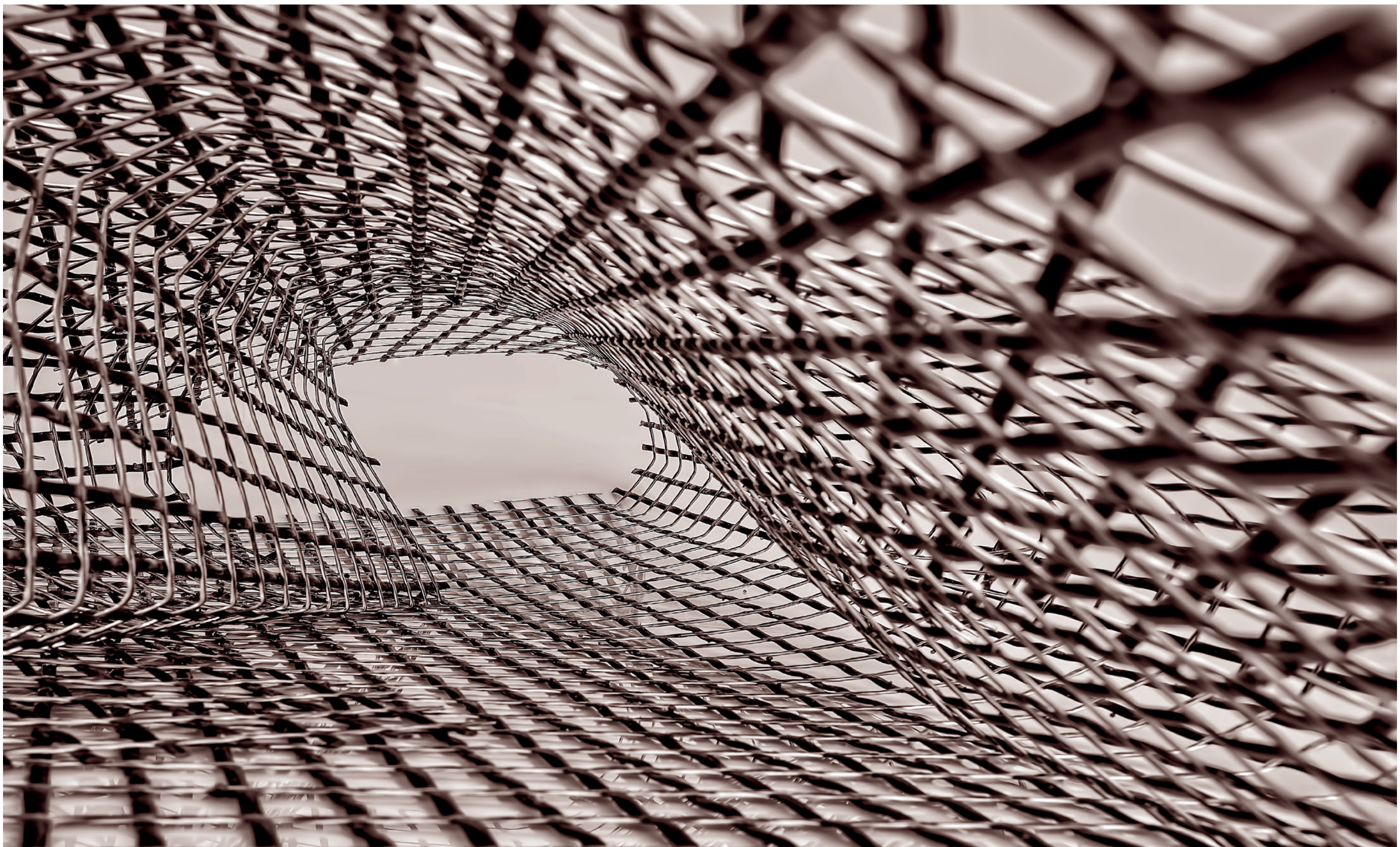
mistra future fashion



possible sustainable fibers on the market and their technical properties

the fiber bible part 1

by
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A Mistra Future Fashion Report
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preface

The Mistra Future Fashion "Fibre Bible" consists of two parts, where this report is Part 2. The two parts are:

- Rex, Okcabol, Roos. Possible sustainable fibers on the market and their technical properties. Fiber Bible part 1. Mistra Future Fashion report 2019:02

- Sandin, Roos, Johansson. Environmental impact of textile fibers – what we know and what we don't know. Fiber Bible part 2. Mistra Future Fashion report 2019:03

This report presents a study of the technical performance of new sustainable textile fibers. The sister report scrutinizes the definition of "new sustainable textile fibers" and quantifies the environmental potential of fibers. Together they aim to identify the fibers with the greatest potential to mitigate the environmental impact of fibers currently dominating the fashion industry.

We wanted to quantify the environmental potential of fibers and compare them on a fair and level playing field, with the aim to guide policy makers, industry and end customers in selecting "winners" and "losers". A multitude of other reports and tools with similar aims exist, though this report includes more types of textile fibers provides more quantitative data on their performance, and to a greater extent discuss the data found, as well as the data not found.

The work with finding sustainable fiber alternatives, but also sustainable yarns and fabrics will be on-going in the Mistra Future Fashion programme until the summer of 2019. If you, as a reader, know about sustainable fibers which are missing in the present report, please let us know by e-mail: sandra.roos@ri.se.

the Mistra Future Fashion criteria for sustainability

The concept of sustainability has no global common definition. The most well-known definition is probably set in the Brundtland Report (World Commission on Environment and Development 1987), though one may argue that the UN Sustainable Development Goals from 2015 (United Nations 2015a) is more relevant today. Other popular attempts to define what sustainability is includes the Planetary Boundaries (Rockström et al. 2009), the Ecological Footprint (Wackernagel et al. 1999), cradle-to-cradle (McDonough & Braungart 2002) or the circular economy (The Ellen MacArthur Foundation 2017).

In the Mistra Future Fashion programme, the perception of the concept sustainability was found to be both inexplicit and at a closer look to differ between researchers (Andersen 2017). To envision what an environmentally sustainable fashion industry would look like and identify technology solutions that have the possibility to make a substantial contribution in moving towards a sustainable textile production, an operative definition of the concept of sustainability was needed.

In the Mistra Future Fashion context, the operative definition emerged as a set of criteria for sustainability and how different solutions take us there. For defining the criteria, Johannesson (2016, p.33) was used as a basis, in which eight criteria of importance for "sustainable emerging textile production technologies" were identified based on semi-structured interviews with researchers at the Swedish School of Textiles and other professionals in the fashion industry. The criteria identified were:

- feedstock availability
- scalability (i.e., the potential to go from lab scale to commercial scale without overwhelming challenges, e.g., in terms of by-products which are impractical to handle or heating/cooling challenges)
- environmental performance (in terms of significant potential to reduce energy, water or chemical use)
- technology readiness level (in terms of potential to implement in a nearby future)
- cost (i.e., economically feasible for the industry)
- flexibility (i.e., adaptability to the fast changes of the fashion industry)
- interest (defined as "the technology meets the requirement from the industry and there is an interest in implementation")
- technical quality

Out of the identified criteria, the following were excluded:

- technology readiness level (as our perspective goes beyond the nearby future)
- flexibility (as this is less relevant for fiber production than for subsequent life cycle processes; also, one can question to what extent the current emphasis on fast fashion changes should be a given in an anticipated future sustainable fashion industry)
- interest (as industry requirements should be sufficiently captured by the other criteria (e.g. feedstock availability, scalability, cost, technical quality), and as the current interest should not limit our selection – we should rather see a lack of current interest in a promising fiber as an opportunity for us to raise interest)

This led to a preliminary list and definition of criteria, which were exposed to both industry partners and researchers within Mistra Future Fashion in a workshop organised in September 2017 with the aim to get feedback on the criteria. The workshop created consensus within the programme, and a set of screening criteria to evaluate the feasibility and sustainability potential of solutions was finalized, see Table 1. These criteria can be seen as "show-stoppers", as each of them needs to be fulfilled for a solution to be assessed as (potentially) sustainable, based on the current knowledge[(1)]. This report analyses in detail criteria 5, environmental potential.

The multidisciplinary scope of the Mistra Future Fashion programme brings another challenge in evaluating sustainable solutions. Solutions can be fibers, materials, design schemes, technologies, business models or policies, which puts high demands on the versatility of the sustainability definition.

In the programme internal work with workshops and article writing it has proven useful to use the different orders on cause-effect connection originally presented by Sandén and Karlström (2007). While life cycle assessment (LCA) research calculate direct sustainability impacts at the level of zero or first order effects, design research develops learning, positive feedback and system change which affects sustainability indirectly at the third order (Goldsworthy et al. 2016). Table 2, below, gives some examples on how solutions will affect sustainability on the different system levels.

1. the concept of "sustainability" can in this sense be compared with the concept of "health". It is difficult to define what health is while what is not health (show-stoppers) is easier to formulate, e.g. coughing, fever, mental illness, pain and so forth.

Table 1: Screening criteria used to evaluate the feasibility and sustainability potential of solutions.

criteria	explanation
1) Feedstock availability	Feedstock and/or auxiliary material feedstock must be available in sufficiently large quantities to allow for large-scale production (e.g. more than 100 000 tonnes of product per year).
2) Process scalability	The solution must be possible to scale up to commercial scale without facing overwhelming technical difficulties (e.g. in terms of a by-product which is impractical to handle). The technology should also be sufficient in small scale, to fit the flexibility of the fashion industry(see criteria 6).
3) Technical quality	The solution must deliver an output of a technical quality of interest for the fashion industry (similar or better quality compared to existing products, or some new quality feature of potential interest).
4) Economic potential	The cost of the solution in commercial scale must be attractive.
5) Environmental potential	The solution must have a potential to make a significant contribution in reducing the environmental impact of the fashion industry. This means that the solution must foremost contribute to solving some environmental issue of the current fashion industry (rather than addressing at first hand some environmental issue of another industry).
6) Flexibility	The time factor, the solution must be able to be adapted to the fast changes in the fashion industry. The solution must be sufficiently adaptable with regards to the demands of flexibility in the fashion industry.
7) Social sustainability	The solution must not have any negative impact on social sustainability[2].

2. see Zamani, B. (2016).

Table 2: Examples of possible effects on sustainability on different system levels from diferent actions (reworked from Sandén and Karlström (2007).

system level	example A) a retailer starts promoting long life garments	example B) a dyehouse changes to renewable fuel	example C) a dyehouse uses less amounts of Chemical X
0 order: direct physical effects	no effect	no effect	e.g. less emission to water of Chemical X.
1st order: linear systemic response (technical or physical mechanism)	no effect	e.g. less emissions of greenhouse gases of fossil origin.	e.g. organisms in the water are not exposed to hazardous levels of Chemical X.
2nd order: systemic response governed by negative feedback (economic mechanisms)	e.g. market demand for long life garments is maintained or increased on the margin.	e.g. market demand for renewable fuels is increased on the margin, and for fossil fuels decreased.	e.g. market demand for hazardous chemicals is decreased on the margin.
3rd order: systemic response governed by positive feedback (socio-technical mechanisms)	e.g. normative influence which affects future costs and have implications for future technology choice and thus future environmental impact.	e.g. investment in renewable energy which changes physical structures such as manufacturing equipment and physical infrastructure.	e.g. acceptance of stricter chemicals' regulation is increased.

summary

Today, the two most commonly used textile fiber types are cotton and polyester. Conventional cotton fibers need to be replaced since pesticide use and irrigation during the cultivation contributes to toxicity and water stress. Polyester is a synthetic fiber that is questioned due to its (mostly) fossil resource origin and the release of microplastics.

The selection of sustainable textile fibers is a current challenge for the fashion industry. There is a multitude of fibers on the market that are claimed to be "new sustainable fibers". However, to reduce the environmental burden caused by production of conventional fibers, it is necessary that the alternatives 1) have a superior environmental performance, and 2) have the technical feasibility to substitute conventional fibers.

The first question is addressed in the sister report, 'the fiber bibel, part 2' by Sandin et al. (2018) where it is stated that from an environmental perspective, both conventional and "new sustainable textile fibers" can - under the right conditions - have the potential to be part of a sustainable fiber future. The present report addresses the question of which "new sustainable fibers" do have the technical potential to replace conventional fibers in practice.

The Part 2 report concludes that selecting the right fiber for the right application is key for optimising its environmental performance throughout its life cycle. To enable such selection, the present report is structured to provide a "library" of new/upcoming /promising textile fibers and their technical as well as chemical properties compared with the conventional fibers that they are supposed to substitute: cotton and polyester. To have recycled, recyclable, biobased, biodegradable, paperbased, compostable and conventional fibers evaluated based on the same parameters is essential for system level decision making.

The selection of fibers to evaluate reflects the aim of this report, to inform the fashion industry about potential of so called "new sustainable fibers". Together with the industry, criteria were developed to guarantee that the included fibers have a certain level of commercial attractiveness and sustainability potential. Some examples of brand names of included fibers are: Econyl®, EVO®, Orange Fiber, Q-Nova®, Repreve®.

The selection of technical properties to evaluate also reflects the aim of this report, to find which fiber types can be used for bulk production of materials for the fashion industry today or in the near future. Thus, the fiber types have been evaluated against the existing technical requirements on fibers that will be used for woven or knitted material. Examples of technical properties are: tenacity, elongation at break, titre and dyeability. These and other technical properties are explained in the Methods chapter.

The results show that there are no fibers neither on the market today nor developed in lab scale for research projects that have the technical feasibility to match the properties of conventional cotton – if the comfort and technical properties of cotton are required. The closest match is found in cotton fibers grown as organic or within the Better Cotton Initiative. However, if the requirements on comfort and/or technical properties can be modified, there are several fibers that can be substitutes to cotton.

Historically, the development of synthetic and regenerated fibers has to a large extent been driven by the high price and uncertainties in the supply of cotton. There are already many companies that have replaced cotton with wood-based regenerated fibers such as viscose or lyocell, and sometimes also polyester can substitute cotton.

The cotton substitution issue can be discussed in two separate topics: development of fibers that behave exactly the same way as cotton (substituting cotton by a drop-in solution, or technical substitution), and selection of fibers that can be used in the same applications as cotton (substituting the market for cotton, or market substitution).

Regarding polyester substitutes (and fossil-based synthetic fibers in general) the results show that there are many substitutes that match the comfort and technical properties of conventional polyester fibers. Chemically recycled synthetic fibers perform on an equal level to virgin fibers and several of the bio-based synthetic fibers can add even more desired properties, for example in terms of elasticity. Here the main challenge is to develop a sustainable production path to substitute the 71 million tonnes yearly produced synthetic fibers that are today fossil-based. Further, the microplastics issue is not solved by changing the raw material entering the synthetic fibers. Similarly to cotton, a market substitution could be proposed, where bio-based fibers substitutes synthetic fibers.
This will be possible for several applications, though in many cases the requirements on strength and water repellence of synthetics cannot be matched.

The polyester substitution issue can also be divided into technical and market substitution. Technical substitution is possible for the raw material aspect, while for the microplastics aspect, market substitution is needed.

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1. introduction

The yearly global fiber production for textiles and non-woven amounts to 101.4 million tonnes, or 14 kg per capita and year (The Fiber Year 2017). The global fiber industry saw an increase in production during 2016 with 3.2%, mainly due to the strong increase in cotton production.

The selection of sustainable textile fibers is a current challenge for the fashion industry as the production of the two most common textile fiber types used - cotton and polyester – are environmental "hotspots"[3] in a life cycle perspective (Roos et al. 2015). Cotton cultivation contributes to toxicity and water stress due to its pesticide use and irrigation, and synthetic fibers are questionable due to their (mostly) fossil resource origin and the release of microplastics.

There is a range of different so called "new sustainable fibers" on the market: recycled fibers, biodegradable fibers, bio-based fibers, fibers made of waste from other industries etc. Words such as ecofriendly, sustainable, green and so forth are used wide and often. It can be difficult to get relevant data about for which applications these sustainable fibers can be used. Which conventional fibers (cotton and/or polyester) will be substituted and how does the technical performance of the garment change in a life cycle perspective?

