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MUDP-sekretariatet i Miljøstyrelsen
Tolderlundsvej 5, 5000 Odense| Tlf. +45 72 54 40 00

Mail: ecoinnovation@mst.dk
MUDP's hjemmeside

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1. Introduction

The textile industry is a position of strength for Denmark, representing the fourth largest product group in the country's total exports. As the textile industry aspires to achieve circularity, there is an urgent need to address the barriers hindering the transition to a circular economy. One barrier is the lack of solutions for recycling.

To address the barrier of missing solutions for textile recycling the project focused on two main development tracks:
1) Creating design guidelines to ensure that future clothing is designed for recyclability
2) Developing and maturing recycling technologies for polycotton, decolorization of polyester and recyclable impregnation agents

1.1 Background

Denmark's textile industry stands as a key economic sector, representing the fourth largest product group in the country's total exports. As this vital industry aspires towards circularity, it faces significant challenges in realizing its sustainability goals. A notable vulnerability within this position of strength is the annual disposal by Danish consumers of up to 53,000 tons (2021) of clothing [1].

Denmark has started household collection of textiles, but the lack of recycling technologies necessitates immediate attention. The textile industry aspires to achieve circularity, and the EU strategy focuses on textile-to-textile recycling instead of, e.g., production of recycled polyester textiles from downcycled plastic bottles.

There are many challenges in the transition of the textile industry towards a circular economy, and many barriers must be overcome before the industry can comply with the upcoming EU legislation. Denmark has identified four primary barriers to overcome through technological development. [2] Two of the barriers are directly addressed in this project:" Textile waste is complex and diverse" and" Lack of new and further development of existing recycling technologies".

To overcome these challenges and support the Danish textile industry, our project focuses on two key development areas:

1. Development of a design guide that ensuring that textiles designed today will be recyclable in the future.
2. Development of robust recycling technologies; decolourisation of polyester, recycling of polycotton that will enable fiber-to-fiber recycling and development of new impregnation agents that enable recycling.

By addressing these critical aspects, the project aims to facilitate the transition of Denmark's textile industry to a more circular and sustainable future.

1.2 Obstacles addressed in the project

The Ellen MacArthur Foundation has previously highlighted that industrial-scale textile-to-textile recycling faces obstacles due to the limited interaction between design and recycling procedures. Textile brands want to support the transition to a circular economy and to launch textiles that in future are easier to recycle at their end-of-life. But there is a lack of knowledge about what needs to be adjusted in the design phase. The brands need knowledge about the recycling technologies to make the possible adjustments to meet the boundaries of the recycling technologies, and the recyclers need knowledge about which additives in the textiles must be removed during the recycling process. This mutual dependence between the design- and recycling requires broad collaborations and knowledge exchange. This we address in the product guide.

A significant obstacle in achieving a circular textile industry is the lack of new and further development of existing technology for recycling of mono-materials and technologies capable to separate various fiber types within mixed textiles. Notably, polyester (PET) and mixed textiles of polyester and cotton, commonly known as polycotton, represent widespread textile materials in the market (section 3.1).

It is a major technological challenge to recycle textiles into new textiles, fiber-to-fiber recycling, as this requires that the material properties are retained as well as a stable level of output quality despite the diversity of the input textile waste. It is necessary to achieve full removal of additives such as dyes, surfactants etc. to achieve sufficiently high-quality materials in the recycling process to produce new textile fibers. However, throughout the years these additives have been developed and refined to resist repeated use and washing (section 3.2).[3]

The presence of impregnation materials is a barrier for recycling of textiles and according to the Danish EPA, textiles which are impregnated, should be diverted from the recycling processes and treated as residual waste, to avoid contamination. It is a big challenge to overcome this obstacle as an impregnation agent needs to be able to withstand repeated washing cycles and keep its performance. To obtain an impregnation agent that meets these criteria while enabling recycling is challenging (section 3.3).

1.3 Project goal

The main purpose of this project is to contribute to the transition of the Danish textile industry towards a circular industry. The project is a collaborative initiative within the textile industry, bringing together Danish and international technology providers to develop recycling technologies that align with future textile designs, and conversely, adapt new designs to fit these technologies. The project is broadly rooted in the Danish textile industry through the active participation of major brands: Mascot International A/S, hummel, Our Units, and KnowledgeCotton Apparel. It has been executed in a strong collaboration between the textile industry and the technology and knowledge partners: Textile Change, Cellugy, NATEX Prozesstechnologie GesmbH, Danish Technological University (DTU), and Danish Technological Institute (DTI).

2. Design for recycling

Circular design of textiles is complex, with numerous aspects to consider, including longevity, purpose, and reuse. These considerations do not always align seamlessly with design for recycling. While several design guides focusing on the circular design process have been published [4, 5, 6], the purpose of this project is to delve deeper into design for recycling, gathering knowledge and insights on what to consider for the future recycling of textiles.

2.1 Choosing the right design

This project aims to accelerate the transition to a more sustainable future for the textile industry by fostering collaboration between textile brands, technology providers, and knowledge experts. To integrate textile brands into the development loop and enable them to make informed decisions throughout the design process, we addressed three key questions:

1. What is the current status, and which requirements can be established for the recycling providers and for the textile brands?
2. Which questions must the textile brands ask when sourcing and introducing new recycled materials?
3. What are the knowledge gaps when focusing on design for recycling?

To tackle these aspects, we organized a series of seven workshops, complementing ongoing project work. These workshops brought together project partners, textile brands, and external experts, placing a strong emphasis on knowledge sharing, requirements for materials and recycling, introduction of reused materials, design and collaborative learning.

The workshop series covered a wide range of topics, progressing from foundational knowledge to more specialized areas:

1. Textile recycling technologies
2. The recycling process at Textile Change
3. Textile production, chemical structure and treatments
4. LCA and simple environmental assessment models
5. Ensuring future relevance - perspectives from plastic recycling
6. Setting the boundaries of the design guide – what is already published
7. Sustainable Business Models

Each workshop built upon the insights from previous sessions, creating a shared comprehensive understanding of the challenges and opportunities in designing for textile recyclability. Key areas of exploration included identifying and sharing experiences with various recycling materials, exploring alternative business models, anticipating international legislative requirements, addressing customer feedback, and tackling technological challenges arising from green initiatives.

Throughout the ongoing project work and workshop series, several crucial insights emerged that directly influenced the development of our design guide. These included:

- The importance of considering the entire lifecycle of textile products
- The main knowledge gap for the project partners exists in design for recycling
- The need for a holistic approach that combines material selection, design choices, and production processes
- The significance of integrating sustainability into business models and decision-making processes

The workshops played a crucial role in shaping the ultimate structure and content of our final goal - a user-friendly design guide. Developed iteratively throughout the project as insights and learnings emerged, the final version, titled "Design for textile-to-textile recyclability," focuses on bridging the recognized knowledge gaps identified during the workshops.

This guide is tailored specifically for its primary audience - designers and product developers at the textile brands in the project consortium. In the following sections, we will delve into each workshop, exploring the key discussions, insights, and how they contributed to our understanding of design for recycling and the development of the design guide.

2.2 Workshops

2.2.1 Workshop 1: Textile recycling technologies

The first workshop, facilitated by DTI, focused on textile recycling technologies. Its primary objective was to establish a shared understanding among all project partners concerning current and future textile recycling technologies, thereby providing a foundation for developing the design guide.
The workshop covered several key topics, including current and future textile recycling technologies, development possibilities and trends, individual partner initiatives for introducing recycled materials, categorization of recycling technologies, and materials suitable for recycling both now and in the future.
The main activities comprised a presentation by DTI, followed by partner presentations on their individual recycling initiatives and future plans regarding the introduction of recycling materials to inspire and share learnings. These presentations were complemented by group discussions on recycling technologies and materials.

Throughout the workshop, participants learned about various recycling technologies, including chemical, mechanical, thermal, and mixed approaches. It became clear that most fiber-to-fiber technologies reduce polymer length, resulting in fiber degradation, and that no single technology can address all industry challenges. Interestingly, one partner revealed they had developed a product entirely from mechanically recycled cotton. The workshop also highlighted that all partners using recycled polyester (rPET) sourced it from recycled bottles, and that even small color variations in rPET can be challenging for customers. Additionally, possibilities for downcycling into other products, such as construction materials and insulation, were explored.

The workshop's outcomes included establishing a common knowledge foundation and language for the project, identifying materials that can be recycled now and in the future. These insights were directly relevant for the design guide, providing crucial information on recyclable materials and technology limitations.

2.2.2 Workshop 2: The recycling process at Textile Change

The second workshop, hosted by Textile Change at their facilities, aimed to help textile brands understand the recycling technology in detail and enable Textile Change to gather input to their recycling technology from the textile brands and build shared knowledge for developing requirement specifications.

Key topics covered during the workshop included the status and development of Textile Change's recycling technology, utilization strategies, project scaling approaches, requirements for textiles in relation to recycling at Textile Change, and challenges in textile recycling such as the presence of surface treatments, halogens, and PVC.
The workshop's main activities began with a tour of Textile Change's laboratory and facilities, followed by a presentation on their recycling technology and capabilities. Participants engaged in group discussions on technology utilization and scaling strategies. A significant portion of the workshop was dedicated to developing a draft specification for input materials at Textile Change and initiating the creation of a questionnaire for the textile brands to use in dialogue with their subcontractors.

Through these activities, participants gained several key insights. They developed a deeper understanding of Textile Change's recycling process and its limitations, identified problematic materials and additives in textiles for recycling, and gained insights into the realistic knowledge obtainable about textiles in the industry. The workshop also highlighted the importance of sourcing and supplier requirements in the context of recyclable textile design.

The outcomes of this workshop included a draft specification for input materials and an initial version of a questionnaire for textile brands to use with their dialogue with subcontractors. Importantly, participants gained an improved understanding of what to avoid when designing for recycling. These outcomes are highly relevant to the design guide, as they provide specific insights into recycling challenges and requirements, particularly in areas of material selection and avoiding problematic additives.

2.2.3 Workshop 3: Textile production, chemical structure and treatments

The third workshop, facilitated by DTI, aimed to establish a common language and basis for developing the questionnaire for dialogue with subcontractors. Building on the knowledge from previous workshops, this session delved deeper into textiles as a material, focusing on setting up requirement specifications and addressing questions about sourcing and introducing new recycled materials.

The workshop was divided into two parts. The first part provided insights into textile creation throughout the entire production chain, identifying areas with significant waste potential, opportunities for influence, and the technical knowledge necessary for Danish textile brands to make informed decisions. There was a particular focus on Manmade Cellulosic Fibers (MMCFs) such as viscose, and natural fibers like cotton, exploring their journey from initial stages through the weaving process.

The second part took a chemical approach, starting from basic building blocks to illustrate and clarify the challenges and potentials related to developing recycling technologies. This section also emphasized the available options for chemical and physical testing, offering participants a new perspective on textiles through the lens of their underlying chemistry.

The outcome of this workshop included a common understand and basis for further engaging in the implementation of new recycled materials and collecting valuable knowledge from the subcontractors necessary in the development of the recycling process at Textile Change and the decolourization process. This included knowledge about treatments and chemicals used in the production of the textiles tested to specify the abilities and limitations of the recycling processes.

2.2.4 Workshop 4: LCA and simple environmental assessment models

The fourth workshop focused on Life Cycle Assessment (LCA) and simple environmental assessment models to guide decision making. Its aim was to gather inspiration from internal and external knowledge providers and to share learnings from the work on LCA conducted at the textile brands during the project.

The workshop was structured in two parts. The first part consisted of three inspirational presentations: an introduction to LCA of Waste and Circular Economy by the project partner from the Department of Environmental and Resource Engineering at DTU; a presentation on LCA according to Product Environmental Footprint (PEF) and its interpretation through MÅLBAR's tool by Anders Koefoed, Founding Partner at MÅLBAR; and a review of mini-LCA tools and their pitfalls by an LCA expert from DTI.

The second part of the workshop centered on knowledge sharing and learnings among the textile brands, focusing on their experiences with LCA and the challenges they had encountered in their work.

Key topics covered included basic concepts and principles of LCA for textile products, the PEF standard and its application in LCA calculations, and a review of popular software for simple environmental LCAs. The main activities comprised the aforementioned presentations and subsequent discussions among participants about their experiences with the activity of environmental assessment.

Several important insights emerged from the workshop. Participants learned that it was very difficult to delimit which measuring points LCA calculations should contain, and that the PEF initiative could potentially alleviate some of these problems. Moreover, it became clear that product comparisons were only possible when small concrete differences existed, which could help identify measures for reducing environmental impact within selected environmental measuring points.

The outcome of this workshop included knowledge sharing on the project activity and a deeper understanding of LCA methodologies and tools, as well as practical application and limitations of LCA in the textile industry. This knowledge is valuable for the design guide, as it can inform decision-making processes related to environmental impact assessment of textile products and designs.

2.2.5 Workshop 5: Ensuring future relevance - perspectives from plastic recycling

The fifth workshop aimed to gain insights on what to expect in the future through perspectives from the plastic industry, which is more advanced than the textile industry in terms of sorting and recycling products. The objective was to understand what to expect and aim for regarding future recycling of textiles, ensuring that textiles designed today will be recyclable in the future and that a relevant design guide can be developed.

The workshop was structured in two parts. The first part introduced plastic and plastic recycling, focusing on initiatives implemented in the industry and ongoing challenges. This was followed by a perspective walkthrough, exploring the overlaps between the plastic and textile industries, identifying areas where existing knowledge from the plastic industry could be leveraged to ensure textile recycling.

Key topics covered included plastic recycling technologies, industry initiatives, challenges in creating a circular industry, and potential synergies between plastic and textile recycling. The main activities comprised presentations on plastic recycling and discussions on the applicability of plastic industry practices to the textile sector.

Participants gained valuable insights into the experiences and progress made within the plastic industry, including optimization of recycling processes and development of analysis and sorting methods. The workshop also identified areas where textiles are expected to diverge from plastics, highlighting the need for innovative thinking and new approaches to address these challenges.

A significant outcome of the workshop was the identification of overlapping areas between industries that should be considered when developing the design guide for textiles. This knowledge will be crucial in ensuring future relevance of the design guide and ensuring that textiles designed today will be recyclable in the future.

2.2.6 Workshop 6: Setting the boundaries of the design guide – what is already published

The sixth workshop focused on setting the boundaries of the design guide by identifying what is already published and where is the gab as well as drawing inspiration and obtaining learnings from existing design guides. This workshop was prompted by the realization that there was a need to understand how to relate the project's design guide to existing guides and how to present the content developed through the project.

Cathryn Anneka Hall, a postdoctoral researcher at Design School Kolding, led the workshop, sharing her experiences and insights from the "ReSuit" project. She discussed the issues and considerations encountered when preparing guidelines to ensure their effectiveness and relevance for various parts of retail companies, from design to sales and marketing.

The workshop included an overview of the most relevant Design Guides currently available, highlighting both their strengths and weaknesses. A key component of the workshop was the presentation of defining questions that participants should consider before creating a guide, covering aspects such as the target audience, level of information required, clarity of key messages, presentation format, information chunking, and strategies for providing additional details.

Following the presentation, a collective discussion was held on the best approach to the design guide for the present project. Key learnings from this discussion included the importance of uncovering the interfaces between parties, finding a common recipient, answering the defining questions, and reviewing existing guides to avoid duplication of content.

The workshop emphasized the need to ensure that the developed guide was unique to the project's results, valuable for those involved, and implementable. This led to the development of a design guide tailored specifically for its primary audience - designers and product developers at the textile brands in the project consortium

2.2.7 Workshop 7: Sustainable Business Models

The seventh and final workshop explored the possibility of shifting businesses and organizational design towards sustainable business models, as well as working towards partnerships with supply chains that promote sustainable solutions. This workshop was led by the consultant house zeal, specialists in sustainable business.

The workshop underscored the importance of considering planetary boundaries beyond carbon dioxide and introduced the concept of the Sustainable Business Model Canvas as a tool for promoting positive reduction strategies. It emphasized the inclusion of sustainability in investments like CAPEX and explored paradigm shifts in textile design.

Key topics covered included sustainable business models, the Sustainable Business Model Canvas, paradigm shifts in textile design, and methods for overcoming barriers when engaging with competing companies. The workshop also addressed best practices for developing and implementing successful sustainability strategies, as well as measuring and communicating their impact to stakeholders.

Participants gained insights into long-term perspectives and sustainability in decision-making, with a focus on critical assessment and seeking opportunities for sustainability enhancements. The workshop's relevance to the design guide development lies in its emphasis on integrating sustainability into business models and decision-making processes. This holistic approach ensures that the design guide will not only focus on technical aspects of recyclability but also consider broader sustainability implications and business model innovations.

2.3 Design Guide: Design for Textile-to-Textile Recyclability

Throughout the project, we developed the design guide focusing on "Design for textile-to-textile recyclability" based on learnings obtained during the technological development, ongoing project activities and knowledge gathered from our workshop series.

The development of the design guide began with a review of each participating textile company's initiatives towards a greener agenda. This initial review revealed the diversity of approaches and priorities among our partners, ranging from fashion items with PET and nylon to pure organic cotton products and technical workwear with multilayers and surface treatments. It became clear that the guide needed to be flexible enough to accommodate different contexts and levels of sustainability maturity among our partners.

The format of the design guide underwent significant evolution throughout the project. This evolution was driven by ongoing feedback and evaluation from the project partners and insights from ongoing project activities and the workshops, particularly Workshop 6, which focused on existing design guides.

Responses from the textile brands to the questions raised in Workshop 6 were central in shaping the final design guide and the following boundaries are set as guide for the development of the design guide:

- Target audience: Primarily designers and product developers at the textile brands in the project consortium.
- Information level: Preference for a simple, functional guide that is easy to use in the daily work.
- Presentation format: Illustrations, clear overviews, lists, roadmaps, or diagrams.
- Future relevance: The guide should be adaptable as recycling technologies evolve.
- Content focus: Current best practices, requirements for textile-to-textile recycling, and project learnings.

Through a review of existing guides, a significant knowledge gap was identified on how to design for recyclability. This finding supported our focus on design for recycling, building on the knowledge collected throughout the project.

Some of the most important learnings came from the interaction between the textile brands and Textile Change and the decolorization development. The opportunity to collaborate on specifications for inputs to recycling processes enabled the development of guidelines for designing textiles that will be recyclable in the future. It also provided the partners with a tool to pose technical questions, source information from their value chain when introducing recycled materials and ask the right follow-up questions when seeking additional information, such as from mechanical recyclers or subcontractors and their use of surface treatment, printing, and dyeing methods.

FIGURE 2.1. Front page of the design guide.

2.4 Sub-conclusion

The resulting design guide successfully addresses the knowledge gap in design for textile-to-textile recyclability, providing a user-friendly tool for designers and product developers at the project partners. It synthesizes the technological developments and insights gathered throughout our project, offering practical guidance for creating more recyclable textile products.

3. Technological developments

An obstacle in achieving a circular textile industry is the lack of technological solutions. This chapter details the technological advancements made in this project regarding recycling of polycotton, decolorization of polyester and recyclable impregnation agents.

3.1 Recycling of polycotton

Blended textile materials are complex, which makes them challenging to recycle. Many technologies often target one type of material, and using such a technology on a blended textile would often result in one material fraction being sacrificed to recycle the other. Additionally, there is a significant issue concerning chemical contaminants from the textiles, such as heavy metals, finishing chemicals, PFAS, and dyes, all of which need to be removed during a recycling process to obtain recycled materials suitable for new fiber production. Polycotton blends are a common textile blend and technological solutions to specifically recycle both material fractions from this blend are highly desired.

Textile Change's technological solution allows recycling of both polyester and cotton from polycotton blends. The technology relies on principles from wood pulping chemistry and conventional polymer dissolution to recycle both material fractions in polycotton.
The ability to handle pure as well as mixed polycotton materials allows for the handling of 86% of all textile fibers produced. [7]

The recycling process developed by Textile Change consists of three steps: 1) Three types of pretreatments 2) Decolorization and 3) PET dissolution. Depending on the textile-input, three different pretreatments can be used either in combination or separately. The textile-input can be any combination of PET, cotton or manmade cellulosic fibers (MMCFs). From any of the listed textile-inputs, elastane can also be removed, but not for recycling purposes. The products from the textile recycling process are cellulose-pulp and/or polyester powder. An overview of the different treatment combinations, depending on the textile-input, can be seen in FIGURE 3.1.

