Lifecycles of Bio-Based Materials: Insights from the HEREWEAR sample collection

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Abstract

The role of designers is pivotal in a shift to circular fashion systems, but often material knowledge is difficult to access and innovation is hard to rationalise or contextualise. We therefore need to create tools to better understand the field of emergent biobased materials and their potential for a decarbonised, circular fashion sector.

The EU-funded HEREWEAR project explores systemic innovation for biobased, local, circular fashion systems as an alternative to current global and fossil-based approaches. This paper presents insights from the creation of a biobased material collection in the early stages of the project. Analysing the collection alongside literature and interviews with experts, produced a map representing the range of options for feedstocks, transformation processes, and end of life for biobased materials.

The biobased material lifecycle map aims to support designers in choosing the appropriate materials for their designs and then implementing adequate circular design strategies for this material. It is already being used with stakeholders inside and outside the project to produce scenarios for biobased, local, and circular fashion that represent systemic understanding of the potential of these materials.

Keywords: biobased, circular, local, information visualisation, systemic design innovation

1. Introduction

Bio-based materials offer promising perspectives for the fashion industry. They can support a shift away from the high environmental impacts associated with the use of conventional cotton and polyester. They also present opportunities for locally sourced and circular fashion systems. However, this category of materials is often misunderstood and miscommunicated. New tools to describe and classify biobased materials are needed to support a shift to sustainable practices.

This paper presents the review and analysis of the field of innovative biobased materials performed in the early stages of the EU Horizon 2020 funded HEREWEAR project. To scope the field of bio-based materials, a collection of samples was gathered to understand and communicate challenges and opportunities for a transition to decarbonised and circular fashion systems. The collection of over 90 samples enabled a review of the current various resources, processes, and end-of-life trajectories relevant to these materials. The research was conducted from a design perspective, with an emphasis on making the technical information concerning material innovation available to design decision-makers.

The European Committee for Standardization (2021) puts forward the following definition for bio-based: “The term bio-based product refers to products wholly or partly derived from biomass, such as plants, trees or animals (the biomass can have undergone physical, chemical or biological treatment).” This definition is very broad, providing little guidance for designers intending to use biobased materials in their products; this further definition was needed. There is also entrenched confusion concerning the biodegradability of biobased materials and their relative environmental benefits compared to other resources.

In the context of a climate emergency, best practice approaches for making, using, and recovering products must function within planetary boundaries and enable social justice. The fashion industry, notorious for its impact on people and the environment, is slowly coming to terms with the transformation ahead (Amed *et al.*, 2022). Within design for sustainability principles - which includes many strategies aimed at reducing impacts - circular design focuses on the circulation of resources within fair and energy efficient systems (McDonough and Braungart, 2002; Ellen MacArthur Foundation, 2017). This can be associated with a shift away from carbon-heavy, fossil-based resources (Biomimicry Institute, 2020; WBCSD, 2020). Fashion and textiles are a key challenge for circularity as the complexity of the supply systems and (blended) materials involved make it difficult to adhere to the biological and technical cradle-to-cradle ‘loops’. However, many researchers have been rethinking textile design, considering ways of revaluing waste materials and pioneering circular solutions in this field.

Design is changing, becoming a practice that is more able to concretely plan for a better future. Traditionally seen largely as a solely creative and aesthetic act in the fashion and textiles industry, the widespread realisation that design makes a significant contribution to global impacts has generated an urgency to use design differently. Researchers and practitioners are realising that it can be a systemic influencer, reaching beyond product conception and production, in both directions along the extended value chain. Thus, tools to enable designers to work in new, more considered ways, are urgently needed.

This paper presents the review of a collection of bio-based materials that was interpreted as a novel lifecycle map showing the feedstocks, transformation processes, and end-of-life trajectories for these materials. Presenting this information in a visual form, and as a tool useable in online and in-person settings to connect technical knowledge with creativity is key to the effective use of these materials for a shift to a decarbonised and circular fashion system.

2. Context

The work presented in this paper is set in the context of the HEREWEAR project which aims to explore innovation for bio-based, local, and circular textiles. The broader context for the research is the field of biomaterials innovation, populated by a range of innovators and designers at all scales of activity. This work aims to provide insights for this community.

2.1. The HEREWEAR project

The HEREWEAR project is based on three pillars which act as a compass for the project aims: local, circular, bio-based. The ambition is to create an approach which enables local eco-systems of garment production, using locally abundant resources such as straw waste, local ‘micro-factories’ and considers the local capacity for collection, sorting and processing.

This approach relies on circular design to ensure that the materials are recoverable and can be cascaded through the waste hierarchy, from repair to re-use to remanufacturing, mechanical recycling and finally to chemical recycling. Circularity demands that material loss from the system is minimised – or at the very least – managed. Therefore, in the HEREWEAR system, production waste is recovered, and micro-fibre loss is prevented, as far as possible.