This report provides information about the fibers that are marketed today as "new sustainable fibers", and they will be compared to the conventional fibers that they are supposed to substitute: cotton and polyester. Also included are some fibers that are upcoming, which means they have not necessary been developed for bulk production, for which both annual production volumes (if any) and cost are unknown factors. Some of the fibers will be mentioned by trade name where this is relevant.

1.1 aims

The present report aims at providing a "library" of new/upcoming/promising textile fibers and their technical as well as chemical properties. To have recycled, bio-based, paper-based, compostable and conventional fibers evaluated based on the same parameters is essential for system level decision making. Selecting the right fiber for the right application is key for analysing and optimising its environmental performance throughout its life cycle.

In addition, we want to clarify the similarities and the differences between conventional and alternative fibers: recycled, recyclable, bio-based, paper-based, compostable or other terms that are used to describe fibers with sustainability claims.

3 "Hotspots" is a common term for aspects with potential for major environmental impact.

1.2 fiber introduction

The report sorts fibers into four groups (the same as in Part 2 (Sandin et al. 2019)): synthetic fibers such as polyester and elastane, natural plant fibers such as cotton and flax (the fabric is known as linen), natural fibers using raw material derived from the animal kingdom (animal fibers, to simplify) such as wool and silk, and regenerated fibers using natural polymers, for example viscose and lyocell.

Figure 1 gives on overview of the four fiber groups and raw materials groups from which they are derived. Noteworthy is that a certain fiber type most often can be produced from different raw materials. For example, synthetics are most often produced from crude oil (a fossil resource) but can also be produced from plants (e.g. corn or sugar cane) or waste (e.g. discarded PET bottles). Another example is regenerated fibers, such as viscose, which can be produced from wood (e.g. birch or eucalyptus), grass (e.g. bamboo) or waste (e.g. discarded textiles) – one producer even adds a small percentage of algae in the production of regenerated fibers (not shown in the below figure). The fibers presented in this report are listed in appendix 1 together with raw material sources and uses. The data in appendix 1 is collected from several sources (for example Textile Exchange 2016; SST 2018). Specific technical properties data per fiber type are found in the Results chapter. A list of terminology and abbreviations used in this report is found in Appendix 2.

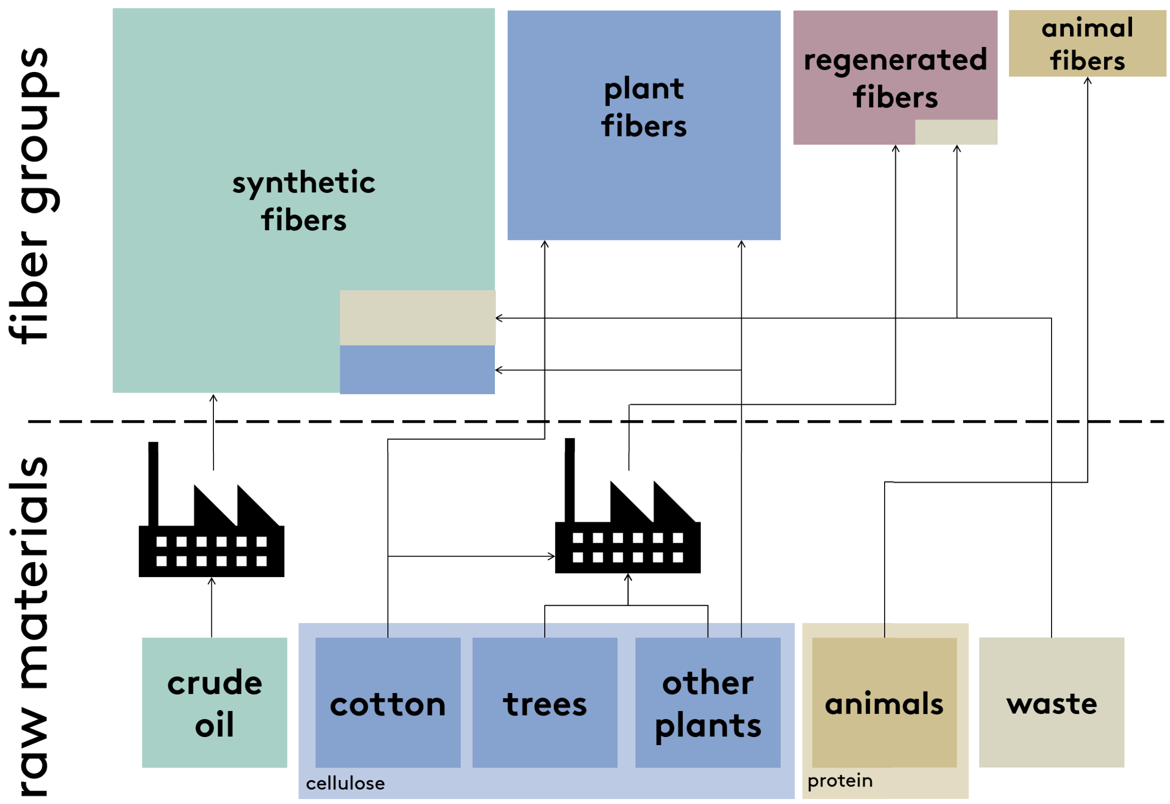


Figure 1 Overview of the four fiber groups and the groups of raw materials from which they are derived. The sizes of the fiber group boxes indicate their relative market shares but are not directly proportional to the market shares. (Sandin et al. 2019)

1.3 recommended use of report

The report can, for example, be used (i) as a basis for screening fiber alternatives, for example by designers and buyers (e.g. in public procurement), and (ii) as a basis for developing technical and comfort requirement on fabrics, considering what can be expected depending on fiber type.

1.4 the role of the study within Mistra Future Fashion

This report was done within Mistra Future Fashion, a cross-disciplinary research programme on sustainable fashion aiming for a systemic change of the fashion industry. The programme is structured into four themes, focussing on design, supply chains, users and recycling. The present report belongs to the supply chain theme and feed into subsequent deliverables, read more at www.mistrafuturefashion.com.

1.5 limitations

The report includes publicly available data on the technical and comfort properties of textile fibers, thus information on yarn or fabrics is not within the scope. Publicly and (for the authors) freely available data is included, which means that confidential data and is excluded. Only data available in the English language is considered which also constitutes a limitation.

'the aim of this report is to find which fiber types can be used for bulk production of materials for the fashion industry today or in the near future.

thus, the fiber types have been evaluated against the existing technical requirements on fibers that will be used for woven or knitted material.'

2. method

This chapter presents how the selection of fiber types and properties to evaluate was made and the methods with which the evaluation was made.

The fiber types have been treated separately, even though so called "mono-materials", i.e. materials that consist of one single fiber type are rare on the market. Today, in most textile materials, a mixture of fiber is used to provide all the desired properties of quality and comfort, which are only possible to achieve by a combination of fiber types. However, the combination of fiber is based on each fiber type's intrinsic properties, described below.

2.1 selection of fibers to evaluate

There is a plethora of fiber types and fiber brand names connected to sustainability claims. To identify which fibers to evaluate in this report, criteria were developed to guarantee that the included fibers have a certain level of commercial attractiveness and sustainability potential. Such fibers could otherwise "disappear in the crowd" in a report that would also consider fibers whose commercial future is still too uncertain or whose sustainability credentials are obviously doubtful. On the other hand, it is important to bring light on fibers which are marketed as "sustainable" especially in the cases where there is little evidence available to support such claims. The report includes thus both fibers with sustainability potential and fibers with sustainability claims.

In the sister report (Sandin et al. 2019), the criteria for feasibility and sustainability for fibers to be used in textile applications are presented. These are based on the work of Johannesson (2016) where criteria for "sustainable emerging textile production technologies" were developed. These were later refined in a Mistra Future Fashion stakeholder workshop together with the textile industry in September 2017. The criteria are feedstock availability, process scalability, technical quality, economic potential and environmental potential, see Table 1.

The criteria were originally thought to be used to narrow down the list of fibers to consider. However, the work led instead to three main conclusions (Sandin et al. 2019):

1. Data is most often lacking for new potentially sustainable fibers – producers andbrands are (understandable) restrictive in disclosing data until large commercial scalehas been realised, and data is scarce even when such scale has been achieved.

2. There is no reason to restrict ourselves to "new" fibers – established fibers produced in new and better ways, or traditional fibers long undervalued, may be the sustainability winners of tomorrow.

3. There are great variations within each fiber type – e.g. viscose produced with nearly closed chemical loops and renewable energy can be among the best alternatives, while viscose produced with poor or lacking chemical management and coal power can be among the worst.

The result of the mapping is shown in Appendix 3.

2.2 selection of technical properties to evaluate

Chapter 1.2 of this report gives an introduction to the large variety of textile fibers available on the market. To decide which application(s) each type of fiber is suitable for, the fiber's properties such as strength, thickness and water uptake is evaluated. For information on the environmental performance of textile fibers, please see part 2 of this report:

- Sandin, Roos, Johansson. Environmental impact of textile fibers – what we know and what we don't know. Fiber Bible part 2. Mistra Future Fashion report 2019:03, Stockholm, Sweden.

The evaluation of technical properties focuses the feasibility for each fiber type to be used for bulk production of materials for the fashion industry today or in the near future. The fiber types will thus be evaluated against the existing technical requirements on fibers that will be used for woven or knitted material. It should be noted that the way that fashion items are produced in the future may look different from today. In the future, it might be that the materials for the fashion industry need no longer to be woven, dyed at high temperatures or washable (which in turn puts demands on fiber strength, flexibility and so forth). However, it is the bulk production of materials for the fashion industry today that causes the heavy environmental burden, and it is these materials for which it is necessary to find substitutes.

Fiber properties such as tenacity, elongation at break, titre, dyeability, cross section, modulus, knot tenacity, loop tenacity, pilling behaviour and fibrillation can be determined to decide which applications a fiber can be constructed for. Furthermore, for the use phase properties such as UV and heat stability, wicking, moisture absorption, crimp and drape can be important. Finally, for end-of-life options, compostability and biodegradability are often measured. The technical requirements that are set today on textile fibers for the fashion industry are listed in Table 3. They are collected from several sources (Röder et al. 2009; Röder et al. 2013; SST 2018).

In the evaluation of technical properties, it should be noted that for a certain fiber type, such as cotton, the properties vary between different producers and locations. These variations make fibers more or less suitable and exchangeable for a certain application and are accounted for when this information is available. It should also be noted that most fibers can be produced with much higher technical performance in the bench / lab scale or at pilot scale compared to industrial scale / bulk production (Röder et al. 2013). When available, figures for all three scales are therefore given to exemplify what performance is needed at bench scale in order to get reasonably high quality at industrial scale.

There are also several ways to modify the properties of fiber, such as addition of biocides to achieve anti-smell properties or super-wash treatment of wool to prevent felting. Such treatments and modifications are also accounted for when this information is available.

Table 3. Technical requirements on textile fibers for the fashion industry.

criteria	unit	explanation
Technical properties		
Acid resistance	-	Excellent, Good, Average, Bad
Alkali resistance	-	Excellent, Good, Average, Bad
Chemical structure	-	Protein, cellulose, polyolefin, polyester, polyamide, polyurethane.
Crimp	% No/25mm	Degree of crimp is measured in %. No of crimps is measured in No/25 mm (1 inch).
Cross section	-	Circular, irregular, outer cuticle layers, optional.
Crystallinity	%	Degree of polymer chain orientation.
Density	g/cm3	Specific mass
Dyeability	-	Excellent, Good, Average, Bad
Elongation	%	Elongation at break, also called extensibility (measured after conditioning the fibers).
Elongation wet	%	Elongation at break of fibers that have maximum uptake of water/moisture.
Fiber length	mm	Length of staple fiber.
Fibrillation	-	Suitability for yarns with high hairiness (High – Low)
Heat endurance	-	Sensitivity to heat. Fibers sensitive to heat needs gentle care, cannot be ironed etc. Heat sensitivity can be an advantage if for example heat setting of creases is desired. (Excellent, Good, Average, Bad)
Tenacity	cN/tex	Dry strength (measured after conditioning the fibers).
Tenacity wet	cN/tex	Wet strength. Strength needed for example for household washing.
Titre	dtex	The fiber thickness (g/10 000 m)
Young's modulus	cN/tex/%	Elastic modulus, the linear slope of stress (tenacity) versus strain (elongation). A higher elastic modulus means a higher resistance of the fiber against deformation (high stiffness)
UV resistance	-	Sensitivity to UV light, some fibers are easily degraded in sunlight. (Excellent, Good, Average, Bad)
Water repellence		Materials capacity to repel water drops.

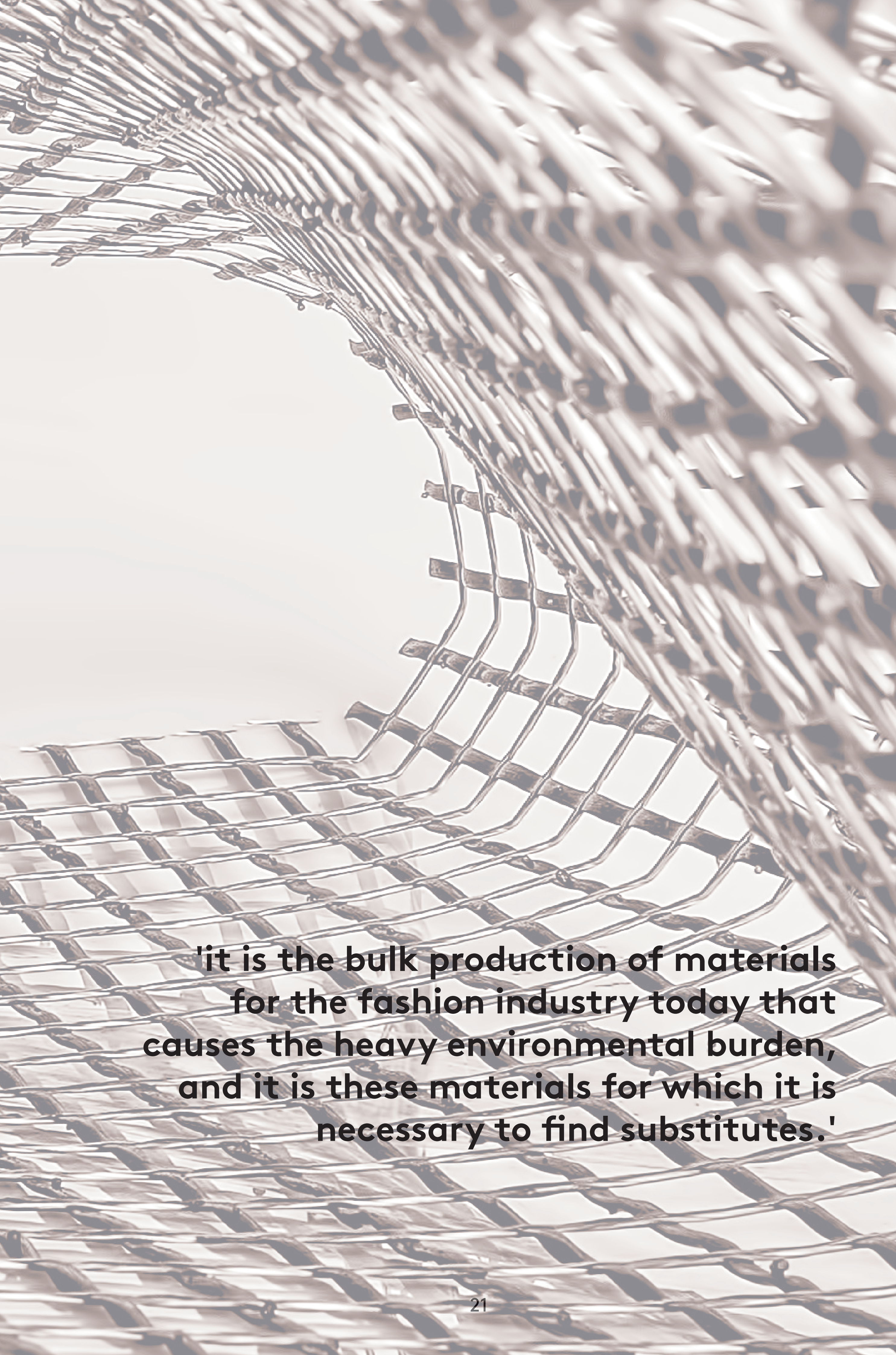
Criteria	unit	explanation
Comfort properties		
Drapability	%	Measured as a drape coefficient. Materials with high drapability are soft and give a graceful fold.
Hand	-	Silky, cotton-like, coarse, dry, soft, cool.
Moisture regain	%	Fiber with good moisture absorption will have good smell properties.
Wicking		The ability to transport perspiration trough the material.
Regenerated cellulose specific properties		
Morphology		The physical form and structure of a fiber.
Degree of polymerization		The number of monomeric units in a polymer.
Molecular weight distribution	-	Distribution of the molar mass.
Degree of orientation	%	Alignment of fibrillar elements relative to the fiber axis.
Knitwear specific properties		
Loop strength	%	Testing fibers tenacity in a loop procedure
Knot strength	%	Testing fiber tenacity in a knot procedure
Synthetic fibers specific properties		
Creep resistance		Fibers ability to maintain shape during constant load or constant position.
Woven specific properties		
Twist ability		Woven yarns often needs higher number of twist in the yarn to get a high production capacity
End-of-life properties		
Biodegradable		Biodegradable according to the European Norm EN 13432. (days)
Compostable		Compostable according to the European Norm EN 13432. (Yes or No)
Recyclability	-	The possibility for the material to be recycled into either new garments or other products. (Mechanically recyclable, Chemically recyclable.)

