparent on their social sustainability efforts |
| | | [DBNH]OAc is a synthetic solvent derived from petrochemical sources | | Dyes or materials must not contain heavy metals | Operational (energy) costs must be low | Something that is perhaps common in all from the social side: helping to establish a more circular paradigm for further innovation |
| | | High dye uptake | | [DBNH]OAc has low toxicity, safe to handle | | |
| | | | | [DBNH]OAc is highly stable, no explosive risks | | |
| | NMMO-Lyocell process | Less water is used in dope dying process | Higher energy demand due to NMMO stabilization requirements | The used NMMO is non-toxic | For non-dyed fibers that is well at the market, there is large scale (ca. 0.8 Mt/a) | Many textile industry players depend on traditional dyeing and risk losses if dope dyeing becomes the standard |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | Little water is used in spinning | Process requires high-yield solvent recycling | Using renewable electricity for spinning can reduce carbon emissions; spinning operations can be integrated into pulp mill operations to utilize its surplus energy | On large scale, spinning line is running continuously with a recovery process of NMMO in place which will decrease cost of the overall process | Raw materials (e.g., solvents) can be sourced from companies that are not transparent on their social sustainability efforts |
| | | Solvent can be recycled (>99.5%) | | Contaminants and dyes can leach into the bath, affecting the entire process | Expensive solvent, but available at large scale | |
| | | Water from dope dyeing wastewater can be separated and reused in the process or for post-spinning washing | | Need to develop strategies to separate and remove contaminants | High operational (energy) cost | |
| | | Need stabilizers propyl gallate and NaOH | | Dyes or materials must not contain heavy metals | | |
| | | NMMO is a synthetic solvent derived from petrochemical sources | | | | |
| | **Viscose process** | Solvent recovery is feasible in the viscose process to some extent, as an example ultrafiltration to remove hemicellulose in the NaOH | Higher energy consumption compared to Lyocell and Ioncell | Carbon disulfide ($CS_2$) is hazardous, highly toxic, and volatile | It is well established at the market, there is large scale; dope-dyed viscose fibers are produced commercially | High risk for worker safety since $CS_2$ exposure can cause neurological damage |
| | | Limited to cellulose-based fabrics (e.g., cotton), not suitable for synthetic fibers | Process totally relies on electricity but in the industry, it is probably based on a combination of other fuels | | It might require constant input of chemicals, particularly in traditional or less regulated operations, as substances are difficult to recycle or may be lost during processing (for some chemicals) | Raw materials (e.g., solvents) can be sourced from companies that are not transparent on their social sustainability efforts |
| | | Uses many chemicals | | | Filtration is needed filtration before spinning to prevent clogging and ensure fiber quality | |
| | | Uses common industrial chemicals ($NaOH$, $CS_2$, $H_2SO_4$), which are widely available | | | NaOH is recycled and $CS_2$ is partially recycled | |
| | | The used chemicals are based on non-renewable raw material | | | | |
| **Use** | (recycled fabric) | The fabric can be reused, reducing demand for virgin textile production | | Avoids the environmental impact of producing new textiles from virgin raw materials | Using recycled fabric can be cheaper than virgin materials | Sorting, reprocessing, and resale create employment opportunities |
| | | | | The recycled fabric can be used for all applications with no restriction for usage | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Disposal** | (recycled fabric) | Fibers can be recycled up to five times before their quality degrades | | Fully biodegradable (if incorporated dyes are so too) | Re-using fabrics reduces the financial burden of landfill disposal | |
| | | | | | | |

The comparative assessment of Ioncell®, Lyocell, and viscose recycling technologies across material, energy, toxicity, economic, and social dimensions identifies Ioncell® as the most promising option for further life cycle assessment (LCA) and industrial scale-up.

**Environmental and material efficiency:**

Ioncell® uses a fully recyclable, non-toxic ionic liquid ([DBNH]OAc), offering superior solvent recovery and minimal environmental risk compared to the toxic carbon disulfide ($CS_2$) used in viscose. It also uses less water in dyeing and spinning, enhancing resource efficiency over traditional methods.

**Energy use:**

Ioncell® has better long-term energy efficiency potential than Lyocell, which requires energy-intensive stabilization of its solvent (NMMO). While viscose uses less energy, its limited chemical recovery and variability across producers reduce its sustainability.

**Safety and toxicity:**

Ioncell® poses fewer health and environmental risks due to its non-volatile, non-toxic solvent. In contrast, viscose involves hazardous $CS_2$, and Lyocell, while generally safe, requires stabilizers that complicate the process and add risk.

**Economic and scalability potential:**

Although not yet commercialized, Ioncell® shows strong economic viability due to its high fiber quality and durability, appealing to premium and sustainable markets. Lyocell's high operational costs and viscose's environmental concerns hinder their long-term expansion potential.