The HEREWEAR project aims at 'systemic materials innovation', meaning that the development of technologies for new materials is located within a framework which actively considers the wider context of the materials: the interrelation of the new materials with people and planet. In line with this, alongside the development of new fibres from agricultural waste, an important aspect of the project is to provide guidelines for designers to use bio-based materials in a circular way in their local context. To support this, a collection of bio-based materials was gathered to better understand this category of materials and what challenges and opportunities exist for their adequate use. This paper focusses on this initial part of the research aimed at understanding bio-based materials.

2.2. Bio-based materials

Interest in the potential of biomaterials for a sustainable transition has brought together a global community of design stakeholders, makers, industry specialists and consumers around an enthusiasm for the potential of these materials to address environmental issues. The words have been used extensively in the last few years as a proxy for "non-oil-derived". Biomaterials are put forward as a part of circular bio economies which acknowledge the incompatibility of oil-based materials with natural systems in which products and fibres inevitably disperse (Biomimicry Institute, 2020). The focus on biomaterials follows the imperative to decarbonise fibre production (Textile Exchange, 2022). However, a common misconception is that the term "bio" means that it is automatically better in terms of environmental impacts, and biodegradable. According to the definition put forward by the European Committee for Standardization, conventional materials such as a poly-cotton blend could claim the bio-based label if they are 50% cotton. This is contentious as it means that materials with a high proportion of fossil-based content could claim the benefits associated with bio-based materials in the eyes of the industry and thus the consumers.

To narrow the definition used in HEREWEAR and focus on innovative fibres that offer an alternative to current extractive practices, the term 'biosynthetic' is helpful. Biosynthetic - or regenerated materials - offers the opportunity to extract compounds that can be transformed into textile materials from renewable resources when the fibre isn't present or usable is the plant or animal itself, as it is for cotton and wool. Textile Exchange (2017) proposes the following definition: "a biosynthetic fibre consists of polymers made from renewable resources, either wholly or partly". This category includes fibres like man-made cellulose from wood pulp or other sources, as well as other processes which transform plant materials into fibres. Rayon, or viscose is a conventional biosynthetic material in which the cellulose contained in wood is transformed to produce a fibre. This process was historically a way to make textile fibres in a very inexpensive way, but recent regulation on air and water pollution have shifted the balance (Changing Markets Foundation, 2020). It is also relevant to note here that the production of regenerated fibres therefore isn't systematically environmentally sustainable, in particular if transformed through the viscose process, and only by controlling all the steps along the supply chain can this category of materials provide a vision for building resilience and accelerating regeneration (Forum for the Future and Textile Exchange, 2020).

The Textile Exchange (2017) defines bio-synthetic feedstocks as corresponding to three “generations” which are classified in terms of their availability to market. As the industry strives to improve performance and reduce impacts for these materials, efforts are made to optimise the use of biomass. First generation feedstocks are based on crops which provide stable and scaled input but can be in competition with land allocated for food. The second generation are feedstock taken from waste sources such as agricultural by-products. This offers the potential to reduce the land needed to produce fibres by using waste from other industries, however this type of feedstock requires additional research as it is currently only available for regenerated fibres at the pilot scale. The third generation defined by Textile Exchange is those that do not enter in competition at all with food as they rely on other types of agriculture which can be off land such as with seaweed or even using bacteria in lab settings.

One of the challenges here, is to effectively communicate that ‘natural’ materials aren’t necessarily better in environment impact terms than bio-synthetic ones, and that with appropriate control over the production processes, these can deliver reduced impacts. Therefore, communicating clearly on the differences in feedstocks and processes is key to handing adequate information on to key decision-makers.

3. Method

The sample collection of bio-based materials gathered in the early stages of the HEREWEAR project has provided the basis for the development of a detailed description of the lifecycle of these materials. The analysis of the collection is core to the methodology presented here. The samples provide a basis for mapping the field and discussing more technical aspects of bio-based lifecycles with stakeholders. Other roles of the designer besides creating or making – such as a facilitator and a communicator - are also drawn upon in this work. Alongside academic research approaches which provide the rigour needed to support the insights and contextualise the work in current literature, the methods demonstrate the central role of design in making the complex issues of circular bio-based and local systems easier to understand and include in fashion design.

3.1. Sample collection

The sample collection was gathered from medium to large material manufacturers, smaller makers, and various distributors across the world, to show the current range of bio-based materials. This included conventional ‘natural’ textiles, as well as more innovative bio-synthetic examples.

A call for interest was launched across the HEREWEAR networks in January 2021, and specific suppliers were also approached by email. The suppliers were identified through online searches as pioneers in the field of biomaterials, providing options that can replace current ‘problematic’ materials. We request included fibres and materials made from agricultural bi-products rather than the crops themselves; or fibres and materials that push the boundaries of production with new, lower impact processes and finishes. Contributors were asked to send a physical sample and fill out an online information sheet providing details on the feedstocks and transformation processes used. The form allowed for some sections to be left blank, acknowledging the discrepancies in the availability of information for novel bio-based materials, as well as information that might be restricted by intellectual property regulation.

