

## D4.2 Framework for “Safe and sustainable by design”

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## LIST OF ABBREVIATIONS

<b>Abbreviation</b>	<b>Definition</b>
ATEX	Explosive Atmospheres
BC	Black Carbon
BOD	Biochemical Oxygen Demand
CEAP	Circular Economy Action Plan
CEN	European Committee for Standardization
CLP	Classification, Labelling and Packaging
DPP	Digital Product Passport
EC	European Commission
ECHA	European Chemicals Agency
E-LCA	Environmental Life Cycle Assessment
ERA	Environmental Risk Assessment
ESPR	EcoDesign for Sustainable Products Regulation
EU	European Union
GHG	Greenhouse Gas
GWP	Global Warming Potential
HRA	Human Risk Assessment
ISO	International Organization for Standardization
JRC	Joint Research Centre
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MCI	Material Circularity Indicator
OECD	Organisation for Economic Co-operation and Development
OELs	Occupational Exposure Limits
PA	Polyamide
PAHs	Polycyclic Aromatic Hydrocarbons
PET	Polyester
PLA	Poly(lactic Acid)
PM	Particulate Matter
PP	Polypropylene
PPE	Personal Protective Equipment
PROCs	Process Categories
PU	Polyurethane
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
RMC	Raw Material Consumption
SDG	Sustainable Development Goals
SEM	Scanning Electron Microscopy
SETAC	Society of Environmental Toxicology and Chemistry
S-LCA	Social Life Cycle Assessment
SOTA	State of the Art
SPERCs	Specific Environmental Release Categories
SRD	Small Rotating Drum

SSbD	Safe and Sustainable by Design
TEA	Techno-Economic Assessment
UN	United Nations
UNEP	UN Environment Programme
VOCs	Volatile Organic Compounds
WP	Work Package

## SUMMARY

Deliverable D4.2 outlines the development and planning of an integrated safety and sustainability assessment framework for bio-based textile materials within the BioFibreLoop project. It presents a structured approach combining human and environmental risk assessment (HRA/ERA), environmental life cycle assessment (E-LCA), circularity assessment, social LCA (S-LCA), and techno-economic assessment (TEA).

The document details the risk scoping methodology conducted, identifying priority exposure scenarios and potential hazards linked to lignin-, cellulose-, and PLA-based materials. While full assessments and experimental testing are planned for later stages, D4.2 establishes the conceptual and methodological work for data collection, stakeholder alignment, and SSbD-driven evaluations.

Moreover, D4.2 outlines how BioFibreLoop’s sustainability framework will contribute to selected UN Sustainable Development Goals (SDGs), such as good health and well-being (SDG 3), responsible consumption and production (SDG 12), and climate action (SDG 13). The use of the JRC SSbD framework will enable alignment between assessment results and product re-design opportunities, reinforcing the project’s commitment to sustainable innovation.

Despite challenges including limited experimental data and the complexity of cross-WP coordination, D4.2 delivers a solid strategic and methodological basis for the next phase of WP4. It ensures that future testing, data collection, and assessments will be consistent, transparent, and directed toward enhancing the safety, performance, and sustainability of circular bio-based textiles.

## 1. Introduction

BioFibreLoop aims at transforming textile production through the development of bio-based, circular, non-toxic, and environmentally sustainable materials, namely: lignin-based, cellulose-based, and polylactic acid (PLA)-based fabrics. This vision aligns with the European Commission’s Green Deal (EC, 2021), the European Chemicals Strategy for Sustainability (ECHA, 2022), and is guided by the Safe and Sustainable by Design (SSbD) framework (Caldeira et al., 2023).

However, achieving this transformation presents complex challenges and systemic barriers across the textile sector. These include, among others, the substitution of hazardous substances without compromising material performance, addressing information gaps on environmental and health impacts, and the pursuit of true circularity (Directory Sustainability, 2024; Oelze, 2017; United Nations Environment Programme, 2020).

### 1.1. Aims and objectives

The aim of D4.2 is to develop a comprehensive SSbD assessment framework tailored to the textile sector and integrated into the BioFibreLoop innovation process. This framework is designed to demonstrate BioFibreLoop’s sustainability by assessing the environmental impact of its processes and materials, as well as potential risks to workers and consumers.

Grounded in a phase-gate innovation risk governance approach, the framework integrates SSbD principles to evaluate the safety and sustainability of BioFibreLoop innovations. It combines top-down alignment with the SSbD framework and the Sustainable Development Goals (SDGs), with bottom-up stakeholder engagement to address the specific regulatory, technical, and operational needs of textile innovation.

This deliverable highlights key industrial challenges and proposes potential solutions emerging from the textile sector through the implementation of SSbD principles. Major challenges include the lack of integrated tools for comprehensive safety and sustainability assessments, as well as limited access to reliable data on chemical exposure, emissions, and end-of-life impacts, and the task of balancing material innovation with regulatory compliance and economic viability.

### 1.2. Safety and sustainability in the textile sector

The textile sector faces pressure to align with environmental and health regulations, reduce its ecological footprint, and transition toward more circular economy models. Traditionally, the textile industry follows linear “take-make-dispose” model, characterized by intensive resource extraction, short product lifespans, and limited consideration for end-of-life impacts

(Dan et al., 2023). Textile production also involves the use of hazardous chemicals, high water and energy consumption, and processes that generate significant waste and emissions. These practices contribute to substantial environmental degradation, including pollution, greenhouse gas emissions, and the accumulation of textile waste, while also raising concerns about worker and consumer health (Shirvanimoghaddam et al., 2020; To et al., 2019). In contrast, a circular approach aims to eliminate waste and pollution, keep materials in use for longer, and regenerate natural systems. Achieving this requires deep structural and technological changes within the industry (Chae & Hineostroza, 2020; Smith et al., 2017).

Regulatory developments such as the Ecodesign for Sustainable Products Regulation (ESPR) introduce life cycle based sustainability requirements, including durability, recyclability, and the restriction of hazardous substances (EC, 2024). Complementing this, the Digital Product Passport (DPP) serves as a key tool for enabling transparency, traceability, and data sharing across the value chain, thereby supporting compliance and facilitating the effective implementation of SSbD principles (EU, 2024).

In this context, the implementation of SSbD principles is crucial for fostering innovation while ensuring that new materials and processes are inherently safer and more sustainable from the design phase onward (Caldeira et al., 2023).

### 1.3. Expected impact of this D4.2

By developing a sector-specific SSbD assessment framework, this work addresses critical gaps in current practices and contributes to the broader transition toward a circular, non-toxic, and climate-resilient textile industry.

The proposed SSbD framework introduces a structured methodology for evaluating environmental, human health, and safety impacts across the entire life cycle of textile processes and materials. By embedding SSbD principles from the earliest stages of innovation, the framework supports the design of inherently safer and more resource-efficient solutions. Furthermore, the framework is designed to be practically applicable for researchers, product developers, and manufacturers. It enables early identification of risks, supports proactive mitigation strategies, and fosters alignment with EU sustainability goals, including the Green Deal, Circular Economy Action Plan (CEAP), and the Chemicals Strategy for Sustainability.

Ultimately, this work encourages innovation while ensuring that the drive for new processes and materials does not compromise the safety of people or the environment.

## 2. Partner contributions and interactions with other WPs

**Involved Partners:** DITF, IDENER, VTT, NIL, FreyZein, BEES, Knopf, BAT, A-Nov

This D4.2 presents the development of the SSbD Framework for BioFibreLoop, integrating a multidimensional assessment approach across Risk Assessment, Environmental Life Cycle Assessment (E-LCA), Social Life Cycle Assessment (S-LCA), Techno-Economic Assessment (TEA), and Circularity. This framework was developed collaboratively under Task 4.2, led by NFA, with contributions from a multidisciplinary consortium including DITF, IDENER, VTT, NIL, FreyZein, BEES, Knopf, BAT, and A-Nov.

NFA, as the task leader, coordinated the overall design and structuring of the framework, ensuring alignment with the JRC SSbD methodology and broader EU sustainability policies. NFA organized and facilitated workshops, synthesized input across domains, and is led the integration of technical, regulatory, and criteria into the framework.

Technical partners (DITF, NIL, FreyZein, BEES, Knopf, BAT, A-Nov) have been providing data on the BioFibreLoop materials and processes, supporting the identification of hazards, resource flows, exposure pathways, and circularity potential. Their contributions made s far also informed the benchmarking of alternative materials and technologies, enabling comparative assessments aligned with SSbD goals.

IDENER is contributing to the digital modelling and techno-economic analysis aspects of the framework, focused on economic cost-benefit analysis. VTT, in turn, holds responsibility for the circularity assessment component.

All partners contributed to collaborative activities including two dedicated workshops on SDGs alignment, held on 3 April and 20 May 2025, as well as a qualitative risk scoping session initiated in February and finalized during the General Assembly in Tampere (3-5 June 2025). Partners also jointly compiled a list of relevant testing needs, and a structured SharePoint repository was established to support centralized data collection on material composition, and process flows.

These contributions enabled the framework to reflect the complexity and specificity of the different material categories, and ensured that safety and sustainability considerations were embedded early in the design and innovation process.

Within WP1 (Material Design and Development), the SSbD framework directly informs early-stage design decisions by introducing structured safety, sustainability, and circularity criteria. This iterative feedback loop enables the integration of SSbD principles into material development, allowing potential risks and sustainability hotspots to be identified and addressed through proactive redesign.

This D4.2 also contributes substantively to WP6 (Communication, Dissemination, and Exploitation). The SSbD framework offers a transparent, policy-aligned structure for articulating the project’s commitment to responsible innovation. Core elements such as SDG integration, life cycle risk analysis, and circularity indicators, support effective stakeholder communication and position BioFibreLoop as a reference model for sustainability in the textile sector.

### 3. Methodological approach and scientific activities

#### 3.1. Development of a conceptual SSbD Framework

A preliminary conceptual version of the framework was developed and shared with the BioFibreLoop project’s partners (Figure 1). The framework was constructed by starting from the expected endpoints (Output), namely the SDGs (UN, 2025) to which the BioFibreLoop project aims to contribute; then tracing backward through the assessment criteria, methodologies (Approaches), and associated indicators to determine the necessary (Inputs) data, across the four dimensions: Safety, Environmental, Social, and Economic. Each dimension will be linked to specific tools and indicators, such as Human and Environmental Risk Assessment (HRA/ERA), Environmental Life Cycle and Social Life Cycle Assessment (E-LCA/S-LCA), and Techno-Economic Assessment (TEA) (Figure 2).

*Figure 1. BioFibreLoop framework’s graphical sketch idea.*

This first version was conceived on life cycle thinking approach aimed to align cross-sectorial sustainability assessments elements and ensure consistency with the United Nations (UN) SDGs and the strategic objectives of the EU Green Deal (EC, 2021).

The framework was further refined through roundtable discussions within project partners, incorporating continuous feedback in a bottom-up approach that integrated case-specific insights into a comprehensive human and environmental risk scoping analysis throughout the life cycle.

