Biotechnology for a sustainable textile industry

A CLIB white paper written in the scope of the HiPerIn 2.0 project.

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Zusammenfassung

Dieses Whitepaper gibt einen Überblick über das Potenzial der Biotechnologie zur Steigerung der Nachhaltigkeit in der Textilindustrie.

Die Textilindustrie, die sowohl Mode wie auch technische Textilien umfasst, hat ein globales Marktvolumen von 920 Mrd. USD und beschäftigt weltweit 75 Millionen Menschen. Es handelt sich damit um einen der größten Konsumgütersektoren. Ihr ökologischer Fußabdruck ist groß, ihre Wertschöpfungsketten sind lang und komplex - und meist linear. In NRW hat die Textilindustrie ihre Blütezeit hinter sich und die Großproduktion ist in andere Länder abgewandert. Dennoch gibt es nach wie vor eine bedeutende Industrie in der Region, die sich auf hochwertige, vor allem technische Textilien für spezielle Anwendungen konzentriert hat. Dabei wird sie von hervorragenden Forschungseinrichtungen im Land unterstützt.

Um die Textilindustrie nachhaltiger zu machen, sind nicht nur Investitionen, sondern auch Innovationen erforderlich, um die Ressourceneffizienz zu erhöhen, den Einsatz giftiger Chemikalien zu vermeiden und Materialkreisläufe zu schließen. In diesen drei Bereichen können die Biotechnologie und durch sie produzierte hochfunktionale Inhaltsstoffe (high-performance ingredients, HiPerIns) Vorteile bieten. Enzyme zum Beispiel werden bereits in der Textilindustrie eingesetzt und können den Energie- und Wasserverbrauch von Verarbeitungsschritten reduzieren, da sie bei milden Temperaturen arbeiten und immobilisiert werden können, wodurch Waschschritte entfallen. Ihr Einsatz kann so präzise abgestimmt werden, dass hochwertigere Fasern und Textilien entstehen, was den Gesamtwert der Ware erhöht. Moderne Textilien, für Bekleidung, aber auch für technische Zwecke, werden üblicherweise mit Chemikalien veredelt. Diese können ein Textil zum Beispiel schmutz-, öl- oder wasserabweisend machen. Diese Funktionalitäten sind zwar für den Verbraucher von Vorteil (und manchmal zwingend erforderlich, wie bei Schutzausrüstungen), gehen aber oft auf Kosten der ökologischen Nachhaltigkeit. Die verwendeten Chemikalien können in die Kategorie der "Ewigkeitschemikalien" fallen, die sich in der Umwelt anreichern und mit schädlichen Auswirkungen auf den Menschen in Verbindung gebracht werden. Hier können biobasierte und biotechnologische HiPerIns dazu beitragen, diese gewünschten Funktionalitäten mit geringeren Auswirkungen auf die Nachhaltigkeit zu gewährleisten. Schließlich kann der Zugang zu nachhaltigen Rohstoffen, entweder durch die Produktion von biobasierten Natur- oder Chemiefasern oder durch Recycling, auch durch Biotechnologie ermöglicht werden.

In NRW verfügen viele Akteure aus dem akademischen Bereich, KMU und der chemischen Industrie über ausgezeichnete Fähigkeiten, um Innovationen für die Textilindustrie zu entwickeln. Eine im weltweiten Vergleich kleine, aber agile und innovative Textilindustrie im Land kann eine Vorreiterrolle bei der Implementierung biotechnologischer Innovationen in diesem Sektor übernehmen.

Summary

This whitepaper gives an overview of the potential for biotechnology to increase the sustainability of the textiles industry.

The textiles industry, split into fashion and technical textiles, has a global market size of 920 bn USD and employs 75 M people worldwide. This makes it one of the biggest consumer good sectors. Its environmental footprint is high, its value chains long and complex – and mostly linear. In NRW, the textile industry has had its heyday and large-scale production has moved to other countries. However, there remains a significant industry in the region, which has focused on high-quality, especially technical textiles for specialised applications. In this, it is supported by excellent research organisations in the state.

Making the textile industry more sustainable will require not only investment, but also innovations to achieve resource efficiency, avoid the use of toxic chemicals, and close the material stream loops. In these three areas, biotechnology, and high-performance ingredients (HiPerIns) produced via biotechnology, can offer benefits. Enzymes for example are already used in the textiles industry and can reduce the energy and water consumption of processing steps, since they work at mild temperatures and can be immobilised, removing the need for washing steps. Their application can be finetuned to yield higher-quality fibres and textiles, increasing the overall value. Modern textiles for garments, but also technical use, often rely on chemicals for finishing. These can render a textile for example stain-, oil-, or wate-repellent. While these functionalities are beneficial to the consumer (and sometimes imperative, as for protective equipment), they often come at the expense of environmental sustainability. Chemicals applied can fall into the category of "forever chemicals", which build up in the environment and are associated with harmful effects on humans. Here, biobased and biotechnological high-performance ingredients can help to provide functionality with reduced sustainability impacts. Lastly, ensuring access to sustainable feedstock, either through the production of bio-based natural or man-made fibres, or via recycling, can also be enabled via biotechnology.

In NRW, many stakeholders from academia, SMEs, and the chemical industry have excellent capabilities to innovate for the textile industry. A small, but agile and innovative textiles industry in the state can become pioneers in implementing their biotech innovations in this sector.

Introduction

For millennia, nature has provided humanity with the four Fs: food, fuel, feed – and fibres, the latter being the basis for all textiles. The textile industry meets one of the basic human needs: protection from the elements by providing clothing and fabrics. It also meets more frivolous desires for self-expression via fashion, far beyond the purely functional. In few other markets can the price of a product be so decoupled from its production cost, making fashion both a cheap commodity, and a luxury segment. This has meant a huge increase of both volume and profit in in the textiles market, with concomitant challenges in sustainability. Since the industrial revolution, of which one of the milestones was the invention of the spinning jenny, fabrics have become faster and cheaper to produce. This, together with the advent of artificial fibres, has led to a huge increase in the offer of textiles, a decoupling of fibre production from agricultural production, and finally to the current fast fashion industry.

In its current state, most value chains in the textiles industry are not sustainable. It follows mainly a linear model, where products are rarely repaired, re-used, or recycled. Indeed, especially in fashion, advertising creates an industry depended on fast turnover of garments and continuing demand for new products, often at low prices. Unsurprisingly, following the fast fashion approach creates problems in all areas of sustainability:

Environmental – mainly linear value chains, a large environmental footprint in production, and high rates of unrecycled waste, as well as microplastics from synthetic fibres

Economical – fragmented, non-resilient supply chains, large disparity between profits generated throughout the value chain

Social – depending on cheap labour, an unskilled workforce, with child labour often reported in the value chains

The EU is targeting these issues through its Strategy for Sustainable and Circular Textiles, adopted by the Commission in 2022. It aims to make the textile sector more competitive and resistant to global shocks. Its intention is that in 2030 "all textile products placed on the EU market are durable, repairable and recyclable, to a great extent made of recycled fibres, free of hazardous substances, produced in respect of social rights and the environment". With only seven years to reach this goal, technological and social innovations will need to be swiftly implemented. A number of regulatory measures will be taken to achieve these aims, among them stricter regulation on chemical use, as well as the collection of post-consumer textile waste. In both cases, the extent of the regulation is as yet unclear. Regarding the collection of textiles, either targets for the share of materials collected could be set, or simply setting up separate collection bins could be enough. It should be noted that in this first step, only a targer for collection, not recycling is set. It can however still provide to be a benefit for textile recycling by providing a heterogenous, but large and continuous feedstock stream in Europe. The end-of-life of textiles is as yet unresolved throughout the EU.

The market for textiles is projected to grow with a CAGR of 4 % until 2030[1]. This will require an increased supply of fibres, either virgin, or recycled. As yet, there are no value chains in place to globally sustainably source the present demand, let alone future increases. The global yield of

[1] https://www.grandviewresearch.com/industry-analysis/textile-market

cotton, the major natural fibre used in the industry, cannot rise to match this increase. Cultivating cotton requires agricultural land, ultimately competing with arable land needed for food production. It also requires large amounts of water as well as fertiliser. This means the global supply is limited. By far the major supply of fibres to date comes from fossil-based synthetic fibres, which by the nature of their feedstock are unsustainable. In addition, these are regarded by many consumers as inferior for clothes unless they are technical fibres for sports or outdoor clothing. It becomes clear that new sources of fibres will be necessary to meet the increased demand. These will need to prove their sustainability but will also have to convince the textile industry and consumers of their tangible benefits. Traditional natural fibres such as hemp or flax have some technical limitations, but also a negative image, which will need to be overcome.