2.3 literature search

After deciding which fibers and which technical properties to include in the study, a literature search was performed. The literature search was based on the Mistra Future Fashion phase one study by Rex (2015). Rex evaluated possible sustainable alternative to cotton, including a screening on the market for biobased fibers and reporting on properties of existing and emerging potential sustainable fibers.

The current report has a wider scope in that it is no longer limited to only cotton alternatives but "new sustainable fibers" from a generic perspective. Thus, the report is complemented with a market screening for synthetic and protein fibers, and the literature search is updated.

For conventional fibers, a lot of information has been retrieved from text books and similar older sources. For the newer and emerging fibers, data has been retrieved from the scientific literature when possible. It can be noted that for several of the fibers on the market which claim to be "new sustainable fibers", no scientific or third-party verified data about the performance is available. It is noted in the result section what type of source(s) that the data comes from.



'it is the bulk production of materials for the fashion industry today that causes the heavy environmental burden, and it is these materials for which it is necessary to find substitutes.'

3 results

This chapter provides an overview of available textile fibers in four subsections, one for each fiber group: animal fibers, plant fibers, regenerated fibers and synthetic fibers, Each fiber type is briefly introduced along with the “new sustainable alternatives” and data on their technical performance.

It should be noted that some fiber types are marketed for a specific content of an additive but consist mainly of for example regenerated cellulose fibers. Such fiber types are sorted after the bulk fiber since the European fiber labelling regulation (EU) No 1007/2011 demands that textile articles are classified and labelled according to their main fiber content (European Commission 2011).

3.1 animal fibers

The global annual production of natural fiber from animals amounts to around 1.4 million tonnes, see Figure 2. Virgin wool fiber dominates in this fiber type, followed by silk, other animal hair (cashmere, angora etc.) and recycled wool. Silk fibers respective wool and hair are presented in two separate subchapters below.

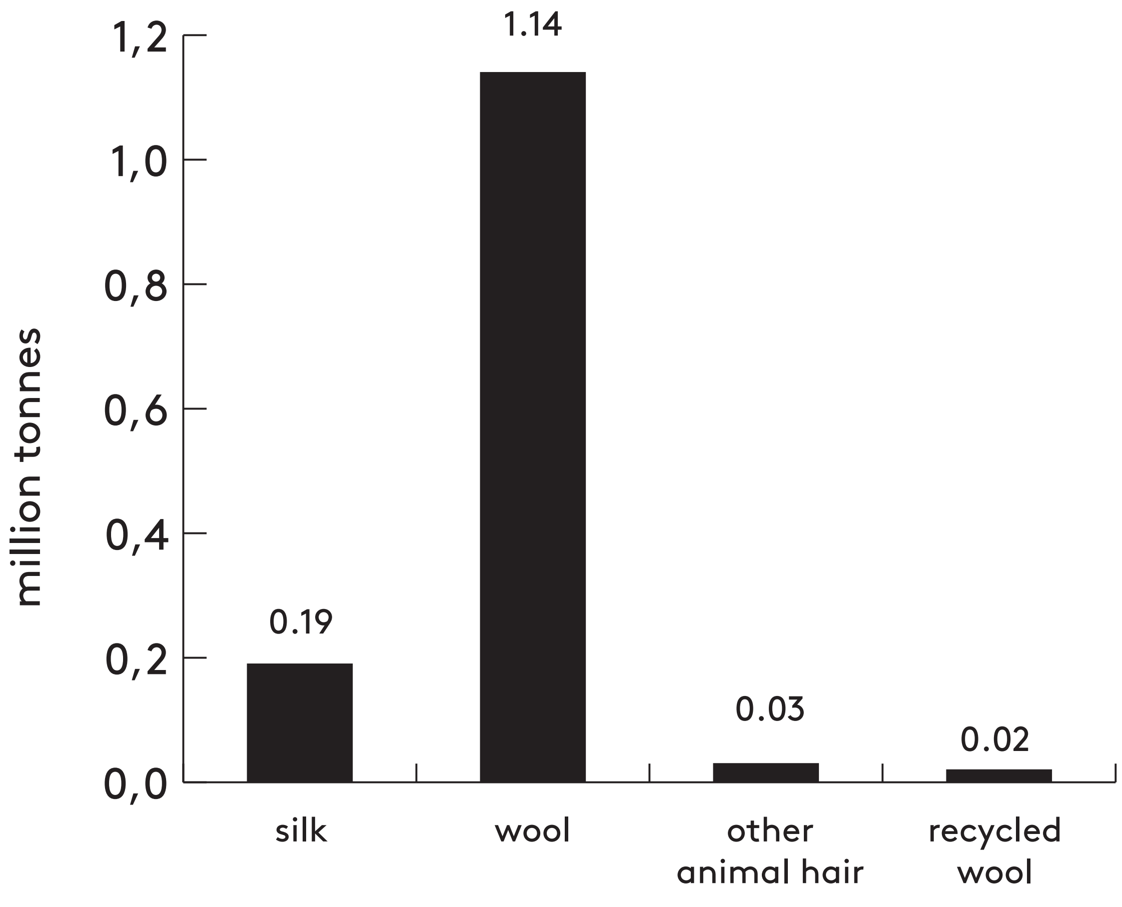
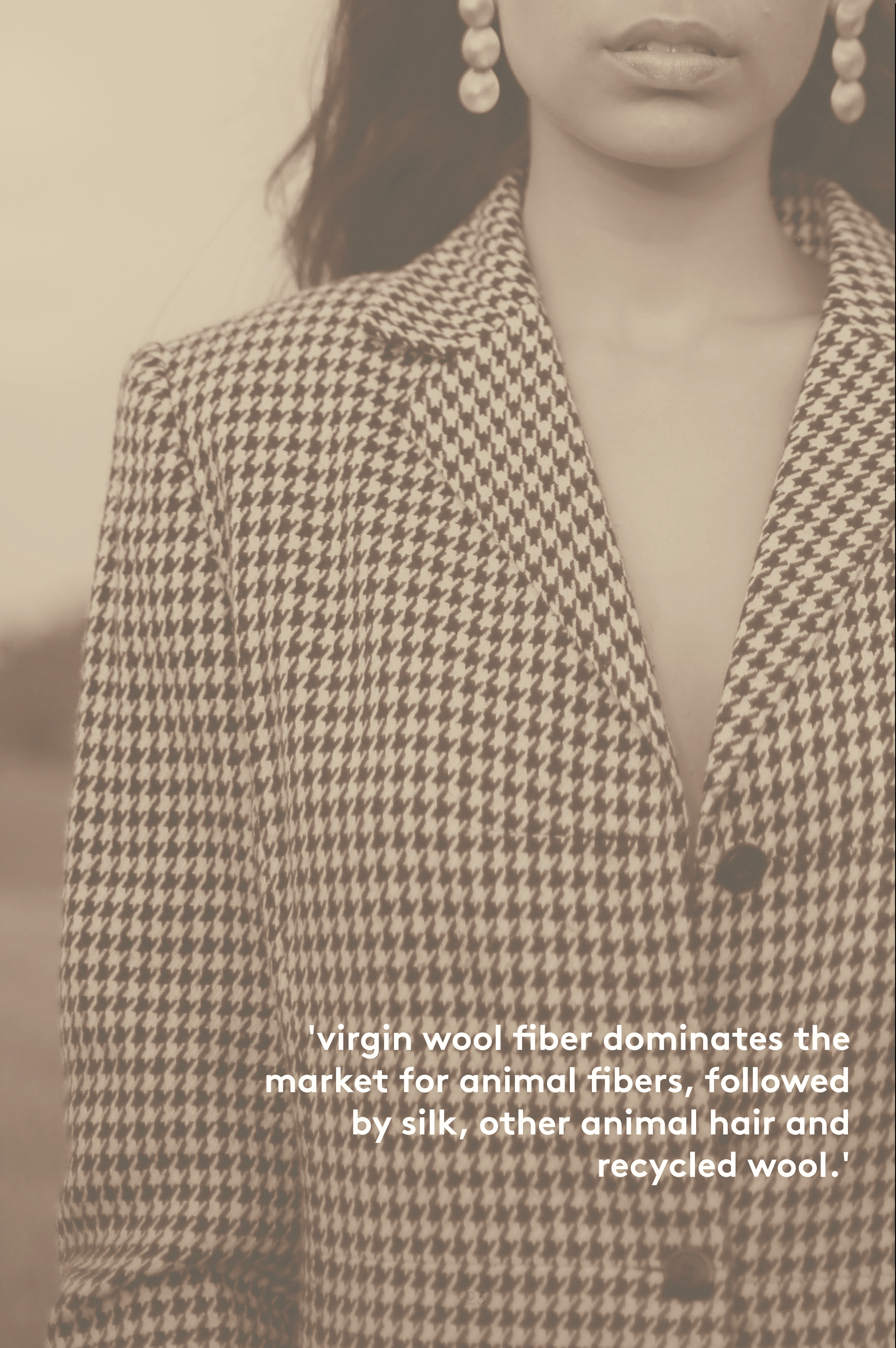


Figure 2. Annual production volume of animal fibers, silk and wool data from 2016 (International Sericultural Commission 2018; The Fiber Year 2017), other animal hair data from 2009 (FAO 2009), recycled wool data current (Cardato 2018).



'virgin wool fiber dominates the market for animal fibers, followed by silk, other animal hair and recycled wool.'

3.1.1 silk fibers

Silk fibers are produced by the larva of certain insects, especially the mulberry silkworm when constructing their cocoons, and harvested by reeling and throwing. There is both wild and commercial produced silk. Silk is an expensive fiber per kg but is lightweight, elastic and strong compared to other protein fibers and can be used for garments with long life length, if treated properly. The type of yarn twisting decides the texture of the fabric: crepe, crepe de chine etc. (Advameg Inc. 2018). Certified organic silk is available.

Table 4. Silk fiber techno-economic data.

criteria for comparison	unit	value
General information		
Fiber classification, (EU) No 1007/2011	-	Silk
Raw materials	-	Silk filaments from insects f
Global annual production	Million tonnes	0.2 d
Estimated cost for 1 kg fiber	$ (USD)	20-80 e
Technical properties		
Acid resistance	-	Excellent a
Alkali resistance	-	Good a
Chemical structure	-	Protein
Crimp	%	unknown
Cross section	-	Circular
Density	g/cm3	1.34-1.38 a
Dyeability	-	Good
Elongation	%	14-35.6 % a,c
Elongation wet	%	unknown
Fiber length	mm	Filament
Fibrillation		unknown
Heat endurance	-	Good (stable when temperature ≤148°C) a
Initial modulus	kg/mm2	650-1250 a
Tenacity	cN/tex	2.6-3.5 a
Tenacity wet	cN/tex	1.9-2.5 a
Titre	dtex	1.1 dtex b
Young's modulus	cN/tex/%	unknown

criteria for comparison	unit	value
UV resistance	-	Bad a
Water repellence		unknown
Comfort properties		
Drapability	%	10 c
Hand	-	Cool and silky
Moisture regain	%	11.0 a
Wicking	-	unknown
Knitwear specific properties		
Loop strength	%	60-80 a
Knot strength	%	80-85 a
Bending elastic modulus		1.47 a
End-of-life properties		
Biodegradable	-	unknown
Compostable	-	unknown
Recyclability	-	unknown

a(Swicofil 2018a), b(Warner 1995), c(Malay et al. 2016), d(International Sericultural Commission 2018), e(International Trade Centre 1999), f(Advameg Inc. 2018)

3.1.2 wool and hair

Many animals are bred for their hair which is a protein fiber that can be sheared and used for textiles. The term wool is generally used for the hair of sheep while other animal hair is usually specified after which animal it is gained from. Wool has high strength, absorbs odours and can be used for garments with long life length, if treated properly. Wool fibers have a tendency to felt (shrink), and often "super-wash" is applied in the production. In the super-wash treatment the fiber is then either etched with chlorine (less common today due to the high environmental impact) or coated with acrylic or polyamide coating to prevent felting. Without super-wash the garment must be washed in wool wash by the consumer.

Recycled wool is reported separately as it is mechanically recycled (sorted, cleaned and cut down to fiber) and renders fibers that are shorter compared to new wool. The strength and pilling performance is therefore reduced. Recycled wool comes from mainly two sources: old garments (post-consumer waste) or left-over and spillage from the production (pre-consumer waste). The pre-consumer waste wool can be spun to new yarn and used for garments. Thompson et al. (2012) describes how recovered acrylic/wool blended garments are recycled into a thermal insulation layer for emergency blankets and IWTO (2014) how post-consumer woollen clothing is converted to for a diversity of industrial uses, including mattress, furniture and automotive components. Woollen fabrics are in both cases shredded and then turned into non-woven.

Table 5.wool and hairfiber techno-economic data.

criteria for comparison	unit	explanation
General information		
Fiber classification, (EU) No 1007/2011	-	1) wool (for fiber from sheep's or lambs' fleeces) 2) alpaca, llama, camel, cashmere, mohair, angora, vicuna, yak, guanaco, cashgora, beaver, otter, followed or not by the word 'wool' or 'hair'
Raw materials	-	Animal hair
Global annual production	Million tonnes	Wool: 1-2 b Other animal hair: 0.032 c Other animal hair: 0.032 c
Estimated cost for 1 kg fiber	$ (USD)	Finer wool (18.5-22 micron): 10-15 b Coarser wool: 3-8 b
Technical properties		
Acid resistance	-	Excellent a
Alkali resistance	-	Bad a
Chemical structure	-	Protein
Crimp	%	unknown
Cross section	-	Outer cuticle layers
Density	g/cm3	1.33 a
Dyeability	-	Good
Elongation	%	25-35 a
Elongation wet	%	unknown
Fiber length	mm	Longer wools: 50-350 (weaving) e Shorter wools: 35-50 e
Fibrillation		unknown
Heat endurance	-	Good a
Initial modulus	kg/mm2	unknown
Tenacity	cN/tex	0.9-1.6 a
Tenacity wet	cN/tex	0.7-1.3 a
Titre	dtex	2.2-38 f
Young's modulus	cN/tex/%	10-22 a
UV resistance	-	Bad a
Water repellence	-	

criteria for comparison	unit	explanation
Comfort properties		
Drapability	%	10 c
Hand	-	High loft
Cashmere etc: soft		
Wool: coarse		
Moisture regain	%	15 a
Wicking	-	unknown
Knitwear specific properties		
Loop strength	%	unknown
Knot strength	%	unknown
End-of-life properties		
Biodegradable	-	Yes (no data on EN 14046) b
Compostable	-	unknown

a (Swicofil 2018b), b (The Fiber Year 2017), c (FAO 2009), d (Cardato 2018), e (Encyclopaedia Brittanica 2018), f (Houck 2009)

' Wool fibers have a tendency to shrink, therefore "super-wash" is often applied in the production. In the super-wash treatment the fiber is either etched with chlorine or coated with acrylic or polyamide coating to prevent felting.'