As the collection grew, the samples were reviewed through various criteria, such as by raw material or type of applications. Other material libraries were reviewed to compare how the industry is currently encountering these materials. Through this review of material libraries, it was found that a resource showing how materials are made could fill a gap in the current offer. The HEREWEAR sample collection therefore shows resources, or feedstocks used, types of transformation and processes, and the end-of-life options to recover and regenerate the resource. The information is presented as a circular lifecycle map, aligned to the HEREWEAR project approach (active areas for research), and in order to support designers in thinking about the whole lifecycle of a product when using these materials. This full lifecycle approach is widely known to be a key component of design for circularity (Sumter *et al.*, 2021).

3.2. Expert interviews

The information concerning biomaterials innovation is diffuse and sometimes not readily available, as it is subject to pending patents or confidentiality agreements. To overcome the complexity of the field and gain insights from current research and innovation, parallel and complementary information was sought through a series of informal interviews. These discussions with experts and material providers act as a first step to the translation of the technical information relating to biomaterials in terms that are useful to informing design decisions (Baule and Caratti, 2016).

The interviews took place both before and after suppliers and innovators sending the samples. This intended to establish trust between the two parties, clarifying the aims and conditions of material sharing. This approach also enabled a review of the classification and the representation of a given material in the collection. These interviews proved to be invaluable to getting first-hand information from the provider concerning the transformation processes and the market-readiness of the materials.

Interviews were also arranged with the HEREWEAR partners particularly involved in technical textile transformation processes from fractionation, to design for end-of-life. These sessions acted as a collaborative approach to building a common glossary and classification of biomaterials for the project, which fuses the expertise of partners from multi-disciplinary perspectives.

All interviews were carried out remotely using an online whiteboard space to present the iterations on the material classification while taking live notes. The interview structure was guided by the visual representation of the material classification and allowed time to discuss the different stages of a material's lifecycle in detail.

4. The HEREWEAR bio-based materials collection

Wilkes (2011) argues that material libraries are a key tool for knowledge transfer. The HEREWEAR collection aims to represent a range of samples from external partners alongside materials produced by members of the HEREWEAR project. It shows a snapshot of the field of biomaterials, identifying key players and innovative processes across the material lifecycle. It is also meant to help position the HEREWEAR materials within this field, by demonstrating some important similarities and differences when compared to other materials.

4.1. Internal materials

The HEREWEAR partners were first asked to contribute materials which had been made by their organisation in previous projects (figure 1). This provides a basis for collaboration and a reference point for what can be achieved in the project. As suggested by Hornbuckle (2020), using samples alongside dialogue can help avoid misunderstandings inside a collaborative project. This category also includes the samples that were produced in the project since its beginning to demonstrate the technology developed by various partners. In this case too, the samples are a key enabler of efficient communication by providing a concrete example of what can – and can't - be achieved.

Figure 1. Samples of naturally dyed regenerated cellulose and PLA produced inside the project

4.2. External materials

External materials were gathered from businesses and innovators not included in the project as partners, but which demonstrate similar interests in transforming materials used for fashion (figure 2). This section of the collection aimed to show the state of the art in the field of bio-based materials, contextualising the innovation provided by the HEREWEAR technologies. To provide this overview, some materials which are somewhat outside of the scope of this research - such as conventional 'natural' bio-based materials like cotton or hemp - were included. On the other side of the spectrum, other materials which are not yet available commercially or even in pilot stage - such as bio-iridescent sequins or bacterial cellulose - were also considered to show the range of possibilities in the future which can inspire design ideation now.

Figure 2. A selection of external materials from the HEREWEAR collection

Reviewing these materials with HEREWEAR expertise, and complemented with interviews with the providers, supported the development of a visualisation of the lifecycle of bio-based materials which encompasses multiple types of innovation across the field.