More than 70 % of greenhouse gas (GHG) emissions in the textile industry come from upstream production (1), of which material production (38 %), yarn preparation (6 %), fabric preparation (8 %), and wet processing (15 %) are the main contributors. With the major global textile exporters China, Vietnam, Bangladesh, and India (together accounting for over 49 % of global exports in 2020) still mainly relying on coal as energy source (2), one major way to decarbonise the textile industry will be by shifting to renewable energy. The CO_2eq savings achieved by energy-related actions are estimated at 63 % by Berg et al. (1). The overall ecological footprint can be decreased further by de-fossilising the material streams in addition to the decarbonisation of the energy input. Areas for improvement are petro-based synthetic fibres such as polyester or agricultural practices in cotton farming. In addition, reducing the overall water and energy use, removing the reliance on hazardous chemicals, and improving the recycling rates will be necessary to achieve sustainability goals in the sector.

Will consumers need to be part of the strategy to achieve sustainability in the textile industry? Certainly yes, in a push towards more long-lasting, higher quality garments, removing fast-fashion trends of up to weekly micro-collections per year[2]. This is where fashion brands find themselves in the peculiar position to encourage their own consumers to buy less – but presumably still from their particular brand and potentially at higher prices to ensure longevity and sustainability. While cotton is still perceived by most consumers as a sustainable and skin-friendly fibre, man-made bio-based fabrics might have a better sustainability profile. In this, it would need a dedicated communication strategy to convince consumers of the tangible benefits of bio-based fibres and clothes, as well the benefit of avoiding fossil-based resources. This discussion would need to be multi-faceted, also considering factors such as fashion trends, price, style, branding, consumer's tastes etc. There is a growing consumer awareness about fast fashion and sustainable clothing, however, this does not translate to directly to the increased sales of such items. The reasons could be manifold: an unwillingness or inability to pay the price difference to more sustainable textiles, the still limited offer, especially in a sector where personal preference or brand loyalty are so prominent, or a perceived lack of quality or style with "greener" products.

During the conception phase of the HiPerIn2.0 project, the textiles sector had been identified as a potential new market segment to biotechnology approaches. During HiPerIn2.0, CLIB started to develop first contacts into this field. On the one hand, this was an ideal moment – over the past three years, numerous research and start-up activities have developed, following the public

[2] The annual total carbon emissions of the seven leading European apparel retailers amounted to 376,333 metric tonnes of CO_2eq in 2021.

pledges of sustainability targets by big fashion brands in particular. On the other hand, the textile industry in NRW was not easily accessible to the project due to the Covid-19 pandemic. In person visits and networking were severely restricted especially during the pandemic, and the regional textile sector was heavily impacted by the subsequent economic consequences of loss of retail as well as disrupted supply chains. Also globally, the textile industry was very badly affected during the first two years of the Covid-19 crisis. Consumer demand dropped, collections either remained in storage, or were ordered, but not sold and piling up around the world. Supply chains were ruptured, exposing their fragility. Many businesses switched to producing personal protective equipment during the first months of the pandemic, which kept the factories running, but did not cover the costs. While in Germany, like in most of Europe, the government stepped in to provide financial aid, for many businesses their existence was threatened, production stalled, and investment into new applications was halted. The industry has since recovered, with the global fashion industry seen back to pre-Covid levels, and the textile industry almost regaining its former size.

This white paper gives an introduction to the textile industry, its market development, and processes. It aims to identify areas where biotechnology, with the use of enzymes themselves as high-performance ingredients themselves, or with biotechnologically produced ingredients, can provide an advantage in the textile value chains to make them more sustainable and circular.

The textile industry – a short overview

The textile industry is regarded as a major contributor to global pollution and produces 8 – 10 % of global CO_2 emissions (2). Its supply chain is long and complex, distributed across the globe, as are its production processes. Most visible to consumers is the (fast) fashion industry, which has almost doubled its production since 2000 (3). It accounts for roughly 2/3 of the textile sector. 75 M people work in the sector globally, which has a market size of 920 bn USD[3]. This makes it the strongest consumer goods sector in the non-food area (by turnover).

The EU textile industry is an important part of the EU manufacturing industry and is a major employer in some regions. Its biggest producers are Italy, France, Germany, Spain, and Portugal, which contribute roughly 75% of the EU production[4]. European companies mainly focus on technical textiles and non-wovens, which are used in the personal care industry or the medical and automotive sectors. Another area of activity is in high-quality garments, i.e. the luxury fashion industry. In 2019, the EU sector comprised 160,000 companies, employing 1.5 million people (90 % of which worked in companies with less than 50 employees).

The textile industry in Germany and NRW

The textile industry in Germany employs about 124,000 people in 1,400 companies, most of which are small or medium enterprises (SMEs). Roughly 1,400 people work in R&D, in addition to those active at the 16 textile RTOs in the country. The combined turnover is 29 bn EUR, of which 60 % are

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[3] Mordor Intelligence

[4] https://single-market-economy.ec.europa.eu/sectors/fashion/textiles-and-clothing-industries/textiles-and-clothing-eu_en

from textiles, 40 % from fashion. This means Germany has the largest textile industry in Europe (4).

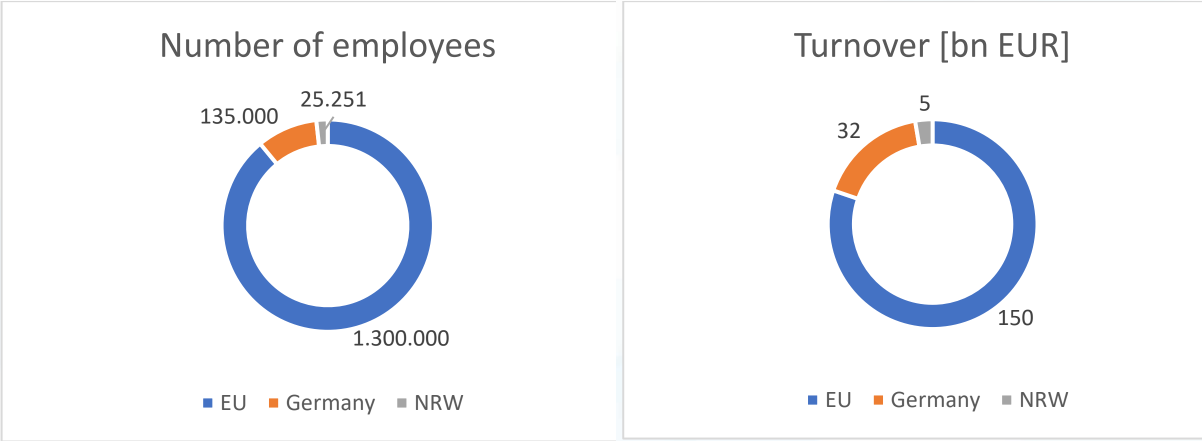

Figure 1: Textile industry in EU, Germany and NRW persons employed and turnover

North Rhine-Westphalia (NRW) is home to 252 companies in the textile sector, 199 in textiles and 53 in fashion. Together, they employ about 25,000 people and generate a turnover of 5 billion euros with an export rate of 40 %, exporting mainly to other EU member states[5].

While the textile industry in NRW is relatively small today, it looks back at a long tradition stemming from the 16th century, which dramatically decreased in size in mid-20th century. The remaining industry today is highly specialised and aims to produce innovative fabrics for protective workwear, sports, and leisure. Also in NRW are a number of world-leading research institutions with connections to the textile industry, such as the International Centre for Sustainable Textiles of RWTH Aachen University (ITA RWTH Aachen), the DWI Leibniz Institute for Interactive Materials, the German Textile Research Center North-West (DTNW), and the Hochschule Niederrhein University of Applied Sciences. With the "Innovationsraum BioTexfuture", jointly coordinated by ITA of RWTH Aachen and adidas, a large innovation space funded by the German Federal Ministry of Education and Research (BMBF) focusing on transitioning the textile value chain from petroleum- to bio-based, has part of its home in NRW.

As mentioned, the fashion or garment industry makes up about 60 % of the textiles industry (3) and is the most noticeable to end consumers. However, the applications for textiles are numerous and go far beyond the garments, including also medical and technical applications. The following list gives an overview:

- Garments/fashion
- Workwear, protective clothing
- Healthcare
- Specialised outdoor or sports clothing
- Home textiles
- Agriculture and aquaculture (growth support, protection, ropes, nets)
- Automotive (seats, textile reinforcement, seat belts)
- Construction (textile-reinforced walls, surfaces, sails, insulation)

[5] IT.NRW/MWIKE: https://www.wirtschaft.nrw/textil-und-bekleidungsindustrie

- Geotextiles
- Textiles for specialised applications, such as carrier material, or electrodes

The textile industry itself has identified the need to innovate and become sustainable. Already in its 2016 Strategic Innovation and Research Agenda, the European Technology Platform for the Future of Textiles and Clothing has identified "Circular Economy and Resource Efficiency" as one of four innovation themes (5). Topics mentioned in this context include resource efficiency in textile processing, such as shifting from wet to dry processing, changes in dyeing, or coating processes. Among the game-changing innovations mentioned, the ones most relevant to circular bioeconomy and biotechnology are the synthetic generation or regeneration of natural fibres such as wool, cotton, or silk, as well as next-generation high performance fibres, based on renewable feedstock (see section on Textile fibres below). Another innovation mentioned are small-scale on-demand production units. These would be very useful as a way to introduce novel fibres, or regional resources.