3.2 plant fibers

In this report we define plant fibers as all fibers that are grown from a plant and used in their natural fiber shape, as bast (stem) fibers. All plant fibers are based on cellulose which has been created in the nature by the photosynthesis. Many natural fibers (hemp, jute etc.) are used both as bast fibers and as chemically regenerated fibers. This chapter excludes plant fibers that have been modified by chemical processing, these are instead found in chapter 3.3 with regenerated fibers.

Cotton is the most dominating plant fiber and is also the fiber that has been most intensely studied in environmental assessment. For a better overview, cotton data has been placed in a table of its own in 3.2.1 and data for bast fibers from hemp, jute, kenaf, kapok and flax are presented separately in 3.2.2.

3.2.1 cotton fibers

Cotton is the most used natural fiber for textiles and one of the oldest fibers under human cultivation; there are traces of cotton cultivation going back as far as 7,000 years (PAN UK 2016). There are further different cotton species but Gossypium hirsutum is today the dominating one. Cotton fibers are combed after harvesting to remove the seeds, the so called ginning process. Conventionally grown cotton fibers are often questioned for the intensive use of pesticides and irrigation during the cultivation, and more sustainable options are requested such as organic cotton (About Organic Cotton 2018), Better Cotton Initiative (BCI 2018) and Cotton made in Africa (CmiA 2018). As CmiA is sometimes sold as BCI cotton, CmiA is not included in Figure 3.

While organic cotton cultivation restricts the use of pesticides, irrigation and GMO-modified crops (Ferrigno et al. 2009), BCI cotton implies that the cotton is grown with less harmful pesticides and more efficient irrigation (BCI 2014). The more damage the cotton suffers due to damage from insects, the larger the short fiber content (SFC).

Short fiber content or SFC is a measure of the number of fibers below 12.7 mm (0.5 inches) in length (Thibodeaux et al. 2008). Cui et al. (2003) reported a study of thirtysix upland cottons grown on experimental plots in Mississippi. The short fiber content ranged from 6.5 to 13.9% in these conventional cotton fibers. A similar number for organic or BCI cotton has not been possible to find.

Cotton can be mechanically recycled via cutting and shredding waste cotton fabrics back into fibers. These fibers are however shorter than virgin cotton and cannot be used to produced yarns of the same quality as from virgin cotton. A mixture can be made with other fibers to increase the strength, as in for example the Recover fiber (Nomadix 2018).

'conventionally grown cotton fibers are often questioned for the intensive use of pesticides and irrigation during the cultivation, and more sustainable options are requested.'

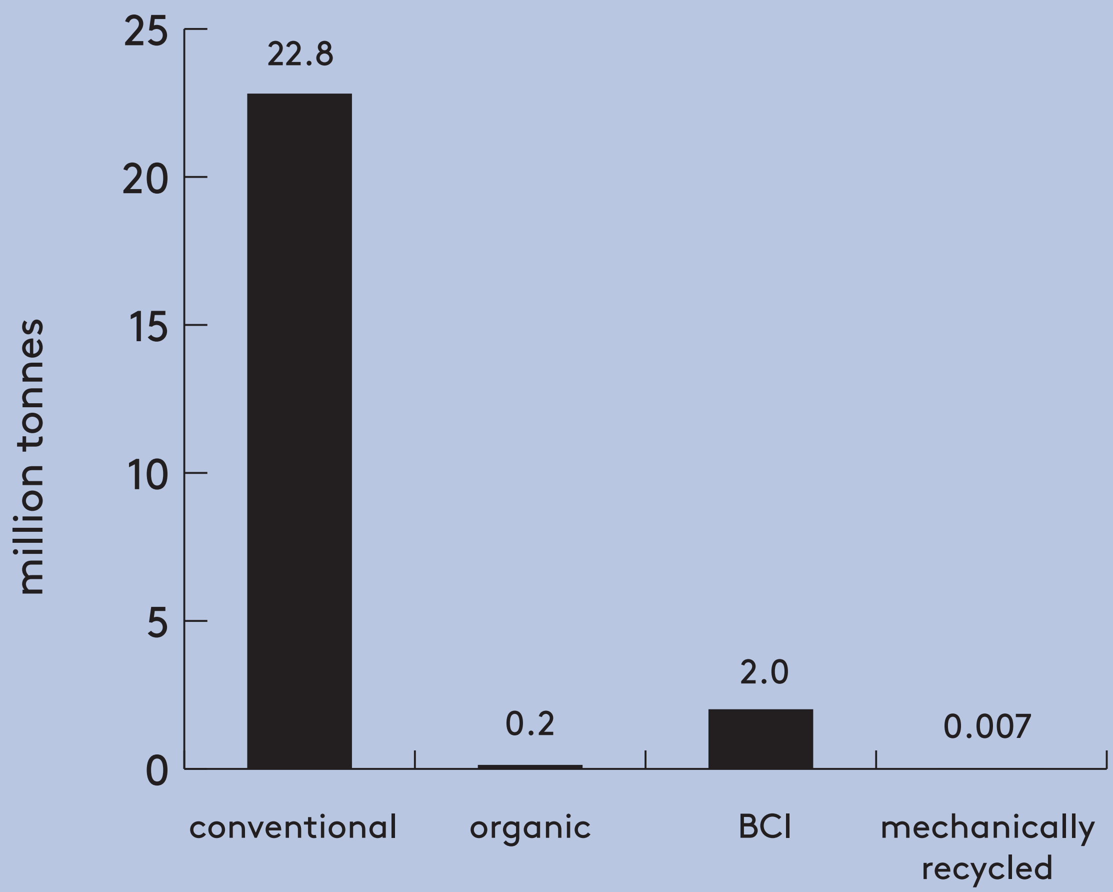


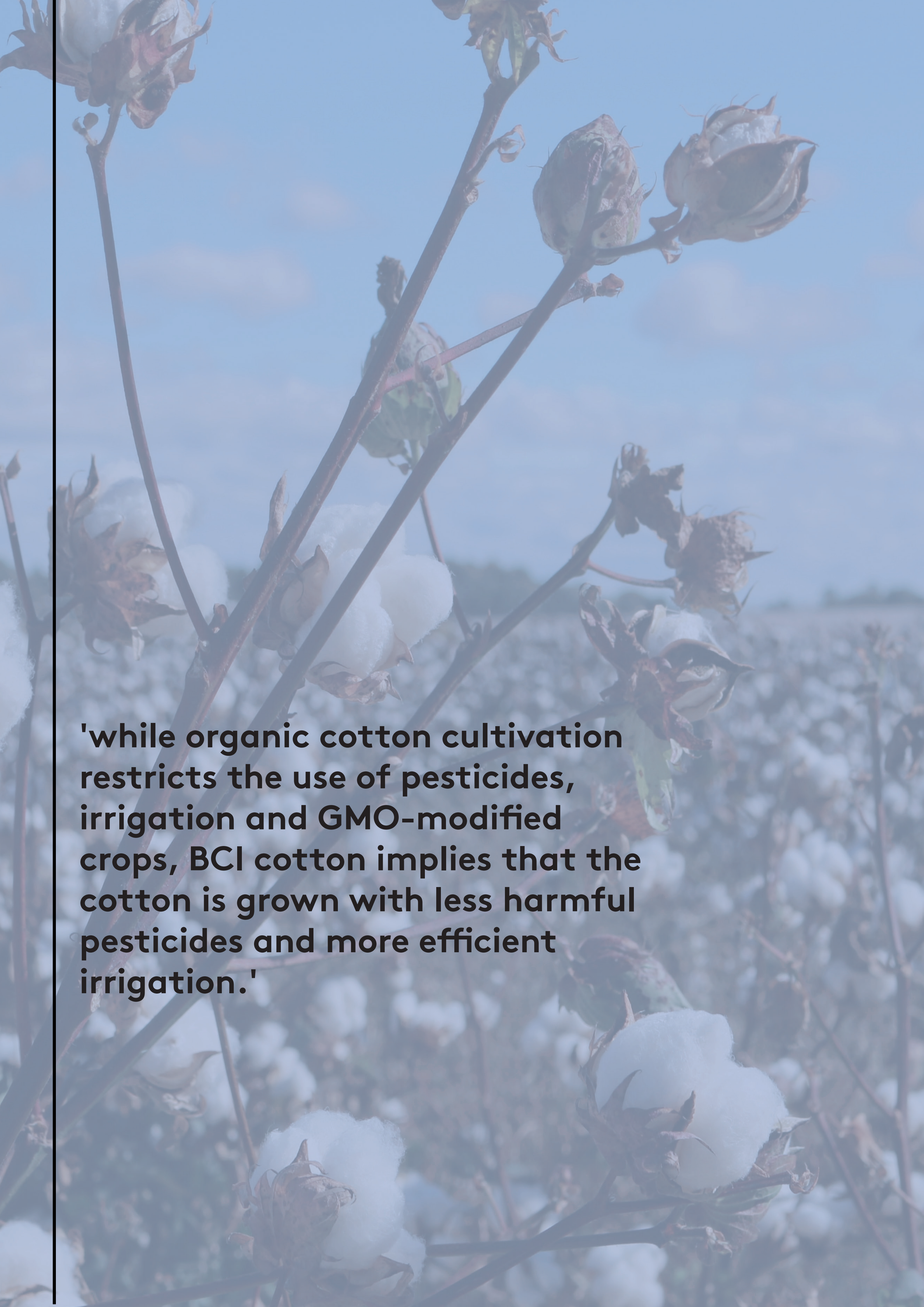
Figure 3 Annual production volume of cotton fibers. Data from conventional cotton fibers from 2016 (The Fiber Year 2017), data for organic and BCI from 2013/2014 (PAN UK 2016).

Table 6. Cotton fiber techno-economic data.

criteria for comparison	unit	explanation
General information		
Fiber classification, (EU) No 1007/2011	-	Cotton
Raw materials	-	Cotton
Global annual production	Million tonnes	Conventional cotton: 22.8 f BCI cotton: 2.0 g Organic cotton: 0.12 g Mechanically recycled cotton: >0.007 h
Estimated cost for 1 kg fiber	$ (USD)	1-4
Technical properties		
Acid resistance	-	Bad a
Alkali resistance	-	Excellent a
Chemical structure	-	Cellulose
Crimp	%	unknown

criteria for comparison	unit	explanation
Cross section	-	Irregular
Crystallinity	%	54 e
Density	g/cm3	1.46-1.52 a
Dyeability	-	Good
Elongation	%	7-10 a
Elongation wet	%	unknown
Fiber length	mm	Conventional: 12.7-40 b, i BCI: unknown Organic: unknown
Fiber length - Short fiber content	%	BCI: unknown Conventional:6.5-13.9 i Organic: unknown
Fibrillation		unknown
Heat endurance	-	Excellent (Becoming brown after long time processing at 150°C) a
Initial modulus	kg/mm2	unknown
Tenacity	cN/tex	1.9-3.1 a
Tenacity wet	cN/tex	2.2-3.1 a
Titre	dtex	1.1-3.3 b
Young's modulus	cN/tex/%	60-82 a
UV resistance	-	Average a
Water repellence	-	
Comfort properties		
Drapability	%	16 d
Hand	-	Cotton-like
Moisture regain	%	8.5 a
Wicking	-	unknown
Knitwear specific properties		
Loop strength	%	unknown
Knot strength	%	unknown
End-of-life properties		
Biodegradable	-	unknown
Compostable	-	unknown
Recyclability	-	Chemically and mechanically recyclable.

a (Swicofil 2018b), b(Lawrence 2003), c(Houck 2009), d(Swicofil 2018a), e(Hatakeyama & Hatakeyama 2006), f(The Fiber Year 2017), g(PAN UK 2016), h(Textile Exchange 2016b), i(Thibodeaux et al. 2008)



'while organic cotton cultivation restricts the use of pesticides, irrigation and GMO-modified crops, BCI cotton implies that the cotton is grown with less harmful pesticides and more efficient irrigation.'

3.2.2 plant fibers other than cotton

There is a great variety of plant fibers on the market. Jute is the dominating fiber type which is almost exclusively cultivated in Bangladesh and India (The Fiber Year 2017). Coir fiber are collected from the coconut plant and is the second largest plant fiber globally. Flax production occurs to a large extent in France and Belgium.

When these types of fibers are used as bast fibers, the fibers are extracted from the stem of the plant and subdued to retting.

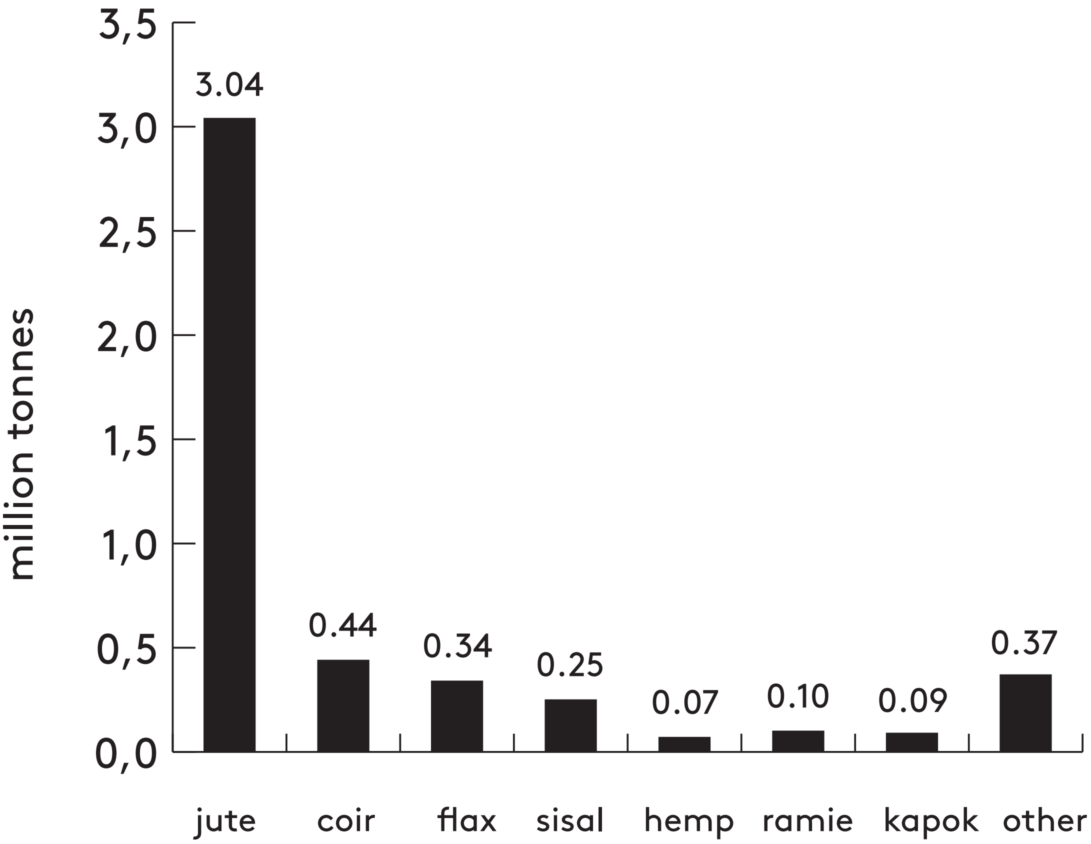


Figure 4. Annual production volume of plant fibers other than cotton. Jute, coir, flax, sisal figures from 2016 (The Fiber Year 2017). Hemp, ramie and kapok figures from 2015 (Fact Fish 2018).