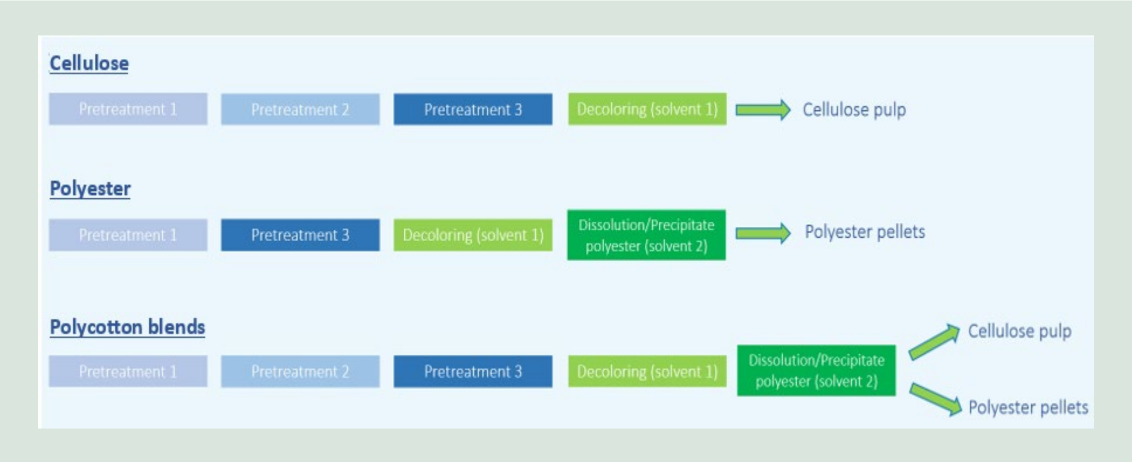

FIGURE 3.2. Overview of treatment combinations depending on input-material.

The order of treatments, as well as their necessity, has been determined through extensive lab-work and follow-up tests of selected treatments on the pilot-plant at Textile Change. The pilot-plant consists of a vessel in which the textile is held, while the chemical used for the relevant treatment is recirculated to ensure effective mixing to obtain a high surface/solvent contact.

3.1.1 Requirement specification for polycotton textiles being recycled

Textiles are often a complex mix of fibers. Each type of fiber has a different chemical composition that reacts in a certain way in each step of Textile Change's recycling process. The main challenge is to remove impurities as e.g. heavy metals, elastane or surface coatings, as well as keeping polyester and/or cotton as a high-quality product.
To learn what can be recycled and how it should be handled, it is important to have information about the textiles being recycled. To determine the robustness of the process, different input materials have been tested in the lab. The results of the lab tests have established the current limitations for the input material. Inputs that fall within these limitations have been proven to be effectively recycled, resulting in properties that comply with the benchmark values required by the fiber manufacturers.
It is often difficult to obtain input material with known specifications, due to the complexity of the textile value chain. The retail partners involved carried out extensive work to gain information about the samples used for experiments that determined the robustness of the process. This work provided the basis for the development of co-learnings in the project consortium and provided pertinent input for the design guide.
In this project, different products were tested to determine if Textile Change can recycle the products.
In the laboratory, it was tested whether different adhesion methods could interfere with the recycling process at Textile Change. Two different PET fabrics from MASCOT were tested - one with PU heated onto the fabric (sample 1) and one with glue/adhesive of PU (sample 2). Both fabrics were treated with all 5 steps of the Textile Change process. Results show that no PU was detected after treating sample 2, meaning that all PU was removed in the process resulting in a fully decolored product. After treating sample 1, PU could still be detected, although it was still possible to get a fully decolored product. Whether the presence of PU in the final product is a problem for the spinning process, needs to be investigated further.
Furthermore, textile samples from hummel were treated on the pilot plant of Textile Change, resulting in 2.5 kg of polyester powder, which was successfully spun to fibers by Fiberpartner (PICTURE 3.1). The intrinsic viscosity of the polyester powder was 45 mL/g (desired 40-70 mL/g).

FIGURE 3.2. Shredded textile before the Textile Change process (left), polyester powder after the Textile Change process (centre),Textile Change's output spun to new fibers by Fiberpartner (right).

3.1.2 Specifications for input textiles in the Textile Change process

All technologies have limitations, and to obtain the highest possible recycling rate of textiles, the recycling technologies as well as the product designs must adapt. Below are the specifications for the input textiles that can be recycled in the Textile Change process. This provides strong insights and input to the design guide, and these were discussed in the workshop with Textile Change.

Fiber material composition:

- 0-15% elastane (PU)
- 0-100% polyester
- 0-100% Natural Cellulose Fiber: Cotton, hemp, jute, etc.
- 0-20% Man Made Cellulose Fiber: Viscose, Lyocell
- 0% PVC
- PFAS: Can be removed
- Nylon, wool/down, other proteins, polyamide, acrylic should be avoided but can be handled in low masses (0.1-0.5% tolerance per item)

Colors

- With the exception of Dope dye, colors can be removed.

Trimmings/accessories

- Less than 0.5%

Wax Print (Wax Coating)

- Less than 0.25%

Reflective materials

- Less than 0.5%

Particular technical textile surfaces

- Examples: Gore-Tex, Silvertech, UV protection etc. less than 0.1%

3.1.3 Requirement specifications for output material

To spin the output material into fibers, certain requirements must be met, to facilitate the possibility of textile-to-textile recycling. These were identified and prepared as a note, and one of these requirements is the length of the polymers. Textile Change’s main technology relies on the principles of dissolution, and therefore it should in theory be possible to avoid the degradation of polymers. However, as the polymers and chosen chemicals are not the only molecules in the process, and as many physical operations must be performed during the full process, degradation of polymers, which the textile-fibers consist of, is inevitable. The degree of degradation that each treatment-step introduces can be calculated by determining the intrinsic viscosity of the polymers in the samples.
The output material from the Textile Change process is polyester powder and cellulose pulp. The aim is to minimize the degree of degradation of both products as much as possible, so the material will live up to the intrinsic viscosity requirements from the fiber manufacturers.

Besides the requirement for the intrinsic viscosity, the output must have a low content of metals, as they can affect the fiber spinning process. Furthermore, the whiteness is important – the colour removal needs to be effective to make a uniform colour in the fibers.

3.1.4 Influence of the recycling process

Recycling textiles can be problematic as many processes and treatments impact the underlying material. Removal of dyes, additives etc. will all have an impact. When separating the polyester/cotton materials, it was expected that the fiber quality after recycling would change the material properties. To quantify the quality of the polyester and cotton materials, intrinsic viscosity (IV) was utilized.

IV is a critical parameter for assessing the PET quality in textile applications. It directly correlates with the polymer's molecular weight, which influences key properties such as tensile strength, elasticity, and abrasion resistance. IV affects fiber formation during extrusion, with optimal ranges ensuring proper drawability and strength. This parameter is particularly important in recycling, as IV can decrease during the process, affecting the quality of recycled PET.

Therefore, IV measurements are utilized to quantify the impact of different processes and conditions on materials. Different PET samples were tested including virgin and recycled samples to quantify the impact of the recycling process on the polyester quality TABLE 3.1.

TABLE 3.1. Intrinsic viscosity of different PET samples.

Sample	IV Huggins [mL/g]
Virgin Bottle grade PET	76
Virgin Filament PET	74
Recycled filament using solvent 1	20
Recycled PET from Hummel using solvent 1	26
Recycled PET from polycotton	37
Recycled PET from Hummel using solvent 2	52

The data compares virgin PET materials with recycled PET processed under different conditions. The virgin bottle grade PET shows the highest intrinsic viscosity at 76 mL/g, closely followed by virgin filament PET at 74 mL/g.

Among the recycled PET samples, there is considerable difference in intrinsic viscosity. The lowest IV is observed in recycled filament using solvent 1, measuring only 20 mL/g. This suggests a significant reduction in molecular weight compared to the virgin materials.

Recycled PET from hummel using solvent 1 shows a slightly higher IV at 26 mL/g, indicating that the source of the recycled PET and potentially the recycling process can influence the resulting intrinsic viscosity.

The recycled PET from polycotton demonstrates an improved IV of 37 mL/g. This higher value might be due to differences in the initial material composition, or the recycling process used for polycotton blends.

Notably, the recycled PET from hummel using solvent 2 exhibits the highest IV among the recycled samples at 52 mL/g. This substantial improvement compared to the same source material processed with solvent 1 (26 mL/g) suggests that solvent 2 may be more effective in preserving the polymer chain length during the recycling process.

Overall, the data illustrates that recycling processes and conditions significantly impact the intrinsic viscosity of PET. The choice of solvent and potentially other processing parameters can lead to varying degrees of polymer degradation as reflected in the IV values. Based on the results, solvent 2 performed better than solvent 1 as the IV values were higher, and therefore it did not degrade the PET material as much during the process conditions.

3.1.5 Adjusting the quality

Obtaining a high and steady quality of the material after a textile recycling process is of utmost importance. The flow of textile waste is complex and diverse; however, the quality of the recycled material needs to meet the quality levels in the requirement specifications, and it has to be consistent in order to use the material in the production of new textiles. The content of viscose compared to the content of cotton in the textile waste stream will vary. Both materials are based on cellulose, but the length of the polymers in the two materials differs. Therefore, it is important to be able to adjust the polymer length and IV of the cellulose pulp so a recycled material suited for new textile production can be obtained.
Obtaining a steady and high-quality material after a textile recycling process is essential for enabling textile-to-textile recycling and fulfilling the environmental and economic benefits of recycling.

To be able to adjust the quality of the recycled material, two methods were tested to reduce the polymer length and to increase the IV of the cellulose pulp, respectively. When the input for a recycling process has a high content of cotton, the fiber length might have to be reduced, whereas when the input has a high proportion of viscose, the output might have to be strengthened. This is possible according to the methods tested in the project. Two development tracks were considered in the project to alter the fiber length and strengthen the textile fiber, so fibers for specific applications could be designed.

- Enzymatic reduction of textile fiber length
- Increased strength of textile pulp using nanocellulose as reinforcement

3.1.6 Enzymatic reduction of textile fiber length

Experiments with enzymatic reduction were conducted to understand if it was possible to reduce the viscosity of the cellulose. Lower viscosity would indicate shortening of the cellulose chains. Several candidates exist that can help reduce the length of the polymer. The enzyme chosen for the experiment was endo-glucanase based on previous experiments where the viscosity was successfully reduced on multiple types of pulp-samples.
In the experiment, two parameters were examined: the concentration of enzymes and the duration of exposure. Additionally, a reference sample was included before measuring the IV of the material.

To test the method, enzymes that can reduce the length of cellulose chains were tested along with their influence on the intrinsic viscosity. The intrinsic viscosity was calculated using both Kraemer and Huggins. The results can be seen in TABLE 3.2.

TABLE 3.2. Intrinsic viscosity of cotton with various enzymatic treatments.

Samples	IV [mL/g] (Huggins)	IV [mL/g] (Kraemer)
FXVII 1 (0.025% E, 30min)	7.8×10^2	5.3×10^2
FXVII 2 (0.025% E, 60min)	7.4×10^2	5.0×10^2
FXVII 3 (0.1% E, 30min)	8.7×10^2	5.7×10^2
FXVII 4 (0.1% E, 60min)	7.2×10^2	5.1×10^2
FXVII 5 (reference)	8.6×10^2	7.5×10^2

Analysis of the data reveals that, in most cases, the IV decreases with longer treatment times, suggesting that extended exposure to the enzyme results in a greater reduction of IV. The Kraemer method consistently shows a more pronounced decrease in IV compared to the Huggins method.
Interestingly, there is no clear trend observed with changes in enzyme concentration. The IV values fluctuate as the concentration increases, indicating that the chosen enzyme concentrations do not have a consistent impact on IV.

It's worth noting that the enzymatic treatments generally resulted in lower IV values compared to the reference sample, suggesting that the enzymes are effective in reducing the length of cellulose chains. However, the lack of a clear concentration-dependent trend implies that other factors may be influencing the results, and further investigation might be needed to optimize the enzymatic treatment process.
The enzymatic treatment process has thus proven to be able to tune the input, in case the polymers are too big for the desired quality, the enzymatic treatment can reduce their size, and thus ensure that the recycled material meets the requirement specifications when the fibers are too long.

3.1.7 Increased IV of textile pulp using nanocellulose

Most often it appears that the recycling procedure lowers/decreases the fiber length. If this is observed for a recycled batch, then the method is considered to ensure a higher IV of the output material from the Textile Change recycling process, and it makes sure that the material can meet the requirement specifications and be used for textile-to-textile recycling. The test was carried out by mixing the recycled cotton material and biofabricated cellulose and measuring the IV (TABLE 3.3).

TABLE 3.3. Intrinsic viscosity of recycled cotton mixed with biofabricated cellulose.

Sample	IV Huggins [mL/g]	IV Kraemer [mL/g]
Reference sample	1.0×10^2	1.2×10^2
Cellugy EcoFLEXY	3.1×10^2	3.1×10^2
Sample A 82 % + EcoFLEXY 18 %	1.2×10^2	1.6×10^2

Cellugy EcoFLEXY shows the highest IV (3.1×10^2 mL/g), significantly exceeding the reference sample (1.0-1.2 x 10^2 mL/g). The mixture (82% reference, 18% EcoFLEXY) demonstrates an intermediate IV (1.2-1.6 x 10^2 mL/g), indicating that even a small addition of EcoFLEXY can notably improve viscosity.
This data suggests that incorporating bacterial nanocellulose into the recycling process can enhance the quality of recycled viscose fibers if higher IV is needed. The increased IV in the mixture implies potential for producing high-quality viscose products, aligning with the goal of enabling textile-to-textile recycling. This method offers a promising approach to support this goal.

3.1.8 Future work

Textile Change will continue to develop and upscale their recycling technology and use the methods and approaches developed in the project to the extent adjustment of the recycled material is needed. The plan is to have a fully upscaled plant within few years.

3.1.9 Sub-conclusion

To ensure high quality of the recycled material, it is important to meet the requirement specifications of the output material. In the project, a method was set up to measure the IV of the output material as the most relevant quality parameter.
To adjust the quality of the recycled material, two methods were tested: enzymatic shortening of fiber length and increased strength of cellulose pulp using nanocellulose. The enzymatic treatment proved effective in reducing IV, while the addition of nanocellulose increased IV, allowing the desired quality to be achieved regardless of the input material composition.

Overall, the project has demonstrated that the Textile Change process can handle a wide range of input materials and produce high-quality recycled polyester and cellulose for textile production, contributing to a more circular textile industry.

3.2 Decolorization of polyester

3.2.1 Motivation for decolorization of polyester

Polyester (PET) is a synthetic plastic fiber, which is derived from fossil oil. The production of a garment made of polyester fibers is schematically illustrated in FIGURE 3.3, where fossil oil is turned into monomers, polymers, fibers, yarn, fabric, and finally garments ready to be used by consumers. Eventually, the produced garment will deteriorate to the point where it is considered waste at end-of-life. Currently, most end-of-life polyester textiles are incinerated or deposited in landfills.

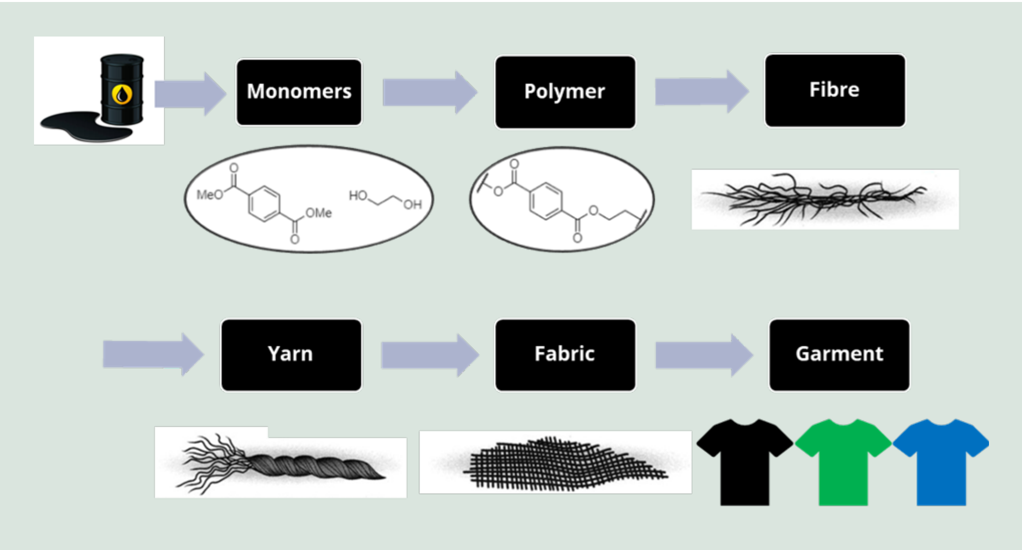

FIGURE 3.3. Schematic illustration of the production of polyester garments from fossil oil.

Polyester is a thermoplastic, which means that the polymer can be melted and used again. In the food industry, polyester bottles are sorted, washed, and remelted into new polyester bottles. Arguably, polyester garments could also be remelted into new polyester garments. However, end-of-life textiles are more complex compared to bottles, with respect to physical modifications such as labels, prints, buttons, and zippers, but also to chemical additives that are added during the many steps from polymer synthesis to garment manufacturing. One type of additives are dyes, and they add to the complexity of end-of-life polyester textiles. Polyester textiles are predominantly dyed with a wide range of azo or diazo compounds. Melting end-of-life unsorted polyester would result in problems with equipment contamination, emissions, odours, and unwanted chemical reactions. This would result in low material quality, e.g., weak fibers and varying colour.
To enable the remelting of the polyester textile, it is necessary to develop effective methods for removing impurities and dyes.

As seen in FIGURE 3.4, the aim of decolorization is to reduce the complexity of end-of-life polyester and thereby enable valorisation of the polyester textile waste. The objective of decolorization technology is to obtain colour-free polyester from post-consumer and pre-consumer polyester textile waste, without degrading the chemical properties of the polyester.

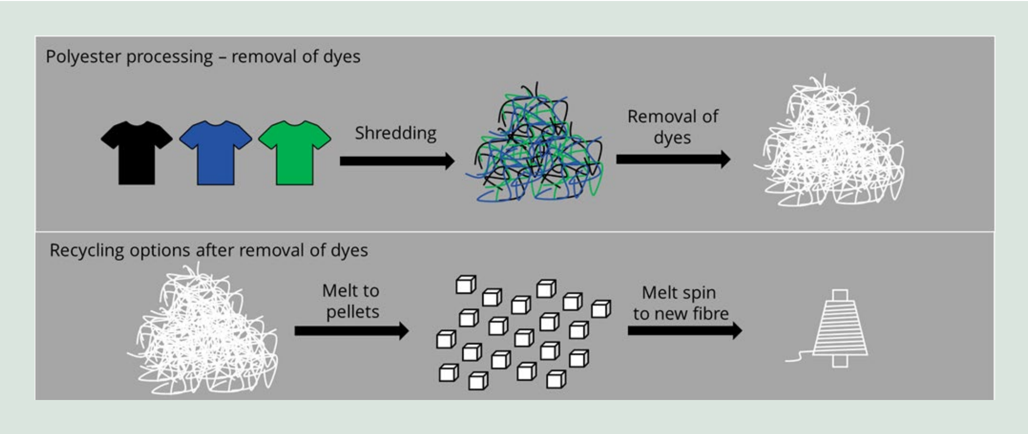

FIGURE 3.4. Top: Objective of the colour removal technology. Polyester is first shredded, and then the dyes are removed to give purified polyester. Bottom: Illustration of potential subsequent recycling by melting polymer into pellets and then obtaining regenerated fibres.

3.2.2 Results

The developed decolorization technology has been demonstrated on cut and shredded polyester on gram and kilogram scale, but also on intact t-shirts (FIGURE 3.5, FIGURE 3.6, and FIGURE 3.7, respectively). The gram scale experiments were conducted at DTI, whereas the kilogram scale experiments were conducted at NATEX Prozesstechnologie.

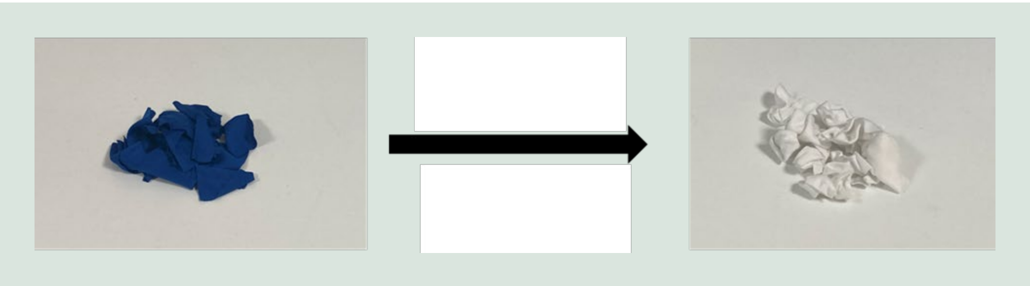

FIGURE 3.5. Blue cut polyester (2x2 cm) sample before (left) and after (right) decolorization technology. Selected example from gram scale experiment conducted at DTI.