The production of a textile end product takes many steps, which depend on the fibre feedstock used, and the resulting processing steps required. Roughly, the textile processing chain can be broken down into the steps of raw material production (polymers, fibres), processing (yarn spinning, fabric production (woven & non-woven), finishing), cut, trim and make, retail and use, and end-of-use/recycling. Table 1 gives an overview of these stages. Several steps in this process could be supported by biotechnological innovations, these are highlighted in blue.

Table 1: Overview of the textile processing chains. Steps accessible to biotechnological innovation highlighted in blue. Modified from Fashion for Good.

Raw materials	Processing/Finishing	Manufacturing, transport, sales, retail, use	End-of-Life/Recycling
Natural fibres (cotton, wool, bast, agri-waste)	Microbial dye/fixing	Additive manufacturing	Digital passport
Synthetics	Plasma, ultrasonic, nano, foam, CO_2	Automation	Automated sorting
	Pre-treatment: enzymes, cationic	Mass customisation	Mechanical recycling
Man-made cellulose fibres	Digital printing, laser finishing	Zero-waste manufacturing	Chemical recycling
Man-made synthetics	Plant-based dyes & pigments	Optimised Yarn & fabric construction	Enzymatical recycling
Man-made biosynthetic fibres (PHA, PLA, etc.)	Coatings	Sustainable transport (also biofuels)	
Leather		Circular business models	Recycled leather
Lab-based leather	Alternative tanning, preservation	Virtual fitting	
Plant/fungi/fish leather alternatives		Laundry detergents	

Biotechnology, sustainability, and textile industry

Biotechnology is a key enabling technology with applications in many sectors. In its high-tech strategy, the German government defines biotechnology as the translation of biological and biochemical knowledge into technical, or technologically implementable elements[6]. It has been used by humans for millennia, from beer brewing to cheese making. In the HiPerIn2.0 project, CLIB aimed to highlight where high performance ingredients, produced via biotechnology, can be employed to improve processes and products, in order to make them more sustainable or improve their functionality to provide a consumer benefit.

Biotechnology can either be the key technology to access processes or products which cannot be produced via e.g. chemical means, or it can be used to make existing processes less energy and water intensive, often also removing the need for fossil-based or hazardous chemicals. Biotechnological solutions could be applied at different stages the textile industry, as shown above in Table 1. Several use cases come to mind, for example:

- Improvements in the production of natural fibres
    - bio-based fertilisers, plant protection (pesticides, etc.)
    - development of plant varieties with desired properties for textile fibres (plant breeding, GMO)
- Production of (semi-)synthetic fibres from (drop-in) bio-based chemicals
- Production of novel biopolymers (man-made fibres)
- Use of enzymes for more sustainable and resource-saving textile processing
- Natural dyes and coatings
- Enzymatic recycling of textiles, especially synthetic textiles such as PET fibres
- Treatment of dye effluents

While in some of these cases biotechnology is already well established, in others significant research or scale-up is still necessary. Several areas will be highlighted further in this whitepaper. Since the focus of HiPerIn2.0 was on high-performance ingredients and the textiles sector, the improvement of agricultural production will not be in scope of this white paper.

The drivers for innovation are the need to become more sustainable and keep up with increased consumer demand, as well as legislation (see also the sections on Finishing and coating and Cross-cutting topics). In the following, several processing steps as well as the potential role of biotechnology will be highlighted.

Textile fibres

Fibres are at the basis of the textiles industry; they are spun into the yarn which is then arranged to create the fabric. Fibres are produced from a range of feedstocks, which is also a method for their classification: natural or man-made. See Figure 1 for an overview.

[6] https://www.bundesregierung.de/breg-de/aktuelles/was-ist-biotechnologie--423190

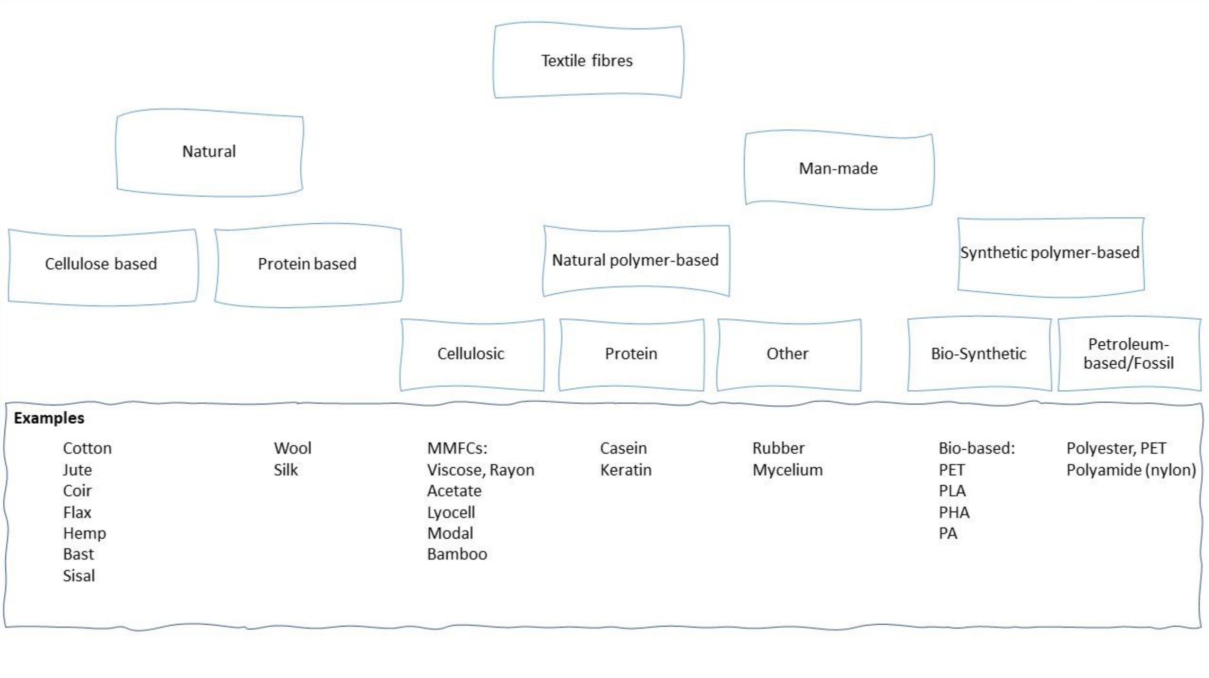

Figure 2: Classification of textile fibres.

Natural fibres include cotton and wool, but also more niche fibres such as hemp, flax, or silk. These are either grown by plants (cellulose-based fibres), or by animals (protein-based fibres such as wool/hair and silk). **Man-made fibres** can either be produced from natural resources, such as viscose from wood, or they can be fossil-based, such as petro-based polyamides, polyester, acrylic etc.

Almost 70 % of fibres used worldwide are man-made, and among these, polyesters are most common with a global fibre market share of 52 % (57,1 M tonnes in 2020, [7], see Figure 3). Polyesters and polyamides are usually fossil-based. While the European Man-Made Fibres Association (CIRFS) points out that the natural or synthetic origin does not automatically specify a level of sustainability, the fact that the vast majority of man-made fibres are fossil-based means these are not sustainable. This is even more true since these fibres are not yet recycled.