Table 7. Plant fiber techno-economic data.

criteria for comparison	unit	explanation
General information		
Fiber classification, (EU) No 1007/2011	-	1) kapok, 2) flax (or linen), 3) true hemp, 4) coir, 5) ramie, or 6) sisal. (not all fibers are listed here)
Raw materials	-	hemp, jute, kenaf, kapok, flax etc.
Global annual production	Million tonnes	Jute: 3.04 c, Coir: 0.44 c, Flax: 0.34 c, Sisal: 0.25 c, Sisal: 0.25 c, Ramie: 0.1 e
Estimated cost for 1 kg fiber	$ (USD)	unknown
Technical properties		
Acid resistance	-	unknown
Alkali resistance	-	unknown
Chemical structure	-	Cellulose
Crimp	%	unknown
Cross section	-	Irregular
Crystallinity	%	Hemp: 69 b, Jute: 36 b
Density	g/cm3	unknown
Dyeability	-	Hemp: low a
Elongation	%	Flax:1.6-3.3, a Hemp: 1-6 a, Jute: 2-8.2 a
Elongation wet	%	unknown
Fiber length	mm	Flax: 15-60 a, Hemp: 120-300 a, Jute: 150-360 a
Fibrillation		unknown
Heat endurance	-	unknown
Initial modulus	kg/mm2	unknown
Tenacity	cN/tex	Flax: 4.1-5.5 a ,Hemp: 3.5-7 a, Jute: 3-3.4 a
Tenacity wet	cN/tex	unknown
Titre	dtex	Flax: 1.7-3.3 a, Hemp: 2-6 a, Jute: 2-3 a
Young's modulus	cN/tex/%	Hemp: low a
UV resistance	-	unknown
Water repellence	-	
Comfort properties		
Drapability	%	10 c

criteria for comparison	unit	explanation
Hand	-	silky
Moisture regain	%	15 a
Wicking	-	unknown
Knitwear specific properties		
Loop strength	%	unknown
Knot strength	%	unknown
End-of-life properties		
Biodegradable	-	unknown
Compostable	-	unknown
Recyclability	-	Chemically and mechanically recyclable.

a(Nawab 2016), b(Hatakeyama & Hatakeyama 2006), c(The Fiber Year 2017), e(Fact Fish 2018)

3.3 regenerated fibers

Regenerated fibers can be divided into regenerated cellulose fiber (viscose, lyocell, acetate) which today has a considerable market share of around 6% (Röder et al. 2013) and regenerated protein fibers which are produced only in small amounts per year, see Figure 5. These two fiber types are presented in two separate subchapters below.

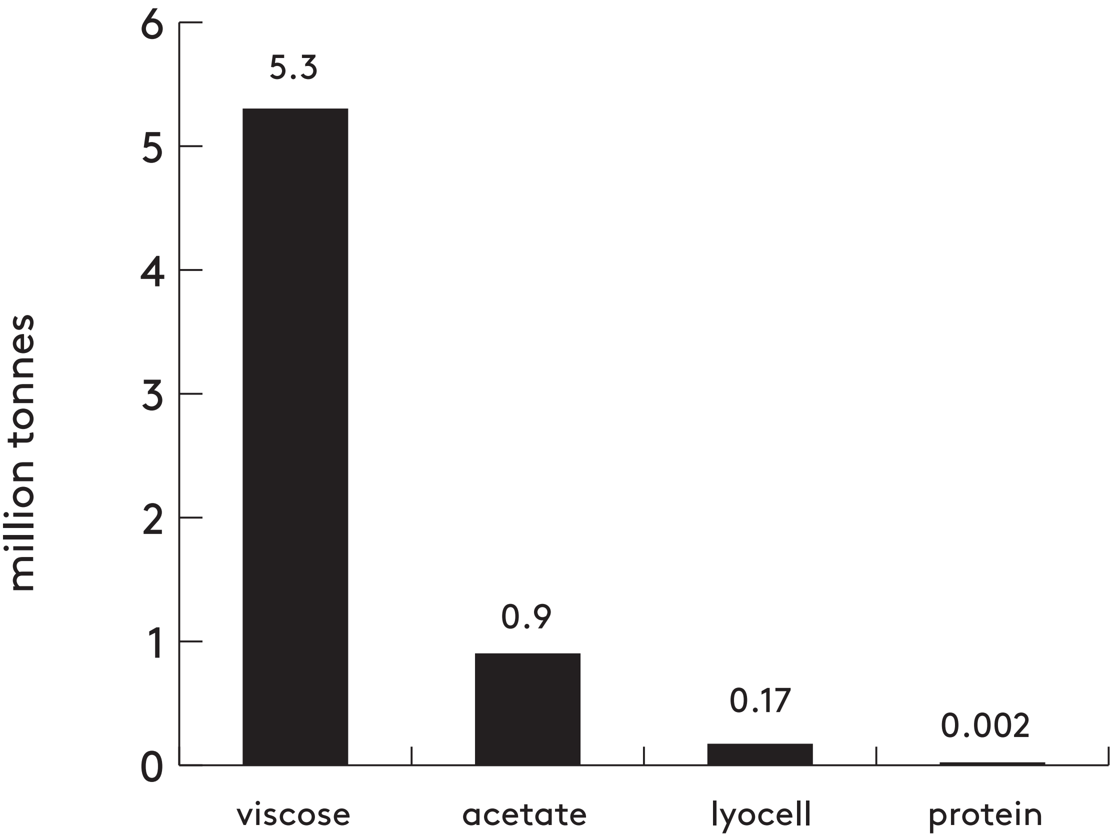


Figure 5. Annual production volume of regenerated fibers. References: (Rijavec & Zupin 2011; The Fiber Year 2017; Textile Exchange 2016b).

'regenerated cellulose fibers are often claimed to be a sustainable alternative to cotton. Since the chemical structure is based on cellulose just as in cotton, there are many similarities in the comfort properties.'

3.3.1 regenerated cellulose fibers

The history of regenerated cellulose fiber started in 1846 (Röder et al. 2009). For several years the term "man-made fibers" dominated, though this term has the last years been less used for the benefit of the more neutral word "regenerated". Regenerated cellulose fibers are often claimed to be a sustainable alternative to cotton. Since the chemical structure is based on cellulose just as in cotton, there are many similarities in the comfort properties. Cellulose fibers (cotton or regenerated) are for example negatively charged and will therefore not create static electricity as synthetic and protein fibers do.

Theoretically, regenerated fibers could be made from any source of cellulose of sufficient concentration and quality, though the most common source is softwood, hardwood, bamboo, cotton, flax and hemp (The Fiber Year 2017). The cellulose sources for the regenerated fibers included in this chapter are:

- Citrus peel
- Waste cotton fibers
- Wood (bamboo, beech, eucalyptus, spruce etc.)

Below is found a short description of included fibers under their brand names when relevant. There are many more regenerated cellulose fiber types not described here: cupro, ioncell modal etc., and also more brand names, for example Ioncell-F (Aalto University 2018) and Monocel® (Monocel 2018).

Acetate and triacetate

Acetate is a cellulose acetate fiber wherein less than 92% but at least 74% of the hydroxyl groups are acetylated according to the European fiber labelling regulation (European Commission 2011). If more than 92% of the hydroxyl groups are acetylated, the fiber is instead called triacetate. Acetate and triacetate fibers are very sensitive to solvents and often dry cleaning is advised against.

Evrnu fiber

Evrnu converts cotton garment waste into new regenerated fibers (Evrnu 2018). The cotton garments are stripped from dyes and other contaminants, before pulping the cotton, breaking it down to its constituent cellulose molecules. The pulp is then directly extruded into fibers (Björquist 2017).

Lyocell

The lyocell fiber is manufactured by Lenzing AG (Lenzing AG 2018c). TencelTM is a brand name for the fiber with the generic name lyocell and entered the consumer market already in 1991. The lyocell fiber is a regenerated cellulose based fiber dissolved in the solvent NMMO and spun to lyocell filaments (Shen & Patel 2010). Most of the Lenzing AG patents on TencelTM expired in 2006 and today there are also other manufactures of this type of fiber.

Orange Fiber

This fiber is a regenerated cellulose fiber from the waste of the citrus industry in Italy (ORANGE FIBER 2018). The ORANGE FIBER company started 2011 and year 2013/2014 they received patent on the product. The fiber has won several sustainability awards. Since the fiber is quite new there is still lack of information regarding this fiber. For example there is no available information about production volumes, colour fastness, durability, washability etc.

RefibraTM

This fiber is a lyocell fiber from 20% industrial cotton textile waste and 80% virgin wood pulp produced by Lenzing AG (Lenzing AG 2018a). Lyocell is a regenerated cellulose based fiber dissolved in the solvent NMMO and spun to lyocell filaments, further described above.

SeaCell®

The SeaCell® fiber is manufactured by smartfiberAG (smartfiber AG 2018). SeaCell fibers are marketed for a specific content of a seaweed additive but consist mainly of regenerated cellulose fibers and classified as regenerated cellulose fibers by the European fiber labelling regulation (EU) No 1007/2011 (European Commission 2011). There are also other manufactures of this type of fiber.

Viscose

Viscose (rayon) is a commodity fiber that has been manufactured by several manufacturers around the world since the beginning of the 20th century (The Fiber Year 2017; Röder et al. 2009). Viscose is a regenerated cellulose based fiber. Carbon disulphide is added to the solution of cellulose pulp in sodium hydroxide to produce cellulose xanthate which is wet spun in a sulphuric acid bath to viscose filaments.

Table 8. Regenerated cellulose fiber techno-economic data. Sources: (Advameg Inc. 2018; Hatch 2006; Malay et al. 2016)

criteria for comparison	unit	explanation
General information		
Fiber classification, (EU) No 1007/2011	-	1) viscose, or 2) lyocel
Raw materials	-	Various cellulose sources
Global annual production	Million tonnes	Total: 6.0 c, Lyocell (Tencel): 0.050-0.172 f,
Estimated cost for 1 tonne yarn	$ (USD)	Evrnu fiber: unknown, Lyocell: unknown, Orange Fiber: unknown, RefibraTM: unknown, SeaCell®: unknown, Viscose: 1.5-4.0 c, Other fibers: unknown
Technical properties		
Acid resistance	-	Excellent (viscose) a
Alkali resistance	-	Bad (viscose) a
Chemical structure	-	Cellulose
Crimp	%	unknown
Cross section	-	Circular
Crystallinity	%	
Density	g/cm3	1.46-1.52 (viscose) a
Dyeability	-	Good
Elongation	%	Evrnu fiber: unknown, Lyocell: 13 d, Orange Fiber: unknown, RefibraTM:, SeaCell®: unknown, Viscose:18-24 a, SeaCell®: unknown
Elongation wet	%	Lyocell: 13 d, Other fibers: unknown
Fiber length	mm	15-98 d Normally cut to 38 mm
Fibrillation		Unknown
Heat endurance	-	Good (viscose) (Strength down after long time processing at 150°C) a
Initial modulus	kg/mm2	850-1150 (viscose) a
Tenacity	cN/tex	Evrnu fiber: unknown, Lyocell: 3.7 d, Orange Fiber: unknown, RefibraTM:, SeaCell®: unknown, Viscose: 1.5-2.0 a
Tenacity wet	cN/tex	Evrnu fiber: unknown, Lyocell: 3.0 d, Orange Fiber: unknown, RefibraTM:, SeaCell®: unknown, Viscose: 0.7-1.1 a

criteria for comparison	unit	explanation
Titre	dtex	Evrnu fiber: unknown, Lyocell: 0.9-6.7 d, Orange Fiber: unknown, RefibraTM:, SeaCell®: unknown, Viscose:
Young's modulus	cN/tex/%	Evrnu fiber: unknown, Lyocell: 10 d, Orange Fiber: unknown, RefibraTM:, SeaCell®: unknown, Viscose:
UV resistance	-	Bad (viscose) a
Water repellence	-	Bad
Comfort properties		
Drapability	%	
Hand	-	Cool and silky
Moisture regain	%	13 (viscose) a
Wicking	-	unknown
Knitwear specific properties		
Loop strength	%	Viscose: 30-65 a, SeaCell®: good b, Other fibers: unknown,
Knot strength	%	Viscose: 45-60 a, SeaCell®: good b, Other fibers: unknown
End-of-life properties		
Biodegradable	-	Lyocell: 55 days (EN 14046) e, Viscose: 45 days (EN 14046) e, Other fibers: unknown
Compostable	-	unknown
Recyclability	-	unknown

a (Swicofil 2018b), b(Rex 2015), c(The Fiber Year 2017), d(Lenzing AG 2018c), e(Lenzing AG 2018b), f(Textile Exchange 2016b)

3.3.2 regenerated protein fibers

The regenerated protein fiber history dates back to the First World War. Milk fiber was patented in the early 1930's and soon after, Henry Ford introduced soy fabrics to the market. But just as many other fibers, they were replaced by less expensive synthetic fibers like nylon after World War II. The regenerated protein fibers have different physical and chemical construction from natural protein fibers such as silk and wool.

Azlon is the generic name for a regenerated protein fiber where the fiber-forming substance can be derived from various naturally occurring proteins such as milk (casein), eggs (albumin), corn and soy (zein), chicken feathers (keratin), or leather and hide waste (collagen). Soy Protein Fiber (SPF) is made from protein distilled from the soybean cake and refined followed by a wet spinning process to produce this fiber (Fiber2Fashion 2018). Milk fiber is a blend of casein protein and the chemical acrylonitrile, which is also used to make acrylic fibers. Milk fibers are manufactured using a process that is similar to viscose (Swicofil 2018a).

Table 9. Regenerated protein fiber techno-economic data.

criteria for comparison	unit	explanation
General information		
Fiber classification, (EU) No 1007/2011	-	protein
Raw materials	-	Various protein sources
Global annual production	Million tonnes	SPF: unknown, Milk fiber: unknown
Estimated cost for 1 tonne yarn	$ (USD)	SPF: unknown, Milk fiber: unknown,
Technical properties		
Acid resistance	-	Excellent (SPF) a
Alkali resistance	-	Average (SPF) a
Chemical structure	-	Protein
Crimp	No/25 mm	SPF ≤ 7 a
Cross section	-	Milk fiber: Irregular
Crystallinity	%	
Density	g/cm3	1.29 (SPF) a
Dyeability	-	Good (soybean poor)
Elongation	%	SPF: 18-21 a, Milk fiber: 25-35 b
Elongation wet	%	SPF: unknown, Milk fiber: 28.8 b
Fiber length	mm	Normally cut to 38 mm b
Fibrillation		unknown
Heat endurance	-	Bad (SPF), (Yellowing and tackifing at about 120°C) a

criteria for comparison	unit	explanation
Initial modulus	kg/mm2	700-1300 (SPF) a
Tenacity	cN/tex	SPF: 3.8-4.0 a, Milk fiber: 2.5-3.5 b
Tenacity wet	cN/tex	SPF: 2.5-3.0 a, Milk fiber: 2.4 b
Titre	dtex	Milk fiber: 0.8-3.0 b
Young's modulus	cN/tex/%	Unknown
UV resistance	-	Good (SPF) a
Water repellence	-	
Comfort properties		
Drapability	%	SPF: unknown, Milk fiber: 8 b
Hand	-	Cool and silky
Moisture regain	%	SPF: 8.6 a, Milk fiber: 5-8 b
Wicking	-	Unknown
Knitwear specific properties		
Loop strength	%	SPF: 75-85 a
Knot strength	%	SPF: 85 a
Bending elastic modulus		Milk fiber: 0.33 b
End-of-life properties		
Biodegradable	-	unknown
Compostable	-	unknown
Recyclability	-	unknown

a (Swicofil 2018b), b (Swicofil 2018a)

'the regenerated protein fiber history dates back to the First World War. Milk fiber was patented in the early 1930's and soon after, Henry Ford introduced soy fabrics to the market.'

3.4 synthetic fibers

Around 65 million tonnes of synthetic fibers are produced annually (The Fiber Year 2017). Polyester stands for 82% and dominates the textile market, followed by polyamide (nylon), polypropylene and acrylics as can be seen in Figure 6. Synthetic fibers are known for their strength and often mixed with other fibers to increase abrasion resistance (SST 2018).

Synthetic fibers can be made from fossil, recycled and biobased sources. Most of the recycle and biobased fibers are so called “drop-in” solutions, to replace existing conventional synthetic fibers, for example polyester, polyamide and acrylics. These fibers have properties very similar to the conventional fibers and data are reported per fiber type.