FIGURE 3.6. Yellow polyester shredded sample before (left) and after (right) decolorization technology. Selected example from kilogram scale experiment conducted at NATEX Prozesstechnologie.

FIGURE 3.7. Intact t-shirt before (left) and after (right) decolorization technology. The experiment was conducted at NATEX Prozesstechnologie.

Development of the decolorization technology
Initially, a small set-up for the decolorization technology was built at DTI for the preliminary optimization on gram scale. The set-up was constructed with input from NATEX Prozesstechnologie.

The gram scale optimization was performed on well-defined pre-consumer polyester samples. Key parameters for the decolorization technology were identified during the initial optimization performed at DTI. Ultimately, this led to a set of parameters used for the continued optimization conducted on kilogram scale at NATEX Prozesstechnologie. LCA of the gram scale operation indicated that reductions in solvent consumption, temperature, and process time would lead to reductions in the environmental impact.
The equipment used at NATEX Prozesstechnologie has a larger parameter space, and by exploring this, milder conditions were identified, while still obtaining decolorized polyester. The conditions identified had reduced temperature and consumption of solvent in the decolorization technology compared to the gram scale. These reductions improved the overall

environmental impact and minimized the risk of deterioration of the polyester material quality during the decolorization process.

At NATEX Prozesstechnologie the optimization of the decolorization technology was conducted on 2-3 kg polyester per experiment. Both pre- and post-consumer waste was tested. Furthermore, successful decolorization was demonstrated on 7 kg of polyester pre-consumer polyester waste.

The textile brands were informed about the progress of the decolorization technology and provided input for the experimental planning. The inputs ensured that the results of the conducted experiments could be used in the design guide.

3.2.3 Evaluation of the quality after decolorization

The quality of the polyester before and after the decolorization technology was examined using IV measurements and differential scanning calorimetry (DSC). The results shown are from pre-consumer polyester waste.

In TABLE 3.4, the requirement specifications for virgin polyester used for fiber production, the reference material values, and the treated sample values are listed. The intrinsic viscosity of the reference PET material as well as the treated PET sample are within the requirement for fiber quality PET (40-70 dL/g). With respect to the melting point, determined by DSC, the reference PET material and the treated PET sample (both 252˚C) both lie within the range of the requirement specifications.

TABLE 3.4. Quality parameters for polyester samples (reference and treated) compared to the requirement specifications.

	Intrinsic viscosity [mL/g]	Melting point [˚C]
Requirement specifications	40-70	240-257
Reference PET material	70	252
Treated PET sample	70	252

The demonstration has been successful on kilogram scale pre-consumer polyester waste and produced polyester with material qualities within the listed requirement specification (M3). Therefore, the decolorization technology might be applicable as a purification step in a future circular textile industry. Nevertheless, the environmental estimations suggest that further development and optimisation are required before the technology has industrially relevant applicability (See chapter 4 for environmental assessment).

3.2.4 Future work

DTI and NATEX Prozesstechnologie will lead the future development and upscaling of the technology. The development will focus on the areas identified by the LCA analysis regarding consumption of solvent and heat in the process.

3.2.5 Sub-conclusion

The decolorization technology developed in this project has successfully demonstrated the removal of dyes from polyester textiles on both gram and kilogram scale. The process was effective on cut and shredded polyester samples and also on intact t-shirts and achieved complete decolorization.

The key parameters of the decolorization process were first optimized on a small gram scale set-up, followed by further optimization on larger kilogram scale equipment at NATEX Prozesstechnologie. The optimization focused on the identification of milder conditions with reduced temperature, solvent consumption, and process time in order to minimize the environmental impact and the risk of polyester degradation.

Evaluation of the polyester quality before and after decolorization, using IV and differential scanning calorimetry (DSC) measurements, showed that the treated polyester samples met the requirement specifications for fiber production. The IV and DSC values were within the required ranges, indicating minimal degradation during the decolorization process.

Overall, the successful demonstration of the decolorization technology on kilogram scale pre-consumer polyester waste where suitable material qualities of polyester were produced suggests its potential applicability as a purification step in the future circular textile industry. However, further development and optimization may be required to address environmental considerations before industrial-scale implementation.

3.3 Recyclable impregnation agents

3.3.1 The need for recyclable impregnation agents

Impregnation agents are widely used in the textile industry, providing water repellence, for instance, to outerwear. However, many of these compounds contain harmful chemicals such as fluorine and require fossil resources for production, and such agents prevent the recycling of the textiles. Bacterial cellulose (a natural product very similar to cotton) aims to overcome these limitations and to ease the recycling of impregnated textiles.

The potential advantage of the cellulose-based impregnation material is that it has the potential to improve the recyclability of impregnated textiles. One barrier for recycling textiles, is the presence of impregnation materials [8]. According to the Danish EPA, impregnated textiles should be diverted from the recycling processes and treated as residual waste to avoid contamination [9].
With a biologically based solution, allowing the textile to be included in the recycling process, minimising contamination could be a major development in increasing textile recycling (FIGURE 3.8).

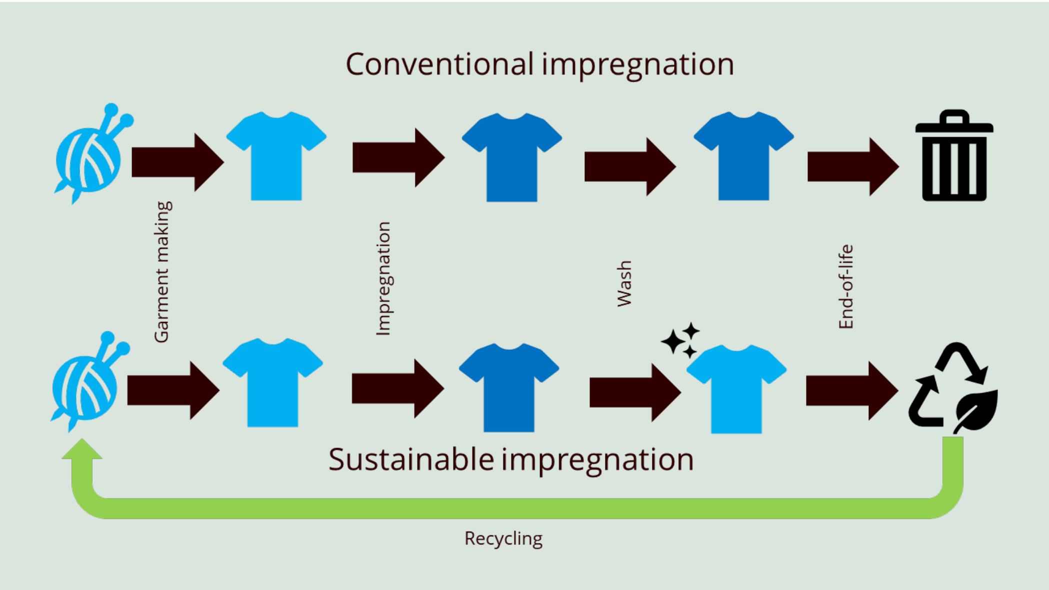

FIGURE 3.8. Material flow for conventional vs sustainable impregnated textiles.

3.3.2 Microbial cellulose

Biofabricated cellulose (BC) is a unique, natural material that can be produced by a variety of bacteria from *Acetobacter, Komagataeibacter* or *Gluconobacter* families. BC is traditionally produced by static or shaking culture methods.

BC has nanoscale fiber size and many free hydroxyl groups. That ensures high inter-fiber hydrogen bonding or functionalization by OH-group substitution (FIGURE 3.9). Therefore, BC has great potential as a reinforcing material and is especially applicable for recycled paper and for paper made of nonw3.oody cellulose fiber. The similarity of paper and textile pulp initiated the idea of reinforced textile pulp or recycled cellulosic textiles with BC. Modified BC shows great potential for production of fire resistant and specialized papers. However, the biotechnological aspects of BC need to be improved to minimize the cost of its production, and to make this process economically feasible.

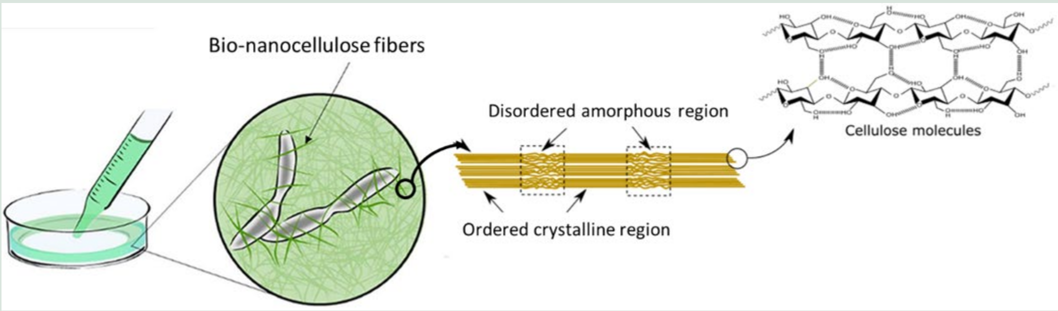

FIGURE 3.9. Biofabricated cellulose (BC) production by acetic/lactic acid bacteria. Produced BC has two main regions that are classified as crystalline and amorphous.

The producer and knowledge partner Cellugy developed a method to isolate high performing BC-producing strains that could pool 24 strains. In addition, Cellugy's BC produced using sucrose-containing minimum medium has a high crystallinity of >94%. High crystalline fermentation-derived cellulose broadens the formulation possibilities for wider applications.

Cellulose is the most abundant polymer on the planet. It is used extensively for textiles (e.g., cotton, linen, regenerated cellulose), paper and construction materials. Many new applications are currently being explored such as cellulose-based textile finishing. Finishing typically takes place to functionalise the textiles, e.g., for water repellence, comfort properties, antimicrobial effect, fire retardancy. Finishing of cellulose-based textiles now takes place with non cellulose materials due to the limitations of current plant-extracted cellulose in the market where it flocculates affecting its ability to integrate to the formula and low crystallinity that makes it necessary to be chemically modified for property modulation. Bacterial cellulose is a pristine cellulose with high crystallinity, which makes it easier to modulate. Therefore, its enhancing fabric properties such as increasing strength and durability, water repellence, and antibacterial properties have been investigated.

3.3.3 Recyclable impregnation agents

Cellugy started their journey within packaging. They produced EcoFLEXY, the first alternative biomaterial to replace fossil-based (e.g., ethylene vinyl alcohol) barrier coating for packaging. EcoFLEXY is biodegradable and home-compostable: if leaked to the environment, it disintegrates in 4 weeks and can safely be eaten by animals. If collected for recycling, EcoFLEXY can be recycled into the paperboard stream, effectively turning multi-material packaging coated with EcoFLEXY into a mono-material.

The bacterial cellulose-based formula works as waterproof coating for packaging that utilizes cellulose-based substrate such as paper. Therefore, it must be investigated if it can be utilized as an impregnation agent for cellulose-based textiles such as cotton, where it would provide a solution enabling the recycling of the impregnated textiles. There is hope that it can phase out the use of harmful petrochemical-based materials and reduce their release into the environment, while also promoting the recyclability of textiles.

EcoFLEXY is the biomaterial that can retain the useful characteristics of plastic and does not harm the environment. It has immediate application in the textiles industry as a replacement for non-cellulosic finish material cellulose-based textile. It can also be refined into a film or used as a strengthening additive for regenerated cellulose in textile (lyocell, viscose).
EcoFLEXY is:

- Fossil free, land neutral. EcoFLEXY is made from land neutral feedstocks such as surplus sugar from table sugar production. This way, pressure is avoided on carbon-emitting fossil sources but also on land, which in return can be used for primary food production.
- Bio-based and edible. EcoFLEXY does not harm animals or humans if leaked into the environment: it disintegrates completely in 4 weeks at room temperature, without leaving microparticles behind like conventional plastics, and beating bioplastics in degradation time. Being made from nanocellulose, a natural fiber Generally Recognized As Safe (GRAS) by the FDA.
- Recyclable in the cellulosic material stream. EcoFLEXY can be recycled alongside cotton to be mixed and milled to be regenerated cellulose, although the biggest challenge will come from color and printing materials.

3.3.4 Development of recyclable impregnation agents

EcoFLEXY production

BC production is a bioprocess involving cultivation of living bacterial cells under controlled conditions in a specialized vessel – a fermenter. The process starts with the cultivation of a seed culture or inoculum. Seed cultivation is a stepwise process throughout which the volume of inoculum is gradually increased to a desired level. Each step requires a properly formulated and sterilized medium for the cells to grow and multiply. Cellugy conducted fermentation experiments in 2L fermenter volumes for which a single step seed cultivation is sufficient. After inoculation of the fermenter the cells grow until they mature and deplete the nutrients in the medium, at which point they are inactivated (cell lysis) and the BC harvested. Then the BC is separated from the fermentation broth and impurities by centrifugation/filtration and water washing, and finally it is dried before being weighed to provide experiment results.
A complete process flow with media preparation and sterilization is summed up in FIGURE 3.10.

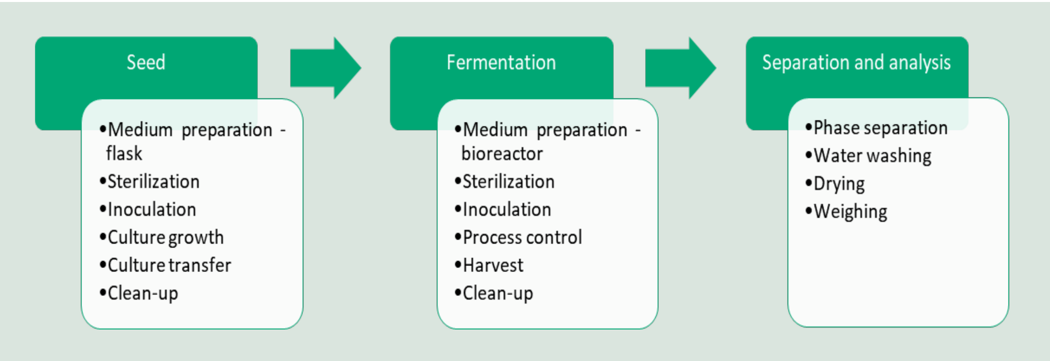

FIGURE 3.10. EcoFLEXY production process: The production of EcoFLEXY is divided into three main sections; seed, fermentation which belong to upstream producing BC and downstream process (separation and analysis) which produce EcoFLEXY with distinctive properties.

Product specifications are instrumental in maintaining quality, efficiency, and consistency, which are crucial factors to sustain partner relationships by ensuring consistent product performance. In the next chapters, efforts to determine product specifications during the scaling process will be elaborated upon, emphasizing the significance of meeting the required performance standards.

EcoFLEXY production for use of, e.g., impregnation agent was scaled up to 300 L fermenters. Purification/downstream process was scaled to purify 250 L in a one-batch process. Spray drying was done on pilot scale with capability up to 100 L per batch. (L4.3, M4)

EcoFLEXY suspensions' quality control to ensure in-specification product properties and performance includes:

- Crystallinity analysis
- Degree of polymerization
- Impurity analysis using FTIR

Parameters for product specification are often determined from the type of quality control that has been established in-house. We have used two types of parameters during the quality control processes which are: Product quality as determined by conductivity and pH, and product features as determined by viscosity and the ability to form networks, these features are critical for BC in these applications.
These parameters collectively provide a comprehensive overview of the EcoFLEXY product's quality and performance, ensuring both purity and specific functional characteristics necessary for intended applications. Regular monitoring of these parameters during the quality control process was crucial to maintaining consistent product quality and features.

3.3.5 Translating BC from paper coatings to use as textile coatings

Both paper and cotton are cellulosic materials, sharing a similar chemical structure. This chemical similarity suggests that coatings or treatments effective for paper could potentially be adapted for cotton textiles. The use of BC as an impregnation agent for paper has shown promising results, and this knowledge could be leveraged for cotton textile applications.
The processing conditions and techniques used for paper coatings may not be directly transferable to cotton textiles. The physical properties of the substrate, such as flexibility, thickness, and surface topography, can influence the coating process and the final performance of the coated material. Adjustments in coating formulations, application methods, and curing/drying conditions may be necessary to accommodate the unique characteristics of cotton textiles.
Furthermore, cotton textiles are subject to more rigorous wear and tear during use, as well as repeated laundering cycles. The coating on cotton textiles must exhibit excellent durability, wash-fastness, and resistance to abrasion and flexing to maintain its functionality over an extended period. Achieving these properties while maintaining the desired breathability, drape, and comfort of the textile can be challenging. One significant challenge arises from the hydrophobic nature of particles needed for cotton impregnation, as the BC in itself was not able to impart the desired water repellence. Cotton textiles are inherently more porous and have a higher surface area compared to paper, making it more difficult to achieve uniform coating and impregnation. The hydrophobic particles may exhibit different interactions and adhesion properties with the cotton fibers, potentially leading to uneven distribution or poor durability of the Impregnation. The impregnation agent was to be evaluated by crystallinity analysis, degree of polymerization, impurity analysis using FTIR, water repellence, water fastness etc.

3.3.6 Initial performance of the impregnation agent

Using EcoFLEXY B on cotton samples imparts water repellence to the samples. The EcoFLEXY B impregnation agent can infuse the textile with barrier properties against water, acting as an impregnation agent.
FIGURE 3.11 illustrates the water repellence of the cotton samples treated with EcoFLEXY B, demonstrating the effectiveness of the impregnation agent in imparting barrier properties against water.

FIGURE 3.11. Water droplets on impregnated textile sample.

Using these formulas, different new batches of EcoFLEXY B impregnation agent were tested on textile samples for water repellence. The data presented in TABLE 3.5 shows the performance of two different batches (Batch 1 and Batch 2) of the impregnation agent EcoFLEXY B on textile samples before and after washing. The performance is evaluated using a water spray test with a score ranging from 0 (worst) to 5 (best).

TABLE 3.5. Performance of a water spray test of impregnated textile samples pre- and post-wash.

Samples	Condition	EcoFLEXY B Batch 1	EcoFLEXY B Batch 2
Sample 1	Pre-wash	1	2
	Post-wash	0	0
Sample 2	Pre-wash	0	3
	Post-wash	0	0
Sample 3	Pre-wash	1	3
	Post-wash	0	0
Sample 4	Pre-wash	2	1
	Post-wash	0	0

Firstly, there is a noticeable batch-to-batch variation in the performance. For Batch 1, the pre-wash scores range from 0 to 2, indicating a relatively low and inconsistent performance. On the other hand, for Batch 2, the pre-wash scores range from 1 to 3, showing slightly better but still varying performance. This variation in scores between the two batches suggests a lack of consistency in the formulation or manufacturing process, leading to batch-to-batch variance. Secondly, the formulations within each batch appear to be heterogeneous. Within Batch 1, the pre-wash scores for different samples are 1, 0, 1, and 2 for Samples 1, 2, 3, and 4,

respectively. Similarly, in Batch 2, the pre-wash scores are 2, 3, 3, and 1 for Samples 1, 2, 3, and 4, respectively. This variation within a single batch indicates that the formulations are not homogeneous, leading to inconsistent performance across samples.
Thirdly, the data reveals poor wash fastness of the impregnation agent. After washing, all samples from both batches scored 0, regardless of their pre-wash performance. This suggests that the impregnation agent has poor wash fastness, meaning it is not durable and gets washed off completely during the washing process.
In summary, the data highlights three major challenges: batch-to-batch variance in performance, heterogeneous formulations within each batch, and poor wash fastness of the impregnation agent. To overcome these challenges, improvements in the formulation, quality control of the manufacturing process, and wash durability of the impregnation agent were necessary and in focus in the present project.

The water repellence from the spray test were correlated against the water contact angle, which are expected to increase with more repellent coatings. The measurements are shown together with other impregnating agents (Bionic, C6), to evaluate whether water contact angle could be used as a faster screening tool (FIGURE 3.12).