5. The biobased material lifecycle map

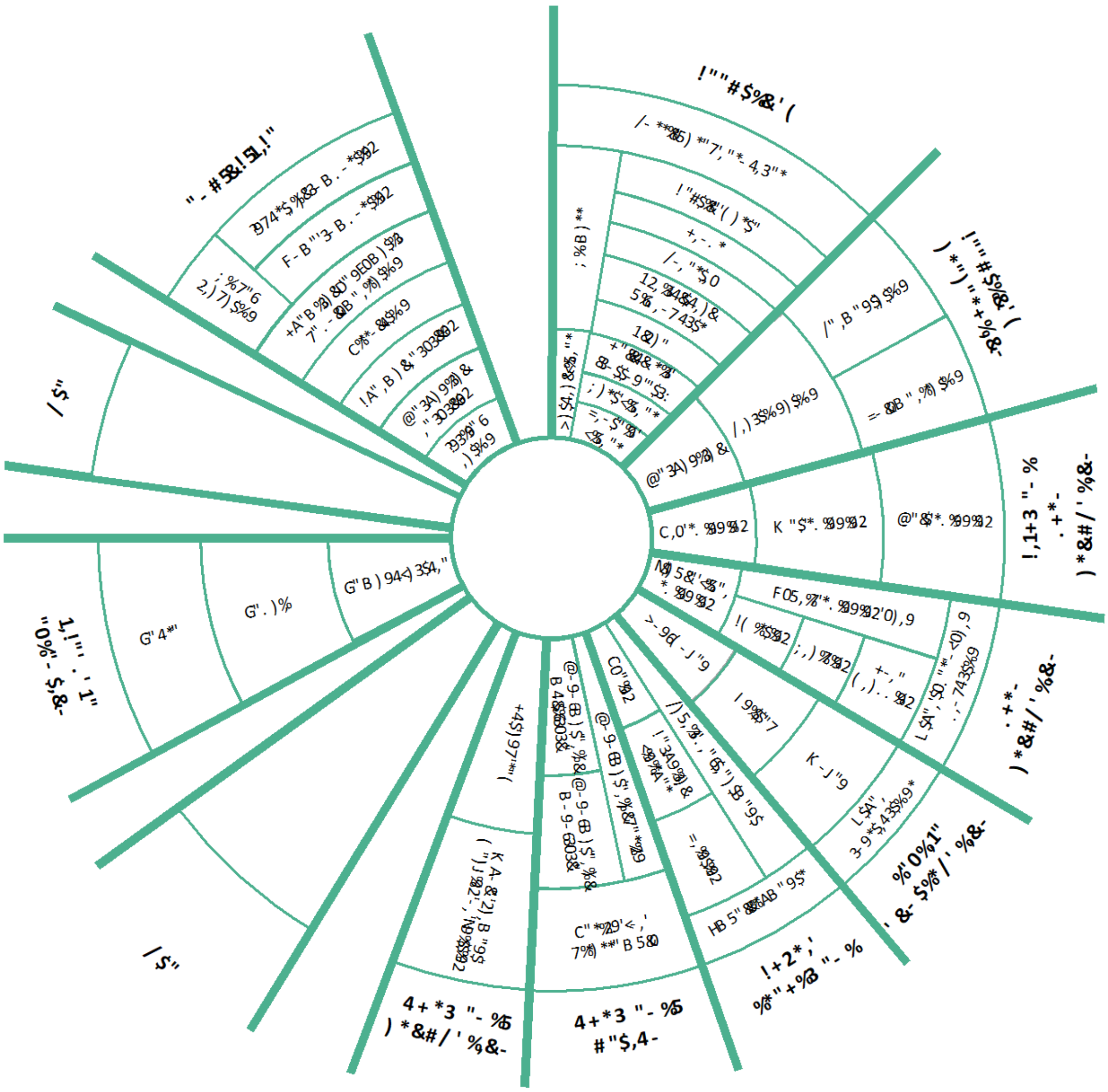


Figure 3. The Biobased Material Lifecycle Map

The sample collection provides the basis for a design-led understanding of the challenges and opportunities for bio-based materials in a circular and local context, grounding the research in the experience of interacting with the materials. The biobased material lifecycle map interprets the knowledge from the collection into a visual diagram that can support designers in better understanding how biobased materials are made and how they can be used. (Figure 3)

5.1. Lifecycle categories for biobased materials

Using the samples to support conversation with material providers and HEREWEAR experts, a categorisation emerged that could describe the bio-material life cycle. The visual representation shown in figure 3 provides a description of the different options of feedstocks and processing available for bio-based materials. The categories presented in the materials mapping were iteratively reviewed through interviews. The aim was to agree on a representation that could balance the level of detail and of scientific accuracy to best inform designers. Each segment of the material lifecycle map represents what options are available in material selection, production and use.

5.1.1. Feedstocks

From a design stakeholder's perspective, understanding the type of raw resource that a textile is made from, not only gives clues as to how it will perform in use, but also points to the end-of-life trajectory and the way in which this can be considered early in the design phase. It is also a critical decision point, as the industry aims to diversify and decarbonise its fibre input, by shifting away from the ubiquitous use of cotton and polyester (Textile Exchange, 2022).

Here the main distinction is between feedstocks in which bio-based fibres are naturally occurring; and feedstocks which can be used for the production of biosynthetic fibres after processing to extract the useful compounds. The former type includes naturally occurring cellulose fibres such as cotton or kapok, lignocellulose bast fibres like hemp and flax, and protein fibres in animal hairs such as wool. These materials are described as 'conventional' biomaterials and are included at the margin of this review.