The biobased part of the global polymer production is still very low, around 1%. However, the annual consumption growth rates for biobased polymers are around 20% (Ravenstjin 2017). Some synthetic fibers are also biodegradable, which is not related to whether the fiber is based on fossil or biobased resources, as Figure 6 explains. Both bio-based and biodegradable fibers are however often marketed as sustainable alternatives to conventional synthetic fibers.

Synthetic fibers have recently also been questioned due to their release of microplastics into the biosphere and reported uptake in animals and humans. The microplastics issue, which is a problem for both fossil and bio-based synthetic fiber, has been previously investigated in the Mistra Future Fashion programme by Roos et al. (2017) and Jönsson et al. (2018).

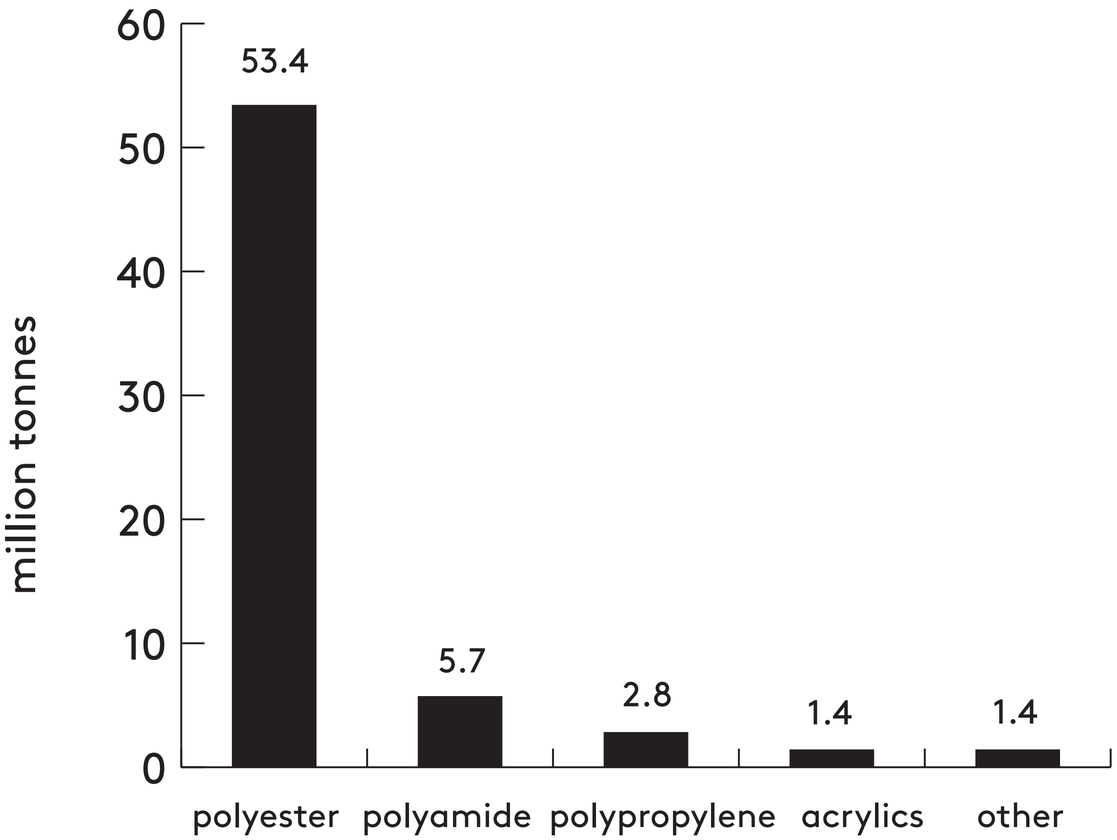


Figure 6. Annual production volume of synthetic fibers (The Fiber Year 2017).

'the biobased part of the global polymer production is still very low, around 1%. However, the annual consumption growth rates for biobased polymers are around 20%.'

3.4.1 polyester fibers

There are several types of polyester fibers with the common denominator being the ester bridge: polyethylene terephthalate (PET), polytrimethyl terephthalate (PTT) and polylactic acid (PLA). Below is found a short description of included fibers under their brand names when relevant.

PET

The major part of the textile polyester fibers is amorphous polyethylene terephthalate (PET). Fully crystalline PET is opaque and stiff while amorphous or partly crystalline PET is transparent. The different qualities dull, semi-dull and bright are achieved by adding for example titanium dioxide in order to make the fibers less transparent. PET fibers can be texturized by the Taslan process and receive a hand similar to cotton.

PLA

Polylactic acid (PLA) has been known since 1845 but only recently, PLA with sufficient high molecular weight to be processable as a plastic has been able to be produced (Ravenstjin 2017). The monomer lactic acid can be obtained via fermentation of corn starch. PLA is sold under different brand names, for example Ingeo (Nature Works LLC 2018).

Polylana®

Polylana® is a patent pending staple fiber composed of a proprietary blend of modified polyester pellets, and rPET flakes. It is marketed as a sustainable alternative fiber to acrylics, since it is based on polyester but has the same properties as polyacrylics (The Movement B.V 2018).

rPET

Polyester can be recycled both mechanically and chemically and is then often termed rPET. Mechanical recycling means that the material is melted and then spun to fiber. Chemical recycling means that the polymers are broken down to their building blocks, the monomers, after which they are used to produce a new polymer. Chemical recycled PET has superior technical properties to mechanically recycled PET. There are several brands for rPET, for example Repreve®, EcoCircle and ECOPET (Textile Exchange 2016b).

Sorona®

Sorona® is a polytrimethyl terephthalate (PTT). This is a biopolymer that contains 37% renewable plant-based ingredients. The bio-based ingredient, Bio-PDO™ (bio-based 1,3 propanediol), is made through a fermentation process that uses glucose as the feedstock, mainly from corn (DuPont 2014).

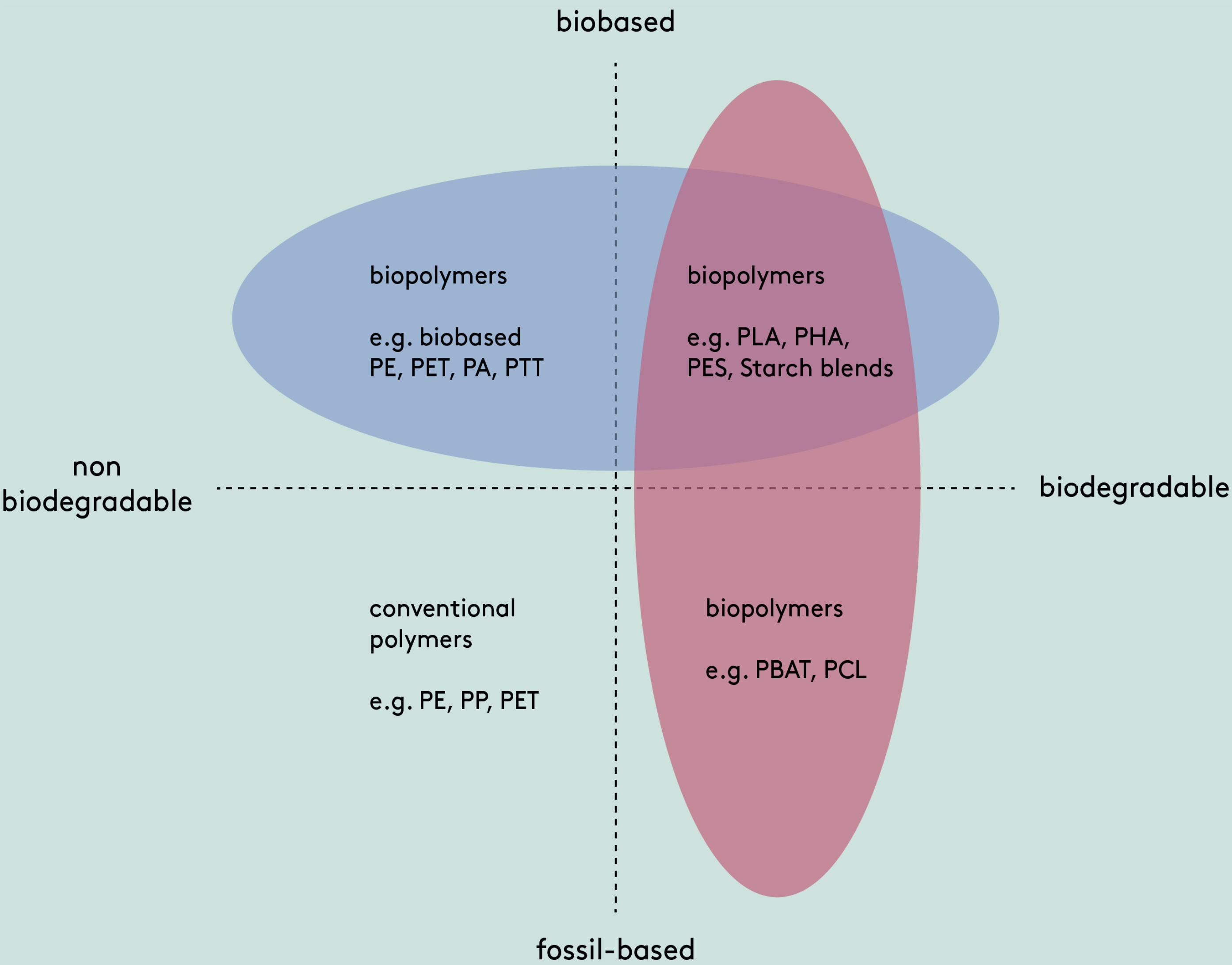


Figure 7. Bio-based content and biodegradability of synthetic fibers (Figure from European Bioplastics 2018).

Table 10. Polyester fiber techno-economic data.

criteria for comparison	unit	value
General information		
Fiber classification, (EU) No 1007/2011	-	Polyester
Raw materials	-	Fossil, recycled or bio-based.
Global annual production	Million tonnes	PLA: 0.2 c Ingeo: 0.015 g PET: 53.4 d rPET: unknown Sorona: unknown
Estimated cost for 1 tonne yarn	$ (USD)	PLA: unknown PET: 0.75-2.0 d rPET: unknown Sorona: unknown

criteria for comparison	unit	value
Technical properties		
Acid resistance	-	unknown
Alkali resistance	-	unknown
Chemical structure	-	polyester
Crimp – number of crimp	No/25 mm	PLA: Good b Ingeo: 30-35 per 10 cm e Sorona ≤ 15.6 a
Crimp – percentage	%	Sorona: 12.8 a
Cross section	-	Circular
Crystallinity	%	unknown
Density	g/cm3	PLA: 1.25 b
Dyeability	-	PET: 1.50-1.54 f Good
Elongation	%	PLA: 55 b
Ingeo: 50-60 e		
PET: 20-50 f		
Sorona: 81.9 a		
Elongation wet	%	unknown
Fiber length	mm	Normally cut to 38 mm a
Fibrillation		unknown
Heat endurance	-	PLA: Excellent (processing temp. ~ 240°C b) Sorona: Good (Dry heat shrinkage at 180°C=6%) a
Initial modulus	kg/ mm2	unknown
Tenacity	cN/tex	PLA: 3.2-3.6 b Ingeo: 3-3.5 e PET: 4.1-5.7 f Sorona: 3.1 a
Tenacity wet	cN/tex	unknown
Titre	dtex	Ingeo: 1.5 e Sorona: 1.5 a

criteria for comparison	unit	value
Young's modulus	cN/ tex/%	PET: 22-62 f Other fibers: unknown
UV resistance	-	PLA: Good b
Water repellence	-	
Comfort properties		
Drapability	%	
Hand	-	Polylana: high loft, wool-like
Moisture regain	%	PLA: 0.4-0.6 b Ingeo: 0.4-0.6 e PET: 0.4-0.5 f Sorona: 0.48 a
Wicking	-	PLA: Excellent b
Knitwear specific properties		
Loop strength	%	unknown
Knot strength	%	unknown
Bending elastic modulus		unknown
End-of-life properties		
Biodegradable	-	PLA: 40 days (EN 14046) b
Compostable	-	PLA: Yes (no data on EN 13432) b
Recyclability	-	PLA: Chemically recyclable b

a(Tenbro 2018),b(Farrington et al. 2005), c(Smith 2005), d(The Fiber Year 2017), e(Nature Works LLC 2018), f(Teijin 2018), g(Textile Exchange 2016b)

3.4.2 polyamide fibers

Polyamide fibers are also known under the brand name Nylon. There are several types of polyamide fibers with the common denominator being the nitrogen bond: PA6, PA66, PA 10,10. Polyamide fibers can be air texturized by the Taslan process, and receive a hand similar to cotton (Fulgar SpA 2018c).

Below is found a short description of included fibers under their brand names when relevant. There are several other brands for recycled nylon, for example Repreve® Nylon, Nilit® Eco Care and Mipan Regen (Textile Exchange 2016b).

Econyl®

Econyl® is a chemically recycled PA6 fiber manufactured by Aquafil. At least 50% of the content is recycled post-consumer waste (mainly carpets and fishing nets) and the rest is pre-consumer waste (industry spillage). The PA6 is transformed back into monomers and separated through distillation and the new raw material holds comparable quality with virgin PA6 fibers (Aquafil 2014).

EVO®

EVO® is a 100% bio-based fiber (polyamide 10.10) manufactured as VESTAMID® Terra DS by Evonik (Evonik Industries AG 2018) and marketed as EVO® by Fulgar SpA (Fulgar SpA 2018a). EVO® has its origin in castor oil seeds (Fulgar SpA 2018a). Certified organic castor oil is available.

Q-Nova®

Q-Nova® is a 100% mechanically recycled fiber (polyamide 6.6) manufactured by Fulgar SpA (Fulgar SpA 2018b). It is made from post-industrial polyamide fiber waste.

S.Café®

The S.Café® fiber is manufactured by SINGTEX Industrial Co., Ltd (SINGTEX 2018). Two percent of the fabric is coffee grounds, the rest is nylon. It is promoted for its odour cotrol advantages.

Table 11. Polyamide fiber techno-economic data.

criteria for comparison	unit	value
General information		
Fiber classification, (EU) No 1007/2011	-	polyamide or nylon
Raw materials	-	Fossil, recycled or bio-based.
Global annual production	Million tonnes	PA6/PA66: 5.7 a Econyl: > 0.01 b EVO: Q-Nova: S.Café:
Estimated cost for 1 tonne yarn	$ (USD)	PA6/PA66: Econyl: EVO: Q-Nova: S.Café:
Technical properties		
Acid resistance	-	unknown
Alkali resistance	-	unknown
Chemical structure	-	Polyamide
Crimp	-	
Cross section	-	
Crystallinity	%	
Density	g/cm3	PA66: 1.14 c
Dyeability	-	Good
Elongation	%	Econyl: EVO: PA6: PA66: 25-60 c Q-Nova: S.Café:
Elongation wet	%	unknown
Fiber length	mm	Normally cut to 38 mm
Fibrillation		unknown
Heat endurance	-	
Initial modulus	kg/mm2	
Tenacity	cN/tex	PA66: 3.9-6.6 c

criteria for comparison	unit	value
Tenacity wet	cN/tex	
Titre	dtex	
Young's modulus	cN/tex/%	PA66: 8-26 c Other fibers: unknown
UV resistance	-	
Water repellence	-	
Comfort properties		
Drapability	%	unknown
Hand	-	
Moisture regain	%	PA66: 3.5-5.0 c
Wicking	-	unknown
Knitwear specific properties		
Loop strength	%	
Knot strength	%	
Bending elastic modulus		unknown
End-of-life properties		
Biodegradable	-	unknown
Compostable	-	unknown

a(Tenbro 2018),b(Farrington et al. 2005), c(Smith 2005), d(The Fiber Year 2017), e(Nature Works LLC 2018), f(-Teijin 2018), g(Textile Exchange 2016b)

3.4.3 other synthetic fibers

Polypropylene and acrylic fibers are the largest synthetic textile fiber types after polyester and polyamide. Elastane is not as large in terms of tonnes per year, but is added in more and more garments to provide stretch, and the production is increasing fast.