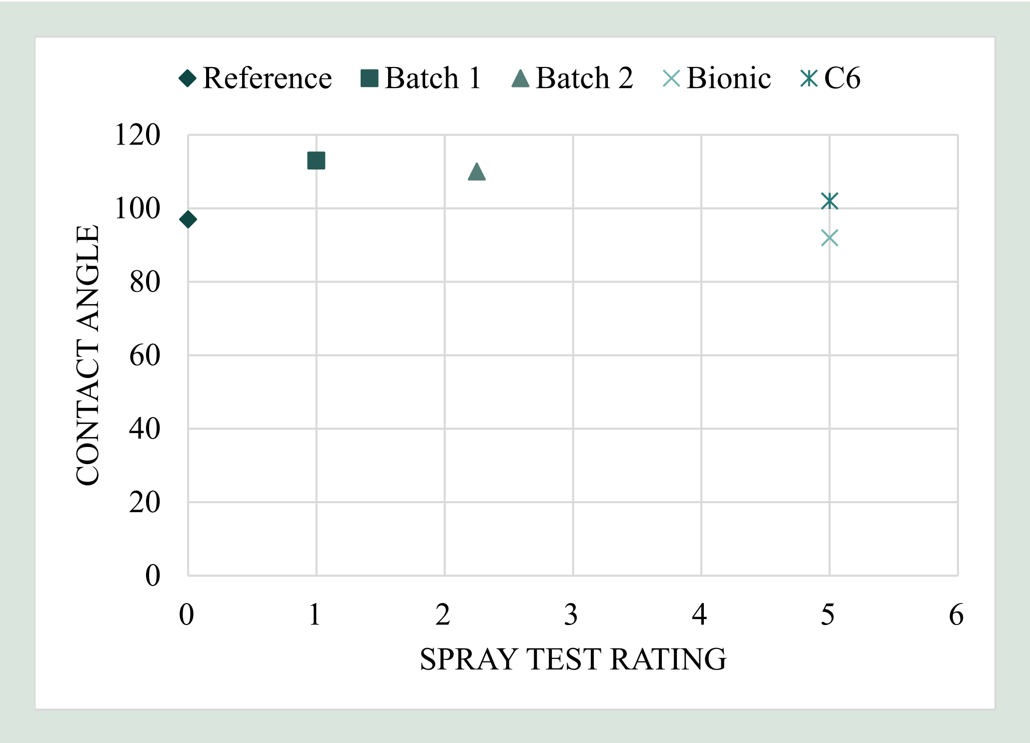

FIGURE 3.12. Spray test rating as a function of water contact angle on impregnated textiles.

The water contact angles, and water spray test rating had very poor correlation. Therefore, water contact angles could not be utilized for faster screening of the coating performance.

3.3.7 Improving the impregnation agents

Firstly test for improvements was carried out with multiple dips in the impregnation agent, seeing whether that would increase the homogeneity and water repellence, TABLE 3.6.

TABLE 3.6. Water spray test of EcoFLEXY B impregnation after multiple impregnations.

Samples	Double dip Impregnation	Triple dip impregnation	Quadruple dip impregnation
Sample 1	1	2	1
Sample 2	1	1	2
Sample 3	2	1	2
Sample 4	2	2	1
Mean	1.5	1.5	1.5

The use of additional impregnation did not improve the water repellence of the impregnated textiles. The values shown in TABLE 3.6 are similar to single dip impregnations and show no improvement in the water repellence with additional dips.

To further develop the impregnation agent, first higher quality control in the BC process and the formulation of the impregnation was needed and following this the development work continued.
LCA analysis showed that formulations containing ethanol, including EcoFLEXY B, had significant impacts. To lower these impacts new formulations called EcoFLEXY RB were utilized eliminating ethanol and as an added benefit also improved batch variations.
Different fixation methods were utilized such as priming with polyvinyl alcohol, presoaking the textiles to expand the fibers for easier impregnation, different fixation temperatures, and regimes etc. However, none of these proved successful in improving washing fastness.
Following this development using different concentrations of hydrophobic particles in the formulations to increase the water repellency was tested.

TABLE 3.7. Result from water spray test impregnated textiles pre- and post-wash.

Samples	Condition	EcoFLEXY RB 1:1	EcoFLEXY RB 1:10	EcoFLEXY RB 1:20
Sample 1	Pre-wash	3	1	1
	Post-wash	0	0	0
Sample 2	Pre-wash	3	1	1
	Post-wash	0	0	0
Sample 3	Pre-wash	3	1	1
	Post-wash	0	0	0

TABLE 3.7 shows the results of the water spray test performed on three different impregnation formulations (EcoFLEXY RB 1:1, EcoFLEXY RB 1:10, and EcoFLEXY RB 1:20) for three different samples (Sample 1, Sample 2, and Sample 3) before washing. The test scores range from 0 to 5, with 0 being the worst and 5 being the best. The EcoFLEXY RB 1:1 formulation performed best with a score of 3 for all three samples before washing. The EcoFLEXY RB 1:10 and EcoFLEXY RB 1:20 formulations both scored 1 for all three samples before washing, indicating poorer water repellency compared to EcoFLEXY RB 1:1. The formulation had significantly improved the homogeneity compared to previous samples. Generally, more hydrophobic particles in the coatings provided better scores in the test.
After washing, all three samples showed a score of 0 for all three impregnation formulations, as shown in TABLE 3.7. This indicates that the washing procedure was able to remove all the impregnation, resulting in the textiles being completely wettable.

The negative implication is the continued need to apply the impregnation agents after each wash, while the positive aspect is easier recycling since the impregnation is removed during washing, making the textiles impregnation-free and more suitable for recycling processes. Overall, the data suggests that the EcoFLEXY RB 1:1 formulation provided the best water repellency before washing, but all formulations were ineffective after washing, necessitating reapplication of the impregnation agents for continued water repellency. The easy removal of the impregnation facilitates recycling but requires more frequent impregnation, making these agents potentially more suitable for textiles that are rarely washed, such as upholstery and shoes, compared to everyday garments. Overall, the homogeneity issues, and the batch variations in the impregnation agents were overcome, however, the issue of stability towards washing was never conquered. The formulations seemed to act like coatings rather than impregnation agents, and therefore only cover the surface of the fibers and are too easily washed off.

3.3.8 Recycling of impregnated textiles

The general purpose of the project is to facilitate the transition to a circular textile industry. Consequently, it is important to test the recyclability of the impregnation agents at an early stage to ensure the relevance of the development. Impregnated textiles were therefore tested for recyclability at Textile Change. The results feed inrto the design guide for which sustainable impregnation agents complement the recycling strategies.

Impregnated samples were tested alongside non-impregnated samples to determine whether it would disrupt the recycling of textiles. They were tested through the process, to evaluate whether the impregnation would pose problems in the process.
TABLE 3.8 displays the weight measurements and mass loss percentages for impregnated and reference (non-impregnated) textile samples during alkaline and decoloring treatments. The second table shows the average brightness percentages of the impregnated and reference textile samples after the alkaline treatment and after decoloring.
From TABLE 3.8, we can observe that the impregnated textile sample had a slightly higher mass loss percentage (10.39%) compared to the reference textile (7.48%) after the alkaline treatment. This higher mass loss could be attributed to the presence of the impregnation agent or coating on the textile fibers, which may have been partially removed or fully removed during the alkaline treatment. The feel of the textiles was different after the alkaline treatment.

TABLE 3.8. Brightness and mass loss after alkaline and decolouring processes.

Samples	Alkaline treatment		Decolouring treatment	
	Brightness [%]	Mass loss [%]	Brightness [%]	Mass loss [%]
Impregnated textile	42.5	10.39	47.8	2.93
Reference textile	43.8	7.48	50.9	2.46

However, during the decoloring treatment, the mass loss percentages were rather similar with 2.93% for the impregnated textile and 2.46% for the reference textile, suggesting that the impregnation did not significantly influence the decoloring process. The feel of the textiles was no longer dissimilar after the decoloring process.
The reference textile had a marginally higher average brightness percentage compared to the impregnated textile after both the alkaline treatment (43.8% vs. 42.5%) and decolorization (50.9% vs. 47.8%).
Overall, the data suggests that there are insignificant differences in the mass loss and brightness values between the impregnated and reference textile samples during the pretreatment steps. The observed differences are relatively small and within an expected range of uncertainty, considering the presence of the impregnation agent or coating on the textile fibers. This implies that the impregnation process does not significantly disrupt the

recycling of textiles, as the impregnation is likely stripped during these pretreatment stages before reaching the actual recycling process.

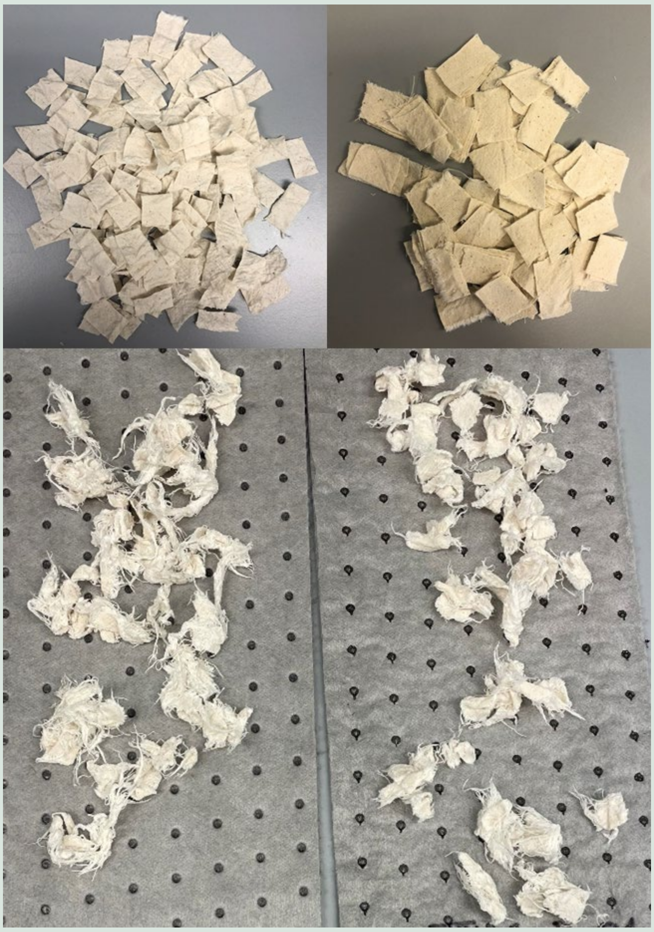

FIGURE 3.13. Textile samples before (top) and after pretreatment at TC impregnated (left), reference (right).

Overall, measurements of feel, brightness, and mass loss indicate that the samples would strip the impregnation during the pretreatment steps before reaching the recycling process. Consequently, this means that the impregnation does not impede the recycling process at Textile Change. These results are also in line with the poor water fastness. Consequently, this innovation enables recycling of impregnated textiles, which previously, when treated with traditional impregnating agents, would have to be either landfilled or incinerated due to their incompatibility with recycling processes. Whether improving the washing fastness will negatively impact the recycling will have to be evaluated further.

3.3.9 Future work

Cellugy holds a patent regarding the application of BC for textiles and will continue to develop treatment for textiles using BC. The future work will focus on methods regarding a BC coating and not impregnation as described in the present project. This will open new approaches in the development.

3.3.10 Sub-conclusion

Throughout this project, the bacterial nanocellulose process was significantly improved and scaled up at Cellugy. The production capacity increased to 300 L fermenters, demonstrating substantial progress in scaling the technology. Initially, there was considerable variation in

batch quality, which prompted Cellugy to focus more intensively on quality control measures. These quality control procedures were developed and implemented during the project, resulting in much lower batch variance being achieved.
The impregnation agent, based on bacterial cellulose, was successfully developed to impart water repellence to cotton fabrics, however, it was not stable to washing. An important finding was that the impregnation did not impede the recycling of textiles, as it could be removed during the pretreatment process at Textile Change. This discovery has positive implications for the circular economy and sustainability of treated textiles.
However, it was observed that the impregnation behaved more like a coating than initially expected. This insight paves the way for exploring other technologies to enhance adhesion in future developments. While the current impregnation was not able to withstand washing, this characteristic suggests its potential applicability in products with less frequent washing requirements, such as shoes, furniture, and similar items.
The project's outcomes highlight both the advancements made in bacterial nanocellulose production and the potential applications of the developed impregnation agent. They also underscore areas for future research and development, particularly in improving the wash resistance of the treatment for broader textile applications.

3.4 Methods

3.4.1 Methods used in polycotton recycling

Intrinsic viscosity

The intrinsic viscosity of the textiles was evaluated by using a Rolling-Ball Viscometer, Lovis 2000M/Me, Anton Paar.
Cellulose: 55 mg of dried sample from samples were dissolved in 11 mL (50:50 mixture of DMSO and ionic liquid) at 50 ˚C while stirring for approximately 4 hours until dissolved, and then passed through a 0.45 µm filter, resulting in a concentration of 5 mg/mL. From this solution, three additional concentrations were made 0.5, 2.0, and 3.5 mg/mL for measurement. The relative viscosity was calculated based on the reference solvent, i.e., solvent without any polymer dissolved. The measurements were conducted at 25 ˚C and at an angle of 30^{o} for each concentration. Cellulose degrades during dissolution, and therefore results are only comparative within the same batch of measurements.

55 mg of polyester samples were dissolved in 11 mL of *o*-chlorophenol at 90 ˚C while stirring for approximately 2 hours until dissolved, and then passed through a 0.45 µm filter, resulting in a concentration of 5 mg/mL From this solution, three additional concentrations were made 0.5, 2.0, and 3.5 mg/mL for measurement. The relative viscosity was calculated based on the reference solvent, i.e., solvent without any polymer dissolved. The measurements were conducted at 25 ˚C and used multiple angles of 18, 38 and 80 ^{o}.

IR

Average IR spectra were measured on an area of 2 mm^2 on a FTIR spectrometer from Agilent, model 4500a, using the ATR method (Attenuated Total Reflectance), with 32 repetitions and a resolution of 2 cm^{-1}. The selected areas of the samples were placed directly on the ATR crystal and contact was ensured by the sample holder on the instrument.

3.4.2 Methods used in decolorization of polyester

Differential Scanning Calorimetry (DSC)

The polyester samples were analysed by Differential Scanning Calorimeter (Perkin Elmer, 400 DSC).
Approximately 10 mg of sample was weighed into special pans and sealed. An empty pan was used in the reference cell. Changes in heat flow during melting were recorded. The following temperature protocol was used: The sample was held at 20 ˚C for 2 minutes and subsequently

heated to 300˚C at 10 ˚C/min and held at 300 ˚C for 1 minute. The sample was then cooled to 20 ˚C at 10 ˚C /min.

3.4.3 Methods used in recyclable impregnation agents

Bacterial cellulose

Production of bacterial cellulose

Biofabricated cellulose (BC) was synthesized in an agitated reactor using bacterial cellulose producing bacteria *Komagataeibacter xylinus,* which was isolated by Cellugy from a commercial symbiotic culture.

Purification of cellulose using NaOH

Broth from the fermenter was treated with 0.25 M NaOH at 60 °C under gentle mixing to purify cellulose. The cellulose fraction was then collected/washed either using centrifugation or filtration.

Formulation with hydrophobic minerals

Hydrophobic minerals (Silica Dimethyl Silylate) were used, purchased under the name HDK H18 from Wacker. The hydrophobic minerals were added to EcoFLEXY B suspension in water. The concentrations of EcoFLEXY B tested were 0.1, 0.5, and 1.0%. Different ratios of BC:HDK18 were prepared, e.g., 1:0.1, 1:0.5, and 1:1. The final mixtures were ultimately homogenized using a Silverson L5M mixer at max speed for 5 minutes.

Drying

The Ecoflexy suspension was dried into a fine powder using a pilot scale spray drier (SiccaDania SD900).

Characterization and quality control of bacterial cellulose

Fourier transform infrared (FTIR)

The FTIR spectra were recorded on a Nicolet Summit FTIR Spectrometer. By averaging 32 scans from 4000 to 400 cm^{-1} at 4 cm^{-1} resolution. All samples were oven dried before their FTIR spectra were obtained. Each FTIR spectrum was normalized at 1056 cm^{-1} (C–O stretching vibration of glucose ring) and the baseline was corrected using Spectraglyph software.

The crystallinity index (CI) or crystallinity % of cellulose was determined with FT-IR spectroscopy according to the method disclosed by [10]. The crystallinity index (CI) was determined by calculating the peak ratio at 1430 and 898 cm^{-1}.

Viscosity measurements

The viscosity measurements were carried out at 25°C under rotational movement measuring the viscosity at shear rates between 0.01-1000 s^{-1} using a Discovery HR-20 Rheometer (TA Instruments). The geometry used was a 40mm plate with the gap set to 1000 µm. Single viscosity values presented are derived at a shear rate of 1 s^{-1}.

Characterization of the impregnating agents

Zetapotential:

The samples were diluted to a nanocellulose concentration of 0.07 w% in distilled water and homogenized before measuring.

Zeta potential was measured in a Malvern Zetasizer Nano – ZS. The Zeta potential measurement was performed by means of phase analysis light scattering (PALS) to measure the electrophoretic mobility of the particles.

The measurements were performed at 25 °C and a two-minute temperature stabilization time was used before the measurements began. The refractive index of 1.440 and an absorption of 0.001 were used for the particles. Standard parameters were used for the water. Three measurements were performed on each sample. Samples were measured at different pH.

Dynamic light scattering:

Dynamic light scattering was measured in a Malvern Zetasizer Nano – ZS. The measurements were performed at 25 °C and a two-minute temperature stabilization time was used before the measurements began. The refractive index of 1.490 and an absorption of 0.01 were used for the particles. Standard parameters were used for the water. Three measurements were performed on each sample.

Static light scattering:
Particle size distribution was determined using a Malvern Mastersizer 2000 instrument with a Hydro S dispersion unit. The measurements were performed by means of laser diffraction and particles in the size interval from 0.02-2000 µm are measured. The sample was measured with constant stirring to avoid sedimentation. The particle size distribution is calculated based on the assumption that the particles are spherical. The result is reported as an average of triplicate measurement.

Impregnated textiles
Homogenization:
Prior to impregnation of textiles the impregnation agents were homogenized. This was achieved by adding the desired amount of impregnation formulation to a beaker and then homogenizing it using high shear. This either took place with a kitchen blender at maximum speed for 15 min. or with an ultra turrax IKA t25 for 25 min. at 10,000 – 12,000 rpm.

Dip impregnation
For dip impregnation, the textile samples were immersed in impregnation formula for approximately 5 seconds. Post immersion, the samples were pressed between two wood sticks to remove excess impregnation agent. The textiles were then fixated at 120 ˚C for 3h in an oven.

Padding mangle coating
The solution was tested by a laboratory padding mangle to imitate full scale production conditions and make a standardized application. The machine was operated manually with a speed of 2 m/min and maximum pressure on the rollers. The impregnated textile was fixated in a heat press at 150 ˚C for 60 seconds.

Water repellence
The impregnated textiles were evaluated according to homogeneity by visual inspection, feel, and water repellence either qualitatively by adding water drops on the textiles and measuring the time or using water spray test reminiscent of DS/EN ISO 4920. Ranking the water repellence on a scale of 0-5 where 0 is the worst and 5 is the best.

Contact angle measurement was conducted on a Krüss drop shape analysis system DSA10 with 5 µL milli-Q water, to determine the interaction between water and surface. The evaluation was based on 3 samples.

Influence on recycling at textile change
Pretreatment before processing at TC
Coated and uncoated samples were treated at TC. This includes an alkaline treatment and a decolouring treatment to test whether the coating was removed. It was evaluated by using weight loss and brightness measurements.

4. Environmental assessment

“What gets measured gets managed” and what does not get measured or is not measurable runs the risk of being neglected. Therefore, it is important to include sustainability of the choices made in relation to, e.g., product design and to have tools to assess it. Life cycle assessment (LCA) is a systematic analysis method to assess the environmental impact of a product, process, or service.
This chapter describes the simple LCA tools that have been tested in the project followed by final environmental assessments of the decolorization process and the impregnation agent. The environmental assessments have been used to guide the development along the project.

4.1 Simple LCA tools for sustainable decisions

With a growing awareness on the environmental impacts of the textile industry several sustainability, carbon footprint and/or simple LCA tools have been developed. The tools are used to assess and compare the environmental impacts of textiles. However, with the many options it can become confusing which tool to choose, what can be concluded from the calculations, and what can be communicated.

To understand the pros and cons of simple LCA tools, a review of some of the available tools has been conducted. Based on the review, attention points and recommendations have been formulated for the textile industry. The tools have been tested in the project to guide the decision-making process and to provide a design guide basis. To use these tools in the development process of the project, a full understanding of the pros and cons was necessary. The review was conducted at the beginning of the project, and the following text is based on the work conducted in 2022. Updates and changes have probably taken place since then.

4.1.1 Calculation tools selection and criteria

In the review of available LCA tools, 10 different options/tools were identified. The identified options/tools are shown in TABLE 4.1. Tools such as SigmaPro, GaBi, and openLCA have not been included in the list as they are perceived as professional LCA tools.

