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environmental impact of textile fibers – what we know and what we don't know

the fiber bible part 2

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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

Part 1 of the report presents the technical performance of new and potentially sustainable textile fibers in comparison with more well-known and established fibers. The technical performance of a fiber decides the feasibility for the fiber to be used in different textile applications, and thus the possible function that can be provided by the fiber, which is essential when assessing and comparing sustainability performance.

The present report, part 2, quantifies the environmental performance of textile fibers by mapping and discussing data available in databases and the literature. Together, the two reports aim to identify the fibers with the greatest potential to mitigate the environmental impact of fibers currently dominating the fashion industry.

A multitude of other reports and tools with similar aims exist, though this report presents the first ever compilation of all currently publicly available data on environmental impact from fiber production. Compared to most other reports and tools, the present report includes more types of textile fibers, provides more quantitative data on their environmental performance, and to a greater extent discuss the data found – as well as the data not found.

If you, as a reader, know about fibers and environmental data which is missing in the present report, please let us know by e-mail: sandra.roos@ri.se

the Mistra Future Fashion criteria for sustainability

A challenge when assessing and comparing the sustainability performance of fibers is that the concept of sustainability has no global common definition. The most well-known is probably the definition of sustainable development from 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 a more relevant definition of the sustainability concept today.

Other popular concepts related to sustainability, that arguably can be seen as definitions of sustainability or subsets of sustainability include 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). A first attempt to clarify what sustainability implies for the Swedish fashion industry was made in the publication by Roos et al. (2016) which addressed the questions: 1) What is the current sustainability performance of the sector? 2) What is an acceptable sustainability performance for the sector? 3) Are proposed interventions enough to reach an acceptable sustainability performance?

At the same time, in the Mistra Future Fashion programme, the perception of the concept of sustainability was found to be inexplicit and at a closer look to differ between the researchers (Andersen 2017). To envision what a sustainable fashion industry would look like and identify technical and other solutions that have the possibility to make a substantial contribution towards this vision, an operative definition of the concept of "more sustainable solutions" was needed[1].

The insight led to several activities aimed at developing an operative definition for the Mistra Future Fashion context. Such a definition emerged as a set of criteria for sustainability and to what extent different solutions take us there. For defining the criteria, the master thesis by Johannesson (2016) provided the 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. Another activity contributing to the understanding of what sustainability can be in the fashion industry was the master thesis about emotional life cycle assessment (Haeggblom 2017) and a book chapter discussing examples on the positive contribution to social sustainability that clothing provides (Roos et al. 2016).

A preliminary list and definitions of criteria 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 sustainability potential of solutions was finalized, see Table P1[2]. 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[3].

[1] In this specific report the scope is "more sustainable fibers".
[2] Please note that the current report analyses in detail criteria 5) environmental potential, for fibers.
[3] 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 P1. 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[4].

[4]See Zamani, B. (2016).

solutions are created at different system levels

The multi-disciplinary 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 P2 gives some examples on how solutions will affect sustainability on the different system levels.

Table P2: 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

Production of cotton and synthetic fibers are known to cause negative environmental effects. For cotton, pesticide use and irrigation during cultivation contributes to emissions of toxic substances that cause damage to both human health and the ecosystem. Irrigation of cotton fields cause water stress due to large water needs. Synthetic fibers are questionable due to their (mostly) fossil resource origin and the release of microplastics. To mitigate the environmental effects of fiber production, there is an urgent need to improve the production of many of the established fibers and to find new, better fiber alternatives.

For the first time ever, this reports compiles all currently publicly available data on the environmental impact of fiber production. By doing this, the report illuminates two things:

- There is a glaring lack of data on the environmental impact of fibers – for several fibers just a few studies were found, and often only one or a few environmental impacts are covered. For new fibers associated with sustainability claims there is often no data available to support such claims.

- There are no ”sustainable” or ”unsustainable” fiber types, it is the suppliers that differ. The span within each fiber type (different suppliers) is often too large, in relation to differences between fiber types, to draw strong conclusions about differences between fiber types.

Further, it is essential to use the life cycle perspective when comparing, promoting or selecting (e.g. by designers or buyers) fibers. To achieve best environmental practice, apart from considering the impact of fiber production, one must consider the functional properties of a fiber and how it fits into an environmentally appropriate product life cycle, including the entire production chain, the use phase and the end-of-life management. Selecting the right fiber for the right application is key for optimising the environmental performance of the product life cycle.