### 3.2.3 Key challenges in more detailed sustainability screening

Conducting a detailed sustainability screening of Ioncell®, Lyocell, and viscose textile recycling technologies faces several key limitations:
Data availability and transparency:
Ioncell® is in the pilot stage, and public data on its environmental performance (e.g., energy use, water consumption, solvent recovery) is limited. For Lyocell and viscose, proprietary data from industry is often inaccessible, hindering robust comparisons and life cycle assessments.
Feedstock variability:
The quality and composition of input materials—such as recycled cotton or blends with synthetics—can significantly affect process efficiency and outcomes, but real-world variability is rarely reflected in lab-scale studies.
Solvent use and recovery:
There is limited information on solvent degradation, recovery efficiency, and toxicity for all three processes. Ioncell® and Lyocell claim solvent recyclability, but practical data is scarce. Viscose uses hazardous carbon disulfide, yet details on emissions and recovery are not publicity available publiclypublicly and vary between companies.

Energy and water footprint uncertainty:
Differences in energy sources, assumptions, and measurement units across studies make it difficult to compare environmental impacts. Regional factors like energy mix and enforcement of environmental regulations are rarely considered.
Social and occupational health impacts:
Although Ioncell® is presumed to be safer, no real-world data exist on worker exposure or job creation. Viscose poses known health risks due to carbon disulfide, but the severity varies by factory and region.
End-of-life and circularity gaps:
There is insufficient data on how well these fibers degrade or can be recycled after use. While viscose is biodegradable, comprehensive end-of-life impact assessments and recyclability over multiple cycles are missing for all technologies.
Addressing these gaps in data, process variability, and end-of-life understanding is critical to enabling more accurate and meaningful sustainability assessments for fiber-to-fiber recycling technologies.

### 3.2.4 Conclusions

This section presents a sustainability evaluation of Ioncell®, Lyocell, and viscose recycling processes using the LCBROM methodology and the MET+Ec+S matrix, which considers material, energy, toxicity, economic, and social factors across production, use, and disposal stages.

Ioncell® is identified as the most sustainable and promising technology due to its non-toxic, recyclable solvent, high material efficiency, and lower environmental footprint. It is well-suited for further life cycle assessment and industrial scale-up.

Lyocell, though commercially established, faces limitations due to its high energy demands and need for stabilizers, which complicate scalability.

Viscose, despite being widely used, raises significant sustainability concerns because of hazardous chemical use and limited solvent recovery.

Recommendations: Ioncell® should be prioritized for development, with improvements in solvent recovery and energy efficiency to support circular textile systems. However, leveraging the operational knowledge from Lyocell and viscose processes can aid in optimizing Ioncell's industrial implementation. Ongoing research and supportive policy frameworks will be essential to scale these innovations sustainably.

## 3.3 WP3 - PFAS-free biobased water repellent coating

### 3.3.1 Technology description

The DWR finish forms a thin polymeric layer (Figure 3-4) on the textile surface that imparts hydrophobicity by increasing the water contact angle, allowing water droplets to roll off. (Schellenberger, 2019) This prevents water absorption while maintaining breathability. The coating is designed to adhere to both cellulosic and synthetic textiles without altering key properties such as fabric hand feel or color appearance.

The textile coating process uses a padding method followed by drying and curing, respectively. This ensures fixation of the DWR layer to the fiber surface.

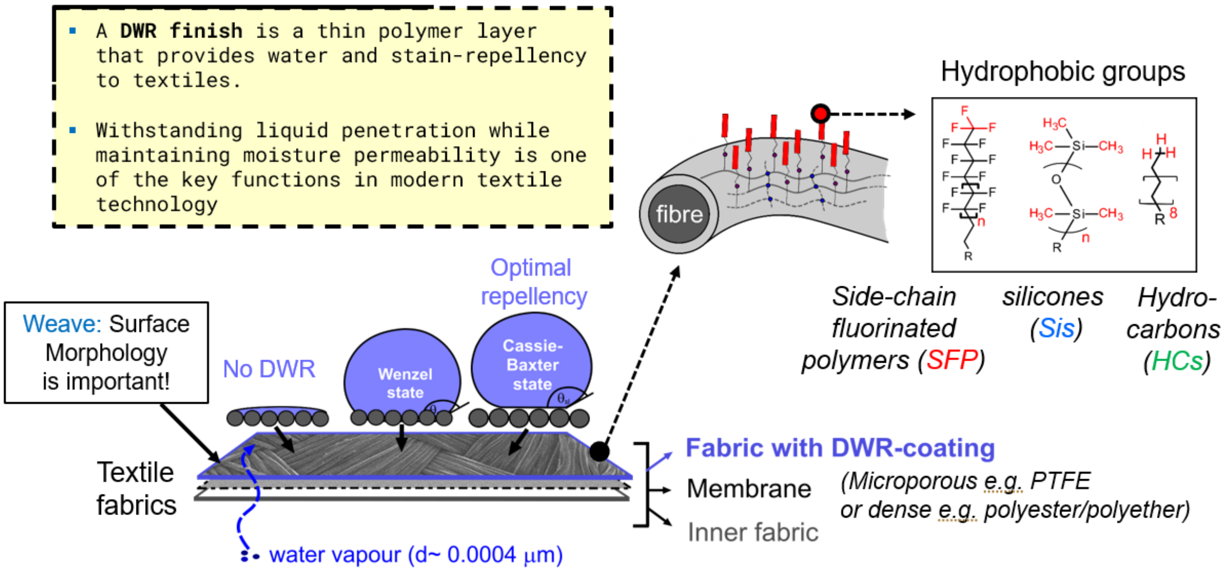


Figure 3-4 Schematic overview of DWR-coated textile structure and mechanism of water repellence. (Schellenberger, 2019)