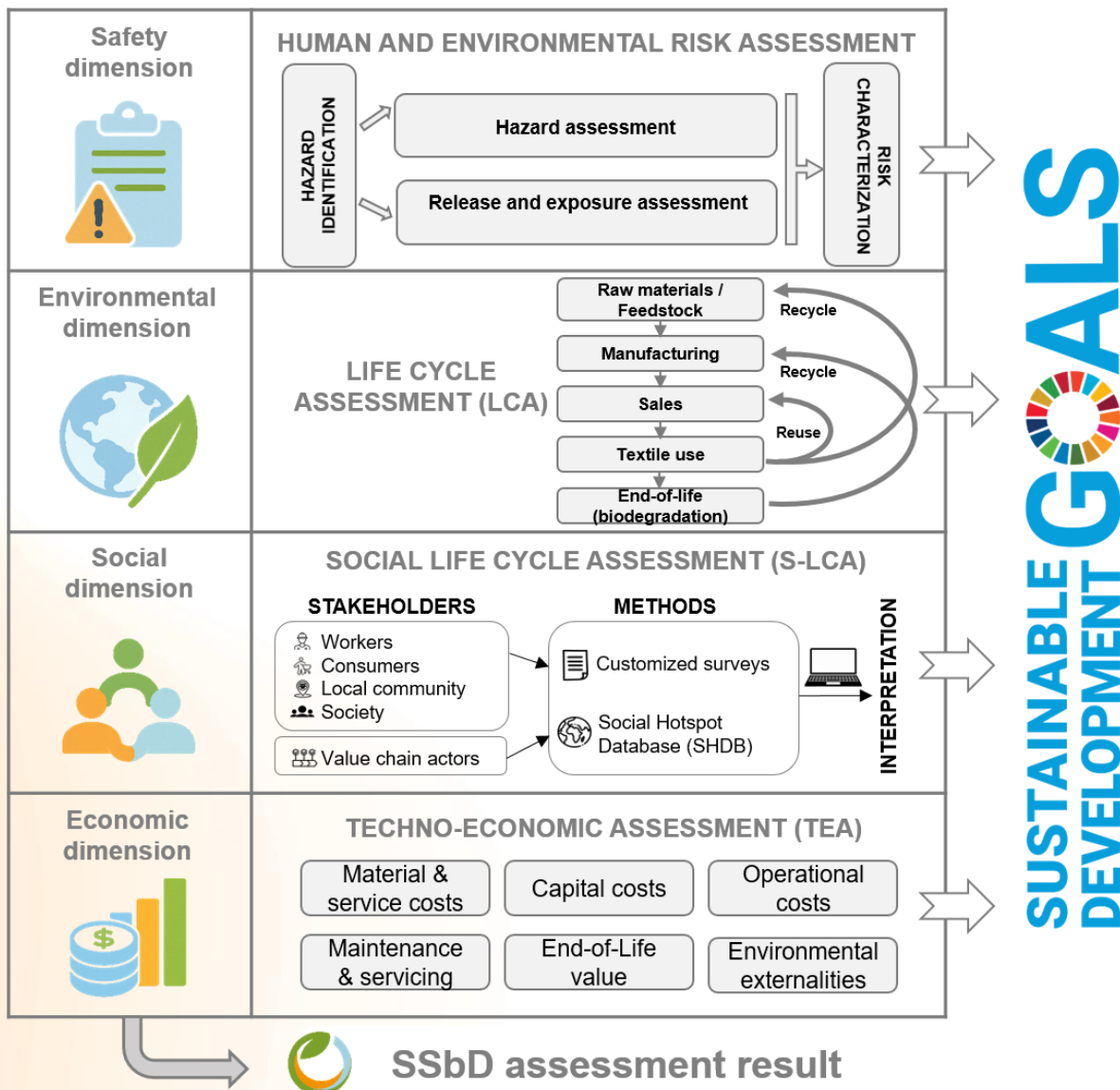


Figure 2. Conceptual framework for the overall sustainability assessment in BioFibreLoop (Fischer et al., 2025).

### 3.2. Identification of SDGs and alignment with the textile industry in the EU context

This section outlines the process followed for identifying the most relevant SDGs within the context of the EU textile industry, in alignment with the objectives of the BioFibreLoop project. The process was complemented by a bottom-up discussion and further refinement in collaboration with project partners; and where possible, these SDG indicators were integrated with additional, specific indicators proposed by expert partners within the BioFibreLoop project.

The process followed a three-step approach, detailed in the following subsections.

### 3.2.1. Building on the innovation goals outlined in the project objectives

As a first step, we referred to the section of the BioFibreLoop project objectives “*Comparison of the State of the Art and BioFibreLoop’s Innovation*”, which outlines the project’s expected innovations and strategic objectives. This provided a foundation for identifying potential SDGs to which BioFibreLoop could contribute, as well as relevant indicators to be used for evaluating the project’s sustainability impacts.

#### ■ Textile Materials

In the textile materials section, the substitution of petroleum-based materials with bio-based textile alternatives is expected to have an impact on:

- **SGD 12 - Responsible Consumption and Production:** with possible indicators identified within: *Circular material use rate; Consumption of hazardous chemicals; Usage of biodegradable materials.*

#### ■ Functionalization

In the functionalization section, BioFibreLoop aims to replace conventional wet chemical treatments, which involve hazardous perfluorinated organic compounds with a multifunctional, laser-enabled mechanical functionalization process. This innovative approach eliminates the use of hazardous substances, significantly reducing environmental, health, and safety risks. Replace existing technologies that rely on high-power pulsed UV lasers and high-frequency electrical discharge plasma with the cost-efficient and scalable BioFibreLoop solution. Moreover, BioFibreLoop avoids the use of composite membranes, which are difficult to recycle. Instead, fabrics are coated solely with lignin and mechanically embossed, enhancing both biodegradability and end-of-life recyclability. Upgrade the existing laser-based master plate system to a continuous roll-to-roll system. All these technological innovations can have an impact on the SDGs:

- **SDG 3 - Good health and well-being:** with possible indicators identified within: *Consumption of hazardous chemicals; People exposed to hazardous substances in the textile production process.*
- **SDG 6 - Clean Water and Sanitation:** with possible indicators identified within: *Volume of wastewater and chemical pollutants discharged (Effluents reduction); Nitrate in groundwater (Water quality); Biochemical oxygen demand in rivers (Water quality)*
- **SDG 7 - Clean energy:** with possible indicators identified within: *Energy consumption per unit of textile produced (Green processing).*

- **SDG 8 - Decent work and economic growth:** with possible indicators identified within: *Sustainable economic growth: Material footprint - also referred to as raw material consumption (RMC).*
- **SDG 9 - Industry, innovation and infrastructure:** Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation.
- **SDG-12 - Responsible Consumption and Production:** with possible indicators identified within: *Consumption of hazardous chemicals; Percentage of biodegradable materials used in the final product (Usage of biodegradable materials); Circular material use rate (Waste generation and management); Generation of waste (Waste generation and management).*
- **SDG 13 - Climate action:** Take urgent action to combat climate change and its impacts; with possible indicators identified within: *Reduction of carbon footprint: Percentage reduction in GHG emissions compared to conventional textile production; Climate mitigation: Net greenhouse gas emissions.*
- **SDG 14 - Life below Water:** with possible indicators identified within: *Conserve and sustainably use the oceans, seas and marine resources for sustainable development; Global mean surface seawater acidity (Ocean health); Marine waters affected by eutrophication (Ocean health).*
- Circularity and Recycling

For the recycling and circularity, BioFibreLoop aims on designing products for durability and reuse, while enabling material-specific recycling strategies such as thermomechanical and solvent-based physical recycling. BioFibreLoop, will moreover, consider sustainability and safety aspects and integrate them into the design and development by exploring strategies for fibre reuse after end-of-life to reduce the amount of textile waste sent to landfills. From these innovations can be foreseen an impact on the SDGs:

- **SDG 12 - Responsible Consumption and Production:** with possible indicators identified within: *Percentage of biodegradable materials used in the final product (Usage of biodegradable materials); Circular material use rate (Waste generation and management); Generation of waste (Waste generation and management).*
- **SDG 3 - Good health and well-being:** Ensure healthy lives and promote well-being for all at all ages; with possible indicators identified within: *Consumption of hazardous chemicals; People exposed to hazardous substances in the textile production process.*
- **SDG 8 - Decent work and economic growth:** Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all; with possible indicators identified within: *Sustainable economic growth: Material footprint - also referred to as RMC.*

- **SDG 11 - Sustainable Cities and Communities:** *Make cities and human settlements inclusive, safe, resilient and sustainable; with possible indicators identified within: Waste recycling: increase the recycling rate of municipal waste; Increase recycling rate 20% by 2035; Circular material use rate (Waste generation and management); Waste minimization: through more efficient processing.*
- **SDG 15 - Life on Land:** *Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss; with possible indicators identified within: Ecosystem status: Phosphate in rivers; Usage of organic fibres: Percentage of natural fibres used sourced from organic agriculture;*

### 3.2.2. Initial SDG selection guided by sector-specific literature

Following the initial alignment of BioFibreLoop’s specific objectives with the official UN SDGs (UN, 2025), a preliminary focus was placed on those most relevant to the textile and fashion industry. This selection was guided by insights from the paper "*Sustainable Development Goals for Textiles and Fashion*" which provides a comprehensive analysis of how the sector intersects with global sustainability targets (Thakker & Sun, 2023).

As a result, it was then determined that BioFibreLoop’s project could contribute to ten of the seventeen SDGs defined by the United Nations (UN, 2025), including:

- **SDG 3 - Good health and well-being:** *Ensure healthy lives and promote well-being for all at all ages;*
- **SDG 6 - Clean Water and Sanitation:** *Ensure availability and sustainable management of water and sanitation for all;*
- **SDG 7 - Clean energy:** *Ensure access to affordable, reliable, sustainable and modern energy for all;*
- **SDG 8 - Decent Work and Economic Growth:** *Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all;*
- **SDG 9 - Industry, innovation and infrastructure:** *Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation;*
- **SDG 11 - Sustainable Cities and Communities:** *Make cities and human settlements inclusive, safe, resilient and sustainable;*
- **SDG 12 - Responsible Consumption and Production:** *Ensure sustainable consumption and production patterns;*
- **SDG 14 - Life Below Water:** *Conserve and sustainably use the oceans, seas and marine resources for sustainable development;*
- **SDG 15 - Life on Land:** *Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss.*

For each SDG were also identified the most appropriate indicators aligned with those selected by the European Union (EUROSTAT, 2025), along with the approaches (methodologies or tools) used to assess them. These include various approaches, such as specific data, quantitative modelling, qualitative assessments, or mixed methods. Each approach is defined by specific operational criteria that guide how data is collected, analysed, and interpreted.

### 3.2.3. Refinement through a collaborative, bottom-up approach

The initially shortlisted SDGs, indicators, and assessment approaches were shared with project partners for discussion, validation, and refinement. This was followed by participatory co-creation workshops to ensure that the selected goals reflected the practical realities, expertise, and perspectives of those directly involved in the implementation of the BioFibreLoop project.

During the workshop, three elements were discussed and refined through a step-wise approach, beginning with the review of the preliminary SDGs list identified for BioFibreLoop:

#### **1. Revision and validation of relevant SDGs**

The preliminary list of SDGs was reviewed to determine which goals were most closely aligned with BioFibreLoop’s objectives and its context within the textile and fashion industry. The selected SDGs were validated, prioritized, and considered for implementation based on their relevance and potential impact.