TABLE 4.9. Identified option/tool for LCA calculations.

Company/tool	Description
Force Technology	Perform LCA
Higg index	LCA-based calculation tool for textile
Målbar	Carbon footprint calculation tool
STeP by OEKO-TEX®/The Impact calculator	Carbon and water footprint calculation tool
Sensitive ® Fabrics	Carbon footprint, water, and energy use calculation tool
ECOMETRICS	Environmental footprint calculation tool

Company/tool	Description
InterTex/InterTex LCA Textile	LCA calculation tool
The 2030 Calculator	Carbon footprint calculation tool for textile
bAwear Score	Carbon footprint, water, and energy use calculation tool for textile

Evaluation parameters were made to assess the simple LCA tools. They appear in TABLE 4.2. 'Accessibility' was selected as the most critical parameter. If the tool was not available for the companies to perform the calculations independently, the tool was not investigated further. Four tools scored 'Yes' in 'Accessibility', and they were further investigated regarding the life cycle perspective, database use, user-friendliness, and price. The four tools are Higg Index, Målbar, The 2030 calculator, and bAwear Score, and a description of each tool is found below.

TABLE 4.2. Simple LCA tool evaluation parameters.

Evaluation parameter	Description	Score
Accessibility	Can the tool be accessed by the companies to independently perform the calculations?	Yes/no
Life cycle perspective	What life cycle stages are included?	Life cycle perspective
Method	What LCA methodology has been used for the calculations?	Name
Database use	Which database is used for background data?	Amount
Multiple output categories	Can the results be reported as multiple environmental impact categories?	Amount
User-friendliness	Is the tool user-friendly or is a crash course required?	✓-✓✓✓ (1-3)
Price	How expensive is the tool?	$-$$$ (1-3)
Use of results	Can the results be used for communication as 'business-to-business' or 'business-to-costumer'?	B2B/B2C

Higg Index

Higg Materials Sustainability Index can evaluate and compare environmental impact of apparel, footwear, and home textiles. Higg Index offers two types of calculation tools: Higg Materials Sustainability Index (Higg MSI) and Higg Product Module (Higg PM). Higg MSI is one of the most widely used tools for evaluating sustainability in the textile industry.

Higg MSI uses life cycle thinking in a cradle-to-gate perspective, meaning environmental impacts from extraction of raw materials, processing and material production are considered in the calculations, and transport and packaging are included. The calculations are based on a functional unit of 1 kg material. The results are displayed in a score-chart, where both absolute and normalised results can be seen. Normalised results express the environmental impact results relative to a reference system. This is done to make comparison easier and answer the question 'is this much?'. Higg MSI uses an 'average material' as their reference system where the average material consists of the weighted volume of the materials used by the textile industry. That means that the average material consists of, e.g., 32% polyester and 15% cotton. [11]

Higg PM considers the entire life cycle of a product (cradle-to-grave), meaning that all steps from raw material extraction to end-of-life is considered in the calculation. The calculation for raw materials to material production is based on Higg MSI and from product finish to end-of-life the calculations are based on data average and assumptions. For instance, the use stage of a product based on a standard consumer usage pattern considering washing frequency and lifespan of the product.

The Higg Index follows ISO 14040 [12] and 14044 [13], which are the ISO standards referring to LCA. Furthermore, the Higg PM is designed to evolve and aims to align with future EU Product Environmental Footprint (PEF) Apparel & Footwear Methodology.

The data used for the calculations consists of primary and secondary data. The primary data is collected from the textile industry and the secondary data is collected from commercial data, Ecoinvent, Gabi, the world *apparel* lifecycle database (WALDB), literature and SAC member input. The results of Higg MSI can be reported as Global Warming Potential (kg CO2 eq.), Eutrophication (kg PO4 eq.), Water Scarcity (m3), Resource/fossil depletion (MJ), and Chemistry (CTU).

Membership is required to gain access to the Higg index tools, and the price depends on the size of the specific company's revenues. A company must buy access to the basic package, which includes access to Higg MSI and PM.

Målbar
Målbar has developed a screening tool where the entire life cycle of a product (cradle-to-grave) is considered. Målbar's screening tool uses a conservative approach when no data or information is available. That can result in a higher carbon footprint compared to when data/information is available. Målbar's results are presented as CO_2 eq. where it is possible to identify potential hotspots. Furthermore, to answer the question *'is this much?'* Målbar for instance translates the product's CO_2 eq. into how many km you can drive in an equivalent car. That makes it easier for the user to make a comparison.

The calculations are aligned with the PEF Apparel & Footwear Methodology, and data is obtained from Ecoinvent, which is one of the most used databases for LCA.

To gain access to Målbar's screening tool a monthly payment is required. if you are only interested in the result, Målbar can conduct the LCA and carry out a single product screening. Furthermore, Målbar also offers a verification service, which is necessary if the results are to be communicated B2C.

The 2030 Calculator
The 2030 Calculator uses life cycle thinking in a cradle-to-gate perspective. A carbon footprint from extraction of raw materials, processing, and material production is considered in the calculations, where transport and packaging are included. The result of the calculation is presented as kg CO_2 eq. together with a hotspot analysis, and the impact of each stage (raw materials, processing, assembly, packaging, and distribution) is shown in percentages.

The calculation uses data from Ecoinvent, ICE (University of Bath), IVL (Swedish Environmental Institute), DEFRA (Department for Environment, Food & Rural Affairs) and own LCI (life cycle inventory)/LCA data.

The tool is free to use. However, if you wish to save your calculations a monthly payment is required.

bAwear Score
bAware Score can evaluate and compare the environmental impact of apparel, footwear, and home textiles. They offer three different types of calculations: YourQuestion, YourScenario, and YourHotspot.

YourQuestion calculates the environmental footprint based on a cradle-to-gate perspective. Product type, material composition, finishing methods, and production location are considered in the calculations. The calculations are based on generic assumptions and contain assumptions made by bAwear. The results of the calculations are presented as absolute values and ranked in a speedometer.

YourScenario calculates the environmental impact based on primary data from a company's supply chain to give a more detailed LCA reporting still based on a cradle-to-gate perspective. bAwear will make the calculations, and the company will merely supply the required data. The output will be a customised report.

YourHotspot follows the same procedure as YourScenario. The customised report will include a hotspot analysis and identify specific impact indicators or impact hotspots in the supply chain.

The results are shown as three impact categories: Global warming potential (kg CO_2 eq.), energy use (MJ), and water usage (L), leaving out the remaining impact categories. The generic data for the calculations is provided from Ecoinvent combined with other databases giving a total of 11 databases.

Summarised scores
A summary of the different tools and the score of each evaluation parameter can be seen in TABLE 4.3.

TABLE 4.3. Overview of the different simple LCA tools. *The price is based on each product. Therefore, it can become an expensive tool depending on the number of products that have to be assessed. **The use of B2C requires validation by a third party.

Company/tool	Life cycle perspective	Method	Database use	Multiple output categories	User-friendliness	Price	Use of results
Higg MSI	Cradle-to-gate	ISO 14040/44	7	5	✓✓	$$-$$$	B2B
Higg PM	Cradle-to-grave	PEF	7	5	✓✓	$$-$$$	B2B/B2C**
Målbar	Cradle-to-grave	PEF	1	1	✓✓	$$$	B2B/B2C**
The 2030 Calculator	Cradle-to-gate	N/D	5	1	✓	$	B2B
bAwear Score YourQuestion	Cradle-to-gate	N/D	11	3	✓✓	$-$$$*	B2B

4.1.2 Comparison of calculation tool results

The results of two of the four tools described above were compared - the Higg MSI and the 2030 Calculator. Free trial versions were used to obtain results. The results of the tools are compared to the results obtained in the LCA software openLCA using data from Ecoinvent. The comparison was carried out to investigate the variation in results.

A scenario was created for the comparison. In the scenario, 1 kg of cotton was processed through spinning, circular knitting, dyeing preparation and batch dyeing. All these processes are assumed to take place in Bangladesh. The results are shown in FIGURE 4.1.

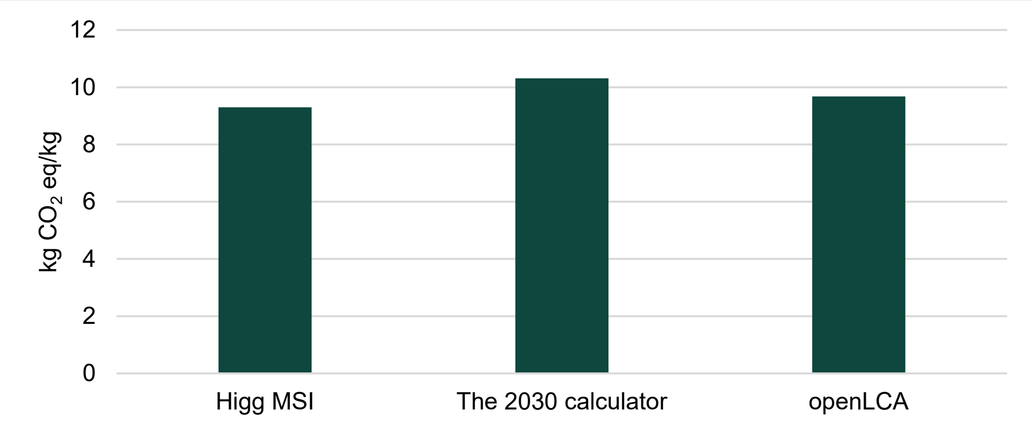

FIGURE 4.14. Comparison of results for processing 1 kg cotton obtained by different LCA calculation tools.

Based on the results of the three tools, a 17%-variation was obtained. The results underline one of the issues when comparing different LCA calculations. To carry out a fair comparison, the calculations must not only include the same processes and location, but it is also necessary to understand which flows and amounts are included in the calculations, and which are not. Furthermore, they need to utilise the same impact assessment method.

4.1.3 Attention points and recommendations

One of the tools identified is Higg MSI, which is one of the most frequently used sustainability tools in the textile industry. In 2022, this tool received media attention when The New York Times accused the tool of favouring synthetic materials. It also came to light that the Norwegian Consumer Authority accused the outdoor brand Norrøna of violating the law by marketing their clothing as environmentally friendly based on calculations using Higg MSI, and that led to greenwashing claims. [14, 15]. All of this comes back to the LCA method and the perspective the tool uses. The accusation of favouring synthetic materials is related to the way Higg MSI normalises their results, and the greenwashing claims are related to which statements you can make from a cradle-to-gate perspective.

In Norway and Denmark, the consumer ombudsman has stated clear rules for which type of documentation is required to market a product as environmentally friendly, sustainable, green etc. The documentation must show that ‘the product in general has a significant lower impact on the environment compared to similar products, by conducting a full life cycle assessment’. [16]

In TABLE 4.3 (Overview of the different simple LCA tools) it appears that only two out of five tools consider the full life cycle (cradle-to-grave perspective). The cradle-to-gate calculations require less data/information, often something the company already has or can easily obtain. The company obtains knowledge of their product’s environmental impact, however, there are some consequences the company must be aware of. When making decisions based on only some parts of the life cycle, you risk shifting the environmental burden to another stage in the life cycle. Furthermore, it can make comparisons difficult.

In the textile industry, fibers do not only have different environmental impacts on production, but they also differ in functionality and durability. In worst case, comparing the production of different fiber types can lead to comparing apple and oranges because lifetime, use, and recyclability matter and will influence the LCA assessment.

An example is the criticism of Higg MSI for favouring synthetic fibers compared to natural fibers. Polyester has a smaller carbon footprint than wool when focusing on the environmental impact of the production. However, wool usually has a longer lifetime than polyester. A Norwegian study shows that a wool sweater has an average lifetime of 10.8 years, whereas a blouse/shirt has an average lifetime of 5.6 years. Furthermore, there is a difference in how you treat the textile when it is washed, and there is a difference in what happens to the garment when it reaches its end-of-life. Regarding wool and wool blends 50% are reused in the form of donating to charity, family, friends, or selling it. 44% of synthetic fiber-based garments are reused in this manner. Furthermore, literature shows that fiber production only constitutes 15% of the total CO2 eq. emissions. Therefore, by focusing only on cradle-to-gate you neglect up to 85% of the CO2 eq. emissions of your product. [17]

The cradle-to-gate perspective calculations can give a good insight into the environmental impact of your product, but when it comes to using the design tools for sustainability the full life cycle (cradle-to-grave) should be considered to avoid burden shift. The good news is that more of the tools investigated are working on the implementation of cradle-to-grave calculation options, and more focus is drawn to this matter by legislation and the introduction of the PEF standard.

When selecting a simple LCA tool to assess sustainability and decision making, the companies need to be aware of pros and cons of the tool and its limitations. The simple LCA tools give a sense of data-driven decision-making, but it is easy to make false conclusions and odd comparisons based on these. The introduction of the PEF standard is expected to help standardise the calculations and calculation tools and to reduce this risk.

4.2 Environmental assessment of the decolorization process

The background for the LCA calculations appears in appendix 1.

4.2.1 Scenarios

The assessment involves the comparison of three scenarios.

- Scenario 1 (S1) - Baseline: The polyester waste was incinerated in Denmark. The heat and electricity produced during the incineration was used in the energy grid, resulting in avoided production of marginal heat and electricity. The treatment of incineration residues, such as fly and bottom ash, and wastewater was included in the scenario.
- Scenario 2 (S2) - Decolorization: The polyester waste was processed in Denmark. The output of the process was a cleaned white polyester, which avoided the production of virgin polyester. Residues from the decolorization process were incinerated in the same manner as in the baseline scenario.

A more relevant scenario where the co-solvent is recovered was included. In essence this scenario corresponds to a 90% reduction in co-solvent consumption, as the modelling did not include the energy, and materials required for the recovery and purification.

- Scenario 3 (S3) - Decolorization with 90% co-solvent recovery: This scenario was identical to the second scenario.

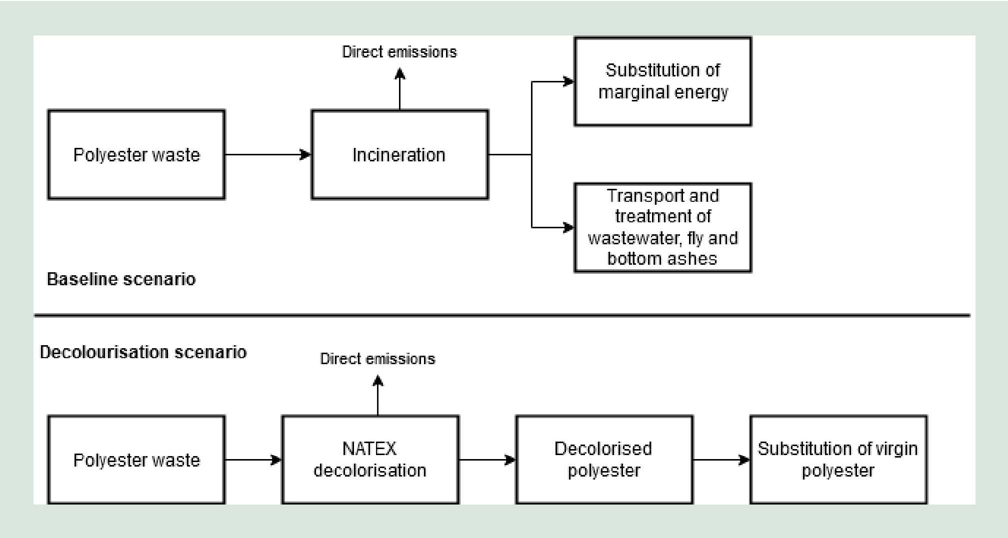

FIGURE 4.2. The processes included in the baseline (incineration) and decolorization scenario. The recycling of co-solvent in scenario 3 is not shown.

It is important to stress that in the decolorization scenario, the polyester must undergo additional treatment prior to substitution of virgin polyester, by either mechanical or chemical recycling. This is not included in the assessment. An overview of the scenarios is given in FIGURE 4.2.

4.2.2 Characterised results

The characterised results present the environmental impacts in their respective unit, as defined by the LCIA method. The characterised results of the scenarios are presented in TABLE 4.4. Focusing on climate change impacts, the incineration scenario resulted in an emission of 2000 kg CO2-eq./tonne waste, whereas the decolorization scenario resulted in -3200 kg CO2-eq./tonne waste. The decolorization with recovery of co-solvent resulted in the emission of 45 kg CO2-eq./tonne waste.

TABLE 4.4. Characterised results of the incineration and decolorization scenarios. Values in bold indicate the scenario with the lower environmental impact. All impacts are per functional unit, i.e. 1000 kg of polyester waste. The abbreviation use in the columns are explained in TABLE A1.1-2.

	CC	**OD**	**HTc**	**HTnc**	**PM**	**IR**	**POF**	**AD**
	kg CO_2-eq	kg CFC-11 eq	CTUh	CTUh	Disease incidence	kBq U-235 eq.	mol H^+ eq	mol N eq
S1: Incineration	2.0E+03	-1.3E-04	**-1.9E-06**	**-4.7E-05**	**-7.9E-05**	2.5E+01	**-5.3E+00**	**-4.9E+00**
S2: Decolorization	**-3.2E+03**	-7.2E-03	9.4E-06	1.4E-03	3.7E-03	**-2.4E+03**	1.1E+02	3.7E+02
S3: Decolorization	4.5E+01	**-1.0E-02**	5.2E-06	3.0E-04	5.3E-04	**-4.8E+02**	2.1E+01	4.8E+01
	EUt	**EUf**	**EUm**	**EF**	**LU**	**WD**	**RUm**	**RUe**
	kg N eq.	kg P eq.	kg N eq	CTUe	-	m^3 water eq	kg SB eq	MJ
S1: Incineration	**-3.5E+01**	-2.2E+00	**-2.2E+00**	**-1.5E+05**	**-1.8E+05**	**5.7E+02**	**-1.2E-02**	-2.1E+03
S2: Decolorization	1.8E+03	**-1.1E+01**	1.8E+02	2.3E+06	1.1E+06	4.8E+04	2.8E-01	1.3E+05
S3: Decolorization	3.0E+02	5.7E+00	2.4E+01	7.1E+05	7.0E+05	1.7E+03	1.4E-01	**-3.2E+04**

In terms of climate change impact, decolorization corresponded to lower impact, but it is important to keep in mind that recycling itself is not included in the assessment -

underestimating the total impact. This means that as long as the impact from the recycling process is within the difference between scenarios 1, 2, or 3, then the decolorization scenario corresponds to environmental savings.
A consequence of the method was that when the ethanol consumption decreased (scenario 3), (by recycling the co-solvent), the impacts increased for climate change, ionising radiation and freshwater eutrophication. That is due to how impacts are allocated in the multi-functional process of ethanol production. A co-product from ethanol production is brewers-grain, which is used as animal feed. In turn it substitutes protein feed from soy. That resulted in large benefits from the consumption of ethanol for a few impact categories.
Despite the preference for decolorization regarding climate change impacts, the incineration scenario in general resulted in lower impacts for most impact categories, apart from climate change, ozone depletion, ionising radiation, and freshwater eutrophication. The difference between the two scenarios was also in several orders of magnitude across most environmental impacts, indicating that the lower impacts from the incineration scenario were significant.

The results were used to guide the development of the decolorization technology. After the first iteration, focus was to decrease ethanol consumption and to lower the process temperature.

Normalised impacts
The benefit of normalised impacts is that the impacts share a common unit, the person equivalent (PE), allowing for better comparison and visualisation. Normalisation converts the characterised impacts (from TABLE 4.4) and normalises them according to the impacts of the global average person, using normalisation factors (see TABLE A1.1-2).
The normalised impacts are shown in FIGURE 4.3, and as previously mentioned, it is evident that the decolorization scenarios in general resulted in larger environmental impacts than the incineration scenario. A large difference between the two decolorization scenarios was also observed, and while the recycling of co-solvent significantly reduced the impact, it was not enough to be comparable to incineration.