### 3.3.2 Relevant environmental, economic, social issues based on literature review

The environmental impact of PFAS in textile coatings is profound. Studies have shown that PFAS can leach into water systems during the washing of treated textiles, leading to contamination of surface and groundwater (Van Der Veen et al., 2022; Zhang et al., 2018). The gradual degradation of textiles under environmental conditions can also release PFAS into the environment, contributing to their accumulation in ecosystems (Schellenberger et al., 2022). Furthermore, the manufacturing processes of PFAS-treated textiles have been linked to occupational exposure among workers, raising concerns about health risks associated with inhalation and dermal contact with PFAS-laden materials (Heydebreck et al., 2016; Paris-Davila et al., 2023). The persistence of PFAS in the environment, coupled with their bioaccumulation potential, poses long-term ecological risks (Morales-McDevitt et al., 2022).

Economically, the textile industry faces increasing pressure to comply with stricter regulations regarding PFAS usage. The transition to PFAS-free alternatives may incur initial costs; however, it could lead to long-term savings by reducing liabilities associated with environmental remediation and health-related costs (Hill et al., 2017; Verbič et al., 2024). The development of sustainable textile coatings from renewable resources is gaining traction, aligning with global sustainability goals and potentially offering cost-effective solutions in the long run (Attia et al., 2022). The shift towards PFAS-free technologies is not only an economic necessity but also a response to consumer demand for environmentally friendly products (Hill et al., 2017; Verbič et al., 2024).

Socially, the implications of PFAS in textiles extend to public health concerns. The presence of PFAS in consumer products, including clothing, raises awareness about potential health risks, particularly among vulnerable populations such as firefighters who are frequently exposed to PFAS-treated gear (Maizel et al., 2023; Peaslee et al., 2020). The growing evidence linking PFAS exposure to adverse health outcomes has catalysed public discourse on the need for safer alternatives in textile coatings (Maizel et al., 2023; Paris-Davila et al., 2023). As consumers become more informed about the risks associated with PFAS, there is an increasing demand for transparency and accountability from manufacturers, which could drive further innovation in the development of safer textile technologies (Hill et al., 2017; Verbič et al., 2024) (Verbič et al., 2024; , Hill et al., 2017).

### 3.3.3 Benchmark selection

The benchmark selected for comparison is a conventional C6-based fluorinated DWR, representing the industry standard due to its widespread use and functional performance. C6-PFAS systems have largely replaced longer-chain compounds due to regulatory restrictions. They provide excellent water repellency but are associated with environmental persistence, bioaccumulation, and potential toxicity.

### 3.3.4 Screening assessment based on the scoping method

**The value proposition of the innovation**

This innovation replaces harmful PFAS-based water repellents (such as PFHxA which is a main degradation prodcuts realted to C6-DWRs) with a bio-based, renewable formulation that significantly reduces environmental emissions and lowers worker exposure risks during production and application. The new durable water repellent (DWR) is designed to meet key functional standards, including high water repellency (ISO 4920 spray score of 5), durability after 10 washes, and abrasion resistance (1000 Martindale cycles). It works on both cellulosic and synthetic fabrics and supports recyclability, contributing to circular textile systems. From a market standpoint, the innovation offers a sustainable alternative for brands producing PFAS-free outdoor textiles, such as children's jackets, tents, and cushions—delivering high performance without compromising look or feel.

**Value chain within the lifecycle of the PFAS-free bio-based durable water repellent (DWR)**

The current value chain of the proposed product—a cotton-based jacket treated with a PFAS-free bio-based durable water repellent (DWR)—includes multiple stages from raw material sourcing to end-of-life management (Figure 3-5).

**Synthesis of chemicals**

The PFAS benchmark is associated with high environmental risks due to fluorinated gas (F-gas) and PFAS emissions, potential safety issues for workers, and an energy-intensive process. In contrast, the bio-based alternative is considered to pose lower occupational hazards, and its chemical production is conducted under EU-standard conditions (including scrubbers and wastewater treatment). However, the economic dimension remains uncertain and is marked for further investigation.

**Fabric manufacturing**

Raw cotton fibers are spun into yarns and woven or knitted into fabrics. The resulting greige fabric is then scoured and prepared for finishing. This textile base serves as the substrate for DWR application and is the same across both bio-based and PFAS-based coatings.