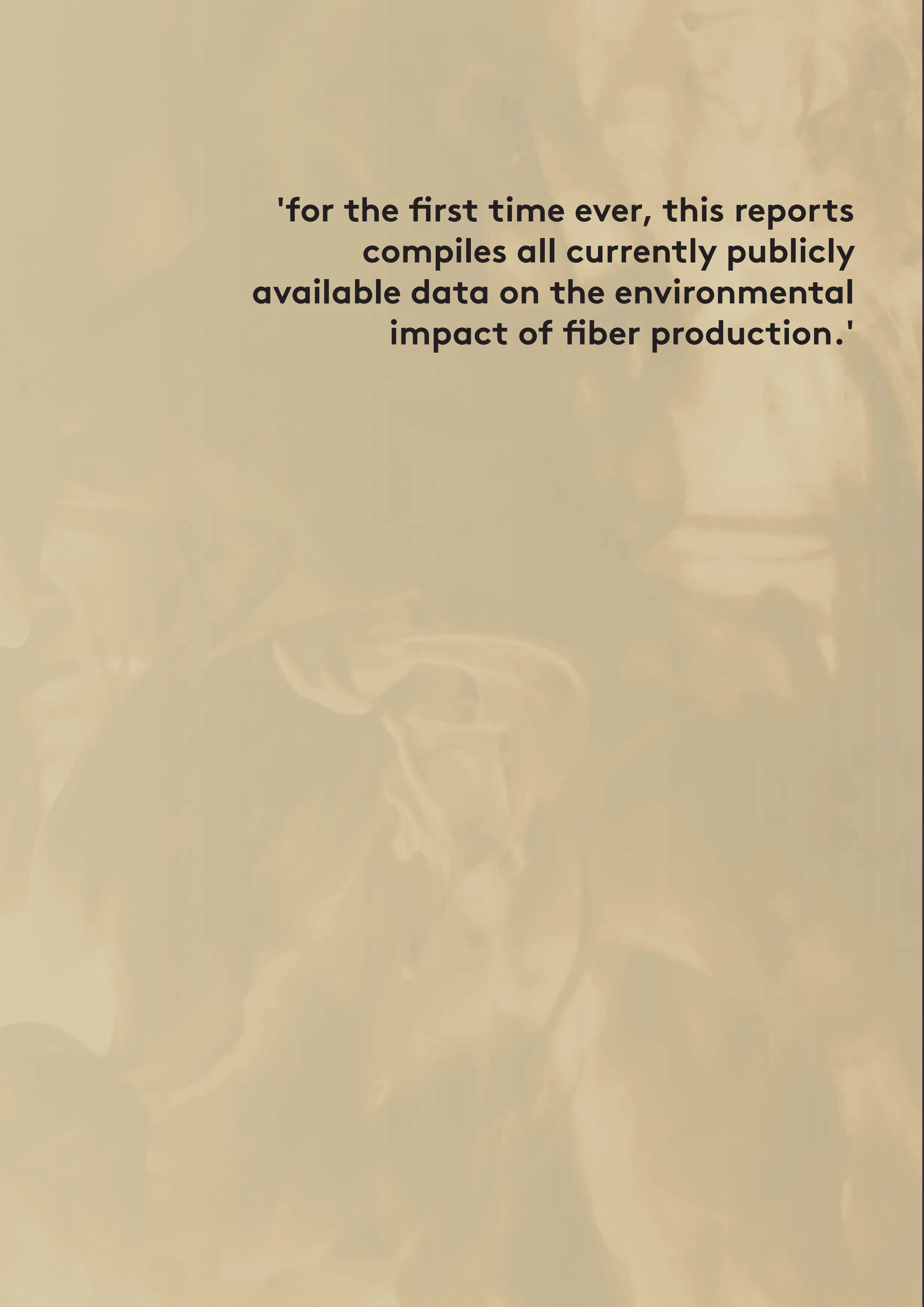
The report is intended to be useful for several purposes:

- as input to broader studies including later life cycle stages of textile products,

- as a map over data gaps in relation to supporting claims on the environmental preferability of certain fibers over others, and

- as a basis for screening fiber alternatives, for example by designers and buyers (e.g. in public procurement).

For the third use it is important to acknowledge that for a full understanding of the environmental consequences of the choice of fiber, a full cradle-to-grave life cycle assessment (LCA) is recommended.



'for the first time ever, this reports compiles all currently publicly available data on the environmental impact of fiber production.'

table of content

list of figures

1. introduction

The authors have previously mapped the current state of the environmental impact of the Swedish fashion consumption (Roos et al. 2015). A key finding was that the production of cotton and synthetic fibers are environmental "hotspots"[5]. 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.

To address the environmental hotspots of fiber production, there is an urgent need to improve the production of many of the established fibers and to find new, better fiber alternatives.