#### **2. Identification of endpoints and indicators**

For each selected SDG, specific and measurable endpoints and indicators were identified to assess the project's contribution. These indicators were refined to address key assessment dimensions (Safety, Environmental, Social, and Economic) and were linked to suitable evaluation approaches such as human and environmental risk assessment, E-LCA, S-LCA, and TEA. Where possible, baseline or reference values were established to measure impact by determining deviations in key indicators over time.

#### **3. Definition of evaluation approaches and methodologies**

Appropriate methodologies were selected for assessing progress against each indicator. These included quantitative, qualitative, and mixed-method approaches, ensure robust data collection, analysis, and interpretation aligned with the project's objectives and reporting requirements.

This collaborative process was undertaken to develop a framework tailored to BioFibreLoop's products and processes, aimed at assessing safety and sustainability in the light of the SDGs.

### 3.3. Establishment of SSbD framework

The sustainability framework was developed by integrating considerations and procedures for HRA/ERA, as well as E-LCA and S-LCA, and TEA.

Once the identification of SDGs and the alignment with the textile industry in the EU context was completed. A case-specific risk scoping analysis was conducted in order to identify the perceivable foreseen risks and relevant data needs (including existing knowledge gaps and priorities for further testing and measurement) and to further shape the indicators to perform the safety and sustainability assessments.

The information requirements for the assessments were identified and data will be a mixture of qualitative and quantities data as well as read-across data due to the innovation stage and practical limitations to map the entire value chain for each of the fabric type and associated processes within the BioFibreLoop project. Data will be collected through a combination of measurements, literature reviews, derived estimates, and modelling techniques.

### 3.4. Risk scoping

Risk scoping is a foundational step in advancing SSbD principles, enabling early identification of potential human health and environmental hazards before full-scale data becomes available. Within the BioFibreLoop project, where novel textile materials based on lignin, cellulose, PLA, and lignin-based coatings are under development, scoping plays a critical role in guiding risk-informed innovation.

While a comprehensive risk assessment typically integrates detailed hazard and exposure data across all life cycle stages, such data is often limited during early-stage development. Therefore, risk scoping was implemented as a qualitative screening tool to evaluate potential exposure scenarios across the textile value chain. This includes human (worker and public) and environmental exposure pathways (e.g., air, water, and soil contamination), allowing early identification of critical risk hotspots and data needs for further testing and refinement.

Important to note that, although raw material production (feedstock extraction and processing) was included in the life cycle mapping, it was considered out of scope for detailed risk characterisation within the project. Risk scoping instead focused on downstream processes where the project partners exert design or process control (Figure 3).

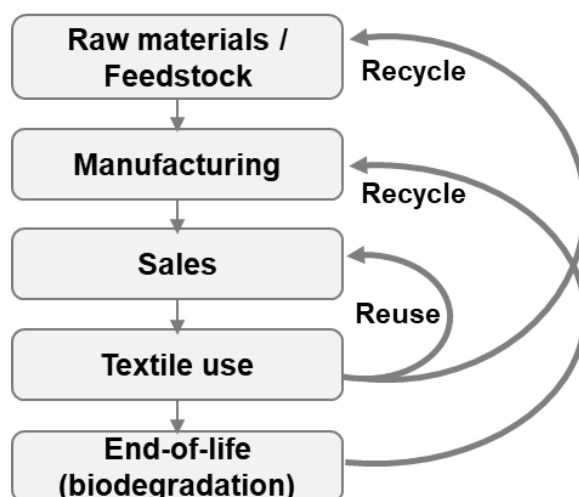


Figure 3. BioFibreLoop life cycle stages (elaborated by NFA).

The risk scoping followed a structured, and qualitative approach comprising:

- Mapping of relevant life cycle stages for each textile type and associated release/exposure scenarios.
- Scoring of release likelihood and exposure duration, each on a 1-10 scale (Figure 4).
- Calculation of a risk score as the product of likelihood and duration, ranging from 1 to 100 (Figure 4), used to rank human and environmental risk potential across compartments (air, water, soil) (Figure 4).

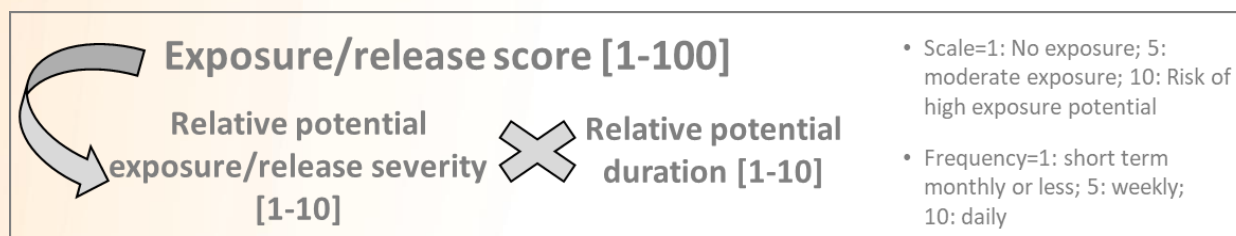


Figure 4. Equation used for calculating exposure/release scores.

The identification of relevant life cycle stages and processes was conducted through consultations with WP1, WP2, and WP3. Initial scoring proposals were made by WP4, followed by collaborative refinement with the contributing WPs to ensure scientific validity and project-wide alignment.

The outcomes of the risk scoping serve as key inputs for HRA, ERA, LCA and Sustainability Assessment (within WP4). Moreover, this approach helps to identify knowledge gaps, data needs, and testing priorities for subsequent stages of the project. Data sources include measured, modelled, literature-derived, and industry-supplied information.

The risk scoping process was initiated during a dedicated workshop on 18 February 2025 and finalized during the General Assembly in Tampere on 3 June 2025, contributing to the Milestone 9.

### 3.5. Identification of benchmark materials and processes

To contextualize and evaluate the performance, sustainability, and safety of the BioFibreLoop textiles and functionalization technologies, relevant benchmark materials and processes were identified. These serve as reference points to assess how the BioFibreLoop innovations compare with existing market standards across multiple benchmarking criteria (e.g. safety, sustainability, market competitiveness, performance, and processing feasibility).


The selection of benchmark materials and processes is guided by:

- Market relevance and prevalence;
- Known environmental and health impacts;
- Performance in similar applications (woven, knitted, or non-woven textiles);
- Potential for meaningful comparison based on LCA, mechanical testing, and user-facing attributes.

These benchmarks provide reference baselines for assessing the relative performance of BioFibreLoop materials in WP4 evaluations, including LCA, sustainability assessments, and SSbD alignment.

The table below summarizes the identification and selection of benchmark materials for each of the three BioFibreLoop textile categories (Table 1).

*Table 1. Identification and selection of benchmark materials. An “X” in the last column denotes materials chosen for further evaluation.*


	Potential benchmark material	Justification for selection	Comparison to BioFibreLoop material	Comments	Selection (X added if selected)
Lignin-based woven or knitted fabrics	Cotton	Widely used in woven textiles; biodegradable and natural	To be evaluated based on mechanical, environmental, and performance KPIs in WP4.	Benchmark relevance and impact to be further validated through LCA and material testing.	
	Polyester (PET)	Industry standard synthetic fibre in woven and/or fabrics; durable, cheap, and strong			X
	Polyamide (PA)	Industry standard synthetic fibre in woven and/or fabrics; durable, cheap, and strong			

Cellulosic-based knitted/woven fabrics	Traditional rayon	First-generation regenerated fibre; benchmark for drape and softness			
	Tencel (Lyocell)	Modern standard for sustainable regenerated fibres; strong, breathable, low-impact			X
	Polyester (PET)	Industry standard synthetic fibre in woven and/or fabrics; durable, cheap, and strong			X
	Bamboo viscose	Popular in active wear; perceived as eco-friendly			
PLA-based knitted, woven and non-woven fabrics	PET (polyester) non-woven	Common in non-woven technical textiles			X
	Polypropylene (PP) & Nylon	Widely used synthetics for non-woven and active wear			
	CLY or viscose blends	Alternative and more sustainable choices for non-woven			

Materials such as Tencel (Lyocell) and PET were selected for detailed comparison due to their strong market presence and well documented sustainable profiles.

Potential benchmark functionalisation and finishing processes were also identified to compare with BioFibreLoop's surface engineering and coating approaches (Table 2).

Table 2. Identification and selection of benchmark processes. An “X” in the last column denotes processes chosen for further evaluation.

 biofibrel loop	Potential benchmark process	Market Products	Justification for selection	Comparison to BioFibreLoop process	Comments	Selection (X added if selected)
Lignin coating (DITF)	Polyurethane coating	PU	Standard industrial method for chemical surface modification and functional finishing	To be assessed based on safety, functionality, resource efficiency, and alignment with SSbD criteria.	Initial benchmark selection; detailed performance analysis ongoing in WP4 activities.	X
Embossing functionalization (ALPHANOV)	Bio-based water-repellent eco-finishes	RUCO-DRY ECO PLUS	Commercially proven bio-based finish; used in textile industry	To be assessed based on safety, functionality, resource efficiency, and alignment with SSbD criteria.	Initial benchmark selection; detailed performance analysis ongoing in WP4 activities.	
		RUCO-DRY BIO CGR / BIO NPE	Bio-based water-repellent eco-finishes - SOTA*			X

		Huntsman ZELAN R3 / PHOBOL UXN	Fluorine-free commercial standards; regulatory-compliant and eco-preferred			
		ECOPERL (CHT Group)	Benchmark in water-repellent coatings from a major supplier			

\* State of the art. The referenced finishes represent the most advanced available technology in their category.

Among these, PU coating and RUCO-DRY BIO CGR were selected for initial benchmarking based on industrial relevance and availability of environmental and safety data. Further comparison of these processes with BioFibreLoop innovations will focus on functionality, resource use, safety, and SSbD compliance.

This benchmarking framework provides the foundation for comparative analysis in WP4, ensuring that BioFibreLoop solutions are not only innovative, but also competitive, sustainable, and safer than conventional alternatives.

## 4. Results

### 4.1. SSbD criteria, indicators and matrices

#### 4.1.1. Relevant SDGs, indicators, and assessment approaches

Table 3 presents the results for the key SDGs, indicators, and assessment approaches defined for the BioFibreLoop. It highlights the specific SDGs the BioFibreLoop project aims to contribute to, the indicators used to measure progress, and the methodological approaches adopted for their evaluation. This structured approach ensures a consistent and transparent assessment of the project's contribution to safety and sustainability objectives.

The first column lists the indicators to be assessed, which are grouped under their relevant SDGs to evaluate the project's impact. The second column outlines the corresponding assessment methods and approaches used to evaluate these indicators. The third column classifies each indicator and its methodology according to its sustainability dimension, providing an overall overview of the project's impact and, consequently, its contribution to sustainability.