**DWR formulation production**

The lifecycle of the PFAS-free bio-based durable water repellent (DWR) coating begins with the sourcing of raw materials. The list of materials used in the production of the PFAS-free bio-based durable water repellent (DWR) coating was provided by RISE, which are the technology developers in WP3. As a starting point, approximately 58% of the formulation consists of bio-based ingredients such as fatty acids and waxes derived from renewable agricultural sources, while the remaining 42% includes petroleum-based components like emulsifiers and crosslinkers (Figure 3-6). The optimization goal is to increase the bio-based content to at least 60%, with the potential to increase it further to 90%. These materials are obtained from established chemical suppliers, including Croda, Cargill, and Sigma-Aldrich. While the chemicals used in the formulation are well known, the synthesis processes involved in their production remain uncertain and may vary depending on supplier practices.

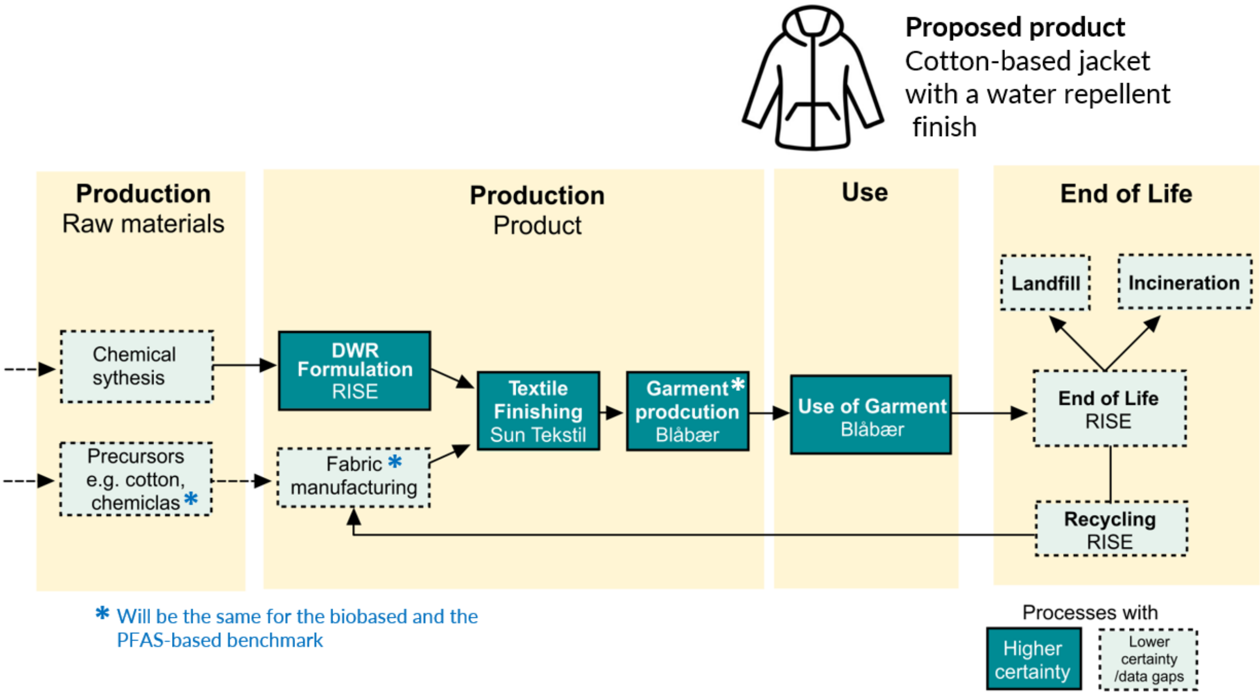


Figure 3-5 Value chain of a cotton-based jacket treated with a PFAS-free bio-based DWR.

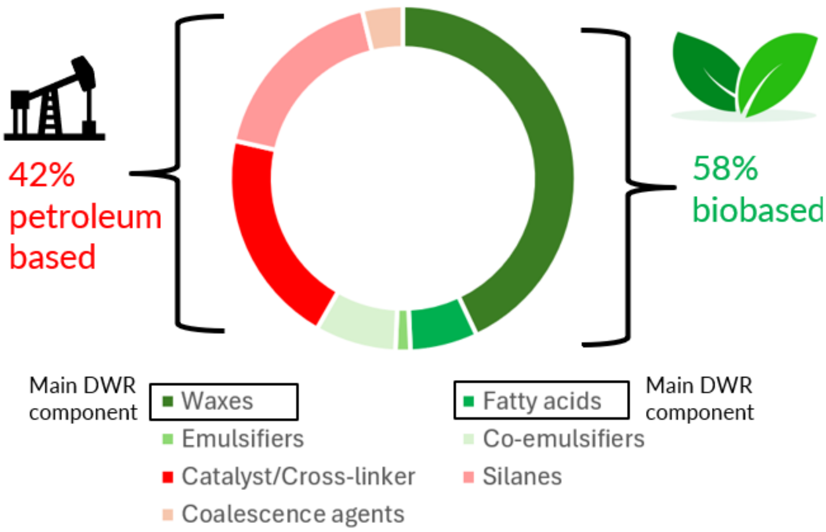

Figure 3-6 Bio-based and petroleum-based composition of the DWR formulation.