1.1 aims

The present report addresses the following questions:

- What do we know about the environmental performance of textile fibers? (considering established as well as non-established fibers)
- What factors influence the environmental performance of textile fibers?
- What are the gaps in our knowledge about the environmental performance of textile fibers?

These questions were addressed by mapping and discussing all the available quantitative data on the environmental impact of textile fibers, regardless of fiber type.

1.2 the art of comparing fibers

Before starting to compare fibers, it is important to stress that the environmental impact of marketed fibers (actual fiber products on the market) depends not only on the fiber type but also on where and how the fibers were manufactured (Chapagain et al. 2006; Shen et al. 2010; Sandin et al. 2013; Henry et al. 2015; Peters et al. 2015; Schultz & Suresh 2017). The context in terms of scale, geography, energy sources, chemical suppliers and waste management can highly influence the environmental impact as will the final use of the fibers in different types of garments and the possibilities for reuse and recycling at end-of-life.

In the present report, key information about the context is therefore reported along with the environmental data, to clarify and illustrate important factors which must be considered when using the data – but for a full understanding of the presented data, the reader is referred to the original reference, listed in the reference list in Chapter 6.

Environmental impact data of fibers are most often expressed per kg fibers, which also is the basis for the data listed in this report. For the final use in textile products, the amount of fibers necessary to provide a certain function will, however, depend on the fiber as well as the product.

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[5] "Hotspot" is a common term for a part of a system (e.g. an industrial sector or a product life cycle) which causes high environmental impact in relation to most other parts of the system.

The potential uses also vary considerably, as fibers have different mechanical and comfort properties. Even 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, which must be accounted for when comparing fibers. In other words, fibers should not be compared, promoted or selected (e.g. by designers or buyers) solely based on the environmental data shown in the present report.

To achieve best environmental practice, one must also consider the functional properties of a fiber and how it fits into an environmentally appropriate product life cycle, including the entire production chain, the use phase and the end-of-life management. Selecting the right fiber for the right application is key for optimising its environmental performance throughout its life cycle. For information on the technical properties of textile fibers, please see part 1 ofthe Fiber Bible.

- Rex D., Okcabol S., Roos S. Technical properties of possible sustainable fibers on the market. "Fiber Bible" part 1. D2.1.1.1 Mistra Future Fashion Report 2019:02

1.3 fiber introduction

The present report sorts fibers into four groups: 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), for example wool and silk, and regenerated fibers using natural polymers, for example viscose and lyocell.

Figure 1 gives an overview of the four fiber groups and the main 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, synthetic fibers 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 cellulose fibers[6], such as viscose, which can be produced from wood (e.g. beech or eucalyptus), other plants (e.g. bamboo or jute) or waste (e.g. discarded textiles or citrus peel) – some producers even add a small percentage of algae in the production of regenerated fibers (not shown in the below figure).

The great diversity of fibers and raw materials makes it difficult to make generic claims about fiber groups and to compare across groups. When assessing a fiber, it is therefore important to consider the influence of the raw material. This report thus specifies the raw material and its origin for all data collected (when such information is available) and considers these factors' influence in the interpretation and discussion of data.

Today, in many textile materials, a mixture of fibers is used to provide the desired properties of quality and comfort, which are often only possible to achieve by combining different fiber types (Rex et al. 2019). For simplicity, data of different fiber types are presented and discussed separately in this report, even though so called "monomaterials", i.e. materials that consist of one single fiber type, are rare on the market.

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[6] The term "cellulose fibers" is often used to describe regenerated cellulose fibers, although for example cotton is also a fiber consisting of cellulose.