[7] https://textileexchange.org/synthetics/

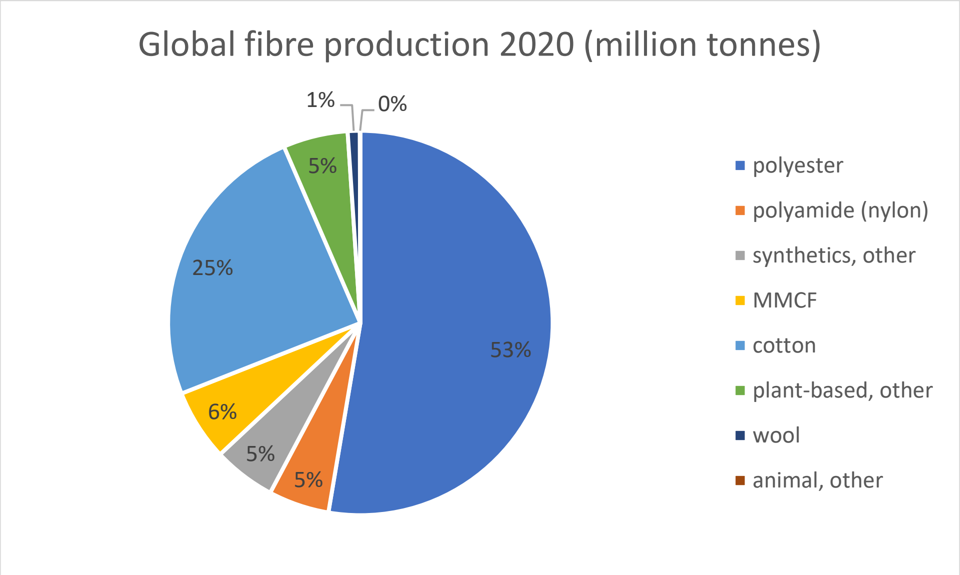

Figure 3: Global fibre production in 2020 (million tonnes). Source: Data from [Textile Exchange Dashboard](https://textileexchange.org/materials-dashboard/).

Amongst the natural fibres, cotton is by far the most prominent, accounting for 24 % of fibres produced in 2020. Natural fibres are an agricultural material, with seasonal availability affecting the price and their natural variability affecting quality. Synthetic fibres are more homogenous, and available year-round. With increased fluctuations in oil price, price volatility and availability are equally becoming an issue for synthetic fibres.

Several different natural fibres are a regional resource in Europe, such as flax, hemp, wool, nettles and even cotton. They make up only a small share of the global fibres market however and play a role in regional value creation only.

While humans have for millennia relied on natural fibres and used quite a varied number of them depending on availability and the desired properties of the fibre, man-made natural fibres only really entered the market at the end of the 19th century with viscose from wood pulp. Today, viscose and other man-made cellulosic fibres (MMFC) represent almost 6 % of the total fibre production.

The interest in sustainable fibres aims to meet several challenges associated with the fibres currently in use:

a) Growing cotton is at present rarely done in a sustainable way. Cotton agriculture competes with food production for arable land, for water, and fertiliser. It relies heavily on the use of irrigation and pesticides. The projected growth in demand for fibres cannot be met by increasing cotton farming, since no additional arable land is available. Some progress can be expected on agricultural practices, both in increasing yields and sustainability. In 2021, only 1.4 % of cotton was produced under organic farming, while about 24 % was farmed under a labelled programme (Fairtrade, Better Cotton, Cotton made in Africa and others)[8].
b) Man-made synthetic fibres are fossil-based and carry the corresponding environmental footprint. In addition, non-biodegradable microplastic is released during their use, laundering, and end-of-life. They are non-biodegradable and not recycled.

[8] https://textileexchange.org/materials-dashboard/

c) Traditional natural fibres like flax and hemp, formerly grown and used throughout Europe, exist, but their production is limited, and their performance is usually considered inferior to the more commonly used cotton or polyesters.

d) The sustainability of viscose and other wood-based cellulosic fibres mainly depends on the wood source and the chemicals used and retained in the pulping process. MMCF production is only economically sustainable in a complex value-generating site using wood for energy, fibres, and chemicals, making the process overall less environmentally sustainable.

Biotechnology has made exciting progress in the field of fibre production (See Table 2 for an overview). For the purposes of this whitepaper, the application of biotechnology to improve the production of natural cellulose fibres will not be analysed. This includes the use of green biotechnology to improve the crops themselves, which is not without conflict, since for example the global organic textile standard (GOTS) specifically excludes GMO in the organic cotton value chain, and consumer perception is sensitive around the issue. It also includes the use of biotech to improve farming, for example for fertiliser or crop protection.

Biotechnology, or bioeconomy can help to create man-made synthetic fibres: these would be chemically similar to the fossil-based PET, aramide, nylon, or PEF, but made from biogenic resources. These drop-in solutions have the benefit of fitting into the current production systems but are usually more expensive and not yet available at sufficient scales. It would be paramount to ensure their recyclability, since only then will they enter fully into a circular bioeconomy. Although bio-based, they are as non-biodegradable as their fossil-based counterparts.

Man-made natural polymer-based fibres can be based on different natural polymers: they can be cellulose-based (such as rayon, acetate, lyocell), protein-based (made from milk or soy), but also based on alginate, rubber, or PLA. An overview of man-made bio-based natural or synthetic fibres is given in Table 2.

Table 2: Selection of man-made (bio-based) fibres on the market and in development.

Fibre	Type	Developed by
Spider silk	Man-made natural fibre, recombinant production in diverse host systems	AMSilk (*E. coli*) Bolt Threads (yeast) Spiber (*Pichia pastoris*)
Bio-based PET	Not (yet) 100% biobased drop-in solution, polyester made from biobased or conventional feedstock via fermentation (bacteria) or fatty acid methyl esters (FAME) from microalgae. Already industrial scale for plastics.	UPM (bio-based MEG) Project Algaetex
Bio-based PEF	Man-made biobased synthetic, Replacement for PET in bottles, potentially also fibres	Avantium
Bio-based aramid	Man-made synthetic	Teijin Aramid/BioBTX

Fibre	Type	Developed by
	Biobased via BTX, also research into fermentation	U Manchester (fermentation, research stage)
Bio-based polyamides/nylon	Man-made synthetic, usually based on castor oil, also adipic acid, and fermentation	Aquafil (via caprolactam, fermentative) Toray Industries (via adipic acid, fermentative)
PLA, polylactic acid	Man-made bio-based synthetic, produced via fermentation.	Trevira (Fermentation) NatureWorks[9] (Fermentation of sugars, working on direct fermentation of C1 gases)
Bio-based acrylic	Man-made synthetic, main use in superabsorbent polymers for personal hygiene. Mass-balance, via bio-based lactic acid, from glycerine no commercial production yet	Arkema (mass balance) KSE (from glycerol) Cargill/Novozymes/BASF (via 3-hydroxypropionic acid) ADM/LG Chem (ingredients from corn processing) Procter & Gamble/Cargill (lactic acid) Axens/Cargill/IFPEN (lactic acid) (6)
PHA, polyhydroxyalkanoates, incl. PHB (polyhydroxybutyrate)	Bio-based and biodegradable, produced via fermentation. A bioplastic, but can also be spun to fibres. Also used in medical applications	Full Cycle Bioplastics, Newlight Technologies, BD
TPU	Thermoplastic polyurethane, based on CO_2, a drop-in solution	CO2TEX project

The fibre innovations listed in the table above are at different stages of their journey to the market, but none have reached a meaningful scale yet. The global production capacity for PLA was listed as 290 kta in 2019[10], which makes it the most advanced in terms of volume – but still a minute fraction of the 109 M tonnes/a global fibre production. PHA capacity was estimated at 48 kta in 2021[11].

Other interesting developments include PEF and biobased nylon, spider silk, and bacterial cellulose – as examples for a drop-in, a high-performance fibre, and a medical application.

When it comes to drop-in solutions, Avantium is pioneering the production of **polyethylene furanoate (PEF)** from biogenic resources via chemical processes. It has formed a collaboration

[9] See also technical note (23)
[10] https://www.fortunebusinessinsights.com/polylactic-acid-pla-market-103429
[11] https://www.ptonline.com/news/pha-production-capacity-projected-to-grow-tenfold

with companies from the textile sector to introduce applications for yarns and fabrics made from PEF[12].

Bio-based polyamides (**nylon**) is being developed for example in the EU-funded project (EFFECTIVE), which also looks at the recycling of this fibre.

An especially alluring application is **synthetic spider silk**. Researchers reported spider silk fibres spun from recombinant silk produced in mammalian cells already in 2002 (7). Recombinant spider silk protein has since been expressed in plants, yeasts, bacteria, insects, mammalian cells, and mammals (8). In heterologous expression systems, scientists produce different kinds of spider silk proteins, which differ in molecular weight and the physical characteristics of the fibres spun from them. While industrial implementation is still a long way off, AMSilk has presented first prototypes of a sports shoe and a luxury wristband made from its BioSteel branded silk fibres[13]. The current production capacity of this German start-up in 2022 was reported at 6 t/a. Other start-ups in this space are Bolt Threads from the USA and Spiber from Japan. It has been reported that scale-up is especially difficult to achieve, with market entry not yet in sight.

Bacterial cellulose is produced by several different bacteria, which excrete it into the environment as microfibrils. Contrary to plant cellulose, bacterial cellulose is chemically pure and very hydrophilic. It presents interesting characteristics, especially relevant for medical textile applications since it doesn't elicit an immune response and is not degraded in the human body. It can be used as a permeable wound dressing, for scaffolds, or even in drug delivery. Research to improve its production via fermentation and scale-up is ongoing (9).