*Table 3. Indicators, evaluation methods, and sustainability dimensions for BioFibreLoop SDG assessment.*

<b>Sustainable Development Goals (SDGs)</b>	<b>Assessment Methods*</b>	<b>Dimension</b>
<b>SDG 3: Good health and well-being:</b> <i>Ensure healthy lives and promote well-being for all at all ages</i>		
Consumption of hazardous chemicals	HRA, LCA	SAFETY, ENVIRONMENTAL
Ozone formation, Human health	LCA	ENVIRONMENTAL
Fine particulate matter formation	LCA	ENVIRONMENTAL
Ionizing radiation	LCA	ENVIRONMENTAL
Human carcinogenic toxicity	LCA	ENVIRONMENTAL
Human non-carcinogenic toxicity	LCA	ENVIRONMENTAL
People exposed to hazardous substances in the textile production process	HRA, S-LCA, EA	SAFETY, SOCIAL, ECONOMIC
<b>SDG 6: Clean Water and Sanitation:</b> <i>Ensure availability and sustainable management of water and sanitation for all</i>		
Nitrate in groundwater (Water quality)	LCA, ERA	ENVIRONMENTAL, SAFETY
Biochemical oxygen demand in rivers (Water quality)	LCA, ERA	ENVIRONMENTAL, SAFETY
Water consumption	LCA	ENVIRONMENTAL
Volume of wastewater and chemical pollutants discharged (Effluents reduction)	ERA	SAFETY
<b>SDG 7: Clean energy:</b> <i>Ensure access to affordable, reliable, sustainable and modern energy for all</i>		
Energy consumption per unit of textile produced (Green processing)	LCA, EA	ENVIRONMENTAL, ECONOMIC
<b>SDG 8: Decent Work and Economic Growth:</b> <i>Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all</i>		
Sustainable economic growth: Material footprint - also referred to as raw material consumption (RMC) - Reduction of Raw Material Use	LCA, EA	ENVIRONMENTAL, ECONOMIC
Employment rate [by sex] (Employment)	S-LCA	SOCIAL

<b>Sustainable Development Goals (SDGs)</b>	<b>Assessment Methods*</b>	<b>Dimension</b>
Fatal accidents at work (Decent work)	S-LCA, EA	SOCIAL, ECONOMIC
<b>SDG 9 - Industry, innovation and infrastructure:</b> <i>Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation</i>		
Reduction of Raw Material Use (Supports eco-innovation and sustainable industrial processes)/ Material footprint - also referred to as raw material consumption (RMC) - [Thousand tons and tons per capita]	LCA, EA	ENVIRONMENTAL, ECONOMIC
Reduction of Greenhouse Gas Emissions (Promotes low-carbon technologies and sustainable infrastructure)	LCA	ENVIRONMENTAL
<b>SDG 11: Sustainable Cities and Communities:</b> <i>Make cities and human settlements inclusive, safe, resilient and sustainable</i>		
Environmental impacts: Recycling rate of municipal waste	ERA	SAFETY
Waste recycling: increase the recycling rate of municipal waste	LCA, EA	ENVIRONMENTAL, ECONOMIC
Increase recycling rate 20% by 2035	ERA, EA	SAFETY, ECONOMIC
Circular material use rate (Waste generation and management)	LCA	ENVIRONMENTAL
Waste minimization: through more efficient processing	EA	ECONOMIC
<b>SDG 12: Responsible Consumption and Production:</b> <i>Ensure sustainable consumption and production patterns</i>		
Fossil resource scarcity	LCA	ENVIRONMENTAL
Circular material use rate (Waste generation and management)	LCA	ENVIRONMENTAL
Generation of waste (Waste generation and management)	LCA, S-LCA, EA	ENVIRONMENTAL, SOCIAL, ECONOMIC
Consumption of hazardous chemicals	HRA, LCA	SAFETY, ENVIRONMENTAL
Land use	LCA	ENVIRONMENTAL
<b>SDG 13 - Climate action:</b> <i>Take urgent action to combat climate change and its impacts</i>		
Net greenhouse gas emissions (Climate mitigation)	LCA	ENVIRONMENTAL
Reduction of carbon footprint: Percentage reduction in GHG emissions compared to conventional textile production	LCA	ENVIRONMENTAL
<b>SDG 14: Life Below Water:</b> <i>Conserve and sustainably use the oceans, seas and marine resources for sustainable development</i>		
Freshwater Ecotoxicity	LCA	ENVIRONMENTAL
Marine Ecotoxicity	LCA	ENVIRONMENTAL
Global mean surface seawater acidity (Ocean health)	LCA, ERA	ENVIRONMENTAL, SAFETY
Marine waters affected by eutrophication (Ocean health)	LCA, ERA	ENVIRONMENTAL, SAFETY
<b>SDG 15: Life on Land:</b> <i>Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss</i>		
Terrestrial acidification	LCA, ERA	ENVIRONMENTAL, SAFETY
Terrestrial Ecotoxicity	LCA, ERA	ENVIRONMENTAL, SAFETY
Ozone formation, Terrestrial ecosystems	LCA, ERA	ENVIRONMENTAL, SAFETY
Phosphate in rivers (Ecosystem status)	LCA, ERA	ENVIRONMENTAL, SAFETY
Usage of organic fibres: Percentage of natural fibres used sourced from organic agriculture	S-LCA, ERA	SOCIAL, SAFETY

\*Assessment Methods: Human Risk Assessment (HRA); Environmental Risk Assessment (ERA); Life Cycle Assessment (LCA); Social Life Cycle Assessment (S-LCA); Economic Assessment (EA).

4.1.2. SSbD framework as a matrix

The BioFibreLoop SSbD framework is structured as a matrix of three interrelated components: the SDGs and their corresponding sustainability indicators, the approaches (methods/tools) which include specific data sources, quantitative modelling, qualitative assessments, or mixed-methods analyses, and the sustainability dimensions, categorized into safety, environmental, social, and economic domains. Each approach is defined by specific operational criteria that guide how data is collected, analysed, and interpreted. This matrix-based structure is visualized in Figure 5, which illustrates how SDGs, indicators, and assessment methods are interconnected to enable a holistic sustainability evaluation.

BioFibreLoop - Framework Overview										
SDG	SDG 3 3 Good Health and Well-being	SDG 6 6 Clean Water and Sanitation	SDG 7 7 Affordable and Clean Energy	SDG 8 8 Decent Work and Economic Growth	SDG 9 9 Industry, Innovation and Infrastructure	SDG 11 11 Sustainable Cities and Communities	SDG 12 12 Responsible Consumption and Production	SDG 13 13 Climate Action	SDG 14 14 Life Below Water	SDG 15 15 Life on Land
Sections										
<b>1) Safety</b>										
Indicator-Sof1										
Indicator-Sof2										
Indicator-Sof3										
Indicator-Sof4										
<b>2) Environmental</b>										
Indicator-Env1										
Indicator-Env2										
Indicator-Env3										
Indicator-Env4										
<b>3) Social</b>										
Indicator-Soc1										
Indicator-Soc2										
Indicator-Soc3										
Indicator-Soc4										
<b>4) Economic</b>										
Indicator-Ecn1										
Indicator-Ecn2										
Indicator-Ecn3										
Indicator-Ecn4										
HR4					X		X			
ER4		X						X		X
LCA		X			X	X	X	X		
S-LCA			X		X	X		X		
TEA/LCC - ESG										

Figure 5. BioFibreLoop SSbD framework matrix structure.

Furthermore, the framework should be applied across all life cycle stages of BioFibreLoop textiles. This life cycle-based application is illustrated in Figure 6.

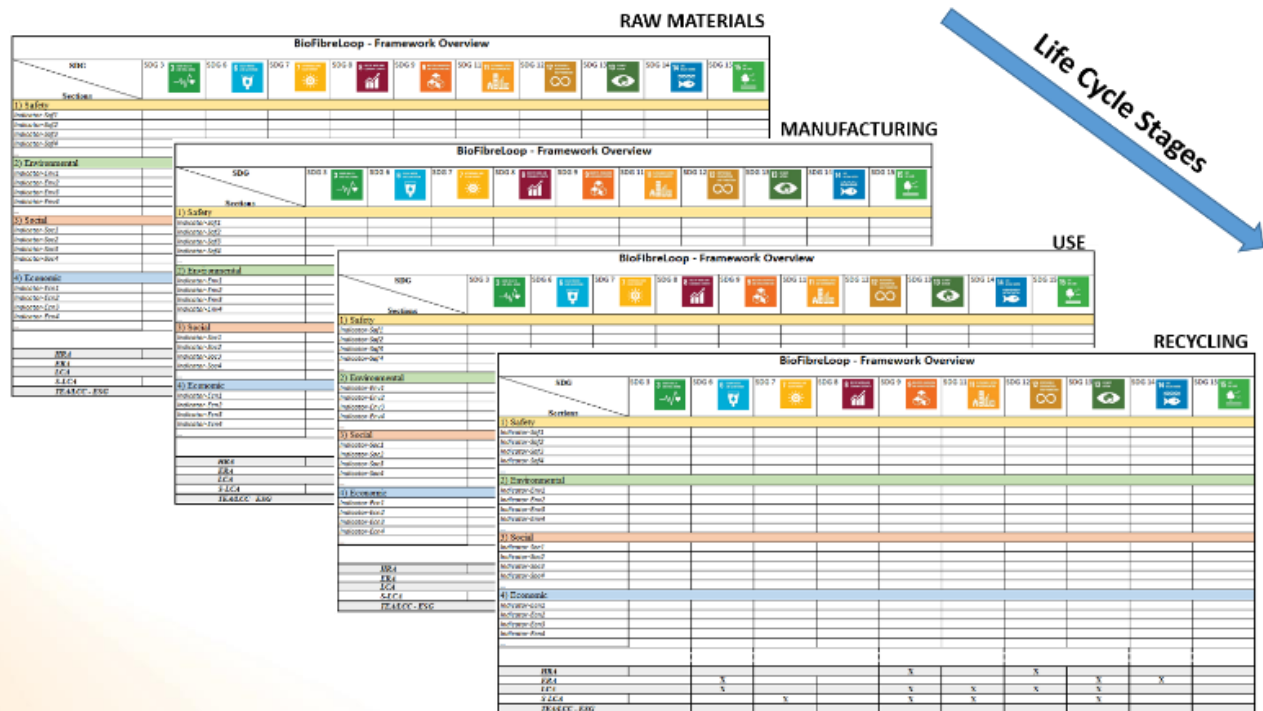


Figure 6. Framework application across the product life cycle.

The assessments must be carried out for each product category and its associated processes, ensuring comparability and capturing process-specific challenges and opportunities.

### Safety dimension

The safety assessment covers both hazard and exposure, with evaluations carried out through HRA and ERA. These identify potential human and ecological risks using experimental data, predictive modelling, and qualitative scaling, particularly important in early development stages where full datasets may be lacking.

### Environmental and Social dimensions

LCA and S-LCA methodologies are used to assess the environmental and social performance of BioFibreLoop textiles. These approaches support decision-making around materials, processes, and supply chains by quantifying impacts such as emissions, resource use, and work-related concerns.