Prediction of environmental, social, and economic impacts at this stage remains difficult. These aspects will require detailed process simulation, which will be done in task 6.2 of BioSusTex and evaluation as the formulation matures. Emissions to wastewater during large-scale production are also a potential concern and must be addressed during process design and environmental risk assessment.

The C6-PFAS formulation raises concerns regarding worker safety, potential PFAS emissions to air and water, and uncertain social impacts. While economic costs are assumed to be stable due to similar process conditions, the environmental footprint remains problematic. In contrast, the bio-based alternative may offer improvements in safety and environmental performance, particularly in closed processing environments and wastewater degradability. However, uncertainties remain regarding formulation emissions, cost implications, and social effects, highlighting the need for further research and in-silico modelling to support sustainability assessment.

**Textile finishing**

For application, the DWR is prepared into a finishing bath with specific concentrations of the active coating agent, crosslinker, and pH modifiers. The coating is applied to textile fabrics using a standard padding process. PFAS coatings pose known worker safety risks and release harmful emissions. The bio-based alternative may reduce these risks and environmental impacts, with similar costs, but requires further investigation to confirm its safety, social, and environmental benefits.

**Garment manufacturing**

The finished, coated fabric is sent to garment manufacture, where it is cut and sewn into garments—specifically, children's outdoor jackets. This production step uses standard apparel manufacturing practices and infrastructure.

**Use phase**

During use, textiles treated with PFAS-free bio-based DWR, commonly used in outdoor garments, face environmental stresses such as moisture, UV exposure, and abrasion. While the coating maintains water repellency, it may degrade over time, especially with repeated washing, necessitating occasional re-impregnation to sustain performance. If the finish remains intact, no significant emissions to air or water are expected.

The durability of the bio-based DWR depends on fabric type, washing frequency, and usage conditions. Compared to PFAS-based coatings, which release harmful substances like microplastics and fluorotelomer alcohols during laundering and wear, the bio-based option poses fewer health and environmental risks. Although it may require more maintenance, it supports a safer and more sustainable alternative, aligning with growing consumer and regulatory demand for PFAS-free products.

**End-of-life (EoL)**

Recycling and disposal of DWR-coated textiles present significant uncertainties and challenges. Coatings, especially on cellulosic fabrics, can hinder fiber separation and pulping, necessitating chemical pre-treatment, which may generate emissions and require substantial energy. Although bio-based DWRs are thought to be more compatible with thermal recovery and composting than PFAS-based alternatives, this remains unproven and requires further study.

Two main end-of-life scenarios are considered. In the recycling route, textiles undergo pre-treatment to remove the DWR before pulping, enabling fiber reuse but at an environmental and energy cost. In the re-impregnation and incineration scenario, garments are used longer with repeated DWR applications, followed by incineration. This process recovers energy but may emit pollutants, particularly with PFAS-based coatings, which release toxic gases if not incinerated at high temperatures.

PFAS-based DWRs carry higher environmental and safety risks during both wastewater treatment and incineration. Bio-based DWRs offer a potentially safer and less polluting alternative, though emissions and treatment effectiveness depend on formulation. Re-impregnation, while extending product life, adds cost and complexity. Social aspects like consumer behavior and acceptance also remain under-researched.

- **Trade-offs involved in enhancing key positive impact and strategies that could be applied**

The development of PFAS-free, bio-based durable water repellent (DWR) coatings presents significant environmental and health benefits by avoiding persistent, toxic fluorinated compounds. However, these benefits come with trade-offs, including potentially reduced durability, higher costs, and added formulation complexity. Frequent reapplication of the coating may increase energy and material use, and some bio-based additives (like emulsifiers and crosslinkers) could pose environmental risks. Functionally, balancing high performance with recyclability and fabric quality is a challenge. Socially and regulatorily, while safer for consumers, the use of new bio-based chemicals requires clear communication and may face regulatory scrutiny.

To address these challenges, several strategies are recommended. At the formulation stage, selecting low-toxicity, biodegradable ingredients with traceable and sustainable sourcing can minimize impacts. For industrial scalability, transitioning to continuous processing and implementing closed-loop systems can enhance efficiency and safety. During use, extending garment lifespan through better performance and consumer education is key, along with offering low-impact re-impregnation options. For end-of-life, developing coatings compatible with recycling and improving labeling and pretreatment methods will support circularity. Finally, engaging with regulators and standard bodies early, along with clear public communication, can facilitate adoption and build trust in the technology choices.

### 3.3.5 Conclusion

The transition away from PFAS-based DWR technologies is both a regulatory imperative and an opportunity to drive sustainable innovation in the textile sector. The PFAS-free bio-based DWR formulation represents a promising alternative that aligns with the principles of SSbD. It offers potential environmental and human health benefits by eliminating persistent PFAS compounds, reducing occupational exposure, and opening pathways for improved end-of-life management.