More bio-based than necessarily produced biotechnologically are fibres based on various biological sources. These can include macroalgae (like kelp), banana leaves, mycelium from fungi[14], and milk fibre[15]. Figure 4 gives some examples of companies active in developing alternative fibres for diverse applications in the textiles industries, including fibres and leather alternatives.

[12] https://www.agro-chemistry.com/news/avantium-forms-pef-textile-community-with-five-companies/
[13] https://www.amsilk.com/industries/fiber/
[14] https://www.fiberjournal.com/mycelium-fibers-of-the-future/
[15] https://cordis.europa.eu/article/id/135536-making-clothes-from-milk

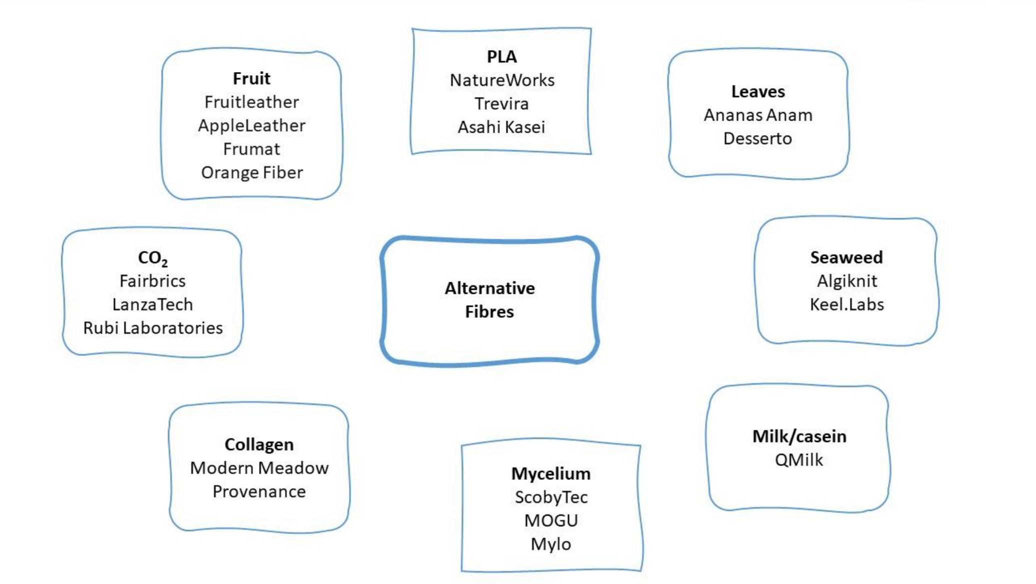

Figure 4: Novel fibres, examples

Although microplastic might be more associated with plastic waste found on beaches, shopping bags, or tyres, shedding of microfibers from textiles is a large contributor to the overall microplastic pollution. According to the Ellen Macarthur Foundation's report on circular economy, A New Textile Economy, half a million tons of microplastics from plastic garments end up in the seas every year. This amount is equivalent to 50 billion plastic bottles. As the report explains, "In this current trend, the amount of microfiber plastic entering the oceans between 2015 and 2050 could reach 22 million tons — about two-thirds of the amount of plastic fiber used to produce clothing annually".

All textiles shed microfibres during the laundry cycle, with celullose-based fabrics releasing more microfibers than polyester. The former are expected to degrade in natural aquatic aerobic environments, abating the problem of microfibres from natural fibres such as cotton or rayon (10). The problem of microfibres released from polyester remains unsolved though.

Biobased and at the same time biodegradable fibres are especially advantageous for applications where the release, either intentional or unintentional, of microplastics or indeed textile products into the environment cannot be avoided. Examples include fishing nets, textiles for growing aquaculture such as mussel socks, or landscaping textiles: geotextiles, trimmer lines, or artificial turf for sports fields. All of these applications shed textiles or fibres into the environment which cannot be recovered for recycling. They must thus be bio-degradable to avoid accumulation in nature. Recent innovations have mainly been based on PLA in these use cases.

Enzyme application in textile industry

In order to withstand the reaction conditions usually employed in textile processing, enzymes have to be able to with stand temperatures of around 80 to 90 degrees °C, high pH, and the presence of salt, alkalis, or surfactants. This can be overcome by either scouting for enzymes from extremophiles (e.g. the INMARE project) or by directed evolution or synthetic biology to modify and optimise enzymes (as will be done in the FuturEnzyme project). While enzymes might be more costly than traditionally used chemicals, they offer strong benefits in the area of sustainability: they are biobased, biodegradable, non-toxic in the environment[16], and can save water and energy by lowering the need for washing steps and process hear. Another big advantage is the fact that the enzymes are very specific in their activity and do not degrade the fabric itself – leading to higher textile quality.

Several classes of enzymes are in use in the textiles industry (see Table 3), to aid in a range of processing steps. The textiles industry has been using enzymes for several decades, however, there has been no significant leap in innovation in the past decades. Instead, well established enzymes such as amylases remain in use. It is unclear whether the shift to novel fibres that are as yet niche applications such as hemp or flax or indeed the use of biosynthetic fibres such as PLA or PHA will necessitate the development of modified enzymes or the use of new classes of enzymes. This would be an interesting field of research. For all industrial enzymes, their effective operating window and kinetics have to be adapted to the conditions (time, temperature, pH) present in the processing operations. This can be overcome via modern enzyme optimisation techniques. The combination of several enzymatic activities in one batch would reduce process steps, and already enzymatic processes are carried out in sequence, where the product of the first step (glucose from starch desizing) becomes the feedstock for the next (for glucose oxidase and peroxide production). Immobilisation of enzymes is another method to improve their application window and effectiveness.

Researchers have also published methods to combine different enzymes in a one-step reaction bath, reducing the amount of steps and rinse water needed. One example is the combination of amyloglucosidase, pectinase and cellulase for desizing and scouring, followed by a glucose oxidase for bleaching (11).

Table 3: Enzyme classes used in the textiles industry.

Enzyme class	Processing step and use
Amylases	Desizing: remove starch-based sizing agents
Glucose oxidase	Bleaching: remove colour from natural fibres via in situ production of hydrogen peroxide
Laccases	Bleaching: remove colour, mainly flavonoids, from natural fibres used in dyeing with natural or chemical precursors
Cellulases	Finishing and polishing: remove microfibres to smoothen fabric (cotton, linen, etc.) Finishing: used in denim finishing to create a stone-washed effect
Pectinases	Scouring: remove non-cellulosic material (such as cotton cuticles) Bleaching: remove colour from natural fibres
Amyloglucosidases	Bleaching: remove colour from natural fibres
Catalase	Bleaching: remove hydrogen peroxide after the bleaching step
Lipase	Scouring: removing waxes, fat, and oils, either natural or processing additives
Proteases	Scouring: remove protein impurity from cotton, increase wettability of animal fibres, degumming of silk Finishing: reduce shrinking and pilling

16 Powdered enzymes can be an irritant, so caution must be exercised when using lyophilised enzyme preparations in the processing. This can be overcome by using stabilised enzyme solutions.

Producers of commercial enzymes for the textile industry include novozymes, AB Enzymes, Creative Enzymes, MK Enzym, Advanced Enzymes, DuPont Industrial Biosciences/Biesterfeld Textilchemie Dr. Petry. The latter also advertises a range of non-GMO enzymes.

While enzyme use has become routine at least for some actors in textile processing, there have been no major innovations reaching market implementation in the last years. Some interesting innovations have been proposed by researchers or are entering the market. A few examples will be presented in the following paragraphs. These include the use of entirely new enzymes, enzymes in novel ways, as well as enzyme immobilisation.

Transglutaminases create isopeptide bonds between glutamine and lysine and are already used industrially in the food industry. In meat or fish processing, they create bindings in structured meat (ham) or fish (surimi, fish cakes); in the dairy industry, they can decrease syneresis and increase the yield of cheese production. They have been published to be interesting enzymes to improve the durability and feel of wool, improving fibre quality, as well as its dyeing properties, and reducing shrinking (12,13).

A rather special case of the use of biotechnology in textiles was developed in Australia. **Biological sheep shearing**, developed by CSIRO Animal Production in Australia in 1998, was a disruptive technology which was never commercialised, but remains on the shelf: sheep are injected with a patented epidermal growth factor (EGF), leading them to shed their fleece after a few days to weeks. Sheep have to be dressed in harvesting nets to ensure the weakened wool is not lost, which might have been one reason for this technology not to become widely available.

The **immobilisation of enzymes** has great potential for use in the textile industry (14). The most obvious benefit is that immobilised enzymes can be reused several times during textile processing, decreasing resource use and thereby costs. They can also be used to capture chemicals or dyes from the effluent, thereby removing potential pollutants from the wastewater of the textile processing plant. Here, the focus is less on the reuse of an enzyme, but on keeping it in place while passing the effluent with the chemical or dye to be removed over the immobilised enzyme.