The other overarching category presented in the lifecycle map is that of feedstocks which are in the form of biomass rather than fibres. These include crops such as sugar cane or maise, and forestry, such as eucalyptus trees from which Lyocell is often made. These feedstocks are grown specifically to make fibres, potentially in competition with food crops. Other feedstocks can be used that are the bi-products or waste of other industries - such as straw or orange peel - contained in the category of 'agricultural biproducts' in the lifecycle map. It is also possible to consider textile waste as a feedstock for new textiles when it is mechanically or chemically recycled into new fibres. Finally, as a third-generation feedstock, algae can be grown offshore and contribute the regeneration of marine biotopes as well as carbon capture. The map still accounts for the presence of some fossil-based feedstocks in the case of blends.

5.1.2. Feedstock preparation

The feedstock is rarely ready to use as it is found, various processes are needed to purify it and make it ready to be made into fibres. For instance, polymers naturally available as fibres like bast fibres or cellulosic fibres like cotton, may need a mechanical cleaning and carding process before they can be spun into yarn. Whereas polymers that need to be extracted and transformed, like the cellulose present in trees, first need to be fractionated and then dissolved before they can be made into a filament yarn. In a bio-polymer process, it is possible that the biomass will be fermented to produce the right type of molecules that can then be made to polymerise.

5.1.3. Filament products

This process is only relevant for fibres that are not naturally occurring, and which need to be produced from a pulp or a master batch. With melt spinning, the polymer pellets are melted and extruded to create the filament. Wet spinning uses a solvent bath from which the fibre is drawn, and dry spinning is a similar process to wet spinning with the solvent being removed from the fibre through evaporation rather than a different bath. In all three cases, this step can be the opportunity to engineer filament fibres and give them specific properties - through texturization for example.

5.1.4. Yarn production

Two main types of yarn production are considered here. On the one hand yarns are considered that are produced by assembling multiple short fibres under the heading 'staple fibre spinning'. On the other hand are 'hybrid yarns' made from multi-filament yarns. Staple fibre yarn-making processes can include conventional ring spinning, open end spinning or rotor spinning, and friction spinning, to name but a few. It involves the twisting of multiple fibres into a yarn - these can be natural fibres, synthetic fibres, or a mix of both. Hybrid yarns can be produced from a range of different yarns including staple fibre yarns. There are many ways to spin fibres together by twisting or wrapping them together. It is important to note how the way in which the fibres are spun into yarns can have a large impact on the performance and look and feel of the final textile.

5.1.5. Textile construction

The lifecycle map defines three different types of textile construction: either woven, knitted or non-woven. In the textile construction phase, 'first order fabrics' - made from only one re-source - can be differentiated from blends which combine different materials. With the fibres assembled as a textile it becomes possible to their behaviour in use, whether this concerns their look and feel, or the way they might fibrillate, or how they behave when wet. In this review, materials which are assembled to form alternative leathers fall in the category of non-woven materials as they are first assembled as a mat, either by mechanical felting or by using a binder, before the finishing stage gives them their final look and properties.

5.1.6. After treatments

This section includes a non-exhaustive listing of possible treatments and finishes that can be applied to materials. These treatments can be applied in any order relevant to their aims and intention. For example, a technical finish can be aimed at improving the dye uptake of a fabric, therefore occurring before the dyeing. These are relevant as some fabrics or yarns will react in different ways to finishing processes; or need an extra step to match the performance afforded by some fossil-based synthetic fibres, or even conventional biomaterials such as cotton. In the HEREWEAR project there are research efforts around developing bio-based finishes and embellishments.

5.1.7. Garment design

Garment design must consider the qualities of the materials afforded by feedstock and the various transformation and finishing processes, to enable the most adequate use of a textile for comfort and longevity, and also address the later stages and end-of-life to enable circular practices and recycling. Here the focus is on the choice of designing garments as mono-material pieces, either for one recycling cycle or for several, or design for disassembly. These decisions are key to enabling the long life and smooth recycling of resources in the form of garments.

5.1.8. Use / reuse

Use is a difficult lifecycle stage to design for, as once a product is in the hands of the user post retail, it is almost impossible to control what happens next. The use and reuse phases are left blank in the lifecycle map to acknowledge that some instructions can be given, and that these phases must be considered as a valid part of the full lifecycle, but that clear paths will be difficult to forecast. Clear product labelling, and digital product passports are areas of opportunity to enhance use and reuse.

5.1.9. Lifecycle extension

Several strategies for lifecycle extension are included in the guidelines produced in other parts of the HEREWEAR project. Some of these guidelines would include actions that can be taken at the start of the design process, and some would cover processes to apply to the garment once it has reached the end of its first use cycle, such as redyeing or other embellishments. These approaches can be considered in relation to the selected bio-based material, how it will age and wear, and how it will react to such processes.

5.1.10. End-of-life

When considering biomaterials in circular systems, the end-of-life stage is of great importance; it is the potential starting point to a new material cycle.

In a biodegradation end-of-life trajectory, textiles can be safely added to home or industrial compost so that they break down into nutrients under the action of micro-organisms (Elsasser, 2016). A common misconception with bio-based materials, is that they are de facto biodegradable, or indeed nutrients. While being made from bio-based materials can in some cases be an element that contributes to biodegradability, many bio-based materials will not decompose safely. Even a material labelled biodegradable might only be so in certain conditions. For instance, some materials can biodegrade in home compost, whereas others need the controlled conditions (such as heat) of industrial composting facilities.