### Economic dimension

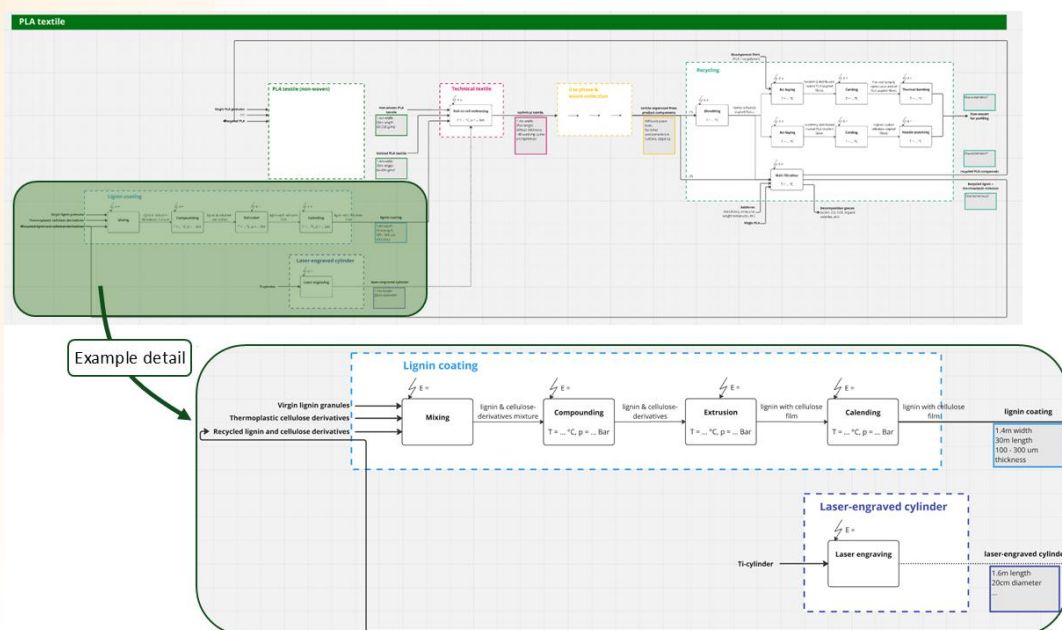
The economic evaluation is conducted through a TEA. Potential economic impacts are closely linked to changes in human health and environmental outcomes across the product life cycle. These impacts influence the overall economic costs and benefits associated with the product or process.

## 4.2. Risk scoping

Risk scoping plays a role in the early identification and prioritization of potential health and environmental impacts associated with new materials and technologies developed in BioFibreLoop. By mapping likely exposure and release scenarios across the full life cycle of the innovative textiles based on lignin, cellulose, and PLA, the project aims to proactively steer development along an SSbD pathway.

This section presents the outcome of a structured, qualitative risk scoping, conducted for both human health (occupational and public exposure) and environmental emissions (air, water, soil), across each stage of the textile life cycle from raw material sourcing and manufacturing to use phase, recycling, and end-of-life. The approach is not intended as a final risk assessment but as a screening and prioritization tool to inform the scope and depth of subsequent evaluations such as LCA, exposure measurements, modelling, and toxicological testing.

To support the identification of relevant scenarios, the project adopted a bottom-up, data-informed approach. Risk scenarios were developed based on detailed process and material flowcharts, which reflect the actual production, treatment, and use pathways of the innovative textiles. These flowcharts were constructed collaboratively by project partners under Tasks 4.2, 4.3, and 4.5, coordinated by DITF. Figure 7 presents a screenshot of one of these flowcharts, developed on the Miro platform, illustrating the PLA textile pathway and a zoomed-in detail on lignin coating. This visualization reflects the level of granularity used to understand each unit operation, including inputs, outputs, process interdependencies, and transformation steps.



*Figure 7. Flowchart for PLA Textile and zoom on Lignin coating as detailed example (Source: BioFibreLoop D4.1 - Guiding design principles).*

Building upon these structured flowcharts, the WP4 team, in close collaboration with WP1, WP2 and WP3, developed a series of risk scenarios, which were assessed for:

- Severity, based on the intrinsic hazard or potential for significant emissions or exposures, and
- Duration, reflecting the frequency or persistence of the scenario (e.g. daily, weekly, batch-based).
- Final risk scores were calculated as the product of severity and duration, yielding a final score ranging from 1 to 100. These scores allow comparison across materials, processes, and life cycle stages, and serve as an evidence base for prioritizing mitigation measures, redesign needs, or further analytical steps.

To ensure transparency, consistency, and alignment with regulatory standards, the risk scoring methodology relied on a combination of project-specific data, including material compositions, operational parameters, expected use, and end-of-life profiles, and established regulatory references. These included the Classification, Labelling and Packaging (CLP) Regulation N° 1272/2008 (EC, 2008), which provides the framework for hazard classification based on physical, health, and environmental risks, the REACH Regulation N° 1907/2006, particularly with regard to substance registration and authorisation requirements (EC, 2006), and ECHA’s harmonised use descriptor system, encompassing Process Categories (PROCs) and Specific Environmental Release Categories (SPERCs), to link exposure scenarios to typical industrial and professional activities (ECHA, 2015).

The resulting matrices and scores are available in Annex I - Human exposure risk scoping (Excel format) and Annex II - Environmental release risk scoping (Excel format).

#### 4.2.1. Human Risk Scoping

The human exposure assessment considered occupational and public risks across all stages of the textile life cycle, using qualitative scoring based on severity and duration of potential exposure. This approach, which is consistent with established frameworks for occupational exposure assessment in industrial environments (ECHA, 2016), assigns exposure scores as the product of severity and frequency, and categorizes them into three tiers: i) high exposure (score  $\geq 40$ ), ii) moderate exposure (25-39), and iii) low to negligible exposure ( $< 25$ ). Figure 8 presents these results in a radar plot format, with part (a) showing worker exposure and part (b) representing public exposure.

Among all assessed processes, the most critical occupational exposure scenarios were observed during manufacturing and end-of-life processing, particularly where lignin-based

materials were involved. Lignin is a complex, polyphenolic biopolymer derived from biomass that is increasingly utilized in bio-based composites, coatings, and textiles (Laurichesse & Avérous, 2014). In early-stage processing, lignin is commonly handled as a fine powder or granulate. These forms exhibit high dustiness and low bulk density, characteristics that contribute to airborne dispersibility under mechanical agitation (Evans et al., 2013; A. S. Fonseca et al., 2023; Lidén, 2006). Consequently, operations such as mechanical mixing and compounding of lignin yielded the highest exposure score of 70, reflecting both high severity and prolonged worker contact with airborne dusts and fumes. These tasks typically involve high shear agitation under open or semi-enclosed conditions, which promote localized particle suspension and increase inhalation risks (A. S. Fonseca et al., 2018; Miller et al., 2014). According to the CLP regulation, these activities are associated with specific target organ toxicity via single exposure (STOT SE, H335) and fall within process categories PROCs 1-4, corresponding to handling with low to moderate technical containment (ECHA, 2016). As a result, they also trigger REACH registration requirements, due to the potential for significant worker exposure to hazardous particulates over time.

Other manufacturing steps involving lignin or PLA, such as melt spinning, were assigned a score of 54. This score reflects the respiratory hazard associated with thermal by-products and fume emissions generated during filament formation. While these emissions are partially mitigated by enclosed systems, they may still present inhalation risks in inadequately ventilated settings (Myojo et al., 2017; Salmatonidis et al., 2019). Weaving processes that involve chemical treatments, such as finishing and sizing, received an exposure score of 42. These are linked to the use of skin and eye irritants, classified under H315 and H319, such as surfactants, resins, and binders (Medeni et al., 2025; Wernli et al., 2006). These processes typically occur in batch operations, often with limited local exhaust ventilation, thereby increasing the likelihood of dermal contact and occasional aerosol formation.

Recycling and shredding of textiles represented the most hazardous occupational scenario in the entire matrix, with an exposure score of 80. This score reflects the combination of high emission potential and limited containment. During end-of-life processing, textiles are mechanically fragmented into fibres and fine particles, which are readily respirable and may contain residual additives or lignin derivatives (Bartl, 2020; Nowack et al., 2021). The chronic nature of this exposure, typically performed in semi-open facilities, is a potential respiratory hazard. These tasks are classified under STOT SE (H335) and trigger REACH obligations due to the scale, frequency, and airborne nature of the emissions. The recycling process nature is therefore a priority for exposure mitigation through engineering controls, and personal protective equipment (PPE).

A comparable concern was identified in the professional use phase of textiles, which reached an exposure score of 50. In this context, textiles may degrade through abrasion, wear, or repeated handling, releasing low doses of inhalable fibres into confined indoor environments.

While the exposure is low, the cumulative nature of this chronic contact, especially in professions requiring prolonged garment use such as healthcare or industrial cleaning, elevates the long-term risk (Nowack et al., 2021; Palacios-Marín & Tausif, 2021). Inhalable particles generated through textile degradation are increasingly recognized in occupational hygiene for their potential contribution to airway inflammation and reduced pulmonary function over time (Lai & Christiani, 2013; Song et al., 2024).

In contrast, a range of processes were categorized within the moderate exposure tier. Film extrusion, calendaring, and chemical washing prior to coating scored 30, reflecting moderate severity due to controlled thermal and chemical emissions. These processes typically occur in structured batch setups with intermittent exposure and established safety protocols. Non-woven PLA processing was assigned a score of 25, mainly due to dust generation in open handling environments. Routine maintenance tasks, including filter cleaning and system checks, scored between 30 and 35, highlighting exposure to deposited residues such as fibre fragments and granulate dust. Similarly, bagging operations for recovered lignin compounds scored 35, as repeated manipulation of dusty materials in dry, large-volume settings can cause particle resuspension if not properly contained (OECD, 2014).

Public exposure, including that arising from consumer use and laundering, was also assessed. This phase received a score of 35, owing to the possibility of particle release from wear, fibre degradation, or repeated washing. Although the emissions are not classified as hazardous under CLP, their widespread and cumulative nature raises questions about chronic low-level exposure, especially in poorly ventilated places or sensitive subpopulations. Indoor air quality studies have linked textile-derived microfibres and particles to general airborne particulate burdens, highlighting the need to consider use-phase emissions in life cycle exposure assessments.

On the other end of the spectrum, processes such as embossing scored 20. These involve mechanical patterning with negligible emissions and minimal chemical use. Logistics-related steps, including transportation, storage, and downstream sales, consistently scored 1, reflecting minimal exposure risk outside of extreme scenarios like spills or combustion. Public exposure through stack emissions, whether near-field or far-field, was assigned a score of 14 and was not classified under CLP, indicating low hazard potential. Accidental damage to textiles during use or downstream handling scored below 10 due to their infrequent nature and low emission intensity.

Figure 8a illustrates the distribution of worker exposure scores across the life cycle and confirms that the highest risks are concentrated in manufacturing and recycling tasks, particularly those involving lignin. In contrast, Figure 8b shows that public exposure is generally limited, with only modest risks identified in association with stack emissions and repeated textile use. Both plots employ logarithmic scaling to highlight the sharp contrast

between high-exposure and low-exposure activities, emphasizing the need to prioritize risk mitigation at the identified hotspots along the chain.



Figure 8. Risk scoping scores of the potential exposure during the different steps along the life cycle considering: a) workers; b) the public.