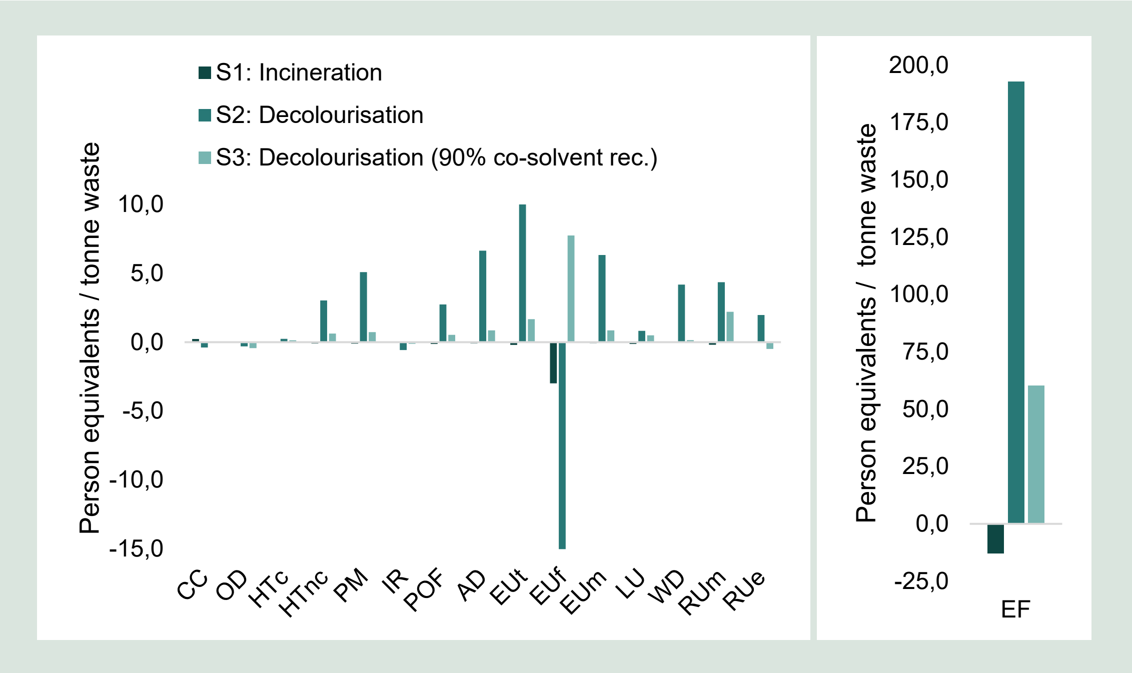

FIGURE 4.315. Normalised impacts for the two scenarios, including a scenario where 90% of the co-solvent is reused. Freshwater ecotoxicity impacts are shown separately due to the difference in scale of the impacts. The abbreviation use on the axis are explained in TABLE A1.1-2.

The normalised impacts differed in scale across most of the impacts. For the scenarios, where the impacts of decolorization were comparable or beneficial in relation to incineration, the impacts were less than one person equivalent in general. Meanwhile, several impacts from decolorization were orders of magnitude greater than incineration, corresponding to the annual emission of several people.

4.2.3 Process contribution

The process contribution gives insight into which processes contribute the most to the environmental impacts. The substitution of heat had the greatest influence, whereas the substitution of electricity only resulted in minor savings, except for the impacts relating to resource use. The input-specific emissions, which are related to waste composition, contributed the most to climate change impacts. That was due to the large fossil carbon content of the fossil-based polyester, emitted during incineration. The process-specific emissions and the operation of the incinerator had minor contributions to the impacts.
This was used to guide the technical development that focused on lowering the heat and co-solvent consumption. Technologies for reuse of the co-solvent are known, and it is believed that they are possible and essential for upscaling and implementation of the decolorization technology. This knowledge was used in the development of an implementation strategy for the technology.

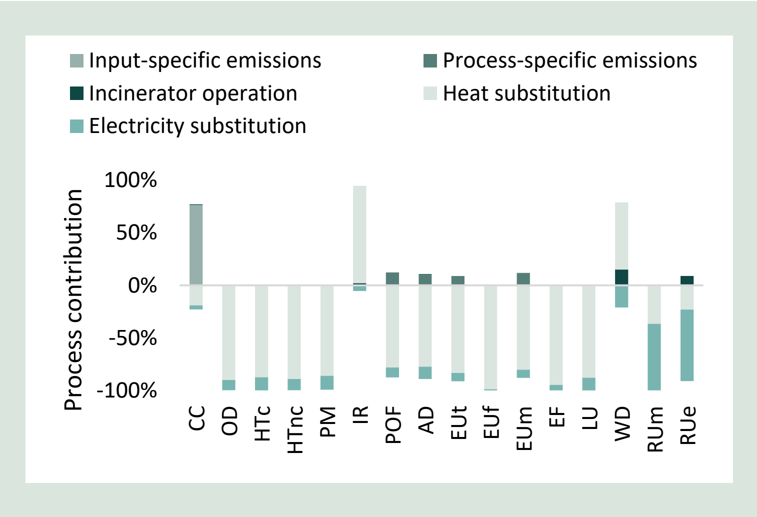

FIGURE 4.4. Process contribution for scenario 1 – incineration of polyester waste. The abbreviation use on the axis are explained in TABLE A1.1-2.

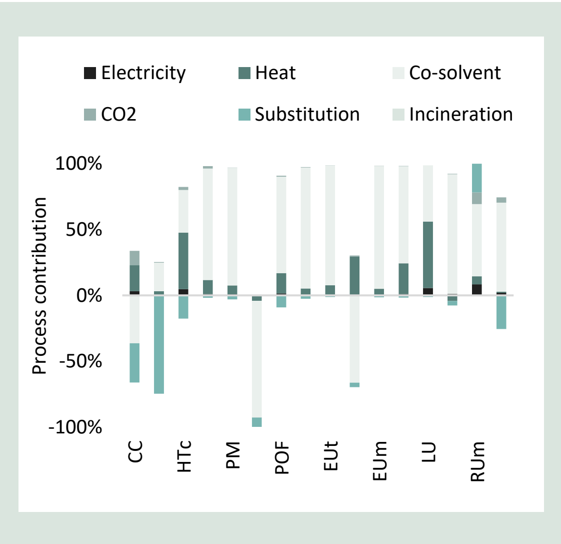

FIGURE 4.5. Process contribution for scenario 2 –decolorization of polyester waste. The abbreviation use on the axis are explained in TABLE A1.1-2.

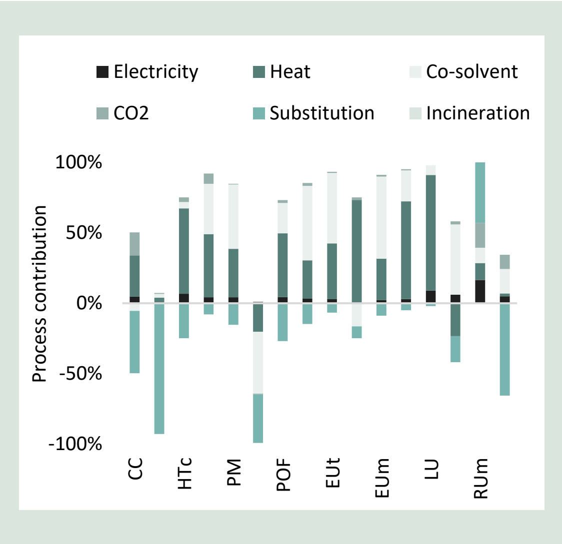

FIGURE 4.6. Process contribution for scenario 3 –decolorization of polyester waste, with a 90% recovery of co-solvent. The abbreviation use on the axis are explained in TABLE A1.1-2.

FIGURE 4.5 shows the process contribution of the decolorization scenario, and once again a dominating source of impact was observed. The co-solvent (mostly ethanol) had the largest contributions to the impacts in most impact categories. The consumption of heat, solvent and the substitution of polyester also resulted in large contributions for some environmental impacts. FIGURE 4.6 shows the decolorization scenario, with a 90% co-solvent recovery. Although the impacts from the co-solvent were greatly reduced, it still resulted in significant impacts in several impact categories. One explanation is that the consumption of co-solvent was in the order of several kilograms per kilogram of waste treated. In scenario 3, the consumption of heat had the greatest contribution to the impacts, indicating another area for potential improvement.
These results indicated that for incineration (Data presented in FIGURE 4.4), the choice of heat source was most important, while the physical-chemical composition of the waste was important for climate change. Regarding the decolorization scenario, the consumption of co-solvent (ethanol) was the most important. The consumption of heat also had relatively large contributions to the decolorization scenarios.

4.2.4 Discussion

Environmental footprint and circularity

To provide white polyester fibers for recycling, it was proven possible to decolorize polyester waste. However, the technology was associated with significant environmental impacts, due to the consumption of solvent, heat, and especially ethanol.
Comparing decolorization to incineration of polyester waste, the decolorization process resulted in significantly larger environmental impacts. The technology resulted in lowering the carbon footprint of polyester waste treatment, but for almost all impact categories incineration was preferable by a large margin. The low carbon footprint was primarily due to the consumption of ethanol, which contributed to savings due to the allocation of by-products. Meanwhile, the use of ethanol resulted in significant impact for other environmental indicators. Taking all 16 impact categories into account, the technology cannot be said to be environmentally sound under the current operating conditions. This is expected as the process is not fully developed.
While the previously mentioned drawbacks are associated with the technology, it is important to keep in mind that the LCA does not quantify the circularity of the waste material, only the

impacts associated with the two treatment technologies. In the decolorization scenario, the material is preserved and can be kept in circulation.
As the technology is still under development, there is potential for improvement. Input reductions or the establishment of industrial symbiosis systems, where other industries can use the excess ethanol and heat, are required if the technology is to be comparable to incineration. The potential for improvement is mostly limited to decreased ethanol consumption and in combination with a more renewable energy grid, the impacts became more similar to the incineration scenario. However, by testing different alternative scenarios, there is still a large gap before the technology becomes comparable to incineration.

Limitations and disclaimer
The LCA presented for the decolorization process has several limitations as the process is under development and no comparable technology or process exists.
The technology has been compared to incineration, but this does not consider the need for recycling of materials for lowering the use of fossil fuels in the future.
A better comparison could be another recycling technology, but this would have introduced a lot of uncertainties as these are in general also under development.
There are several limitations associated with the LCA. The major limitation is associated with the basis for comparison. The role of the decolorization technology in combination with different recycling technologies is essential for a proper understanding of the benefits and the drawbacks. There are many unanswered questions regarding the final process parameters and combinations with other technologies.
Chemical recycling has been proposed as a method of treating polyester waste [18], but the output will enter the value chain at a much earlier stage and more processing is required when compared to mechanical recycling. Understanding the role of decolorization in this technology track is also important.
The stage of development is also a limitation as upscaling is required, and this is associated with uncertainties in performance and operating conditions, which have not been investigated in this LCA. The use of prospective LCA and future scenarios could be a way of investigating these issues and uncertainties [19]. These are processes such as co-solvent pumping, recovery and purification, as well as the treatment of residues from the process.
The incineration of the polyester waste was limited, as it was modelled as a generic incineration plant, with generic physical-chemical properties for soft plastic products.

4.2.5 Sub conclusions

When it is fully optimized and in combination with the relevant process, a further evaluation of the technology is necessary. This would make it possible to use a more relevant recycling scenario as baseline. However, the LCA study indicated the following:

- The decolorization of polyester needs further optimization as it resulted in significant environmental impacts when compared to incineration.
- Two parameters were the primary limiting factors of the technology.
    - The consumption of ethanol. Reduction or recovery of ethanol is essential if the environmental profile of the technology is to be improved.
    - The consumption of heat. Especially important when ethanol is reduced. Reduction or utilisation of excess heat is required.

4.3 Environmental assessment of impregnation process

The background for the LCA calculations can be seen in appendix 1.

4.3.1 Scenarios

To investigate the environmental impacts of durable water repellent (DWR) impregnation, a LCA was conducted regarding the production of a novel cellulose-based and a silicone-based impregnation material.

The comparative assessment involves the comparison of three scenarios:
- Scenario 1 (S1): EcoFLEXY B: Involves the production of the cellulose-based impregnation material from Cellugy in a liquid form.
- Scenario 2 (S2): Si-DWR 1: The production of the silicone-based DWR is based on information from [20] The active chemical is polydimethylsiloxane (PDMS) dissolved in methanol and water.
- Scenario 3 (S3): Si-DWR 2: The production of the silicone-based DWR is based on information from [20], but the data regarding PDMS amount and solvent is changed to tetrahydrofuran based on [21].

FIGURE 4.7 shows the system boundaries and the processes included in the modelling of scenario 1. The system starts with the growth of the bacteria for seed production, followed by the fermentation of the seed culture. The fermented product is then purified in the downstream process, resulting in the EcoFLEXY output. The EcoFLEXY is dissolved and homogenised resulting in the EcoFLEXY B. EcoFLEXY B can be dried into a powder, EcoFLEXY BP, which once again can be resuspended.
FIGURE 4.8 shows the system boundaries and the processes included in the modelling of scenario 2 and 3. The two scenarios were modelled almost identically. The differences between the two scenarios were the quantities of the impregnation agents, the solvents used, and the direct emissions related to the impregnation agents.
The analysis considers the production of 1 kg of EcoFLEXY, EcoFLEXY B, and EcoFLEXY BP.

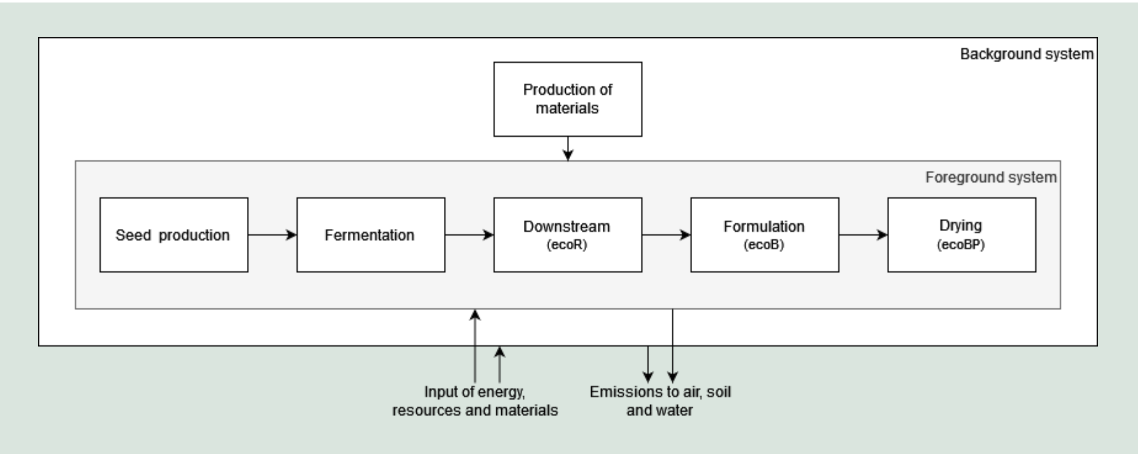

FIGURE 4.7. The system boundaries and included processes for scenario 1, the production of the different cellulose-based impregnation agents.

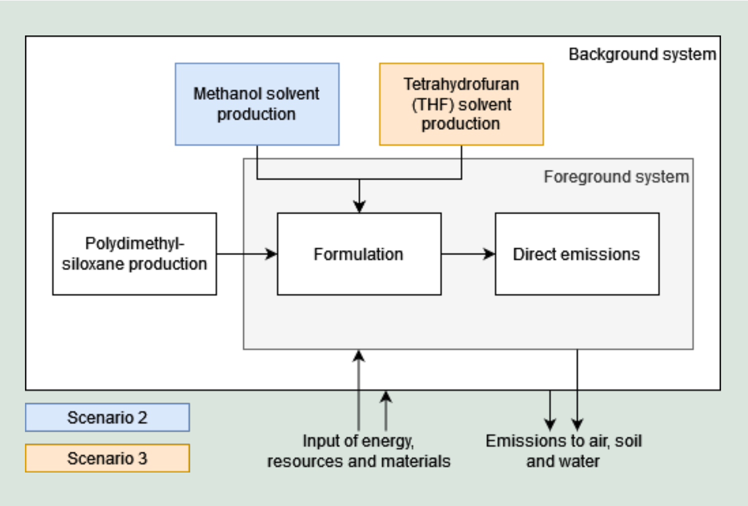

FIGURE 4.8. The system boundaries and included processes for scenarios 2 and 3, the production of the polydimethylsiloxane impregnation agents dissolved in methanol and tetrahydrofuran, respectively.

4.3.2 Characterised impacts

The characterised impact of the three different Cellugy products or stages in the production process are presented in TABLE 4.5. It is important to note that the materials do not have the same function, and therefore they are not directly comparable. The impacts are given per kilogram product. An increasing environmental footprint was observed from EcoFLEXY to EcoFLEXY BP, but in the intermediate step, the impact decreases per kilogram product. The decrease was due to the large addition of water during this step resulting in a large amount of EcoFLEXY B. Normalising the impacts to amount to 1 kg of EcoFLEXY B output, significantly decreases the impacts of EcoFLEXY B compared to the others.

TABLE 4.5. The characterised impacts per kilogram product for the three products. The three products are not comparable in function. The abbreviation use in the columns are explained in TABLE A1.1-2.

	CC	**OD**	**HTc**	**HTnc**	**PM**	**IR**	**POF**	**AD**
	kg CO_2-eq	kg CFC-11 eq	CTUh	CTUh	Disease incidence	kBq U-235 eq.	mol H^+ eq	mol N eq
EcoFLEXY	3.5E+01	7.4E-06	3.1E-08	7.1E-07	3.2E-06	1.1E+00	1.2E-01	3.7E-01
EcoFLEXY B	9.5E-02	1.3E-07	3.1E-10	3.9E-08	1.1E-07	-5.3E-02	3.5E-03	1.2E-02
EcoFLEXY BP	4.2E+01	3.1E-05	1.2E-07	9.8E-06	2.8E-05	-1.1E+01	9.1E-01	2.8E+00
	EUt	**EUf**	**EUm**	**EF**	**LU**	**WD**	**RUm**	**Rue**
	kg N eq.	kg P eq.	kg N eq	CTUe	-	m^3 water eq	kg SB eq	MJ
EcoFLEXY	1.4E+00	7.0E-03	5.7E-02	1.4E+03	2.0E+03	1.9E+01	1.3E-03	5.6E+02
EcoFLEXY B	5.5E-02	-4.8E-04	5.1E-03	5.6E+01	2.5E+01	1.6E+00	1.2E-05	8.1E+00
EcoFLEXY BP	1.3E+01	-1.0E-01	1.2E+00	1.4E+04	1.0E+04	3.9E+02	4.1E-03	2.2E+03

Normalised impacts

FIGURE 4.9 shows the normalised impacts related to the production of 1 kg product. The large difference between the products can clearly be seen. The impacts from EcoFLEXY BP, which corresponded to the full production line, were clearly the largest. The impacts from EcoFLEXY B were orders of magnitude smaller, and not visible on the figure. The freshwater eutrophication and freshwater ecotoxicity impacts are not shown on FIGURE 4.9, due to a large difference in magnitude. EcoFLEXY BP had the smallest freshwater eutrophication impacts and by far the largest freshwater ecotoxicity impacts.

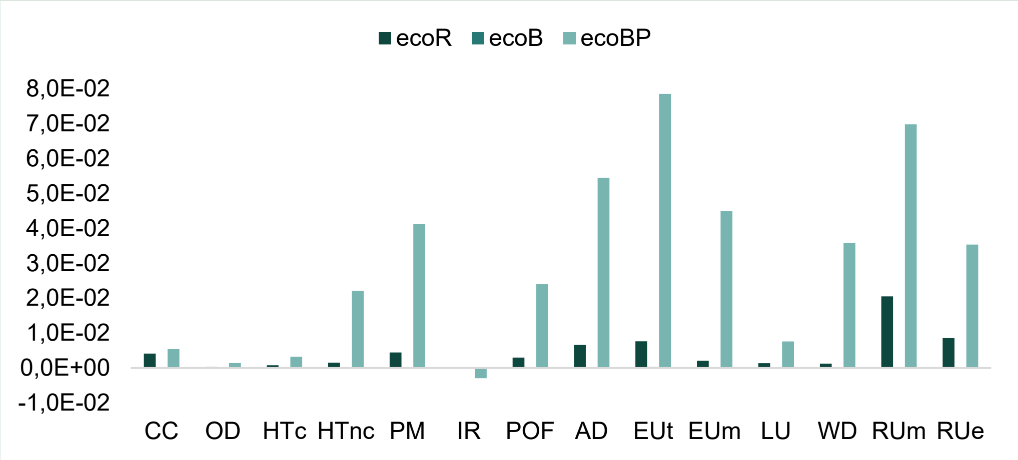

FIGURE 4.9. Normalised results for the manufacture of 1 kg product. The impact categories freshwater eutrophication and freshwater ecotoxicity are excluded in the figure. he abbreviation use in the columns are explained in TABLE A1.1-2.

4.3.3 Process contribution

The process contribution, as seen in FIGURE 4.10 to FIGURE 4.12, revealed that for EcoFLEXY, the fermentation step resulted in the largest impacts, whereas the formulation resulted in the largest impacts for both EcoFLEXY B and EcoFLEXY BP. In general, the drying of EcoFLEXY BP resulted in relatively small impacts compared to the formulation. For both EcoFLEXY B and EcoFLEXY BP, the fermentation step also resulted in relatively large impacts for a few environmental indicators.