With mechanical recycling waste textiles are shredded for fibres to be recovered for a new spinning process. This shortens the length of the fibres which means the addition of virgin fibres is often needed to strengthen the recycled yarn (Elsasser, 2016). Mechanical recycling can be a trajectory for both bio-based and fossil-based materials. Effective mechanical recycling is very dependent on a thorough sorting process (Hall, 2018).

Thermal recycling is an option for thermoplastic materials which can be melted down to reform pellets and spun through an extrusion process. This is a common route for polyester materials; at the moment more commonly in clear packaging form, rather than in textiles, but it is also applicable to well-sorted textiles. Bio-based materials which are polymerised to become similar in molecular structure to conventional polyester or nylon can be thermally recycled in the same way as their petroleum-based counterparts.

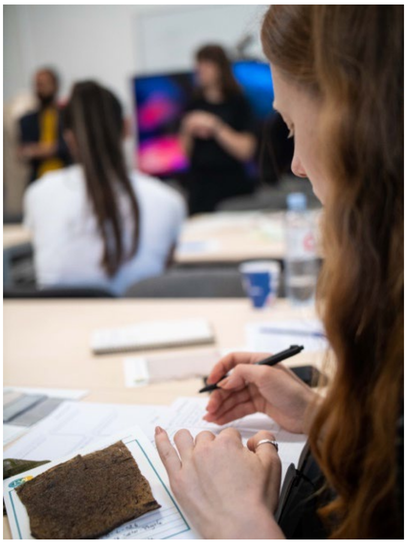
In the case of man-made cellulosic fibres, end-of-life textiles can be dissolved with chemicals which will extract the cellulose to recover it for wet spinning processes (Elsasser, 2016). Materials can be chemically broken down further into their polymers or even monomers. Chemicals or enzymes are used to break down the polymer chains so that the result can be polymerised and melt-spun once more (Elsasser, 2016). This reverse chemical reaction can enable the removal of impurities from the sludge, and hence produce quality polymers that can then be made into new regenerated textiles.

5.2. Using the Biobased material lifecycle map

The collection of samples, and the lifecycle map that came from it, were then used to support designers in taking bio-based, local, and circular principles into their work. These resources form the basis of new tools for discussion and design, for use in workshops (Figure 4).

5.2.1. Common language for biobased materials

The material collection, presented to the workshop participants through the lens of the lifecycle map to provide a circular view of the landscape of bio-based materials, offered a starting point for discussion on the qualities and challenges of these materials. With the physical material in hand, participants could discuss their ideas for its use in a concrete way, aligning descriptors such as 'soft', or 'luxurious' with other designers. The material postcard format (Figure 5) was devised to gather the questions designers ask about the use of these materials in fashion applications and their effect on the lifecycle of the product - from durability to recyclability.



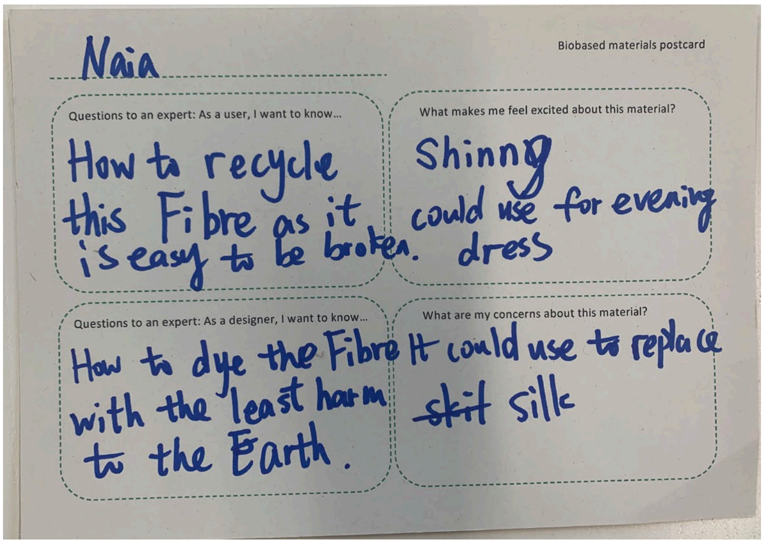


Figure 4 (left). A designer participating in a workshop using a selection of materials from the HEREWEAR collection.
Figure 5 (right). A material postcard reviewing a reference from the HEREWEAR collection.