Recycling of textiles is a major challenge for the textiles industry, which is as yet unsolved. This can also be done enzymatically. Several research groups have for example suggested to completely dissolve cellulose from mixed-material garments, in order to separate out a clean polyester fraction, which can then be recycled[17](15). See section Recycling for more information.

Textile processing

Textile processing is a multi-step process, from fibre-spinning to textile production to the finishing steps in order to create the final fabric with its desired feel, or characteristics. These can be water-repelling, oil- or fire-resistant, low odour development, or others. The various steps require large amounts of energy for heating and water for rinsing between steps, as well as a range of process and auxiliary agents, most of which are fossil-based. Not handled appropriately, these often release as hazardous chemicals into the environment. Large chemical companies, which even had their roots in textile processing, have often divested of their textile chemicals business units. This

[17]https://boku.ac.at/docservice/doktoratsstudien/doktoratsschulen/biomaterials-and-biointerfaces/research/projects/investigation-of-enzyme-mechanisms-for-total-hydrolysis-of-cellulosic-materials-for-recycling-purposes

can be seen as an indication that the challenge to shift to less-hazardous chemicals is high, while the market is under strong price pressure making new developments seem risky and potentially non-profitable. Textile processing often takes place in the global South, where it is poorly regulated and health, environment, and safety aspects not well monitored. The pressure on delivering fabric at lowest cost hinders innovations and investment into better technology, or more sustainable processes.

While this is a challenging field, biotechnological processes can replace chemicals in several processing steps, as shown in the section above. Enzymes have been used in the textiles industry, but their use is not universal, mainly due to cost constraints. Increasing their uptake would allow for large improvements, reducing the amount of water and energy used, in addition to replacing hazardous chemicals. In the following, some processing steps and biotechnology applications for them will be highlighted.

Surfactants are used in textile processing, for the purposes of wetting, anti-foaming, dispersing, washing, or as level-dyeing agents. While surfactants are to date mainly fossil-based, there are already some **biobased surfactants** on the market, with more in the pipeline. See the CLIB HiPerIn Whitepaper "Biosurfactants – Trends and Perspectives" for more information on current developments.

Prior to weaving, the yarn needs to be covered in a protective coating (size). This keeps the fibres together, protects the yarn from abrasion, and lubricates it for the weaving process. A good sizing chemical can be easily applied, performs its function, and can easily be desized again as well. The textile industry uses a range of sizing agents and auxiliaries, or blends of them, also depending on the type of yarn. These can be synthetic or bio-based, examples include polyvinyl alcohol and starch as the most common, but also waxes, oils, surfactants, or cellulose polymers. Desizing can be done via hydrolytic or oxidative techniques or using solvents. In **enzymatic desizing**, amylases are often used to remove starch-based sizes. They liquefy the starch before it is washed out. The reaction takes place at 50 – 60 °C, with a reaction time of about five minutes[18]. Compared to other processes, amylases save water and energy, cause no deterioration of the fabric, and are biodegradable. Instead of using isolated enzymes, fabrics can also be incubated in a solution with microorganisms (so-called **fermentative desizing**). This process takes longer, cannot be as well controlled and risks the fabric getting stained from mildew.

Scouring prepares the fabric for dyeing. Depending on the fibre material used, this could include removing impurities (pectin, wax, protein, or colours), or increasing the wettability to improve the dyeing step. **Enzymatic scouring** can be achieved with pectinases, proteinases or lipases. The benefit is not only in the increased resource efficiency, but also in the very specific action of the enzyme. It either leaves the underlying fabric entirely unscathed (for example removal of cuticles from cotton with a pectinase) or can be dosed very specifically (when preparing a wool fibre with protease), so as to keep the quality of the fabric high.

Dyeing

Biogenic textile dyes have been used by humans for millennia. They are a part of natural dyes, whose use can be traced back by more than 5,000 years. Commonly used in Europe were *Reseda*

[18] https://www.textilesphere.com/2021/05/desizing-textile.html

luteola (weld) for yellow, *Rubia tinctorum* (madder) for red or *Isatis tinctoria* (dyer's woad, German indigo), later also *Indigofera tinctoria* (true indigo) for blue colours. Typically, the fibres or fabric were mixed in water with the dye, heated, and a fixating agent (mordant) such as salt or urine added.

Markets and markets[19] states that the global textile dyes market was 10.7 bn USD in 2021 and is projected to reach USD 14 bn in 2027, a CAGR of 4.6 %. They see a surging demand in textile dyes from growth in the Asia Pacific market, but also increased R&D in sustainable and eco-friendly products. In the most recent past, however, the recession felt by the textile industry has led to decreased demand for textile dyes.

The industry today relies mainly on synthetic dyes, which can be classified as dyes for cellulose fibres, protein fibres, or synthetics. During the dyeing process, up to 50 % of the dye is not retained by the fibre and instead discharged with the effluent[20], quite literally tinting the view of the textile industry as major polluter of rivers and waterways. Overall, dyes only make up 3 % of the chemicals discharged into textile wastewater, however. [21] Immobilised enzymes could be used to catch these unspent dyes and help to reduce the colouration of wastewater effluents.

Considering the public view of the textile industry and its environmental problems, pictures of coloured rivers, especially in South-East Asia, come to mind (16). It is no surprise that with an increasing awareness of the sustainability problems of the textile industry, a range of stakeholders have entered the field to improve dyestuffs, for example with reactive dyes requiring less water, or with biogenic dyes which are less environmentally damaging.

Start-ups like Vienna Textile Lab, Pili, Colorifix, or Bluegene Technologies are using different approaches to produce biogenic dyes from microorganisms.

One challenge is this market is the potential consumer segment of environmentally conscious consumers willing to pay a higher price for sustainable clothes, and the labels guaranteeing the product specifications. The GOTS label for example does not allow for GMO products anywhere in its value chain, including enzymes and dyes. Some companies thus rely on strain collections to provide colour variety, while others use synthetic biology and forgo the label.

In another application related to dyeing, microorganisms can be used as biocatalysts to decompose synthetic dyes . Azo dyes are widely used in the textile industry today but are difficult to remove either from material or effluent. The relevant enzymes are laccases, azo reductases, peroxidases, and hydrogenases (17).

Finishing and coating

Textiles for garments are often treated to create a certain finish, pleasant feel, or decorative effect. Technical textiles, meaning textiles not produced for their aesthetic appearance but their technical or performance properties, usually have special finishings or coatings. These can include anti-static agents, oil or water repellents, flame-retardants, anti-pilling agents, tear strength improvers, and

[19]https://www.marketsandmarkets.com/Market-Reports/textile-dye-market-226167405.html
[20] https://www.dyes-pigment.com/textile-dyes.html
[21] https://www.ecotextile.com/2018102223813/dyes-chemicals-news/revealed-hidden-source-of-hazardous-textile-pollutants/all-pages.html

stiffeners[22]. A range of textile auxiliaries exist to introduce these characteristics in a textile. However, these often include toxic substances, which may only be used in specialised clothing, such as uniforms or protective clothing (e.g. for firefighters). Even so, the use of the agents can be problematic for textile processors, if they want to keep their production plant within specifications required by the eco-standards applied by retailers.

As a prominent example, PFASs are per- and polyfluoroalkyl substances, which are used in many different sectors. In the textile industry, PFAS are used to impart water-, oil- or stain resistance across a variety of products such as outdoor garments, carpets, napkins, or tablecloths. During the use of the textile product, its laundry and wear, these chemicals are released into the environment. Here they are often found in dust and accumulate, since they are not degraded. They enter the food chain and drinking water and have been found across all environments around the globe, including the Antarctic (18). Because PFAS accumulate in the environment and are linked to negative effect on human health, some specific chemicals from this class have already been banned, both in the EU as well as the US. Their use in firefighting foams is supposed to be banned following outstanding opinions of scientific committees. More far-reaching bans on thousands of substances are being prepared by the European Commission in a proposal submitted in January 2023, which will be open for a consultation between March and September 2023[23].

Several outdoor apparel brands (among the biggest are VauDe and Patagonia) have been very active in promoting their eco- or sustainable products. This is an interesting niche because of the high technological demands on the textiles, but also the relatively high price and specific retail niche of these products. Consumers buying outdoor equipment might be more willing to pay more and choose a “green” alternative to suit their outdoor lifestyle. However, a recent study showed that 60 % of clothes labelled as “eco-green”, “non-toxic”, “waterproof” and “stain-resistant” were found to contain PFAS (19).