Throughout this assessment, the bio-based DWR was evaluated across multiple life cycle stages—formulation, application, use, and disposal—and compared to the C6-PFAS benchmark. The results indicate that while the innovation demonstrates a favorable safety and environmental profile, several uncertainties and trade-offs remain. These include the durability of the coating under real-world use conditions, compatibility with textile recycling systems, and the economic implications of frequent re-impregnation or process adjustments at industrial scale.

Key challenges such as formulation optimization, emissions control during upscaling, and the recyclability of coated fabrics must be addressed through targeted research and stakeholder collaboration. Strategies including ingredient traceability, advanced process design, performance monitoring, and public engagement will be essential to ensure the technology delivers on its sustainability promise.

## 3.4 WP4 - PVC-free biobased print with in-built recycling feature

### 3.4.1 Problem definition: insights from LCBROM and literature

Screen printing remains a widely used textile printing technique due to its scalability, simplicity, and versatility across materials like cotton and polyester (Lin, 2023). However, traditional practices raise serious environmental concerns, particularly through the use of PVC-based plastisol inks and VOC-emitting solvents. These contribute to air pollution, ozone depletion, and toxic waste, with significant health risks linked to substances like vinyl chloride and dioxins (HCWH, 2021).

To address these issues, the industry is shifting toward more sustainable alternatives, including water-based inks, biodegradable binders, and green solvents (Shukla, 2023). Innovative formulations—such as washing-free or nanosphere-based inks—reduce water use and dye discharge. Compared to rotary screen printing, digital textile printing shows lower energy and water consumption and reduced waste (Hoque, 2024). Hybrid approaches, like reusing digital ink waste, further enhance resource efficiency.

Economically, screen printing remains attractive for mass production due to low operating costs and streamlined workflows, especially when using recycled inks and eliminating pre-treatment steps (Lin, 2023; Shukla, 2023).

Socially, replacing hazardous ingredients with non-toxic alternatives improves workplace safety (Pan, 2018), while sustainable practices benefit surrounding communities through cleaner air and water (Hoque, 2024). The technology is also expanding into functional textiles such as wearable electronics, driving innovation (Gorjanc, 2022).

In BioSusTex WP4, a semi-biobased removable ink has been developed. While the formulation is mostly sustainable, it currently relies on fossil-based binder, limiting its biodegradability. Alternatives are being explored, but face performance challenges. Achieving full biobased composition is essential for compostability and long-term sustainability, though it may reduce technology readiness level (TRL) as revalidation is needed.

### 3.4.2 Technology description

- **Production of the removable PVC-free ink**

The production of the removable, PVC-free ink involves dissolving a biopolymer and incorporating pigments, additives, and binder in a single reactor, yielding 0.5 kg of ink per batch. The process is environmentally friendly, producing no direct emissions or waste. The ink is fully water-based, and all components—except for the fossil-based binder—are biobased. Efforts are underway to replace the binder with a biobased alternative.

Key materials include iron oxide-based pigments, a polysaccharide biopolymer, cellulose-based thickener, plasticizer, and water. All raw materials are sourced from within the EU, and the energy demand is comparable to standard paint production.

The ink serves as a drop-in solution, requiring no changes to existing screen-printing equipment. It is suitable for both cotton and synthetic textiles, with current development focused on cotton fabrics and color ranges including red and purple.

- **Production of the removal formulation**

The removal formulation is produced by blending a surface-active component, a surfactant, which is commercially available and biodegradable, with water (70%) and carbonate solvent, which is an organic solvent.

By dipping the textile that is printed with the ink described above, and applying mechanical action such as rubbing, the film (ink) can then be detached from the textile.

### 3.4.3 Value chain mapping

The value chain that is relevant for the novel ink is identified and showed in Figure 3-7. In the production process, raw materials and components required to produce the ink are included. The ink is then printed to a fabric in the screen-printing process. The fabric can be supplied by the industry representative. The printed fabric is used by the consumers and ideally reach recycling facility once it is being disposed by the consumer.