5.2.2. Material portraits

The material lifecycle map, built from the review of materials from the HEREWEAR collection, was later used to visually represent the 'profile' or 'portrait' for a given material from the collection. These 'material portraits' were first built by interviewing the innovators or suppliers who provided the material for the collection, in order to test the portrait-making process. Further material portraits were then made with the information given for each fabric reference. These portraits show how materials in the same broad category of bio-based materials can differ widely in terms of their feedstocks or processes. The way that the lifecycle map is used accounts for the fact that often, all the information is not available for a given fabric, but some reasonable assumptions can be made regarding its composition, structure, or how to design with it based on labels or touch. This visualisation aims to communicate the diversity of biomaterials to designers in a clear and visual way.

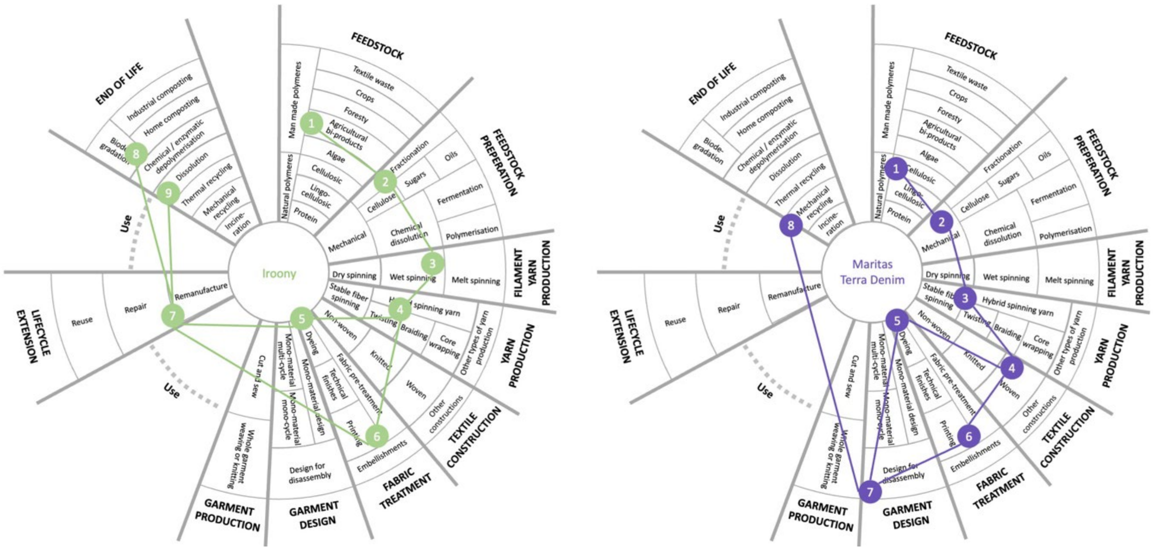


Figure 6. Two material portraits showing a visualisation of the lifecycle of materials from the HEREWEAR collection.

5.2.3. Supporting key design decisions

The aim of developing a better understanding of bio-based materials is for designers to be able to implement novel and reduced-impact fabrics into their work. By segmenting the information related to bio-based materials into stages of a lifecycle, discussion on the impacts of the choices made at each stage can take place between designers and experts. In particular, the material lifecycle map was used with Life Cycle Assessment experts inside the HEREWEAR project to discuss how a change in feedstock or process might affect the product's environmental score.