Several companies have developed textile finished based on biotechnology or bio-based feedstocks. These usually include green chemistry processes to produce the final chemical, leading to final products with a bio-based content of 75 – 85 %. Table 4 gives an overview of some textile finishers available today. Since their exact composition is not divulged, it is difficult to say whether some of the issues known with PFAS will apply to them as well.

Table 4: Examples of companies offering bio-based textile finishing chemicals

Company	Feedstock	Functionality
Devan	Vegetable oils	Quick-dry, softener,
Beyond ST	Plant seed oils, microalgae oils	Water- and stain repellent, softener
CHT Germany	bio-based bee wax	Softener and processing aid
Rudolf Group	Plant-derived processing waste	Water- and stain repellent

[22] https://www.transparencymarketresearch.com/textile-auxiliaries-market.html
[23] https://echa.europa.eu/de/-/echa-publishes-pfas-restriction-proposal

Beyond replacing finishing chemicals, further research is being conducted into using bio-based materials, peptides, or even enzymes to convey advanced functionalities to textile products. Examples include:

- Soy polymer coatings[24]
- Chitosan for hydrophobicity, water repellent (20)
- Anchor peptides to e.g. functionalise PLA textiles, or add antimicrobial, UV-protective, or colourising agents[25]
- Microencapsulation for slow or controlled release of insect repellent, antimicrobial agents, scent, or other[26].

Recycling

The European Environment Agency (EEA) reports in a briefing that almost 1.7 million tons of textiles were exported from the EU in 2019[27]. This was 25 % of the 15 kg of textiles bought per person per year in the EU. While some textiles are sold as second-hand clothes, the majority are downcycled to rags, or end up in landfill. Making the so far almost entirely linear value chain circular is a huge challenge, as current recycling rates for textiles are very low. In an increasingly circular economy, the lack of scalable recycling technology for textiles is an urgent challenge. The EU Textiles Strategy envisions that in 2030, textiles products sold in the EU are made "to a great extent" of recycled fibres. All products should also be durable, repairable, and recyclable. To achieve this, the Commission will take actions to set design requirements and a digital product passport. As of early 2023, there are many start-ups and processes piloted in textile recycling, but no industrial scale processes in operation. Large fashion companies have already stated their goals of going sustainable. H&M, for example, pledged in 2019 to "to only use recycled or other sustainably sourced materials by 2030"[28].

Textile recycling can, like plastic recycling, be classified into mechanical, chemical, and enzymatic recycling. A problem lies in the fact that organic fibres cannot be re-polymerised, meaning once a cotton fibre has been shortened by recycling, it cannot be re-used in a high-quality textile.

Most textiles are a mix of different fibres and additives, the details of which producers do not necessarily want to expose via the planned digital passports. Currently, most of the recycling relies on industrial waste, i.e. cut-offs of fabrics which can easily be sourced and whose composition is known. Dealing with the heterogenous feedstock presented by post-consumer textile waste is a challenge which remains to be solved. Another aspect is the fact that this changes the global value chains, by potentially generating renewed textile feedstock close to the consumer, whereas the current processing and production facilities are located elsewhere. The social sustainability dimension here is highly relevant, as workers developing nations, heavily dependent on employment in the textile or fashion industry, might be left without livelihood. A sudden shift in the globalised value chains might be more than local governments can compensate for.

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[24] https://soynewuses.org/products/dupont-soy-polymers/, and Centexbel
[25] https://www.dwi.rwth-aachen.de/files/redaktion/Projekte/Projekt_280.pdf
[26] https://incaptek.com/textile/
[27] https://www.eea.europa.eu/publications/eu-exports-of-used-textiles/eu-exports-of-used-textiles
[28]https://about.hm.com/news/general-news-2019/on-the-way-towards-using-100--sustainable-materials.html

Biotechnology could offer a way to tackle multi-materials to recycle mixed fibres back to virgin material. One suggestion for mixed cotton materials is to use cellulases to digest the cotton into glucose, leaving other fibres for recycling. Bartl et al. (21) have shown that this approach is in theory possible, yielding a glucose solution as feedstock for further biotech processes, as well as PET fibres, which can be dried, re-extruded to pellets, and spun to rPET fibres and woven to yield a mixed textile.

Recycling of polyester-containing textiles and the re-use of polyester poses an interesting challenge in circular economy: both the textile industry and the plastics industry compete for the same raw and recycled feedstock: polyethylene terephthalate, which is polyester or PET. PET bottles are easier to collect and recycle than post-consumer mixed-material fabric, and both bottle manufacturers and other plastics producers, as well as textile companies compete for the rPET to use in their supply chains[29]. In NRW, the project MixUp is being coordinated, which is researching the use of microbial communities for bioplastics degradation and upcycling. This project sits at the interface between plastics and textile sectors, where some of the used polymers (PET, PLA, PHA) are the same.

Wool recycling has a long tradition, and continues to be processed mainly mechanically, resulting in materials of low quality, usually used for insulation, or padding. Chemical recycling methods via wool keratin are being proposed (22) but have yet to be shown in pilot scale.Table 5 gives a short overview of companies active in the chemical textile recycling area, this list in non-exhaustive.

Table 5: Examples of companies/projects active in chemical or enzymatical textile recycling.

Company	Feedstock, approach	Scale
EREMA	PET fibre materials	In development
Infinited Fiber	Recycling of cotton-rich textiles, potentially other cellulose-rich materials such as cardboard, crop residues. Chemical recycling.	Commercial plant expected in 2026, capacity 30 kt/a
eeden	Cotton textiles, chemical process for use in lyocell/viscose production	Start-up, lab scale
renewcell	Cellulosic textile waste into a new fibre material. Feedstock can be post-consumer cotton clothes or production scraps.	Pilot plant, 1000 t/month Commercial plant under construction, capacity 60 kt/a. EIB co-funding.

Recycling of post-consumer waste usually starts by shredding the materials, removing buttons, zippers, other accessories and colour. This is energy-intensive and in turn generates waste streams which can be difficult to process. One example of an innovation in this area is a monomaterial bio-based zipper by Nyguard (Italy), where both the fabric tape and the zipper itself are made from the same bio-based plastic, in this case one made by Evonik (Germany), from castor oil feedstock[30].

While no recycling technologies for textiles exist as yet, brand owners, increasingly confronted with reports about discarded clothes being exported to developing countries and textile mountains

[29] https://www.euractiv.com/section/circular-economy/news/eu-commission-rejects-priority-industry-access-to-recycled-pet-bottles/
[30] https://www.vestamid.com/en/products-services/VESTAMID-terra

piling up, have started to initiate return schemes, where consumers can drop off their old clothes in return for small vouchers (e.g. H&M, C&A, Primark UK). At the same time, innovative start-ups are developing recycling processes, most often via chemical recycling, to step up to the challenge (see Table 5 or also GEC Textile Award Winners & Finalists). It remains to be seen how quickly effective recycling technologies can be scaled to deal with the textile waste. This in an urgent challenge also because textile waste streams will be collected separately in the EU as of 2025 and will require processing. They will also present a resource of locally available feedstock, which needs to be made accessible through technological innovation.

In conclusion, biotechnology can offer improvements to many steps in the textile processing chain. This interest is not only theoretical; indeed several companies are taking a proactive approach in collaborative innovation. Schoeller Textil, a Swiss-based company who is, together with CLIB, a partner in the FuturEnzyme project, is reaching out to research consortia to harness biotechnology solutions. The company wants to use enzymatic processes to reduce energy and water consumption to make textile processing more sustainable and resource-saving. Concrete applications developments are the enzymatic cleaning of raw yarn of spinning oils or the enzymatic degradation of excess dye chemicals after dyeing.

Cross-cutting topics

In the preceding sections, cross-cutting topics such as regulation, public perception, and circularity/end-of-life, have been mentioned several times. Indeed, during the project, it became clear that all of the cross-cutting topics highlighted in HiPerIn2.0 are relevant to the textile industry. The following paragraphs give a short overview.

Regulatory framework

Like any other sector, the textile industry is subject to diverse regulations. It is, via the EU Textile Strategy, being required to take measures to become more sustainable, with more detailed regulations to follow. The textile sector is specifically included in the EU Circular Economy Strategy. Ambitious goals have been set, and it will remain to be seen whether they can be reached. Investments into new sustainable processes, new fibres, and recycling have been initiated. The extended producer responsibility (EPR) also requires more oversight along the value chain, which will become especially relevant for the textile industry's feedstock, but also working conditions.

Other initiatives such as the safe and sustainable by design (SSBD) or bans on hazardous chemicals mean that conventional processing chemicals might need to be replaced. As discussed, PFAS (so-called "forever-chemicals") are becoming subject to stricter regulation and will need to be phased out. The textile sector accounts for about half of the global PFAS use, so the industry will have to look for replacements if it cannot claim their use to be critical (as might be deemed the case in specialist clothing such as firefighter's protective gear etc.).