The process contribution analysis indicated that depending on the product, different aspects could be investigated to reduce the impacts.

The formulation step contributed the most to the impacts of EcoFLEXY B and EcoFLEXY BP. The contribution analysis revealed that the ethanol consumption contributed to all of the impacts from the formulation. The consumption of other materials had no influence on the impacts. Reduction in ethanol would be the largest improvement to the environmental footprints of the products. Processing the EcoFLEXY B solution into a powder consumed electricity, and that was also an area of improvement. Regarding EcoFLEXY, the fermentation step was the most important. Consumption of process steam, electricity, and sugar resulted in the largest impacts from the fermentation.

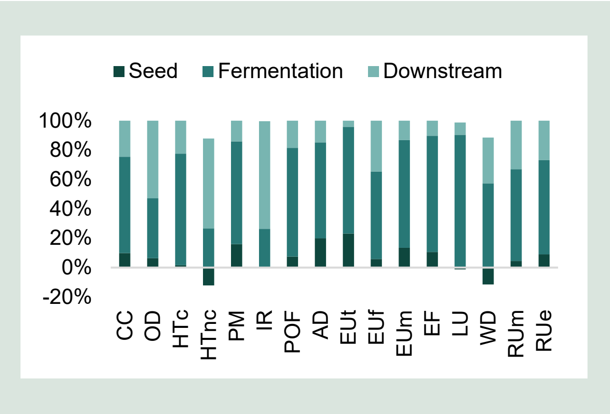

FIGURE 4.10. Process contribution for 1 kg EcoFLEXY. The abbreviation use on the axis are explained in TABLE A1.1-2.

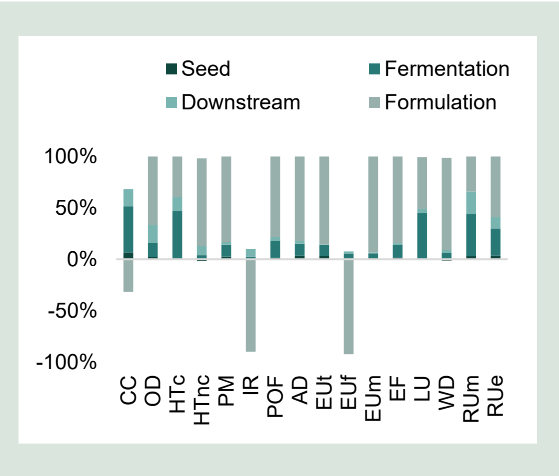

FIGURE 4.11. Process contribution for 1 kg EcoFLEXY B. The abbreviation use on the axis are explained in TABLE A1.1-2.

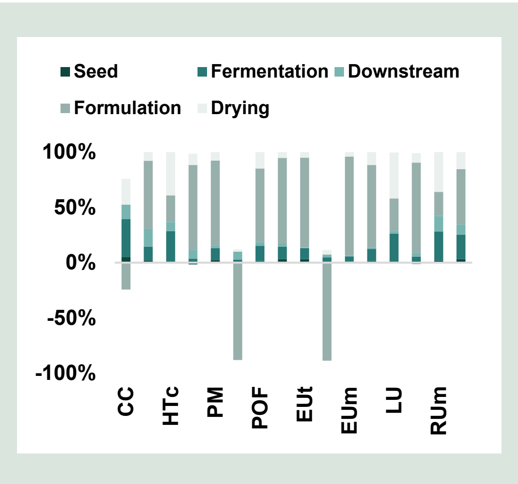

FIGURE 4.1216. Process contribution for 1 kg EcoFLEXY BP. The abbreviation use on the axis are explained in TABLE A1.1-2.

4.3.4 Comparative Life Cycle Impact Assessment

Characterised Results

The characterised results are presented in TABLE 4.6, and scenario 2, Si-DWR 1, generally resulted in the lowest impacts across most environmental indicators, whereas Scenario 3, Si-DWR 2, resulted in the largest impacts.

TABLE 4.6. Characterised results for the incineration and decolorization scenarios. Values in bold indicate the scenario with the lower environmental impact. All impacts are per functional unit.

	CC	**OD**	**HTc**	**HTnc**	**PM**	**IR**	**POF**	**AD**
	kg CO_2-eq	kg CFC-11 eq	CTUh	CTUh	Disease incidence	kBq U-235 eq.	mol H^+ eq	mol N eq
EcoFLEXY B	4.3E-04	5.8E-10	1.4E-12	1.8E-10	5.2E-10	-2.4E-04	1.6E-05	5.4E-05
Si-DWR 1 (methanol)	1.0E-04	6.9E-09	1.6E-13	1.0E-11	7.4E-12	-5.0E-07	4.2E-07	6.0E-07
Si-DWR 2 (THF)	1.5E-02	2.0E-08	7.9E-12	7.0E-10	2.4E-10	-8.6E-05	3.9E-05	5.6E-05
	EUt	**EUf**	**EUm**	**EF**	**LU**	**WD**	**RUm**	**Rue**
	kg N eq.	kg P eq.	kg N eq	CTUe	-	m^3 water eq	kg SB eq	MJ
EcoFLEXY B	2.5E-04	-2.1E-06	2.3E-05	2.6E-01	1.2E-01	7.1E-03	5.6E-08	3.8E-02
Si-DWR 1 (methanol)	1.4E-06	3.9E-08	1.1E-07	5.6E-02	8.8E-04	3.9E-05	2.0E-09	1.5E-03
Si-DWR 2 (THF)	1.1E-04	7.7E-06	1.1E-05	2.5E+00	1.0E-01	2.9E-02	1.8E-07	2.8E-01

TABLE 4.7 shows the ranking of the three scenarios based on the characterised results (TABLE 4.4), giving a better overview of which scenarios are preferable. For this development state of EcoFLEXY B, TABLE 4.7 clearly shows the preference for Si-DWR 1. Combined with the fact that the impacts from EcoFLEXY B in general were more like the impacts of Si-DWR 2, it was probably the solution with the lowest impact.

TABLE 4.7. Ranking of the scenarios from lowest to largest environmental impact. A score of 1 (green) indicates the scenario with the smallest impact, while 3 (red) indicates the largest impact. The abbreviation use in the columns are explained in TABLE A1.1-2.

	CC	**OD**	**HTc**	**HTnc**	**PM**	**IR**	**POF**	**AD**	**EUt**	**EUf**	**EUm**	**EF**	**LU**	**WD**	**RUm**	**RUe**
EcoFLEXY B	2	1	2	2	3	1	2	2	3	1	3	2	3	2	2	2
Si-DWR 1 (Methanol)	1	2	1	1	1	3	1	1	1	2	1	1	1	1	1	1
Si-DWR 2 (THF)	3	3	3	3	2	2	3	3	2	3	2	3	2	3	3	3

Normalised impacts

The normalised impacts are shown in FIGURE 4.13, and a general observation is that the Si-DWR 2 resulted in the largest impacts across most impact categories. The EcoFLEXY B material resulted in similar impacts as the Si-DWR 2 for several impacts. While by far the lowest impacts were found for the Si-DWR 1. This highlights the large dependency on choice of solvent used in the process.

The amount of material required to impart the effect of the impregnation agents to the textiles could be an explanation of the large disparity between Si-DWR 1 and the two other impregnation agents. The quantity of Si-DWR 1 required to fulfil the functional unit was approximately two orders of magnitude smaller than the other materials. That difference could explain the materials' large difference in impact. An optimization of the water repellent performance of EcoFLEXY B could lower the required material and thereby improve the impacts.

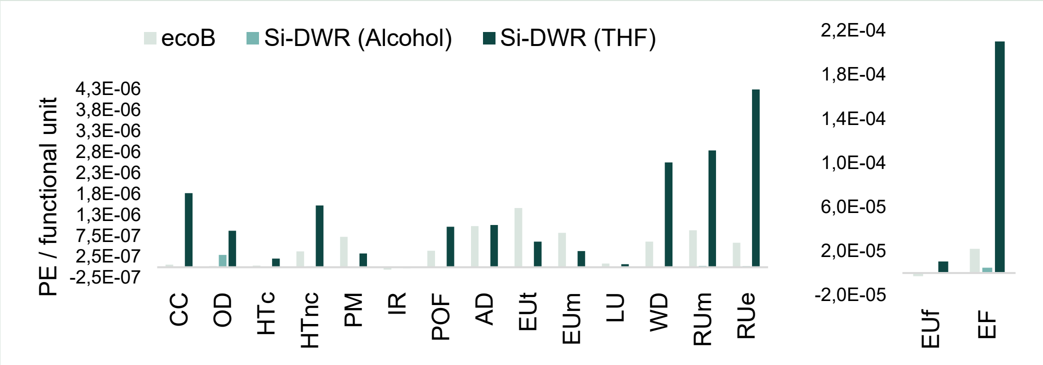

FIGURE 4.13. Normalised impacts for the three scenarios. Notice the difference in scale of the two axes. The abbreviation use in the columns are explained in TABLE A1.1-2.

4.3.5 Process contribution

The process contribution for EcoFLEXY B is shown in FIGURE 4.11. As previously mentioned, the formulation step had the greatest contribution to the impacts for most environmental impacts, whereas the fermentation step was important for climate change, human toxicity (cancer), land use, and resource impacts. The downstream process, which included the purification of the material only contributed by relatively minor impacts. The development of the seed for fermentation had minor impacts. The large impact of the formulation step is due to the large addition of water and alcohol increasing the mass of the material by two orders of magnitude. The addition of alcohol was almost exclusively responsible for impacts. Improvements made to this production step have the greatest potential for reducing the footprint of the EcoFLEXY B material. The impacts from the fermentation step were mostly due to the consumption of energy, but the consumption of materials also had relatively large impacts for some environmental indicators.
The process contribution was almost identical for the two Si-DWR, as shown in FIGURE 4.5 and FIGURE 4.6. This was due to the large similarity in the modelling of the two materials. Most of the impacts were due to the input of materials and products for the impregnation agent.

One reason for drying EcoFLEXY BP was to allow lowered transportation impacts, as water and ethanol make up most of the composition of EcoFLEXY B. The mass of EcoFLEXY BP is only 0.5% of the mass of EcoFLEXY B. However, the materials must be transported vast distances before the impacts of EcoFLEXY BP become lower. For most impact categories, the materials would have to be transported more than 10000 km by truck, before the environmental breakeven point was reached. The distances for sea transport were even greater. However, in terms of impact reduction from transport, drying the material cannot be recommended under the current conditions.

The data was used to guide the development at Cellugy during the project and will continue to be used in the development of impregnation agents.

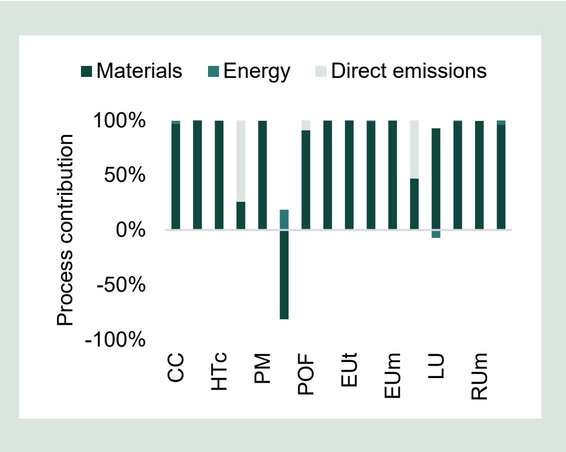

FIGURE 4.14. Process contribution for scenario 2 - the production of Si-DWR 1. The abbreviation use on the axis are explained in TABLE A1.1-2.

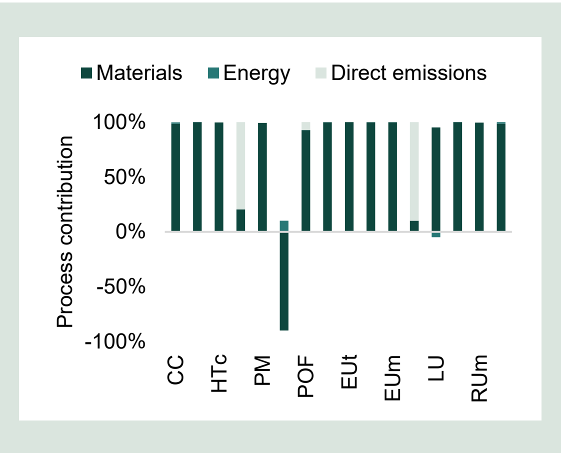

FIGURE 4.15. Process contribution for scenario 3 - the production of Si-DWR 2. The abbreviation use on the axis are explained in TABLE A1.1-2.

4.3.6 Discussion

Environmental footprint and circularity

The ethanol consumption during the formulation of EcoFLEXY B was the main contributor to the environmental impact. The solvents used during the formulation were evenly distributed between water and ethanol, and increasing the fraction of water could improve the environmental footprint.

The LCA analysis indicated that the cellulose-based impregnation agents did not have the lowest impacts for most environmental indicators. However, the uncertainties associated with the functional unit and the exact composition of the Si-DWRs makes comparison and interpretation difficult. It is important to consider that the cellulose-based impregnation agents are under development, and the main argument for changing to a cellulose-based impregnation agent is to dramatically increase the recycling potential of impregnated textiles. The potential benefit of increased recycling of textiles has not been taken into consideration in the LCA analysis performed as data for this is lacking.
In general, the results indicated that the amount of material used to impart the water repellent properties was the determining factor. The environmental footprint per kilogram material was similar for the two Si-DWRs, whereas the impacts from EcoFLEXY B were smaller. As the

amount of the Si-DWR 1 was two orders of magnitude smaller than the other impregnation agents, it resulted in the smallest impacts in the comparison.
The amount of EcoFLEXY B and the Si-DWR 2 had much higher concentrations of impregnation agent on the textile. Regarding Si-DWR 2, this difference could be because the focus of the study was on testing of material properties and not on efficient production of impregnation agents. Similarly, EcoFLEXY B is a novel material, still under development. The final amounts required for imparting impregnation agent might be different than those used in this LCA. Further research is required to ensure a fair comparison.
The results indicated that EcoFLEXY B had a lower environmental footprint as long as the amount of EcoFLEXY B used did not exceed the amount of Si-DWR by more than a factor of five. If conventional Si-DWRs are typically in the order of 1% of the textile weight, then the EcoFLEXY B DWR should not exceed 5% of the textile weight.
The impacts of the Si-DWRs might be underestimated, as the characterisation factors of chemicals in LCA are lacking. The work of [22] included several, but not all, characterisation factors relevant to produce Si-DWR. However, these are all uncertain, and the coverage of several of the elements in EASETECH was not sufficient. The same is true for EcoFLEXY B, but the importance is not expected to be the same.

Limitations and disclaimer

The major limitations of this LCA are related to the availability of data for the conventional impregnation materials. The composition of the materials is generally considered to be trade secrets, and therefore the information available is scarce. The coverage of impacts regarding emissions from several of the chemicals used in the production of impregnation agent was also limited, potentially underestimating the environmental impacts of the impregnation materials.
Information regarding the quantity of material used was also difficult to obtain, and assumptions had to be made. The water contact angle, which was used as the functional unit, also varied depending on the composition of the material and the quantities used, further limiting the study. The functional unit of the comparative LCA is another major limitation, as the defined functional unit does not necessarily ensure a fair comparison.
Regarding the production of the cellulose-based impregnation material, the limitation was mainly associated with the data coverage and uncertainties of certain material inputs. Some materials were not available in the database, making the coverage of all flows limited. Furthermore, a limitation is the uncertainties associated with technology under development. Consumption of e.g. solvent and energy during the process have been dramatically reduced during the project and might be reduced even further during further development. It is therefore problematic to draw clear conclusions at this point in the development process.
Finally, the LCA only considered the production of the materials. Considering the entire life cycle of an impregnated textile, in particular the use of the textile, potential reimpregnation, and then the implications for the end-of-life treatment of the textiles is essential to understand the consequences of the different materials.

Disclaimer: It is important to note that the comparative life cycle assessment (LCA) presented here has major limitations regarding its comparative study. The functional unit, which has the goal of ensuring a fair comparison across products by comparing products with the same functionalities, is flawed. The functional unit does not consider differences throughout the lifetime of the products, which could drastically change the results of the study. Furthermore, the exact unit of comparison, which in this case is the water contact angle, cannot be said to be the same across the products. Proxies have been used from literature, which are in the same range, to see what a comparative result could look like. This LCA lacks important aspects of the life cycle of impregnation materials, such as longevity, loss of functionality due to use, reapplication, and end-of-life. All these aspects are important and could influence the conclusion of the LCA. Decision should not be based on the results of the comparative study.

4.3.7 Sub conclusions

The following points can be concluded regarding the hotspot analysis of Cellugy's products.

- The impacts from the production of 1 kg of coating material in powder form, EcoFLEXY BP, were several orders of magnitude greater than the impacts from 1 kg of coating material in liquid form, EcoFLEXY B.
- The large difference is primarily due to large inputs of ethanol in order to produce 1 kg of powdered coating material. The additional use of energy resulted in relatively large impacts for some environmental impacts, but mostly it was minor compared to the impacts from the production of EcoFLEXY B.
- The use of ethanol during the formulation resulted in most of the environmental impacts across most of the indicators for both EcoFLEXY B and EcoFLEXY BP. Reductions or recovery of the ethanol consumption should be prioritised.
- The production of the precursor to both coating materials, EcoFLEXY, was important for some environmental impacts. The impacts from the production of EcoFLEXY occurred primarily due to energy use during the fermentation process. Material inputs had minor importance, apart from sugar.

The conclusions drawn from the comparative LCA are limited, due to issues with data availability regarding the conventional impregnation materials and uncertainties associated with the definition of the functional unit. The following general points can be concluded regarding the manufacturing of different impregnation materials.

- The EcoFLEXY B solution could result in smaller or larger impacts than the silicone-based impregnation agents.
- The amount of material used on the textile was crucial.
- Per kilogram of impregnation material, EcoFLEXY B generally resulted in the lowest impacts.
- EcoFLEXY B resulted in a smaller environmental footprint as long as the amount used was no more than five times greater than the Si-DWRs.
- The choice of solvent for the Si-DWRs was important for some impacts.
- Further research is needed to ensure a fair comparison between the different materials.

5. Conclusion

This project has made significant contributions towards the transition of the Danish textile industry to a more circular model. Through an extensive collaboration between textile brands, technology providers, and knowledge partners, key barriers related to textile waste complexity and lack of recycling technologies have been addressed.

The development of a design guide titled "Design for Textile-to-Textile Recyclability" bridges an important knowledge gap by providing tailored guidelines for designers and product developers. Focusing on best practices, learnings from the technological development within the project, recycling possibilities, removability of trimmings, and environmental impacts of material choices, the guide equips the project textile brands with practical insights for designing recyclable textiles.

Technological advancements have been achieved for two technologies in textile-to-textile recycling: recycling polycotton blends and decolorizing polyester textiles.
The Textile Change process that can recycle polycotton textiles demonstrated the capability to handle a wide range of input materials, and the boundaries of the technology were clarified in collaboration with the textile brands in the consortium. It was possible to adjust the properties of the recycled output textile pulp to ensure a steady and high quality of the output material which is essential in the further production of new recycled textiles.
The newly developed decolorization technology was developed and optimised on gram scale and further scaled to kilogram scale. The technology successfully removed dyes from polyester while preserving material quality within fiber production requirements.

Furthermore, the development of a novel bacterial cellulose-based impregnation agent offers a promising solution for water-repellent finishes without impeding recyclability. While further improvements are needed for wash resistance, the impregnation agent did not hinder the recycling process at Textile Change, enabling the recycling of previously non-recyclable impregnated textiles.

Environmental assessments guided the technological developments, highlighting areas for optimization, such as reducing solvent consumption and heat requirements for the decolorization process, and minimizing ethanol usage in the impregnation agent formulation. Final LCA calculations identified focus areas for further development.

Overall, this project has advanced the Danish textile industry's transition to circularity by fostering knowledge exchange, developing practical design guidelines, and pioneering innovative recycling technologies, and recyclable impregnation agents. These achievements pave the way for a more resource-efficient and environmentally responsible textile sector in Denmark.

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Appendix 1. Background for the LCA analysis - methodology, definitions and modelling

Appendix 1.1 Methodology and modelling

Methodology
The LCA carried out for this study was conducted according to the requirements outlined in the International Standards 14040 and 14044 [12, 13]. This section provides a detailed description of the LCA methodology utilised for the study: the goal of the LCA, functional unit and reference flow, the system boundaries, the choices for the modelling approach for addressing multi-functionality, the modelling tools, data requirements, impact assessment method, assumptions, and limitations.