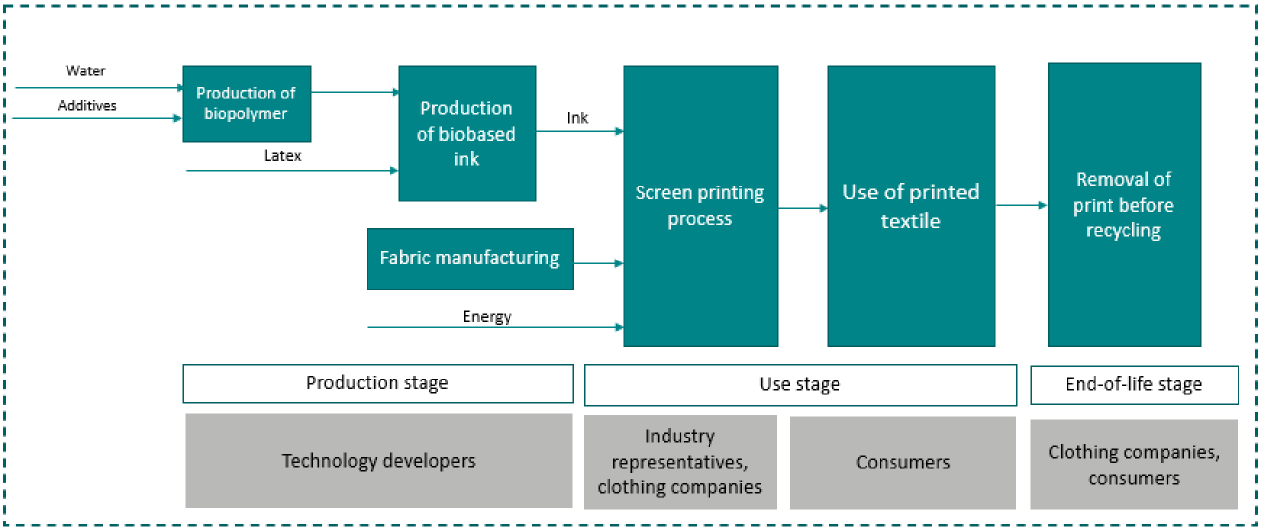


Figure 3-7. Mapping of the value chain of ink technology.

### 3.4.4 Identifying risks and opportunities: MET matrix evaluation

The results of the qualitative sustainability screening for the biobased ink technology, structured according to the MET matrix framework, explained in section 2.1 (Table 3-4). The evaluation captures key risks, opportunities, and areas of uncertainty across the life cycle stages—production, use, and end-of-life—based on five dimensions: material, energy, toxicity, economic, and social aspects.

The findings are based on:

Stakeholder input from two dedicated LCBROM workshops,

Responses to LCBROM questionnaires (Q1 and Q2),

Supporting literature and process data provided by technology developers.

Table 3-4 MET+Ec+S matrix for sustainability screening of biobased ink technology.

| | Material (M) | Energy (E) | Toxicity (T) | Economic (Ec) | Social (S) |
|---|---|---|---|---|---|
| Production | Bio-based products tends to have higher environmental impacts on land use and water use. (Brizga et al., 2020; Sandin et al., 2013) | The production of ink does not require more energy than the production of commercial ink/paint. | The new ink uses non-toxic chemicals compared to the PVC-based ink. | Higher production cost due to higher price on the biobased materials. | Workers work in safer working environments as less toxic and harmful chemical are used. |
| | The ink is made of non-toxic components and most of raw materials are biobased which is more sustainable compared to the PVC-based ink. | The ink has the same performance as the PVC-based ink in terms of properties, stability, and bacteria resistance. | The biobased ingredients in the ink are the same ingredients used in other industry e.g., cosmetic where they are acknowledged as safe. | New market opportunity for biobased- and removable printing ink. | Reduced risk of emissions and exposure to hazardous materials for workers |
| | Using biobased component reduces $CO_2$ emissions during production. | Energy source when scaling up requires further investigation. | It could be an occupational risk associated with auxiliary materials. | | Reduces the demand for unsustainable ink production in developing countries can potentially improve labour conditions. |
| | The biobased materials can come from by-products or waste streams from e.g., agriculture. | | | | |
| | No waste is generated during production of the ink. No emissions to air, soil and water are known. | | | | |
| | The ink removal formulation is biobased, biodegradable, and reusable. | | | | |
| | No challenges in the supply chain of the biobased raw materials. | | | | |
| | All raw materials used to produce the ink comes from within EU. | | | | |
| | The ink does not have problem with microplastic, which is the case for PVC-based ink. | | | | |
| | The biobased binder may have a poor performance. | | | | |

| | Material (M) | Energy (E) | Toxicity (T) | Economic (Ec) | Social (S) |
|---|---|---|---|---|---|
| | How much can the biobased content and biodegradability increase with the new ink. | | | | |
| Use | Lower durability as the print can be washed out easily. | No change in energy consumption during the printing process as the ink is a drop-in solution and existing printing machine can be used. | May create by-products that are hazardous and impose risk for workers. | As the production cost of the new ink is higher, the printed textile may cost more for consumers. | Less exposure to harmful materials for consumers. |
| | The ink can be applied to both natural and synthetic textiles. | If the bio-based ink will contain more water, it may require more energy to dry. | Only water is used as solvent in the removal formulation. | Risk for market scepticism towards removable print. | The ink complies with future EU regulations on sustainable materials which gives competitive advantage as an early adopter of the technology. |
| | | | | The new ink can be used as an alternative sustainable product, which means that companies can avoid regulatory penalties for not complying with sustainable policies. | Safer working conditions gives a positive consumer perception. |
| | | | | No new printing machine is needed since the ink can be replaced with the existing machine directly. | |
| Disposal (End-of-life) | The print has poorer performance against wear and washing which leads to early disposal of textile. | The print removal process such as dipping, and rubbing is not yet efficient as they are still done by hand. An automation of these step is needed. | Reduced problem with landfill or disposal of textile due to the ink removal feature. | The new ink is not distinguishable from the conventional printing ink which makes the sorting difficult and require manpower which is an additional cost. | Since the print can only be removed with special removal formulation, collection needs to be done and be delivered to the right place for recycling. |
| | The ink removal formulation does not affect the mechanical properties of the fibers which means that the textile can be reuse directly after the ink is removed and washed. | | If the printed textile is disposed in a landfill, it will pose less harm to the environment as the ink will be biodegradable. | New machines need to be integrated in the existing recycling facility | Ink removability is only effective and has a noticeable impact if it is widely adopted by a sufficient number of recycling facilities. |