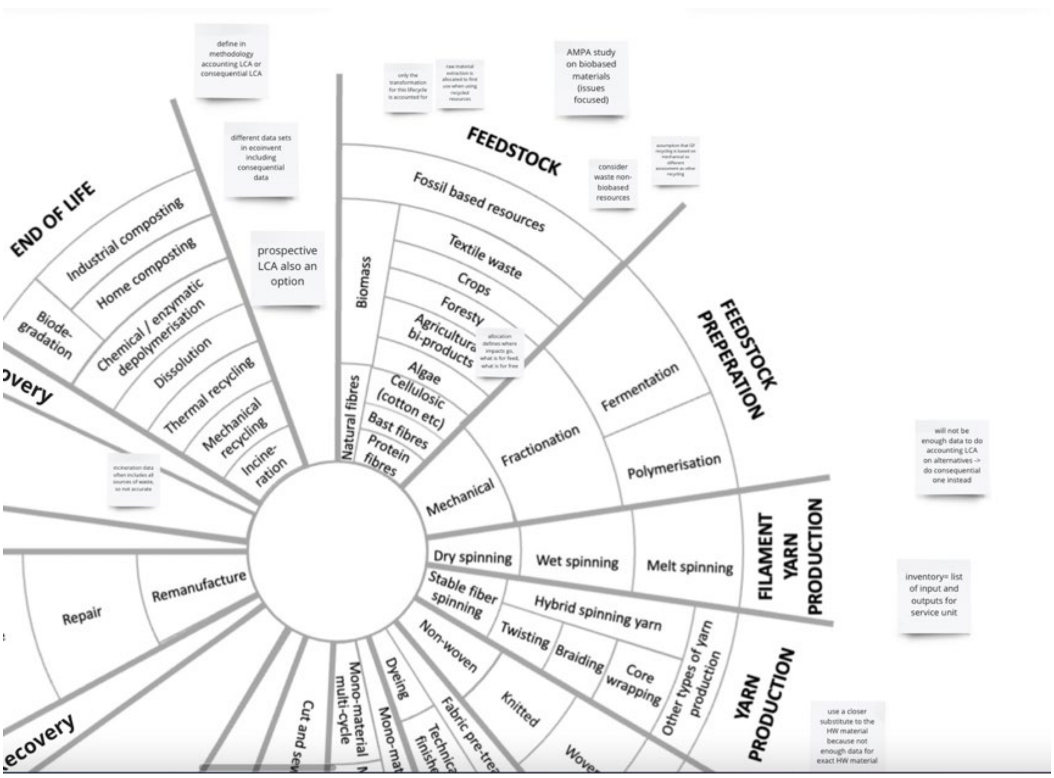


Figure 7. A screenshot from an online collaborative workshop using the Biobased Material Lifecycle Map to highlight key decision points based on Life Cycle Assessment knowledge.

6. <u>Discussion</u>

This review of bio-based materials through the HEREWEAR sample collection and its interpretation into the bio-based material lifecycle map aims to support designers in furthering their understanding of biomaterials through a visual tool that can inform design decision-making. Some key elements of the diagram contribute to this aim.

6.1. Translating experiential knowledge

As the knowledge relating to textiles ranges from the highly technical, to the deeply tacit (Igoe, 2010), it is often difficult to communicate effectively around innovation in this area (Tubito *et al.*, 2018). In particular, with the challenges of a shift to circularity, the scale that is scrutinised can go from the micro and chemical, to the macro and meta. Thus, finding tools and processes that can facilitate effective communication between different experts in this area is key to innovation for sustainability. There is most noticeably a gap between designers' expectations and what science can provide, which is important to bridge through transparent information sharing (Lee *et al.*, 2020).

As designers generally respond more easily to visual material (Brand, 2017), it was therefore relevant to represent the technical information for different feedstocks and processes in a way that could give an overview of the main samples in the collection in term of their trajectory from raw material to end-of-life. The original aim of the representation was to demonstrate how materials made from the same feedstock could be processed in different ways, drawing different paths to end-of-life recycling. It quickly became apparent that this type of visualisation could be useful as a way of gaining a broader understanding of lifecycles and design decisions for bio-based materials. While the lifecycle map cannot hold a large amount of technical detail about a material, it can quickly convey the main characteristics concerning its production, use and recovery trajectories. This can support a joining-up of the conversation between designers who require guidelines on how to use a material, and technical experts, who will understand this information in relation to the production and finishing processes.

6.2. Tools for designers

To evolve fashion and textiles within the circular economy an interdisciplinary approach encompassing a range of lifecycle perspectives is required. Facilitating this collaboration requires new thinking and tools. Lifecycle thinking is at the heart of this bio-based material lifecycle map - aiming to help designers 'do' more circular and sustainable design.

Forms of collaborative 'lifecycle thinking' (LCT) tools have been developed to integrate the essential, multiple-expert perspectives within the design process. This is intended to place material, environmental and social scientists, technologists, industry stakeholders and users all together at the core of an iterative design process. The value in the use of these interdisciplinary LCT methods, have been established through multiple research projects (Goldsworthy, Peters and Sandin, 2017; Tubito *et al.*, 2018). The sharing of knowledge in this context provides an important basis for understanding how to bring the theory of circularity into an established industry practice. The work presented here draws from these previous projects to offer a model for lifecycle thinking that is particularly relevant to bio-based materials. This is relevant as a step to overcome the misconceptions around the benefits and challenges pertaining to novel bio-based materials and their perceived role in a circular economy.

The practice of textile and fashion design can no longer be limited to the creation of a product for pleasure. Design stakeholders need to hold on to their ability to create joy and beauty for the wearer, whilst also becoming embedded in a process as systems-thinkers. Knowing the loops and processes of materials and products will be an essential part of their practice, enabled by better communication between technical and creative disciplines.

7. Conclusion

The understanding of biomaterials and the different processes and end-of-life trajectories that relate to them has been gathered through a sample collection of bio-based textiles. In this work the sample collection has been instrumental in many ways: it forms the basis of a field review, highlighting key areas for innovation; it has engaged networks of biomaterials experts and makers; and it has provided the basis for a lifecycle map relevant to bio-based materials.

Whilst the HEREWEAR sample collection isn't a repository or catalogue that designers can choose from - many other material libraries are currently available for this - it has produced insights useful to designers. The collection has been used to identify the lifecycle stages that are common to bio-based materials, enabling designers to learn about and to better understand these materials for their potential use in circular fashion products and systems. It was also found that the tool functions as a communication device between technical knowledge and creative approaches. The material portrait format offers a full lifecycle view of a range of materials, at a glance. This format can be used in future developments to gather more references of novel bio-based materials for the HEREWEAR collection and other uses.

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