#### 4.2.2. Environmental Risk Scoping

This section provides a qualitative assessment of environmental exposure potential across three compartments: ambient air, water, and soil. Each scenario along the textile life cycle was evaluated for emission likelihood, severity, and duration. Scores were calculated as the product of relative severity and frequency, following established environmental risk frameworks (ECHA, 2016; OECD, 2014), and categorized into high ( $\geq 40$ ), moderate (25–39), and low ( $< 25$ ) risk levels. As with the human risk scoping, the aim was to identify environmental hotspots to guide LCA refinement, exposure modelling, and SSbD decision-making.

##### *Ambient air risk*

The distribution of ambient air risk scores is shown in Figure 9. Airborne emissions were found to be most critical during the manufacturing and end-of-life stages, with processes such as compounding, melt spinning, film extrusion, and coating-calendering consistently scoring 42. These operations involve elevated temperatures, mechanical agitation, and chemical processing that contribute to the release of volatile organic compounds (VOCs), thermal degradation products, and particulate matter, particularly in open or semi-enclosed systems (Altun Kurtoğlu, 2021; Hu et al., 2018). Stack emissions, even with filtration systems, were associated with particle release near-field and far-field (scores of 56 and 54, respectively), reflecting both the release of ultrafine particles and the limits of emission capture technologies.

Fire and explosion scenarios (ATEX risks; Geng et al. 2020; Jespen, 2016) posed acute but highly severe air release events (score: 56), associated with uncontained combustion of fibre residues and volatile additives. In addition, cleaning and maintenance tasks during manufacturing phases (score: 35) contributed to airborne risks due to re-aerosolization of dust, fine residues, and detergent-derived VOCs, particularly in the absence of local exhaust ventilation (Medeiros et al., 2025).

Air emissions during the end-of-life stage were also significant, particularly from potential residual dry waste (score: 42) and recycling/shredding (score: 35), which released particulates and decomposition fumes under thermal and mechanical stress. These stages are often under less stringent control compared to production facilities and are a growing focus of environmental concern (Amicarelli et al., 2022; Fonseca et al., 2023).

In contrast, embossing, non-woven PLA processing, and closed-loop filtration systems showed negligible air emission scores, reflecting their physical nature and process containment. Such operations demonstrate high potential for inclusion in SSbD-aligned industrial strategies.

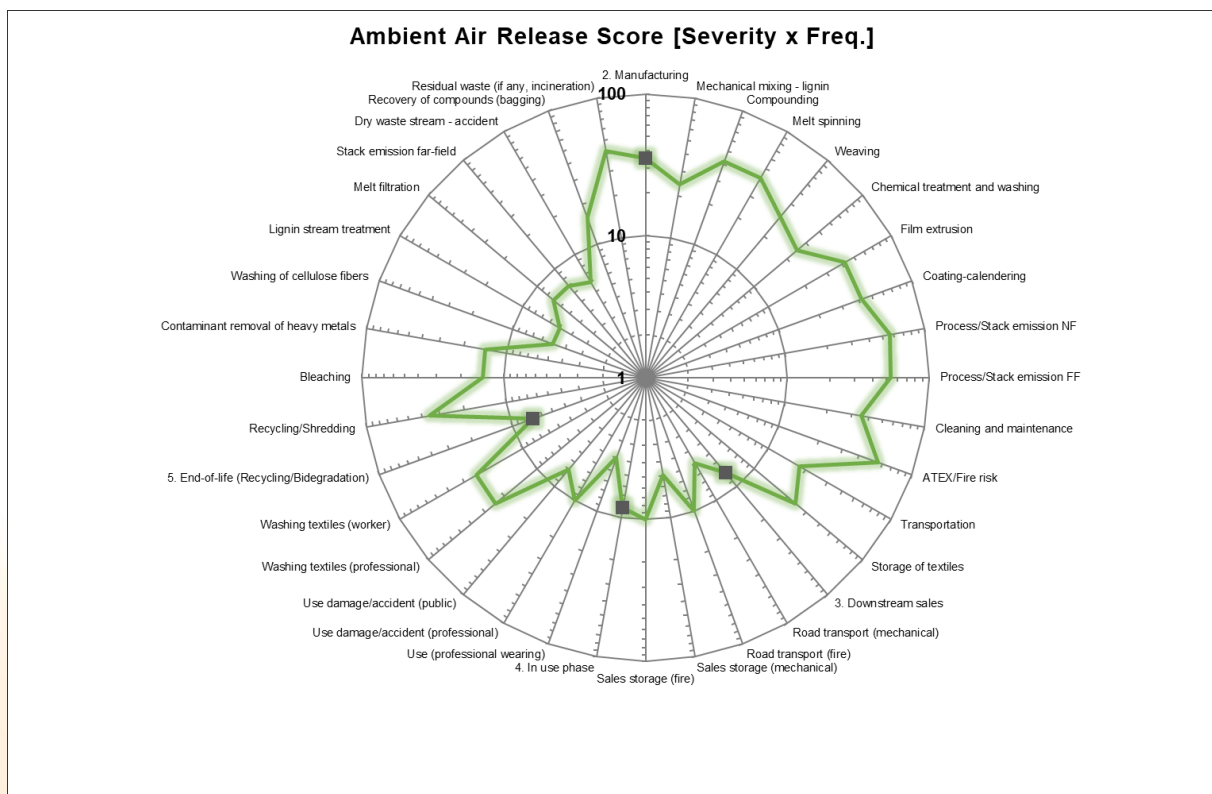


Figure 9. Risk scoping scores for potential environmental exposure to ambient air across the textile life cycle. Each axis represents a specific process step, and plotted values reflect the qualitative exposure score (severity  $\times$  frequency). Square symbols indicate the median score for each life cycle stage.

### Aquatic risk

Figure 10 shows the aquatic exposure scores across all life cycle stages. These risks were mainly associated with wet processing, washing operations, and cleaning cycles during textile production and use. Weaving with chemical treatment, chemical washing before coating, and cleaning and maintenance tasks all received aquatic exposure scores of 42, driven by frequent release of water-soluble substances such as surfactants, resins, and process chemicals into wastewater systems. These emissions are particularly concerning in facilities without closed-loop treatment or advanced filtration technologies and are often only partially removed during municipal wastewater treatment (Gambino et al., 2025; Khan et al., 2023).

Use-phase laundering, particularly in professional or industrial contexts, also received high aquatic risk scores (40). Repeated washing of textiles has been shown to release microfibres and fine polymer particles into wastewater, potentially contributing to microplastic pollution downstream (Tedesco et al., 2024).

Moderate aquatic emissions were observed in mechanical mixing, coating-calendering, film extrusion, and stack emissions, typically due to cleaning cycles, condensate recovery, or chemical rinsing which may lead to indirect water discharge. These activities received scores

ranging from 24 to 35, with variability depending on whether cleaning is automated or manual, and whether discharges are treated before release.

Low aquatic risk scenarios included compounding, melt filtration, and most end-of-life handling steps. These processes generally operate under dry, enclosed conditions with negligible contact with water systems. However, some minor aquatic risks were noted for bagging operations, residual waste, and washing of fibres, where scores ranged between 5 and 15 due to isolated handling or rinsing steps.

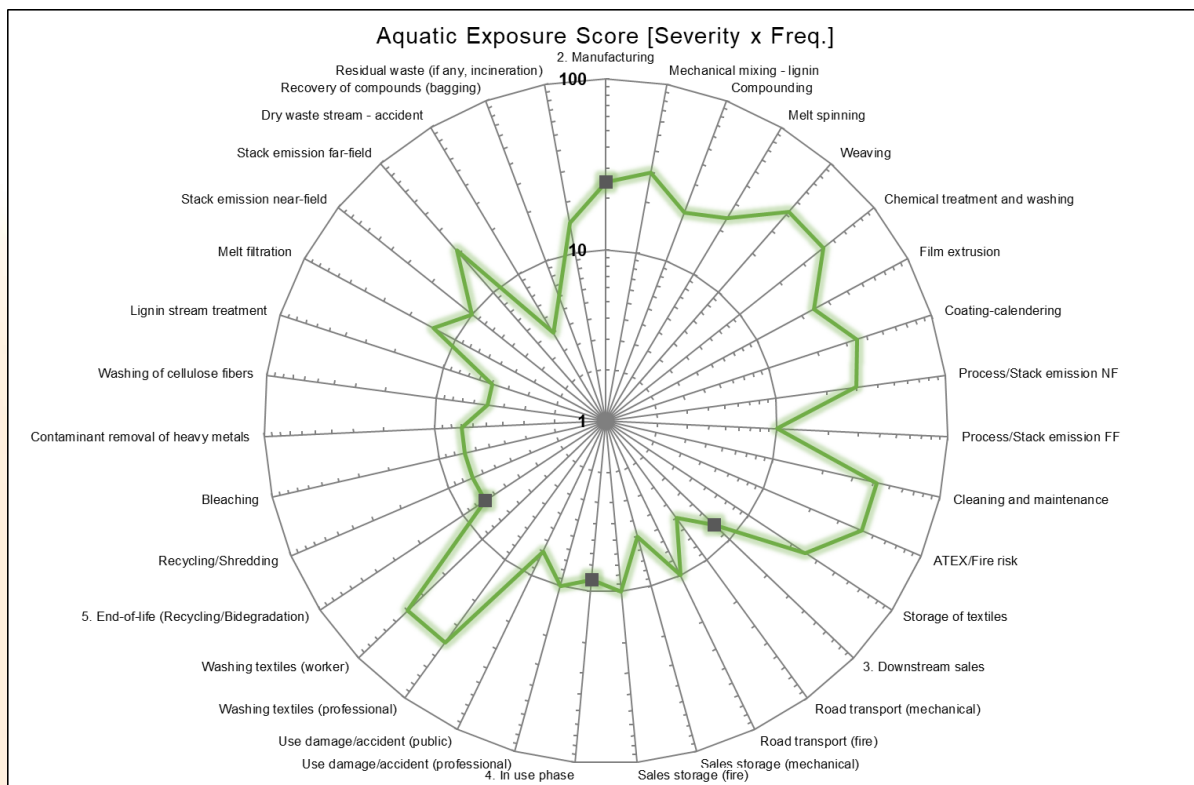


Figure 10. Risk scoping scores for potential environmental exposure to water during different life cycle steps. Exposure scores are based on estimated release severity and frequency. Square symbols denote the median aquatic exposure associated with each life cycle stage.

Soil risk

The soil exposure risk profile is summarized in Figure 11, which shows a narrower range of scores compared to air and water. Highest scores ( $\geq 30$ ) were attributed to ATEX/fire incidents, textile storage, and routine cleaning and maintenance. These scores reflect the potential for deposition of residues, chemical leaks, and settled dusts, which may accumulate in surrounding soil over time. Fire events (score: 35) while episodic, can result in persistent deposition of combustion by-products, unburnt fibre fragments, especially near poorly drained production sites.

Moderate soil risks (15-29) were linked to weaving with chemical treatment, waste from shredding and coating, and washing fibres, where solids or semi-solids could enter the

environment through poor handling, cleaning, or drainage. While not acutely hazardous, these residues may contain substances of concern and add to cumulative site contamination, particularly if unmanaged or frequently repeated.

Low soil risks (<14) were attributed to well-contained or thermally stable operations such as embossing, PLA processing, and standard transport and storage. Use-phase emissions, including wear or accidental fibre degradation, contributed minimally to soil exposure and were rated as very low risk.