Acrylic fibers

Acrylic fibers are often found mixed with wool which it resembles. For a fiber to be classified as an acrylic fiber according to the European fiber labelling regulation (European Commission 2011)the fiber should comprise at least 85 % in the chain of the acrylonitrilic pattern (if between 50 % and 85% it should be named modacrylic). Common copolymers are vinyl acetate or methyl acrylate.

Acrylic fibers are dry spun (solvent spun) and the solvent type used (aprotic solvents) are often toxic. Polylana® is marketed as a sustainable alternative fiber to acrylics, since it is based on polyester but has the same properties as polyacrylics (see chapter 4.4.1).

Elastane

Elastane is commonly called by the trade names Spandex or Lycra and is an exceptionally elastic fiber (The Fiber Year 2017). Elastane has more and more replaced natural rubber in textile applications, since natural rubber in some cases causes allergic reactions. Elastane is extremely elastic; it can be extended to as long 8 times its original length (Senthilkumaran et al. 2011).

Elastane fibers are dry spun (solvent spun) and the solvent type used (aprotic solvents) are often toxic. There are few alternatives if the same elasticity as with elastane is required. Sorona is sometimes marketed as stretchable polyester (see chapter 4.4.1).

Polypropylene

Polypropylene (PP) fibers have the lowest specific gravity of all fibers; thus, yield the greatest fiber volume for a given weight. For example, the density of PP fibers is 40% lower than those of polyester (Polymerdatabase 2018). PP is commonly used in sports wear as it has excellent wicking properties that keeps the wearer with a dry feeling.

Table 12. Other synthetic fibers techno-economic data.

criteria for comparison	unit	value
General information		
Fiber classification, (EU) No 1007/2011	-	1) acrylic, 2) modacrylic, 3) elastane, or 4) polypropylene. (not all fibers are listed here)
Raw materials	-	Petroleum
Global annual production	Million tonnes	Acrylics: 1.4 d Elastane: 1.2 d PP: 2.8 d
Estimated cost for 1 tonne yarn	$ (USD)	unknown
Technical properties		
Acid resistance	-	Acrylics: Good c
Alkali resistance	-	Acrylics: Good c
Chemical structure	-	Acrylics: Acrylonitrili c
Crimp	-	unknown
Cross section	-	unknown
Crystallinity	%	unknown
Density	g/cm3	unknown
Dyeability	-	Acrylics: Good PP: Poor b
Elongation	%	Acrylic: 15-17 a Elastane: 400-800 e
Elongation wet	%	unknown
Fiber length	mm	Normally cut to 38 mm b
Fibrillation		unknown
Heat endurance	-	Acrylics: Average b
Initial modulus	kg/mm2	unknown
Tenacity	cN/tex	Acrylics: 4.15-4.59 a
Tenacity wet	cN/tex	unknown
Titre	dtex	

criteria for comparison	unit	value
Young's modulus	cN/tex/%	unknown
UV resistance	-	Acrylics: Excellent b
Water repellence	-	unknown
Comfort properties		
Drapability	%	Acrylics: Poor
Hand	-	Acrylics: Wool-like
Moisture regain	%	Acrylics: 1.5-2.5 c
Wicking	-	Acrylics: Excellent b PP: Excellent b
Knitwear specific properties		
Loop strength	%	unknown
Knot strength	%	unknown
Bending elastic modulus		unknown
End-of-life properties		
Biodegradable	-	unknown
Compostable	-	unknown
Recyclability	-	unknown

a(Tenbro 2018),b(Farrington et al. 2005), c(Smith 2005), d(The Fiber Year 2017), e(Nature Works LLC 2018), f(-Teijin 2018), g(Textile Exchange 2016b) 'the results show that there are no fibers neither on the market today nor developed in lab scale for research projects that have the technical feasibility to match the properties of conventional cotton.'

4. discussion

Firstly, it can be noted that for several of the fibers on the market which claim to be "new sustainable fibers", no scientific or third-party verified data about either the technical or the environmental performance is available. Furthermore, some fibers with claims of novelty are found to be "ordinary" fibers that contain 1-2% percent of seaweed or coffee ground, which does not change the sustainability profile. There is also a larger variation in the brand names than in fiber types.

4.1 no cotton substitute matches all cotton properties

The results show that there are no fibers neither on the market today nor developed in lab scale for research projects that have the technical feasibility to match the properties of conventional cotton, if the comfort and technical properties of cotton are required. The closest match is found in cotton fibers grown as organic or within the Better Cotton Initiative. However, if the requirements on comfort and/or technical properties can be modified, there are several fibers that can be substitutes to cotton. Historically, the development of synthetic and regenerated fibers has to a large extent been driven by the high price and uncertainties in the supply of cotton. There are already many companies that have replaced cotton with wood-based regenerated fibers such as viscose or lyocell, and sometimes also polyester can substitute cotton.

4.2 polyester substitutes available but scale is an issue

Regarding polyester substitutes (and fossil-based synthetic fibers in general) the results show that there are many substitutes that match the comfort and technical properties of conventional polyester fibers. Chemically recycled synthetic fibers perform on an equal level to virgin fibers and several of the biobased synthetic fibers can add even more desired properties, for example in terms of elasticity. Here the main challenge is to build up sustainable production routes to substitute the 71 million tonnes yearly produced synthetic fibers that are today fossil-based. Further, the microplastics issue is not solved by changing the raw material entering the synthetic fibers. Similarly to cotton, a market substitution could be proposed, where biobased fibers substitutes synthetic fibers. This will be possible for several applications, though in many cases the requirements on strength and water repellence of synthetics cannot be matched.

For the fashion industry it is important with scalability and flexibility as fashion is produced in large volumes and the products can vary a lot between seasons. For this reason, utilizing waste from other industries, such as citrus peel or waste fishing nets, as a raw material for the fashion industry implies a limitation in supply. However, it is most probable that the sustainable fashion future requires a diversity in fibers (Sandin et al. 2019) and small-scale fiber types, such as alpaca or camel hair, can have their role to play.

4.3 fiber content is only a fraction of the resource consumption in a life cycle perspective

The final use of the fiber in different types of garments and the possibilities for reuse and recycling at end-of-life will decide the sustainability performance. In the complementary report (Sandin et al. 2019) is shown how on a garment level, a doubled life span decreases the climate impact by half. Thus, the fiber quality should neither be over-dimensioned nor under-dimensioned. Selecting the right fiber for the right application is key for optimising its environmental performance throughout its life cycle.

When considering alternatives for fossil-polyester, it is important to remember that in the life cycle perspective, fossil resources are used not only as a material resource but also as an energy resource. In Part 2, chapter 5.3, is illustrated that the fiber production is only a minor part of the total environmental impact from the garment life cycle. Figure 9 below show the consumption of fossil resources for a polyester dress over the life cycle expressed in kg oil-equivalents per kg garment. By removing the fossil fiber content, only a fraction of the total fossil resource use is addressed and the t-shirt is by no means "fossil-free" in a life cycle perspective.

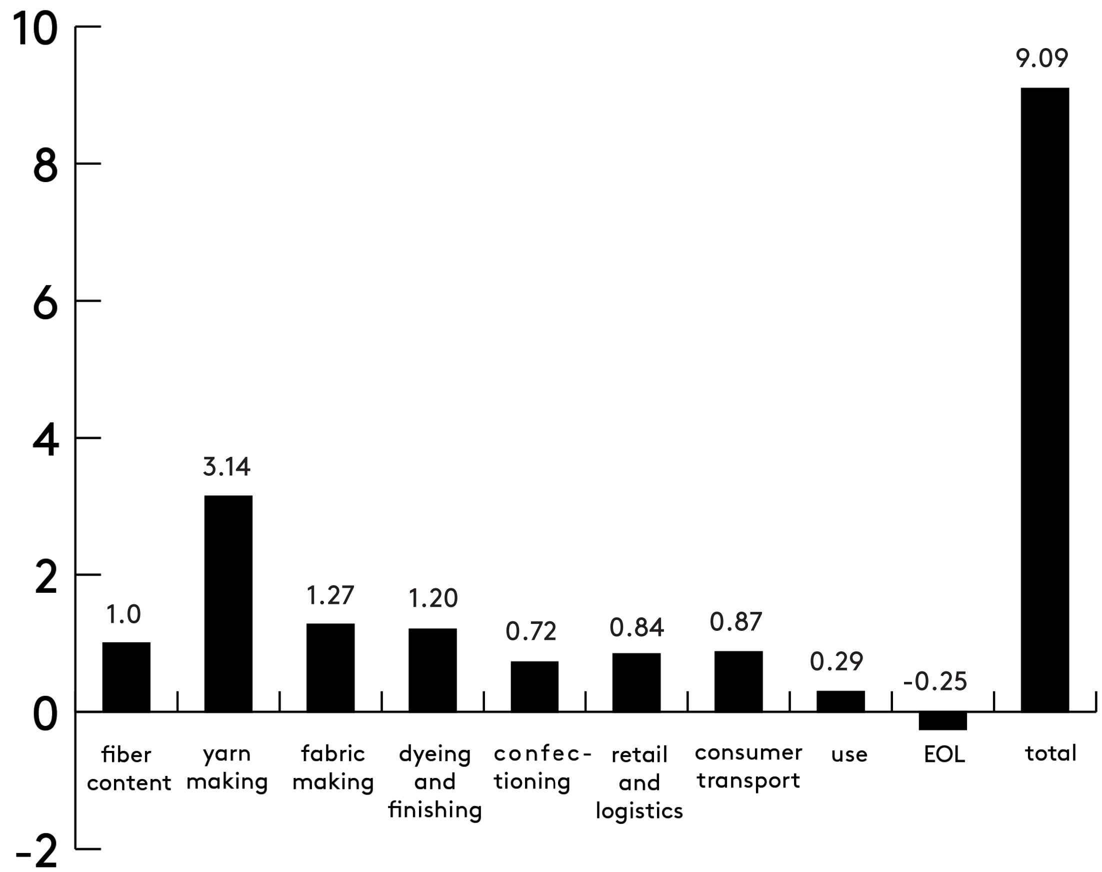
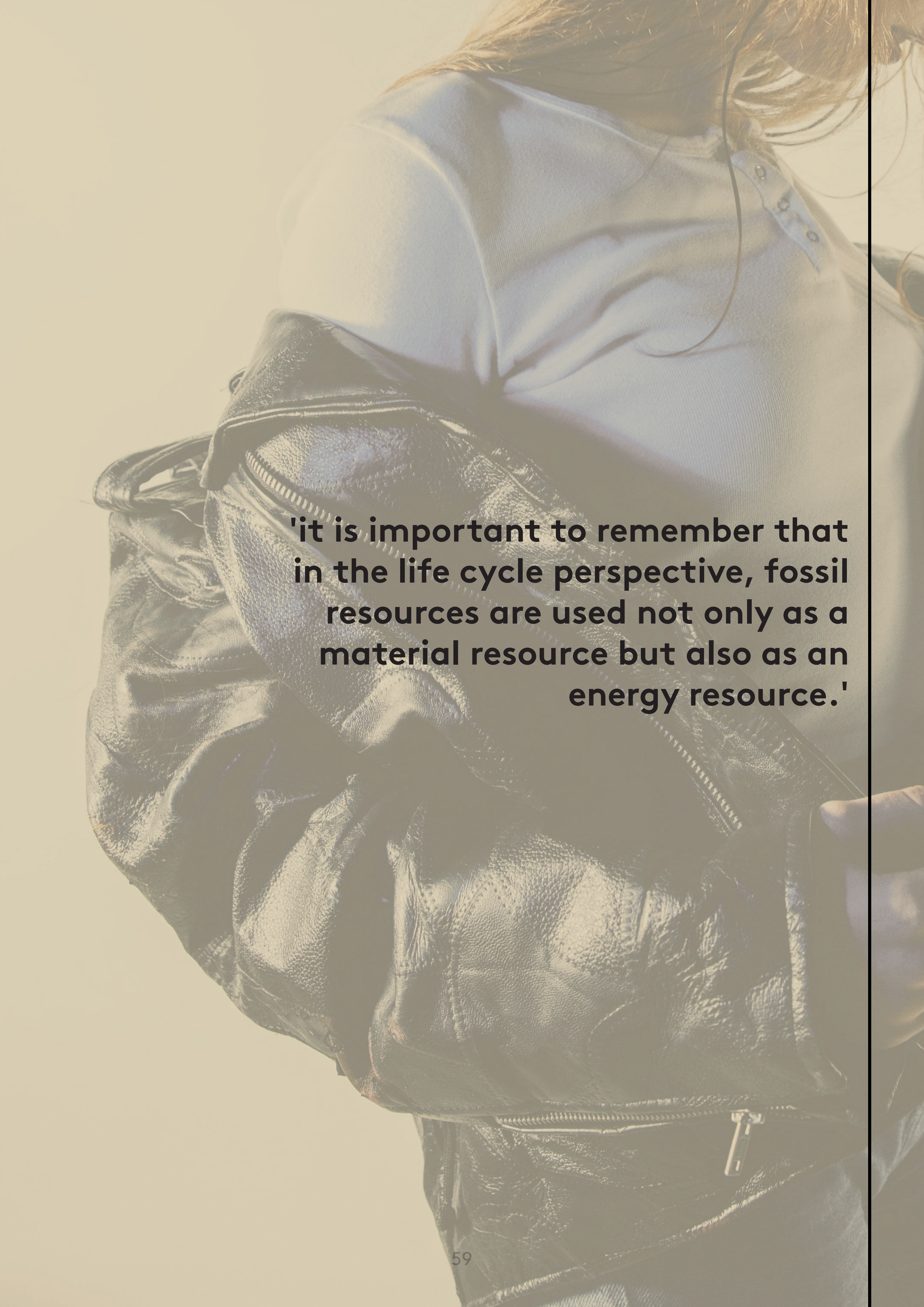


Figure 8. The consumption of fossil resources for a polyester dress over the life cycle expressed in kg oil-equivalents per kg garment (figures from Roos et al. (2015)). All energy is translated into oil-equivalents, including the energy recovery at end-of-life (EOL) where oil is assumed to be the replaced energy source by the textile.



'it is important to remember that in the life cycle perspective, fossil resources are used not only as a material resource but also as an energy resource.'

5. conclusions

This report provides information about the “new sustainable fibers” that are marketed today compared with the conventional fibers that they are supposed to substitute: cotton and polyester. The fiber types have been treated separately, even though so called “mono-materials”, i.e. materials that consist of one single fiber type are rare on the market. Today, in most textile materials, a mixture of fiber is used to provide all the desired properties of quality and comfort, which are only possible to achieve by a combination of fiber types. Tables 13 and 14 shows the possible alternatives and in which situation substitution is applicable for cotton and polyester respectively.

The cotton substitution discussion can be divided in two separate topics: development of fibers that behave exactly the same way as cotton (substituting cotton by a drop-in solution, or technical substitution), and selection of fibers that can be used in the same applications as cotton (substituting the market for cotton, or market substitution).

For polyester substitution the discussion can also be divided into technical and market substitution. Technical substitution is possible for the raw material aspect, while for the microplastics aspect, market substitution is needed.

Table 13. Possible substitutes to conventional cotton.

type of substitution	technical properties	examples of fibers
Technical substitution	No alternatives	-
Market substitution	Hand: as cotton Drapability: as cotton Static electricity: as cotton Strength: less than cotton Compostability: same as cotton	Blends of fibers with virgin cotton and mechanically recycled cotton fibers or regenerated cellulose fibers
	Hand: as cotton Drapability: as cotton Static electricity: as cotton Strength: same as cotton Compostability: no	Blends of fibers with synthetic fibers and mechanically recycled cotton fibers or regenerated cellulose fibers
	Hand: silky and cool Drapability: silky Static electricity: as cotton Strength: much less than cotton Compostability: same as cotton	Regenerated cellulose fibers(4)
	Hand: as cotton Drapability: as cotton Static electricity: as synthetics (5) Strength: better than cotton Compostability: no	Taslan and other "cotton-like" synthetic fibers
	No specific requirements	All fibers

(4) Please note that regenerated cellulose fibers include chemically recycled cotton.
(5) Chemical anti-static treatment can be applied, though this will increase the environmental burden.