In the textile industry, as well as in other sectors, there is a danger of technological challenges becoming conflated with governance challenges. Textiles in landfill are a problem, but without governments mandating separate collection (as is being prepared in the EU), consumers have little choice but to dispose of their textiles with their trash. Rivers running colourful with dyestuff in the effluent or washing toxic amounts of salt into the ecosystem are a problem created by the industry, but also an underlying failure of meaningful and enacted regulation. Similarly is the social sustainability dimension of working conditions in the sector less a technological, but rather a governance issue.

Public perception

The fashion industry is obviously close to its end consumers, making public perception very relevant to business success. Brands owner in fashion rely on loyalty and emotional attachment maybe more than brands any other market, since objectively, there is often little difference between the purely protective qualities of one garment over another. Still, fashion is of huge importance to many people, and thus a brand's actions and image influence their market position. This means brand owners are very conscious of their public image and have moved quickly in ambitious pledges to become climate neutral fully circular unsustainable. However, the textile industry value chain is not moving at the same speed. Here, more conservative stakeholders need to become more innovative and also embrace the chances of biotechnology to help make good on those pledges and achieve the sustainability goals.

While consumers respond in interviews that green products are important to them, this is not necessarily reflected in their purchasing decisions. Brands aiming for a green premium must then consider how to convince consumers to pay more for their products. This can be either achieved through influencers, touting the sustainability of a product, or by providing a true customer benefit, such as better functionality of the final product. This is especially the case for sports, leisure, or outdoor equipment.

Sustainability is increasingly becoming a way for companies to signal a positive image, stepping outside the area of niche products for environmentally conscious consumers it occupied previously. There is a large potential for greenwashing in this system: of fast fashion not significantly recycled with valuable material kept in the loop, of banned chemicals replaced by similar ones, as hazardous, but not on an exclusion list, or of labels with fuzzy or empty meaning.

Digitalisation

Digitalisation related to HiPerIns is only tangentially relevant for the textile sector – as advances in synthetic biology will help speed up the development of biotechnology solutions for textiles. Other aspects of digitalisation are for example blockchain, to help stakeholders better monitor their supply chains and products. Digital passports can help to store information about a textiles' composition, knowledge which is essential for recycling. The sector itself has identified areas such as virtual fitting, improving the online shopping experience leading to less travel and fewer returns; improvements in cutting of fabric, leading to less waste, and customised tailoring as potential benefits of digitalisation.

Circularity/End-of-life

As was already extensively discussed in the chapter on recycling, end-of-life and circularity is a major challenge for the textile industry. Ensuring circular feedstock for the textile industry means growing fibres in a sustainable manner and closing the loop or getting the right feedstock for bio-synthetic fibres. Textile recycling intersects with plastic recycling, when synthetic fibres are recycled, which can also be a feedstock for the plastics industry, or where plastic bottles become the feedstock for the textile industry. This means the potential for new collaboration, but also for competition.

Taken together, especially regulation and public perception have spurred the sector into action, which can be seen by the public pledges of fashion brands, the number of start-ups active in developing new technologies and products, and also the investments funding them. At the same time, the fashion industry faces a conundrum: to be more sustainable, brand owners remind consumers to reduce, repair, and recycle – the first two of which cannot be entirely in the best interests of a company aiming to sell its products.

With the production cost of especially fashion items not different by much, yet the sales tag e.g. for a t-shirt ranging from a few euros to several hundred euros, there certainly should be room to manoeuvre for the fashion industry to embrace new technologies that would increase sustainability even at the expense cutting into the margin. To date, this is hardly the case. Instead textile processing as well as the make, cut, trim steps are localised in developing countries, with strong price pressure making investment into innovations difficult, even if the overall price is measured in cents per textile piece.

Outlook

The textile industry needs to embrace innovations to become more sustainable. It will need to find alternative sources for fibres, be they man-made, natural, or recycled, in order to reduce its carbon footprint. It will also need to comply with upcoming stricter regulations pending in the EU and the USA. Both of these issues need to be solved in the short- to medium-term: the planned post-consumer textile collection quotas will put on pressure to recycle, brands have committed to circular value chains, and are required to publish sustainability reports. While regulation can sometimes proceed at glacial pace, at other times it can be relatively swift as was the case with the EU's Directive on single-use plastics[31], which banned 10 household items, such as plastic straws, on relatively short notice.

While the textile industry has identified resource efficiency, decreased use or replacement of hazardous chemicals, and increases in recycling rates as targets already a few years ago, game-changing innovations have been slow to reach an industrial impact. In the current setup of fast-moving brand owners, a conservative supply chain, and extreme price pressure in the long value chains, meaningful innovations, maybe even requiring investment into new processes, are difficult to imagine. Regulation, oversight, and labour conditions vary widely in the global textile industries. Innovations realised in one area might not be possible in others or might even be impossible in the first place due to price pressure from other regions.

As has been shown in this whitepaper, biotechnology already plays a significant role in some processes of the textile industry, but it has the potential to offer yet more efficient and diverse solutions. The following Figure 5 summarises the chances and hurdles for biotechnology in the textiles industry.

Chances

- **Enzymes are already used**
- **Man-made, bio-based fibres used**
- **Reactions in water, at mild temperatures**
- **Biotech potential in many steps**
- **Synergies with recycling**
- **Sustainability as key driver**
- **Strongly image-driven market, consumer interest**
- **Public pledges by brand owners**

Hurdles

- **Fragmented global value chain**
- **Very price competitive**
- **Environmental factor valued differently in different regions**
- **Discrepancy between brand owners (innovative, sustainability as image factor) and suppliers (conservative)**
- **Competing technology solutions**

Figure 5: Chances and hurdles for biotechnology in the textiles industry.

NRW has strong innovators from academia and SMEs, with an expertise in enzyme development. They are working to improve the current processes or devise new ways to utilise enzymes in

[31] https://environment.ec.europa.eu/topics/plastics/single-use-plastics_en

textiles. At several world-class research centres in NRW, research groups are focussing on textiles, materials, and processing (see page 8).

The strong chemical industry in NRW is, amongst products for many other sectors, also producing textile processing chemicals, as well as coatings. Local stakeholders are committed to their sustainability goals and are working on innovations to de-fossilise not only their energy but also their material use. This includes finding alternatives e.g. for fossil-based coatings. Also here, biotechnology can play a part to produce HiPerIns for the textile industry.

The textile industry will be disrupted by several trends in the coming years: a shift in public perception and changing consumer habits, increased regulatory pressure on the chemicals used, the need to become more resource- and energy efficient, regulatory pressure towards durability and recyclability, and a change to the global value chain when feedstock from post-consumer waste becomes available in regions like NRW, which previously imported textile products and feedstocks.

It remains a challenge to create connections between the biotechnology and textile sectors. The communication about both needs to be improved. Only with a better understanding of each other's challenges and opportunities, innovators will be able to apply themselves to these challenges and provide solutions. To embark on collaborative projects and open innovation, stakeholders in both sectors and along the value chains will need to be brought into contact. It is with this idea in mind that CLIB has initiated this foray into the textile industry, to take help advantage of the chances offered by modern biotechnology.

About CLIB - Cluster Industrial Biotechnology e.V.

CLIB (Cluster Industrial Biotechnology) is an international open innovation cluster of large companies, SME, investors, academic institutes, and universities, as well as other stakeholders active in bioeconomy. The cluster comprises over 100 members with a share of about 25 % international members. The overall goal of CLIB is to network stakeholders in Germany and beyond and to identify new opportunities for innovation, projects, and business. Through this, the cluster develops cross-sectoral biotechnological solutions for sustainable processes and products. CLIB is a non-profit association, with its members shaping the cluster's interests and activities. The cluster is involved in several associated programs which cover different aspects of bioeconomy and invites members to become involved. To this end, CLIB organises several events throughout the year: the annual CLIB International Conference (CIC), the CLIB Networking Day (CND), forum events, topic-specific workshops, and dedicated small partnering meetings.

About HiPerIn 2.0

HiPerIn 2.0 is a project funded by the Ministry of Economic Affairs, Industry, Climate Action and Energy of the State of North Rhine-Westphalia (MWIKE). HiPerIn 2.0 reflects the rapid change in biotechnology and includes cross-cutting issues which had been identified and validated by CLIB and in an exploratory phase. The increasing digitalisation of biotechnology, the renewed concept of a circular economy, the end-of-life debate, the public perception of biotechnology, and increased regulatory requirements are cross-cutting topics which are of interest to many stakeholders. CLIB pursues the topics of biosurfactants, textiles, flavours and fragrances, and food/alternative proteins. Another focus in the HiPerIn 2.0 project is the support for project consortia and the identification of potential funding lines.

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