| | Material (M) | Energy (E) | Toxicity (T) | Economic (Ec) | Social (S) |
|---|---|---|---|---|---|
| | The ink removal feature can increase the recycling rate/reuse and circularity of the textile waste. | | The wastewater from the removal of ink needs to be investigated further. | . | The sorting and print removal create job opportunity. |
| | Supply of recycled materials increases due to easier removal of print. | | Concerns around microplastic release during washing and disposal needs to be investigated further. | | |
| | Less consumption of water and resources when the supply of recycled materials increases. | | | | |
| | Less CO2 emissions from textile production due to increased recycling/reuse. | | | | |
| | The compostability of the ink is being explored through the development of biodegradable formulations. | | | | |

### 3.4.5 Conclusion

The MET+Ec+S matrix developed using the LCBROM method highlights that the novel bio-based, removable screen-printing ink offers substantial sustainability benefits over traditional PVC-based plastisol inks.

Environmentally, the ink and its removal formulation are largely biobased, biodegradable, and low in toxicity. Key advantages include the absence of microplastic release during wear or washing, a potentially lower carbon footprint, and compostability if fully biobased. However, trade-offs exist: 1. biobased production can increase land and water use, and 2. water-based inks generally require more energy for drying.

Economically, the ink functions as a drop-in solution requiring no new equipment, reducing barriers to adoption. While biobased inputs raise production costs, the ink aligns well with EU sustainability goals, offering regulatory and market advantages. Nonetheless, higher prices and consumer skepticism toward removable prints may hinder early adoption.

Socially, the ink improves worker safety by eliminating hazardous chemicals like phthalates and vinyl chloride. It supports better labor conditions in global supply chains and is safer for end users, particularly in children's clothing. These features may boost consumer trust and open pathways for eco-labeling and sustainability ratings.

To fully realize its potential, the innovation must overcome challenges such as replacing the fossil-based binder, improving data for end-of-life scenarios, and refining assumptions for life cycle assessments. Despite these hurdles, the ink is a promising step toward safer, more circular textile printing solutions.

# 4 Conclusions and Recommendations

The qualitative sustainability screening conducted under BioSusTex Task 6.1 provided early-stage insights into the environmental, economic, and social performance of innovative textile technologies developed in WP1 to WP4. The assessments applied the LCBROM method for WP1, WP2, and WP4, and the SSbD Scoping Method for WP3, enabling a structured evaluation of risks and opportunities across the life cycle—from raw material extraction to end-of-life.

WP1 – Pre-processing: Bio-based solvents such as GVL and DMSO show promise for sustainable dye and elastane removal, but present trade-offs related to energy demand, solvent recovery, and toxicity for some chemicals.

WP2 – Fibre-to-fibre recycling: Ioncell® stands out as the most sustainable among the assessed options due to low toxicity, high solvent recyclability, and potential integration with renewable energy. Viscose and Lyocell processes face challenges in energy use and chemical hazards.

WP3 – PFAS-free water-repellent coating: SSbD scoping workshops highlighted performance-related trade-offs such as reduced durability and re-application needs, along with data gaps regarding the toxicity of some formulation components.

WP4 – Biobased printable ink with removability feature: The technology supports circularity through print removal and reuse, but unresolved issues remain around binder performance, end-of-life impacts, and scalability.

Across all cases, shared challenges include limited data on solvent recovery, occupational safety, system boundary definitions, and environmental impacts during disposal. These uncertainties underscore the need for further data development and iterative refinement.

Task 6.1 served as a crucial first step in identifying the sustainability potential and trade-offs of low-TRL textile innovations. By applying qualitative screening tools, it:

- Enabled early identification of key risks and opportunities across environmental, economic, and social dimensions;
- Provided structured decision-support for the technology developers in WP1–4;
- Highlighted knowledge gaps that require further investigation before proceeding to detailed assessments;
- Aligned early-stage innovation with the principles of Safe and Sustainable by Design (SSbD);
- Established a foundation for more targeted quantitative assessments and future process improvements.

Based on the outcomes of Task 6.1, the following recommendations are proposed:

Prioritize further development of the most balanced and promising technologies (e.g. Ioncell, GVL, DMSO-based systems) while addressing highlighted sustainability risks.

Conduct deeper analysis of solvent recovery efficiency, toxicity profiles, and end-of-life behavior of materials to fill critical data gaps.

Integrate early findings into ongoing design iterations to improve safety, circularity, and economic viability.

Continue stakeholder engagement to validate assumptions, refine trade-offs, and co-develop optimization strategies.

The results of Task 6.1 offer a valuable baseline to guide the next stages of innovation, ensuring that sustainability is embedded from the outset in the development of novel textile solutions.

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