Table 14. Possible substitutes to fossil-based polyester.

type of substitution	technical properties	examples of fibers
Technical substitution	Identical to fossil-based polyester.	Bio-based polyesters
Market substitution	Hand and drapability: as polyester Strength: less than fossil-based polyester Compostability: no Odour control properties: as synthetics (6)	Mechanically recycled polyester
	Hand and drapability: as polyester Strength: less than fossil-based polyester Compostability: yes Odour control properties: as synthetics	PLA and other bio-based and compostable polyesters
	Hand and drapability: as polyester Strength: same as polyester Compostability: no Odour control properties: as synthetics	Bio-based polyamide (nylon) fibers
	Hand and drapability: as polyester Strength: same as polyester Compostability: no Odour control properties: better	Synthetic fibers with functional additives
	No specific requirements	All fibers

(6) Chemical anti-static treatment can be applied, though this will increase the environmental burden.

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appendix 1. names of fibers

Table 1. Names of fibers covered in this report in alphabetic order together with raw material source(s) and usage.

Materials/Name	Type of fiber	Raw material source(s)	Usage
Acetate	Regenerated cellulose fiber	Wood	Fabrics with high drapability
Acrylic	Acrylonitrilic	Petroleum	Coarse knitwear
Alpaca	Protein	Alpaca	Fine knitwear
Azlon	Regenerated protein fiber	Milk (casein), eggs (albumin), corn and soy (zein), chicken feathers (keratin), or leather and hide waste (collagen)	Woven and knitted, high drapability
Bamboo (linen)	Bast fiber	Bamboo	Woven and knitted, coarse
Bamboo (viscose)	Regenerated cellulose fiber	Bamboo	Woven and knitted, high drapability
CELSOL	Regenerated cellulose fiber		Woven and knitted, high drapability
Econyl®	Polyamide	Post-consumer and post-industrial polyamide (50/50)	Woven and knitted
Eco Circle Fiber	Polyester	Post-consumer PET waste	Woven and knitted
ECOPET	Polyester	Post-consumer PET waste	Woven and knitted
Elastane (Lycra®)	Polyurethane	Petroleum	Elasticity in mixed fabrics or elastic cords
EVO	Polyamide	Castor oil	Woven and knitted
Evrnu	Regenerated cellulose fiber	Post-consumer cotton waste (20%) and virgin cotton	Woven and knitted, high drapability
Fortisan	Regenerated cellulose fiber	Wood and plants	Not in use any more
Hemp	Bast fiber	Hemp	Woven coarse fabric
Ingeo	Polyester	PLA from corn	Woven and knitted
Ioncell	Regenerated cellulose fiber	Wood	Woven and knitted, high drapability
Lycra® (elastane)	Polyurethane	Petroleum	Elasticity in mixed fabrics or elastic cords
Lyocell	Regenerated cellulose fiber	Wood and plants	Woven and knitted, high drapability

Materials/Name	Type of fiber	Raw material source(s)	Usage
Monocel®	Regenerated cellulose fiber	Bamboo	Woven and knitted, high drapability
Milk fiber	Regenerated protein fiber	Milk	Woven and knitted, high drapability
Mipan Regen	Polyamide	Post-industrial PA waste	Woven and knitted
Nilit® EcoCare	Polyamide	Post-industrial PA waste	Woven and knitted
Nylon	Polyamide	Petroleum (bio-based/ recycled)	Woven and knitted
Orange Fiber	Regenerated cellulose fiber	Citrus peel	Woven and knitted
Polylana®	Polyester	Petroleum	Woven and knitted
Qmilch®	Regenerated protein fiber	Milk	Woven and knitted, high drapability
Q-Nova®	Polyamide	Post-industrial PA waste	Woven and knitted
Rayon (viscose)	Regenerated cellulose fiber	Wood and plants	Woven and knitted, high drapability
Recover	Cotton and polyester blend	Mechanically recycled cotton waste (50% and recycled polyester (50%)	Woven and knitted
Recycled wool	Protein	Post-industrial waste wool (post-consumer waste)	Woven and knitted
Refibra®	Regenerated cellulose fiber	Post-industrial cotton (20%) and wood	Woven and knitted, high drapability
Regen®	Polyester	Post consumer PET waste	Woven and knitted
Repreve®	Polyester	Post-consumer PET waste	Woven and knitted
Repreve® nylon	Polyamide	Post-industrial PA waste	Woven and knitted
rPET	Polyester	Generic name for recycled polyester	Woven and knitted
S.cafe®	Polyamide	Coffee grounds (2%) and petroleum	Woven and knitted
Seacell®	Regenerated cellulose fiber	Seaweed (1%) and wood	Woven and knitted, high drapability
Silk	Protein	Mulberry silk worms and other insects	Woven and knitted
Sorona®	Polyester	Corn (32%) and petroleum	Woven and knitted
Soybean	Regenerated protein fiber	Soy beans	Woven and knitted, high drapability
Tencel®	Regenerated cellulose fiber	Eucalyptus and other wood types	From coarse casual denim to silky products
Triacetate	Regenerated cellulose fiber	Wood	Fabrics with high drapability
Viscose (rayon)	Regenerated cellulose fiber	Wood and plants	Woven and knitted, high drapability

appendix 2. terminology and abbreviations

Table 2 includes abbreviations and definitions of technical terms of relevance for this report.

Term	Definition
Bast fiber	Also called stem fiber. The fiber is collected from bast surrounding the stem of certain plants.
Bio-based	Material or product derived from biological or renewable resources.
Biodegradable	Biodegradable according to the European Norm EN 13432. Capable of being broken down (decomposed) rapidly by the action of microorganisms.
Chemical recycling	For cellulose and protein fibers, chemical recycling means fibers are dissolved and wet spun into regenerated cellulose fibers (cellulose does not melt). For synthetic fibers, chemical recycling means depolymerisation (the polymer is broken down to its “building blocks”, the monomers), separation of monomers and contaminants, and repolymerisation back into a polymer again.
Compostable	Compostable according to the European Norm EN 13432. Composting means that a controlled decomposition can be performed in industrial composting system. This does not guarantee compostability under other conditions nor of any additives.
Elastane	Elastic fiber also known as Spandex or Lycra.
EVO®	Bio-based polyamide (Nylon 10,10), commonly from castor oil
Fiber (or fiber)	A single piece of a given material that is significantly longer than it is wide and often round in cross-section (made up of polymers).
Filament fibers	Fibers of continuous or near continuous length produced by industrial spinning (melt, dry or wet spinning) or natural processes e.g. silk.
Filament yarn	A yarn made by filament fibers. A long, continuous strand of interlocked fibers.
ISO	International Organization for Standardization
Knitted fabric (or knit fabric)	A fabric in which a continuous yarn is looped and interlocked symmetrically above and below the mean path of the yarn (e.g. jersey, fleece).
Manufactured fibers	Fibers produced by humans, commonly a reprocessed natural fiber (e.g. viscose, lyocell, modal) produced from wood fibers, or a fiber produced from petrochemicals (e.g. polyester, nylon (polyamide 6 or 66), elastane). The former fibers are sometimes referred to as regenerated cellulose fibers, man-made natural fibers, or manufactured fibers from natural polymers. The latter are sometimes referred to as manufactured fibers from synthetic polymers. Both can be referred to as synthetic fibers or man-made fibers.

Term	Definition
Mechanical recycling	For cellulose and protein fibers, mechanical recycling means cutting and tearing fabrics into fibers. This treatment gives a somewhat shorter fiber length compared with virgin fibers. For synthetic fibers, mechanical recycling can be performed either via cutting and shearing as above, but also via melting the plastic and extruding them into new fibers.
Microplastics	Microplastics are synthetic, water-insoluble polymer items smaller than 5 mm, which are considered to be of particular concern for the aquatic environment.
Mono-material	A textile material made from just one fiber type (100%).
Monomer	A relatively small and simple molecule that can be linked together to form a larger molecule (a polymer).
Natural fibers	Fibers produced by plants (e.g. cotton, flax, jute) or animals (e.g. silk, wool, fur) (outside the textile industry, natural fibers can also refer to mineral fibers produced by geological processes, e.g. asbestos).
NMMO	N-Methylmorpholine N-oxide (a solvent)
Non-woven fabric	A fabric made from long fibers (or yarn, but this is not necessary), without a structured orientation, bonded together by chemical, mechanical, heat or solvent treatment (e.g. felt).
PA6	Polyamide 6 (Nylon 6) – polymer consisting of repeated blocks of caprolactame and amide bonds.
PA66	Polyamide 66 (Nylon 66) – polymer built from adipic acid and hexamethylenediamine and amide bonds.
Paper-based fabric	Papers are made of cellulose fibers (often wood-based) just like viscose, lyocell and other regenerated fibers. The paper-based fabric is different in that the pulp is used directly without the regeneration step and that the fabric has been produced in the paper machine.
PE	Polyethylene, a polyolefine polymer
PET	Polyethylene terephthalate, a polyester polymer
PLA	Polylactic acid, a polyester polymer
Polymer (chain)	A compound made of many (up to millions) linked simpler molecules (monomers).
Polymerisation	The process of linking monomers into polymers.
PP	Polypropylene, a polyolefine polymer
PTFE	Polytetrafluoroethylene
Staple fibers	Fibers of discrete length (natural fibers e.g. cotton, wool, but also synthetic fibers can be cut to staple fibers).
Staple yarn (or spun yarn)	A yarn made by staple fibers.
Textile fibers	Fibers used for textile applications (in this report, the term "fibers" always refers to textile fibers).
Thread	A type of yarn intended for sewing.
Woven fabric	A fabric in which two sets of yarns/threads are interlaced at right angles (longitudinal yarns are called warp, lateral threads are called weft).

Appendix 3. Outcome of first initial sustainability screening – "new sustainable fibers" as alternatives to cotton and polyester

As described in chapter 3.1, criteria for selecting fibers to evaluate in this report, to assure that the included fibers have a certain level of commercial attractiveness and sustainability potential. This led to a preliminary list and definition of criteria, which were exposed to stakeholders in a workshop organised in September 2017 with the aim to get feedback on the criteria.

Table A1 presents the final criteria which were defined. The division into "OK" or "Not OK" was made in order to identify potential "show stoppers" for the fibers at an early stage. Natural fibers and regenerated fibers are examined for their ability to substitute cotton, while synthetic fibers are seen as possible substitutes for polyester.

Table A2 presents the results of the initial screening. Please note that the initial screening did not cover all the fibers discussed in the report. In this screening, the full market overview and literature study had not been performed.

Fiber type/ Trade name	Description of fiber	Feedstock availability (for the possibility of large-scale production)	Process scalability	Technical quality	Economic potential	Environmental potential
Natural fibers from plants (per fiber type)						
Hemp	Bast fiber from the hemp plant	Small scale1	OK	OK	Unknown	OK
Jute/kenaf	Bast fiber from the jute/kenaf plant	OK2	OK	OK	OK	OK
Flax	Bast fiber from the flax plant. There are two kinds: line flax (for linen) and short fiber flax (by-pro-duct).	OK3	OK	OK	OK	OK
Kapok	Bast fiber from the kapok plant	Small scale4	Not OK	OK	Unknown	Unknown
Recycled cot-ton	Mechanically recycled cotton fibers	OK5	Unknown	Not OK	Unknown	OK
Organic cotton	Cotton fibers adhe-ring to some organic cotton certifi-cation standard.	OK6	OK	OK	OK	OK

Fiber type/ Trade name	Description of fiber	Feedstock availability (for the possibility of large-scale production)	Process scalability	Technical quality	Economic potential	Environmental potential
BCI cotton	Cotton fibers certified according to the Bet-ter Cotton Initiative (BCI) standard.	OK7	OK	OK	OK	Unknown
Natural fibers from animals (per fiber type)						
Silk	Protein fiber produced by the larva of certain insects, especially the silkworm.	OK8	OK	OK	OK	Unknown
Wool	Fiber from sheep's or lambs' fleeces.	OK9	OK	OK	OK	OK
Goat fibers	Cashmere, mohair	Small scale10	OK	OK	OK	Unknown
Llama fibers	Alpaca	Small scale11	OK	OK	OK	Unknown
Camel fi-bers	Camel	Small scale12	OK	OK	OK	Unknown
Rabbit fibers	Angora	Small scale13	OK	OK	OK	Unknown
Recycled wool	Recycled wool for gar-ments is mainly from cuttings from new garments.	OK14	OK	OK	OK	OK
Manufactured fibers from natural polymers (per trade name or fiber type)						
Qmilk	Protein fiber from raw milk not suitable for food pro-duction	Unknown15	Unknown	Unknown	Unknown	Unknown
SeaCell LT	Cellulose fiber from wood and seaweed (algae) using the lyo-cell process	OK (as main feedstock is wood)	OK	Not rele-vant	OK	Unknown
SeaCell MT	Cellulose fiber from wood and seaweed (algae) using the mo-dal process	OK (as main feedstock is wood)	Limita-tions	Not rele-vant	OK	Unknown
Soybean fiber	Protein fiber made from soybean cake	OK	OK	OK	OK	Unknown
Smartcel sensi-tive	Tencel fiber with the zinc preserved and embedded into the fiber	OK	OK	OK	OK	Unknown
Orange fiber	Cellulose fiber from citrus juice by pro-ducts (using an unk-nown process)	Unknown	Limita-tions	Unknown	Unknown	Unknown
Tencel	Cellulose fiber from wood using the lyocell process	OK	OK	OK	OK	OK

Fiber type/ Trade name	Description of fiber	Feedstock availability (for the possibility of large-scale production)	Process scalability	Technical quality	Economic potential	Environmental potential
Refibra	Celloluse fiber from recycled cotton scraps and wood using the lyocell process	OK	OK	OK	OK	OK
Monocel	Cellulose fiber from bamboo using the lyocell process	OK	OK	OK	OK	OK
Evrnu	Celloluse fiber from recycled cotton (using an un-known process)	OK	Unknown	OK	OK	Unknown
SaxCell	Celloluse fiber from recycled cotton using either the lyocell or the viscose process	OK	OK	OK	OK	Unknown
IONCELL-F	Cellulose fiber from wood using the ION-CELL-F process	OK	Unknown	NOT OK	NOT OK	Unknown
Cold caustic	Cellulose fiber from wood using cold caus-tic process	OK	Limita-tions	NOT OK	NOT OK	Unknown
Manufactured fibers from synthetic polymers (per trade name or fiber type)						
Recycled poly-ester	Chemically or mecha-nically recycled	OK	OK	OK	OK	OK
Inego PLA	Synthetic fiber (bio-based)	OK	OK	OK	OK	Unknown
S.Café	Polyamide fiber from petroleum and coffee grounds (2%)	OK (as main feedstock is wood)	OK	OK	OK	Unknown
Sorona	Synthetic fiber (bio-based)	OK	OK	OK	OK	Unknown
EVO	Synthetic nylon from a bio-based resource (castor oil seeds)	OK	OK	OK	OK	Unknown
Econyl	Chemically recycled nylon	OK	OK	OK	OK	Unknown
Recyclon	Recycled nylon from nylon waste	Unknown	OK	OK	Unknown	Unknown
EcoCircle Plant Fiber	Chemically recycled polyester	Unknown	OK	OK	Unknown	Unknown

1 current production: 68 kt
2 current production: 304 kt
3 current production: 340 kt
4 current production: 96 kt
5 assuming 24.3% of disposed fibers (the cotton share), whereof 50% collected = 12 Mt
6 current production: 120 kt
7 current production: 2.0 Mt
8 current production: 200 kt
9 current production: 1-2 Mt 10 current production: 15 kt for cashmere, 5 kt for mohair
11 current production: 6.5 kt
12 current production: 2.5 kt
13 current production: 3 kt
14 assuming 1% of disposed fibers (the wool share), whereof 50% collected = 0.5 Mt (current production is only 22 kt)
15 2 Mt/year waste milk in Germany according to website.

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Mistra Future Fashion is a research program that focuses on how to turn today's fashion industry and consumer habits toward sustainable fashion and behavior. Guided by the principles of the circular economy model, the program operates cross disciplinary and involves 60+ partners from the fashion ecosystem. Its unique system perspective combines new methods for design, production, use and recycling with relevant aspects such as new business models, policies, consumer science, life-cycle-assessments, system analysis, chemistry, engineering etc.

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