The final receiver of the study is the project consortium. The report has not undergone external peer review by a panel of experts throughout the development of the project and does not strictly comply with the standard.

Goal definition
The intended application of this LCA is to evaluate the environmental impacts of the decolorization of waste polyester as a pretreatment to recycling. The aim of the study was to:
- Compare the impacts of treating polyester waste by incineration and decolorization.
- Identify the main hotspots of the decolorization technology.

Modelling approach and allocation of multi-functionality
The LCA was associated with consequences that required the installation of additional equipment or changes in capacity to existing equipment. Therefore, the LCA modelling was conducted as consequential LCA. Multi-functionality in LCA arises when products or systems have multiple functions or outputs, such as processes that produce a primary product and a co-product. In this LCA, the multi-functionality was addressed by system expansion, meaning that co-products were assumed to displace those products on the market likely to react to such changes in supply and demand. This is what is referred to as marginal products or technologies. One example is the generation of heat and electricity from incineration, which then displaced marginal heat and electricity in Denmark.
The marginal energies were calculated by identifying marginal suppliers, who saw an increase in market share and technologies that were not constrained [23]. The marginal energies are shown in TABLE A1.1-1.

For the impregnation technology, multi-functionality was mostly related to the use of background data from the ecoinvent database.

TABLE A10.1-1. Marginal heat and electricity used in the modelling.

Marginal Heat		Marginal electricity	
Biomass	81.5%	Wind	42.6%
Biogas	7.5%	Biofuels	16.8%
Electricity	5.7%	Solar PV	4.4%
Solar thermal	3.5%	Imports from Norway	21.9%
Heat pumps	1.8%	Imports from Sweden	14.2%

Modelling tools and Basis for Impact Assessment

The LCA was modelled with the waste-LCA model EASETECH [24]. EASETECH allows modelling of the flow of material in the LCA as a single or a mix of material fractions, such as plastic, and keeps track of their physico-chemical properties (e.g., energy content, fossil carbon, etc.) throughout the modelled life-cycle stages. The tracking of the material composition on top of the mass flow-based LCA allows for the production and consumption of resources and materials to be based on the physico-chemical properties of the functional unit, and in particular to express emissions occurring during the end-of-life phases as a function of its physical-chemical composition (e.g., fossil carbon emitted during incineration).

The Environmental Footprint 3.0 (EF3.0) life cycle impact assessment (LCIA) method was chosen for the quantification of the environmental impacts in this LCA. The EF3.0 LCIA method was developed by the Joint Research Councils and is recommended by the European Commission. The method covers 16 environmental indicators, referred to as impact categories, see TABLE A1.1-2 for an overview of the included impacts.

TABLE A11.1-2. The included impact categories of the EF3.0 LCIA method, the abbreviations used in impact reporting, units, and the normalisation reference.

Impact category	Abbreviation	Unit	Normalisation factor
Climate change - wo LT	CC	kg CO_2-eq	8.40E+03
Ozone depletion - wo LT	OD	kg CFC-11 eq	2.34E-02
Human toxicity, cancer	HTc	CTUh	3.85E-05
Human toxicity, non-carcinogenic	HTnc	CTUh	4.75E-04
Particulate matter - wo LT	PM	Disease incidences	7.18E-04
Ionising radiation - wo LT	IR	kBq U-235 eq.	4.22E+03
Photochemical ozone formation - wo LT	POF	mol H-H eq	4.06E+01
Acidification - wo LT	AD	mol N eq	5.55E+01
Eutrophication, terrestrial - wo LT	EUt	kg N eq.	1.77E+02
Eutrophication, freshwater - wo LT	EUf	kg P eq.	7.34E-01
Eutrophication, marine - wo LT	EUm	kg N eq	2.83E+01
Ecotoxicity freshwater	ETf	CTUe	1.18E+04
Land use	LU	-	1.40E+06
Water use	WD	m^3 water eq	1.15E+04
Resource use, minerals and metals	RUm	kg SB eq	6.36E-02
Resource use, energy carrier	RUe	MJ	6.53E+04

Appendix 1.2 Functional unit, boundaries, data and limitations - decolorization

Functional unit

In LCA, the functional unit defines the specific function of a product or system that is being assessed. It serves as a reference point for comparing environmental impacts, enabling standardized evaluations of different alternatives, and facilitating meaningful comparisons in sustainability assessments.
The functional unit for this LCA was defined as; *The treatment of 1000 kg of polyester waste in Denmark in 2023.*

The reference flow defines the quantity of material in order to fulfil the functional unit. The reference flow in this LCA was defined as 1000 kg of polyester waste, containing no impurities.

System boundaries

The geographical scope was Denmark, where the technologies were to be implemented. Resources and materials originating outside of Denmark were included. The temporal scope was 2023, as this was when the experiments took place, and the data was collected. Older data from the database was used when recent data was not available. The technological scope covered a novel technology to decolorize polyester, whereas incineration was modelled as a generic Danish incineration plant. The LCA only considered the end-of-life of the polyester waste. All life cycle stages prior to the generation of waste were excluded. The LCA was conducted using the zero-burden approach, meaning the waste was not associated with any environmental impacts when entering the system. The time horizon of the impacts in this LCA was 100 years.
The foreground system involved the incineration or decolorization. The background system included the extraction of resources, the production of energy and materials required as inputs to the foreground system, as well as the substitution of materials, resources, and the treatment of residues FIGURE A1.2-1.

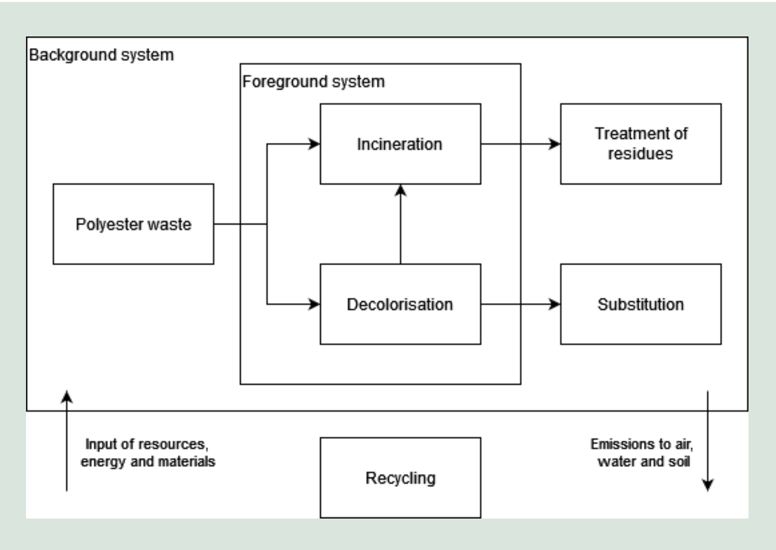

FIGURE A1.2-1. Illustration of the system boundaries. Recycling is shown outside the system boundaries to highlight that the recycling of waste polyester fibre into recycled polyester fibre has not been included in the assessment due to lack of information.

After decolorization, the polyester must be processed into recycled fibers, prior to the substitution of virgin polyester fibers. However, this processing was not included in the modelling due to lack of information. Instead, the products were assumed to be substituted directly after decolorization. Other relevant processes were also not included in the assessment: capital goods, such as the construction of a decolorization facility, and the process of collecting the waste.

Data requirements
This LCA required inventory data on the emissions from the production of energy, resources, and materials, as well as data on the energy and material consumption required for the process, and data connected to emissions from the production of virgin polyester. Furthermore, data regarding the incineration of polyester waste was needed.
The project involved the collection of primary data for the decolorization process. This was data related to energy and material consumption, and the material quality of the output. The data was provided by NATEX and DTI. For the incineration of polyester waste, the focus was not on data collection, but instead existing data from the EASETECH database was used. The physical-chemical composition of the polyester waste also came from the EASETECH database. The life cycle inventories of all materials, resources, and energy sources, which connect the elementary flows to environmental emissions, came from the ecoinvent database (version 3.8).
The data regarding the decolorization process were collected by the technology provider, NATEX, and DTI.

Assumptions and limitations
First, it was assumed that the current treatment of all polyester waste in Denmark was incineration. The collection of textile waste for recycling in Denmark started in 2023. Therefore, new ways of managing this waste fraction must be established, and a better comparison could be the comparison of different recycling technologies with and without decolorization as a pre-treatment step. However, this project focuses on the decolorization process, and therefore such a comparison was not included.
It was assumed that there were no material losses during the processing and that all the polyester waste was decolorized to a sufficient degree. There was a slight loss of material quality, as the viscosity of the polyester decreased after processing. The decrease of viscosity was approximately 30%, and this was reflected in the substitution of virgin polyester. The substitution factor was set to 0.7, meaning that 1 kg of polyester waste substituted 0.7 kg of virgin polyester.
The assessment did not include data on energy use for pumping and potential recovery of the co-solvent. After early screening results, it was estimated that the data would not cause significant changes to the conclusions of the LCA. However, this exclusion does mean that the actual impacts of the decolorization process will be larger than the modelled impacts. Furthermore, the treatment of the co-solvent and ink waste was not included.
The main limitation of the LCA is the exclusion of any recycling technology. This makes interpretation of the LCA more difficult as context is missing, and the full picture of the technology is not available. If the decolorization improves the potential for recycling, it changes how the results should be interpreted. Another major limitation is that the decolorization technology is still being developed and optimised. This potentially makes the input data less representative of the actual or final process and is associated with large uncertainties.

Appendix 1.3 Functional unit, boundaries, data and limitations - impregnation

Functional unit
In LCA, the functional unit defines the specific quantity or function of the product or system being assessed. It serves as a reference point for comparing environmental impacts, enabling standardised evaluations of different alternatives, and facilitating meaningful comparisons in sustainability assessments.

The main function of an impregnation material is protection against water, oil, and dirt. However, in this case the main function was a durable water repellent (DWR). The functional unit of the LCA was defined as: *The production of impregnation material for coating 25 cm^2 of cotton at a minimum of a 120-degree water contact angle.*
The water contact angle is a measure of how well the impregnation material protects against the penetration of water. The reference flow defines the quantity of material in order to fulfil the functional unit. The reference flow for this LCA is composed of different materials for different cases, as shown in TABLE A1.3-1.

TABLE A12.3-1. Reference flows needed to fulfil the functional unit. The quantity is for the DWR and solvents. WCA = water contact angle.

Material	Active ingredient	Solvents	Volume [mL]	Quantity [g]	WCA [degrees]	Source
EcoFLEXY B	Cellulose and silicon oxide	Water and ethanol	5	4.5*	120	Cellugy
Si-DWR 1	PDMS	Methanol	-	0.02**	>120	[20]
Si-DWR 2	PDMS	Tetrahydrofuran	-	2.09***	150-160	[21]

* Estimated based on volume **Estimated based on DWR weight on textile *** based on the source provided.

The amount of EcoFLEXY B required to coat the functional unit was 5 mL, based on information from Cellugy. The main components of the material were water and ethanol, while the active ingredients were present in small quantities. Based on the material composition of EcoFLEXY B, this volume was estimated as 4.5 grams EcoFLEXY B per functional unit.
The reference flow of the SI-DWRs was based on the work of [20]. In this work, it was stated that the DWR makes up 1-2% of the textile on a mass basis. Other studies have mentioned that 1% is the amount after which no improvement in water contact angle is observed [24]. The amount required for Si-DWR 1, which had methanol as the solvent, was then calculated based on cotton with a grade of 200 GSM. The weight of the fabric was 0.5 g (200 GSM x 0.0025 m^2), and for the impregnation material to make up 1% of the textile weight, 0.002 g of PDMS was required and a total weight of 0.005 g of Si-DWR 1 was required, including all components.
Regarding SI-DWR 2, which used tetrahydrofuran (THF) as solvent, the amount required to coat the textile was based on the work of [21]. Here, 8.25 g of PDMS was dissolved in 15 g of THF, and 0.75 g of SiO_2 was needed to coat 287 cm^2 of polyester. Converting this into 25 cm^2 of cotton, required a conversion factor of 0.087 (25 cm^2/287 cm^2), assuming a linear relationship between amount of material and size of textile and also that the same amounts were used for cotton and polyester. The resulting reference flow of Si-DWR 2 was 0.72 g PDMS, 1.31 g THF and 0.07 g SiO_2, with a total weight of 2.09 g.
It is important to note that the functional unit has flaws as explained in the introduction, limiting the comparison.

System boundaries
The cellulose-based products were manufactured in Denmark, requiring materials from the global market. The Si-DWRs were produced on the global market, using global data. The geographical scope for the production of EcoFLEXY B was Denmark, while the scope was global for the Si-DWRs. Resources and materials originating outside of Denmark were included. The temporal scope was 2023, as this was when the experiments took place, and the data was collected. Older data from literature and databases were used when recent data was not available. The technological scope covered a novel cellulose-based DWR, whereas

the Si-DWRs were modelled based on one generic dataset and one specific dataset. The time horizon of the impacts in this LCA was 100 years.

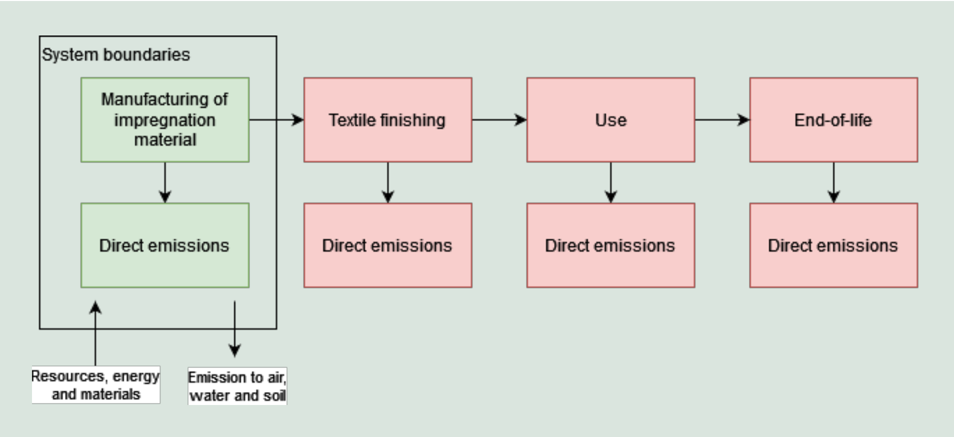

FIGURE A17.3-1. The system boundaries of the LCA. The green boxes within the boundaries include the modelled processes, while the red boxes show processes that were not included.

FIGURE A1.3-1 shows the system boundaries used in the study. The LCA was conducted as a cradle-to-gate study, which considered impacts from the extraction of resources to the finished DWR product. The application on textiles, the production of textiles, the use by consumers and the end-of-life treatment of the products were not included due to the scope of the project. The excluded life cycle stages could have a significant impact on the results of the study, and their exclusion is a limitation of the LCA.

Data requirements

This LCA required inventory data on the emissions related to the production of primary materials, chemicals, and energy to produce impregnation materials. The study was conducted as a cradle-to-gate LCA, meaning that impacts were only considered until the material was ready for application. The application, curing, use, and end-of-life were not considered.

The project involved experimental tests for data collection regarding the input material for the Cellugy impregnation materials, but for the alternative impregnation material data based on existing databases and studies were used. The life cycle inventories for all materials, resources, and energy sources, which connect the elementary flows to environmental emissions were from the ecoinvent database (version 3.8).

Production of biologically based impregnation material

Data regarding the production of Cellugy's impregnation material was collected directly from Cellugy. Therefore, the data is expected to be highly representative of the actual product, but uncertainties are associated with the process, as the product is still under development. That data was collected directly, but the associated emissions were calculated using datasets from the ecoinvent database, which introduce potential differences to the emissions regarding Cellugy's process. The full LCI is presented in the appendix.

Long-term impacts, durability, and other user-related impacts were not available and have therefore not been included in the assessment.

Production of alternative impregnation materials

LCI data regarding the production of conventional impregnation materials is difficult to find, as the exact compositions are generally considered trade secrets [20]. First and foremost, it was

decided not to include PFAS compounds, due to lack of data and because there is a growing trend in society and industry towards removing PFAS compounds from the products we use. However, it is also known that the longer chain PFAS compounds have been substituted by shorter chain compounds, which could also be a relevant comparison.
The only detailed LCI was found in the work of [20]. It contained LCIs for five different DWRs, and together with the project group it was decided to compare the biological impregnation material to a silicone-based DWR, due to expected similarities in production and function. The active ingredient in the Si-DWR was PDMS. One issue was that Si-DWRs have a wide range of water contact angles and other properties, depending on the exact composition of the DWR, which potentially could influence the functional unit. Furthermore, several different solvents exist for dissolving the silicone compound prior to application. [25] dissolved PDMS in THF, toluene, hexadecane, and dichloromethane, while methanol was used in the study by [20]. Therefore, two different solvents were included (alcohol and THF), as they had specifications of the exact formulation. The PDMS and alcohol DWR were based on [20], while the PDMS and THF DWR was based on [21]. However, as the study only considered the formulation of the DWR, it was combined with the energy required for the formulation as provided by [20].
An issue with the use of chemicals and their direct emissions to the environment is that they are not always covered by characterisation factors in the existing LCIA methods. Therefore, for the use and emission of PDMS, characterisation factors had to be implemented to cover impacts related to human toxicity and ecotoxicity, based on the work of [22]. The full life cycle inventory is presented in the appendix.

As explained previously, long-term impacts, durability, and other user-related impacts were not available, and that is why they have not been included in the assessment.

Assumptions and limitations
First of all, it was assumed that the different impregnation materials provided the same functions. As the performance of the materials was not tested by the partners in this project, we had to rely on literature data. As previously mentioned, Si-DWRs are known to have a wide range of potential water contact angles, and therefore it is possible that the functional unit does not provide a fair comparison, which is the major limitation of the LCA. However, data in the literature is scarce and when available it is rarely applicable to LCA.
The two different Si-DWRs were modelled similarly, and it was assumed that the only difference was in the DWR formulation, and the quantity used. It was assumed that both Si-DWRs required the same energy inputs and had the same direct emissions for the shared inputs. The quantity of the Si-DWR 1 required to fulfil the functional unit was assumed to be 1% of the textile weight. The amount of Si-DWR 1 was much lower than the amount of Si-DWR 2. For Si-DWR 2, it was assumed that the amount required to coat polyester and cotton were identical, as [21] only considered polyester.
There are many limitations to the LCA, the major being the potential issues with the functional unit. Additional limitations are mainly related to the lack of representative and transparent data, especially regarding the Si-DWRs. While some characterisation factors were added for the emissions of PDMS and related compounds, there is still a large information gap regarding these factors for several compounds used for manufacturing DWR materials [20, 22].
The quantity of DWR used to coat the cotton is another limitation. The reference flow for the EcoFLEXY B and the Si-DWR and THF were similar, whereas the amount of Si-DWR and methanol was two orders of magnitude smaller than the others. As the active ingredient is the same for the two Si-DWRs this discrepancy is considered large and uncertain.
Additionally, this LCA only considers the manufacturing of the DWRs. Including the actual application of the material on the textiles, could indicate differences in the amount used for ensuring full impregnation of the material. That could influence the direct emissions to the environment. During the use phase, there is a potential for reimpregnation, differences in longevity, which is currently not reflected in the functional unit, and that could have a great influence on the product impact. The end-of-life stage is one of the most crucial stages that is

missing, as it has the potential to have a great influence on the conclusion of the study. The presence of additives and impregnation materials is known to be a potential barrier to the recycling of textiles [8]. If one material has the potential to allow for textile recycling and the other does not, then it has the potential to be decisive for which DWR material should be used in the future.

Den Cirkulære Tekstilindustri

The textile industry is a position of strength for Denmark, representing the fourth largest product group in the country's total exports. As the textile industry aspires to achieve circularity, there is an urgent need to address the barriers hindering the transition to a circular economy. One barrier is the lack of solutions for recycling.
To address the barrier of missing solutions for textile recycling the project focused on two main development tracks:
1) Creating design guidelines to ensure that future clothing is designed for recyclability
2) Developing and maturing recycling technologies for polycotton, decolorization of polyester and recyclable impregnation agents
Overall, this project has advanced the Danish textile industry's transition to circularity by fostering knowledge exchange, developing practical design guidelines, and pioneering innovative recycling technologies, and recyclable impregnation agents. These achievements pave the way for a more resource-efficient and environmentally responsible textile sector in Denmark.

The Danish Environmental
Protection Agency
Tolderlundsvej 5
DK - 5000 Odense C

www.mst.dk