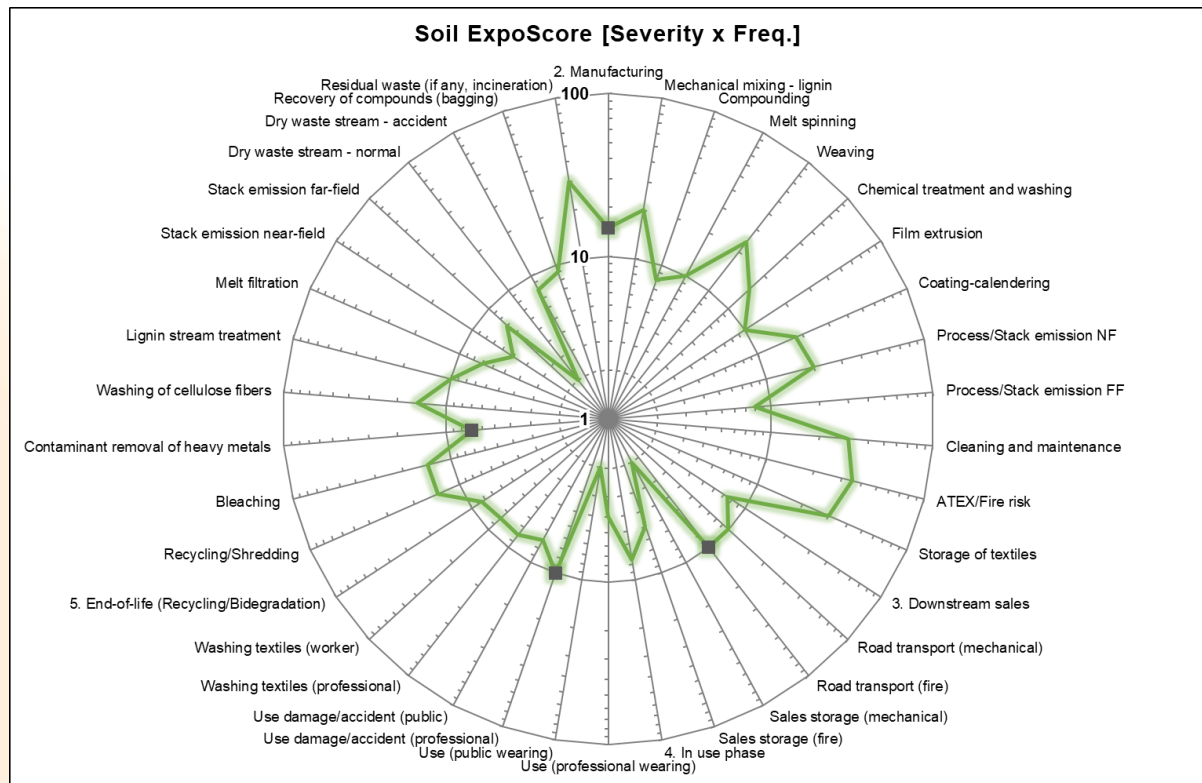


Figure 11. Risk scoping scores for potential environmental exposure to soil across the textile life cycle. Scores represent the relative potential for ground contamination based on process characteristics. Square symbols show the median soil exposure score for each stage.

## 5. Planning of integrated assessments

The BioFibreLoop project implements a multi-dimensional assessment framework to evaluate the sustainability and safety of bio-based textile innovations. Five complementary assessment dimensions are planned: 1) HRA/ERA, 2) E-LCA, 3) S-LCA, 4) Circularity Assessment, and 5) TEA. Together, these provide the methodological foundation for the SSbD approach, informing both environmental and health evaluations in WP4 and supporting commercialisation strategies in WP6. The following subsections outline the approaches, tools, and data sources foreseen for each assessment.

### 5.1. Human Risk Assessment (HRA)

Human exposure to airborne particulates is a critical concern, as inhalation of fine and ultrafine particles has been causally linked to respiratory diseases, cardiovascular morbidity, and cancer (Sharma et al., 2024; Thompson, 2018). While BioFibreLoop materials aim to enhance environmental sustainability, several stages in their life cycle, particularly compounding, melt processing, and recycling, present conditions likely to generate dusts, fumes, and thermal degradation by-products with inhalation relevance.

Lignin, often processed in powder or granulate form, can release respirable particles during high-energy operations. Due to its complex polyphenolic structure, lignin particles may induce pulmonary inflammation and oxidative stress, partly mediated by reactive oxygen species (Bhattacharya et al., 2007; Li et al., 2003). Although lignin is not classified as carcinogenic, its chemical heterogeneity and potential for oxidative reactivity necessitate toxicological scrutiny.

Cellulose fibres, especially regenerated or mechanically refined forms, may also contribute to inhalable dusts during non-woven formation, cutting, or weaving. These fibres exhibit high biopersistence and, depending on size and morphology, can behave similarly to poorly soluble fibrous particles. Short-term exposure studies in animals have shown that cellulose fibres can induce transient inflammation, granulomas, alveolitis, and fibrosis (Cullen et al., 2000, 2002).

PLA, generally considered biocompatible, may emit volatile by-products such as acetaldehyde and lactide during thermal processing, which are known mucosal and respiratory irritants (Gomes & Meek, 2001; Roe & Wood, 1992; Wojnowski et al., 2022). Dusts generated from cutting of PLA-based products could also contribute to workplace exposure, particularly in open or poorly ventilated settings.

Additional concerns arise from lignin-based coatings applied. Volatile solvents or aerosolised droplets may pose inhalation and dermal risks during application, while post-application, abrasion or wear of coatings could result in secondary release of microparticles, especially if coatings are porous or nanostructured.

The risk scoping carried out in WP4 identified mixing, melt spinning, chemical treatment, and mechanical shredding as the most exposure-intensive scenarios, particularly for lignin-based textiles. These overlap with well-established high-risk processes (e.g., composite sanding,

welding fume exposure) associated with inflammation and chronic lung effects. To characterize hazard potential, in vitro studies using A549 lung epithelial cells and THP-1 macrophage-like cells are underway. Endpoints include cytotoxicity, IL-8 mRNA expression for inflammation, and DNA strand breakage via Comet assay. These tests, combined with exposure data and material characterization, will enable a tiered risk assessment strategy aligned with SSbD principles.

#### 5.1.1. Exposure assessment

The risk scoping identified several high-risk exposure scenarios throughout the processing and recycling of lignin, cellulose, and PLA-based materials. Dust and fume generation are most prevalent during open-system tasks such as compounding, recycling, film extrusion, and thermal processing. Shredding yielded some of the highest risk scores due to chronic exposure to fine and potentially respirable particles. Airborne fibre release from matrices during cutting or wear has also been noted.

To characterize exposure, a multi-tiered approach will be implemented, combining real-time measurements, offline sample collection (CEN, 2018; OECD, 2015; Fonseca et al., 2021). Measurement campaigns at selected production and recycling facilities will target particle mass fractions (PM<sub>10</sub>, PM<sub>4</sub>/PM<sub>5</sub>, PM<sub>2.5</sub>), particle number concentration, particle size distributions, black carbon (BC), elemental carbon, and specific organics including polycyclic aromatic hydrocarbons (PAHs) and VOCs. Particular emphasis will be placed on quantifying ultrafine particles (<100 nm), given their disproportionate role in inducing oxidative stress and inflammation in pulmonary tissue. Particle morphology and chemical composition of collected filters will be characterized by using a scanning electron microscopy (SEM), enabling high-resolution imaging and identification of potentially hazardous structures, such as respirable fibres with high aspect ratios, known to contribute to chronic pulmonary effects.

In cases where direct measurements are not feasible due to accessibility or early development status, predictive exposure modelling will be performed using literature-derived release factors or read-across from analogous processes and materials.

To systematically evaluate the dust release potential of powders and granulates, the project will conduct dustiness experiments by using a Small Rotating Drum (SRD) method, in accordance with EN 17199-4:2019. This method simulates mechanical agitation processes such as pouring, and mixing, enabling reproducible generation of airborne particles under controlled conditions. The SRD enables both real-time data collection and offline sampling for SEM analysis

Exposure simulations in controlled exposure chambers will complement field measurements. These experiments will recreate specific handling and processing scenarios under standardized airflow and volume conditions, enabling reproducible evaluation of emission rates and particle behaviour.

### 5.1.2. Hazard assessment

Hazard characterization in the BioFibreLoop project will be based on both literature data and standardized in vitro testing strategies to evaluate the toxicological potential of lignin-, cellulose-, PLA-based materials, and lignin-coated fibres. These assessments focus on three key endpoints: cytotoxicity, inflammation, and genotoxicity, considered central biomarkers of adverse pulmonary and cardiovascular health effects.

Previous animal and human studies have consistently shown that inhalable particulate matter, including nanoparticles and textile-derived particles, can trigger acute phase responses in the lungs and are linked to diseases such as asthma, lung cancer, and cardiovascular disorders (Hadrup et al., 2020; Saber et al., 2013, 2014; Vogel et al., 2023). These biological responses are often mediated through oxidative stress, persistent inflammation, and DNA damage.

For BioFibreLoop materials, hazard assessment will be performed using two commercially available human cell lines: A549 (lung epithelial) and THP-1 (macrophage-like). These models will be exposed to lignin, cellulose, PLA particles, and lignin-coated fibres under submerged conditions to evaluate cytotoxicity, IL-8 mRNA expression (inflammatory response), and DNA damage (Comet assay for genotoxicity). This battery of assays is in alignment with OECD-recommended test strategies and has previously shown strong correlation with in vivo outcomes when normalized to particle-specific surface area (Di Ianni et al., 2021). The testing concentration range will be informed by particle surface area and expected workplace exposure levels.

In parallel, physicochemical characterization of the test materials will be performed to support hazard interpretation and possible read-across. Key properties will include particle size distribution, shape (assessed using scanning electron microscopy, SEM), and surface chemistry. These factors are known to influence cellular uptake, reactivity, and biological persistence, and thus are critical for understanding mode-of-action and inter-material comparability.

### 5.1.3. Risk assessment

The human risk assessment in BioFibreLoop integrates exposure characterization and hazard profiling to estimate health risks associated with lignin-, cellulose-, and PLA-based materials across their life cycle. This includes both acute and chronic exposure scenarios such as high-priority scenarios like compounding, shredding, and coating processes, as well as prolonged low-dose exposures during use or laundering.

Risk estimation will be based on a combination of methods: quantitative dose-response modelling where applicable toxicological or epidemiological data exist, qualitative assessments using risk matrices, and comparison with established occupational exposure limits (OELs). Where specific dose-effect relationships are lacking for novel materials, analogue approaches will be used, referencing known hazards from similar exposures.

The exposure component is grounded in empirical data from WP4 measurement campaigns and complemented by dustiness testing, particle characterization, and simulated exposure chamber scenarios. Migration and leaching studies, using human simulant fluids, will further inform potential systemic exposure through dermal routes.

## 5.2. Environmental Risk Assessment (ERA)

The environmental risk assessment in BioFibreLoop aims to characterize the potential environmental impacts of lignin-, PLA-, and cellulose-based textile materials, with particular attention to their degradability and ecotoxicological effects under realistic environmental conditions. While comprehensive exposure and fate modelling is beyond the project scope, two key experimental pillars (biodegradation testing and ecotoxicity screening) will be used to inform risk considerations related to water and soil compartments.

To assess the environmental fate of the developed materials, biodegradation will be measured using respirometric techniques, which quantify microbial oxygen consumption during degradation. The test setup involves incubating the textile material, used as the sole carbon source, in mineral medium inoculated with environmental microorganisms (e.g., activated sludge). As the material is metabolized, oxygen is consumed, and carbon dioxide (CO<sub>2</sub>) is produced. The CO<sub>2</sub> is chemically absorbed, creating a pressure drop in the sealed system. This is compensated by an automated oxygen generator, allowing precise tracking of Biochemical Oxygen Demand (BOD) over time. This method provides a quantitative profile of the degradation process, including lag phase duration, degradation rate, and total oxygen demand relative to theoretical values. Materials showing significant oxygen uptake are classified as readily biodegradable. Test conditions (e.g., temperature, pH, inoculum origin) will be controlled and follow relevant OECD guidelines. These data will support WP4’s evaluation of environmental compatibility and feed into LCA endpoint modelling for degradation potential.

Complementing biodegradation testing, acute aquatic toxicity will be screened using the *Vibrio fischeri* luminescent bacteria assay (DIN EN ISO 11348-2). This test measures the inhibition of natural light emission from marine bacteria exposed to leachates or extracts of BioFibreLoop textiles. A reduction in luminescence indicates metabolic stress and serves as a proxy for ecotoxic potential. The test will use freeze-dried *Vibrio fischeri*, reconstituted in salt-adjusted medium. Textile samples or their degradation products will be extracted into saline solution, pH-adjusted (to 6-8), and incubated with the bacteria for a fixed period. Luminescence will be measured with a luminometer (e.g., LUMISmini), and results expressed as a percentage inhibition relative to controls. Zinc sulfate and sodium chloride will be used as positive and negative references, respectively. This method provides a rapid, sensitive tool for identifying materials or additives that may release harmful substances upon environmental contact, particularly important for lignin-based coatings and PLA degradation byproducts.

Together, these biodegradation and ecotoxicity tests offer a practical screening framework to evaluate the environmental safety of BioFibreLoop textile innovations under laboratory conditions simulating aquatic or soil exposure.

### 5.3. Environmental Life cycle Assessment (E-LCA)

The E-LCA in BioFibreLoop aims to quantify the environmental impacts of textile developed from bio-based materials across all relevant life cycle stages. The assessment supports the project's SSbD approach by identifying environmental hotspots, guiding material choices, and enabling comparison with conventional textile products.

The LCA will follow the internationally recognized ISO 14040/14044 framework and be conducted using two complementary software tools: SimaPro 10 (NTT) and Umberto LCA (DITF). The assessment covers four main phases:

1. **Goal and scope definition** - The purpose is to evaluate and compare the environmental performance of the novel bio-based textiles with market alternatives. Functional units (e.g., per kg of textile or per m<sup>2</sup> of finished product) and system boundaries (e.g., cradle-to-grave) will be clearly defined. Multiple scenarios will be modelled for different end-of-life options (e.g., composting, recycling).
2. **Life Cycle Inventory (LCI)** - Data collection will be based on project-specific information from WP1 and WP3, including input-output flows for energy, materials, emissions, and waste associated with textile production processes such as polymerization, coating, extrusion, and finishing. Secondary datasets (e.g., Ecoinvent, GaBi) will supplement where necessary. While feedstock extraction is considered out of scope in this phase, its relevance is acknowledged for future assessments.
3. **Life Cycle Impact Assessment (LCIA)** - Environmental impacts will be assessed using the ReCiPe 2016 or comparable method, focusing on midpoint indicators relevant to the textile sector. These include global warming potential (GWP), human toxicity, ecotoxicity (aquatic and terrestrial), resource use and depletion, and water consumption.
4. **Interpretation and integration** - Results will be interpreted for reliability, completeness, and significance. Findings will feed into T4.6 for integrated SSbD performance evaluation. Where appropriate, sensitivity and uncertainty analyses will be performed.

The LCA will allow for direct comparisons between BioFibreLoop materials and conventional textiles, highlighting potential advantages in terms of carbon footprint, toxicity reduction, and biodegradability. End-of-life scenarios such as recycling, and biodegradation will be modelled to reflect realistic application routes.

### 5.4. Social Life cycle Assessment (S-LCA)

The S-LCA in BioFibreLoop aims to evaluate the social and socio-economic performance of bio-based textile materials across their life cycle. S-LCA will be carried out by NTT using a structured methodology aligned with the UNEP/SETAC guidelines and informed by ISO 14040/14044 standards.

The S-LCA will follow four core phases:

1. **Goal and scope definition** -The main goal is to assess potential positive and negative social impacts of BioFibreLoop materials in comparison to conventional textile products. The assessment will focus on manufacturing, use, and end-of-life stages, with particular attention to circular value chains and occupational health.
2. **Life cycle inventory** - A detailed and stakeholder-specific inventory will be constructed based on real data collected through customized surveys and interviews. Social impact indicators will be developed for key stakeholder groups, including workers (e.g., health and safety, fair wages, training), consumers (e.g., product safety, information transparency), local communities (e.g., air quality, employment opportunities), society (e.g., public acceptance of bio-based textiles), and value chain actors (e.g., equitable partnerships, procurement practices).
3. **Impact assessment** - The collected data will be evaluated using both qualitative and semi-quantitative methods. Impacts will be categorized by stakeholder group and assessed across key dimensions such as working conditions, social well-being, access to innovation, and community engagement. This will help identify both social risks and co-benefits associated with BioFibreLoop materials.
4. **Interpretation of Results** - Results will be used to support strategic decision-making in WP4 and to inform stakeholder engagement and commercialization planning in WP6. They will guide the design of measures to enhance job creation, improve worker safety, and increase public and stakeholder acceptance of novel bio-based textiles.

The S-LCA will not only identify social hotspots but also highlight opportunities for positive impact, such as empowering green jobs, promoting responsible sourcing of bio-based materials, and improving awareness of safe material handling practices. This assessment will contribute essential inputs to the broader sustainability assessment framework, influencing the preference and adoption of BioFibreLoop products across industries and society.

### 5.5. Circularity assessment

The circularity of BioFibreLoop textile materials will be assessed by VTT using the Material Circularity Indicator (MCI) developed by the Ellen MacArthur Foundation. This method evaluates product circularity based on recycled content, recovery potential, product lifespan, and waste generation.

Data from all technical WPs (WP1-WP3) will inform material flow mapping across life cycle stages, from raw material sourcing to end-of-life. Different scenarios will be compared to identify design and process choices that maximize circularity.

The outcomes will guide decisions on feedstock selection, process settings, and product design, with the overall goal of increasing resource efficiency and aligning with SSbD principles.

## 5.6. Techno-Economic Assessment (TEA)

The TEA of BioFibreLoop will be led by IDENER, with contributions from all partners, to evaluate the economic performance of the developed materials and processes. The TEA will quantify capital expenditures, operational expenditures, and potential cost reductions across the full life cycle.

The assessment will consider both direct costs (e.g., raw materials, energy, labour, maintenance) and indirect costs linked to environmental externalities, such as emissions mitigation and waste handling. Environmental and social impacts identified in the LCA and S-LCA will be integrated as monetized impacts where feasible, ensuring a holistic view of economic and sustainability trade-offs.

The TEA results will inform recommendations for process optimization, cost-efficient scale-up strategies, and sustainable product development. This analysis will feed into the digital twin (DT) tool developed in WP2, enabling simulation-based decision-making for improved process design and resource efficiency. Ultimately, the TEA will support WP6’s commercialisation roadmap by highlighting the economic viability and sustainability advantages of BioFibreLoop innovations.

## 6. Final Remarks and outlook

Deliverable D4.2 represents a crucial milestone in the BioFibreLoop project by laying the groundwork for a comprehensive safety and sustainability assessment framework. Through the integrated development of HRA/ERA, E-LCA, S-LCA, circularity metrics, and TEA, the project moves decisively towards embedding SSbD principles in the development of bio-based textile materials.

One of the key achievements has been the establishment of a flexible and scalable sustainability framework tailored to the innovation stage of the BioFibreLoop materials. This framework integrates a qualitative risk scoping, harmonized testing strategies, and iterative data collection aligned with regulatory and industrial needs.

Particular emphasis was placed on aligning the BioFibreLoop approach with key SDGs, especially SDG 3 (Good Health and Well-being), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 14 (Life Below Water). These alignments are reflected in the project’s aims to reduce microplastic emissions, minimize CO<sub>2</sub> footprint, ensure safer material profiles for workers and consumers, and extend product life through circularity.

Moreover, the BioFibreLoop methodology has been contextualized within the European textile sector’s sustainability transition, including its alignment with the EU Strategy for Sustainable and Circular Textiles, the Chemicals Strategy for Sustainability, and the Zero

Pollution Action Plan. The risk-based and life cycle-informed design of biobased alternatives directly supports current policy goals such as reducing hazardous substances, improving product durability and recyclability, and promoting circular business models in the textile value chain.

Looking forward, the next phase of the project (within WP4) will focus on operationalizing this framework through data collection, lab testings, and iterative modelling. Planned exposure measurements, in vitro hazard testing, and biodegradation experiments will provide critical evidence to complete the sustainability profiles of the three BioFibreLoop product lines.

Ultimately, the insights gained through D4.2 not only contribute to the technical goals of BioFibreLoop but also serve as a template for broader adoption of SSbD practices in the European bioeconomy and textile innovation landscape.

### 6.1. Main challenges encountered

During the development of D4.2, several challenges emerged, reflecting the complexity of establishing an integrated safety and sustainability assessment framework for novel bio-based textile materials. A key challenge was the limited availability of experimental data. As many materials and processes are still under development in WP1 and WP3, the risk scoping exercise had to rely heavily on literature data, analogue materials, and conservative assumptions. This limited the precision of early hazard and exposure estimations and will require validation through future measurements and testing.

Another major difficulty foreseen is the harmonisation of data inputs across the diverse WPs. The implementation of HRA/ERA, circularity analysis, LCA, and TEA demands a high degree of alignment in terminology, process definitions, and data structures. Discrepancies in the maturity level of technical descriptions and the availability of inventory data may complicate the integration of these assessments into the overarching SSbD framework.

Despite these limitations, the successful completion of the risk scoping matrix, the definition of life cycle boundaries, and the structured planning of assessment methodologies provide a solid foundation for the upcoming project phase. These preparatory steps will enable targeted data collection, testing, and integrated sustainability assessments in the next stages of WP4.

### 6.2. Deviations from the plan and mitigation

There are no deviations from the plan.

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## Annex I

This annex contains the human exposure risk scoping matrix presented in the form of an Excel spreadsheet named as “*Human Exposure Risk Scoping*”. It summarizes the qualitative assessment of occupational and public exposure potential across different life cycle stages of the BioFibreLoop materials and processes.

## Annex II

This annex provides the environmental release risk scoping matrix as an Excel spreadsheet named as “*Environmental Release Risk Scoping*”. It outlines potential releases to air, water, and soil throughout the product life cycle, supporting the identification of environmental hotspots and prioritization of further assessments.