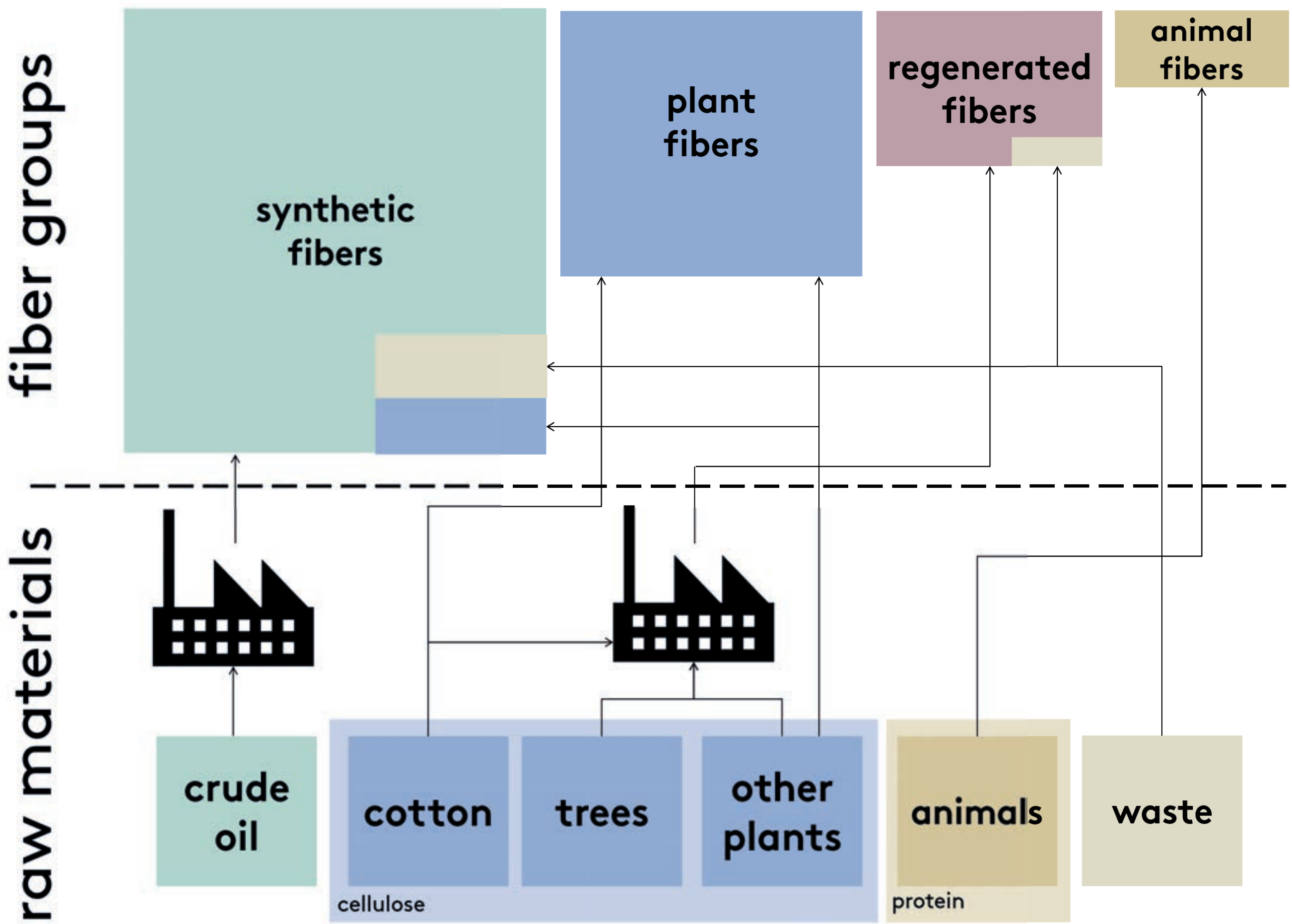


Figure 1 Overview of the four fiber groups and the groups of raw materials from which they are derived. The sizes of the fiber group boxes indicate their relative market shares but are not directly proportional to the market shares.

1.4 recommended use of the report

The report can, for example, be used (i) as input to broader studies including later life cycle stages, (ii) as a basis for deciding what needs to be studied further in order to, for example, be able to support claims on the environmental preferability of certain fibers over others, and (iii) as a basis for screening fiber alternatives, for example by designers and buyers (e.g. in public procurement). For the third use it is important to acknowledge that for a full understanding of the environmental consequences of the choice of fiber, a full cradle-to-grave life cycle assessment (LCA) is recommended.

1.5 limitations

The report includes available data on the environmental sustainability of textile fibers, thus data on social or economic sustainability is not within the scope, nor is information on yarn, fabrics or end products. Focus has been on finding data on six key areas of environmental impact, which means that other potentially important environmental impacts are excluded.

Publicly and (for the authors) freely available data is included, which means that confidential data and some data behind pay-walls are excluded.

To only consider data available in the English language also constitutes a limitation, as there is further data available in other languages.

Further information on the inclusion and exclusion of data can be found in Chapter 3.2.

1.6 structure of report

Key terminology for textile production is defined in Appendix 1, including terms such as polymer chains, natural fibers, man-made fibers and filament yarn.

Chapter 2.1 outlines criteria which were developed for selecting fibers to be included in the report – criteria that were to guarantee a certain feasibility and sustainability potential of the considered fibers – and how the use of these criteria changed as they were applied and as data collection began. Chapter 2.2 describes the considered environmental impact categories, the method of collecting data on these impact categories, and assumptions and choices that had to be done when interpreting and presenting the data.

Chapter 3 provides an illustration of the studied textile fibers, their feedstock and examples of fiber and yarn brands, before presenting the identified quantitative data on environmental impact, separated into four fiber groups (tables avaliable in Appendix 2)

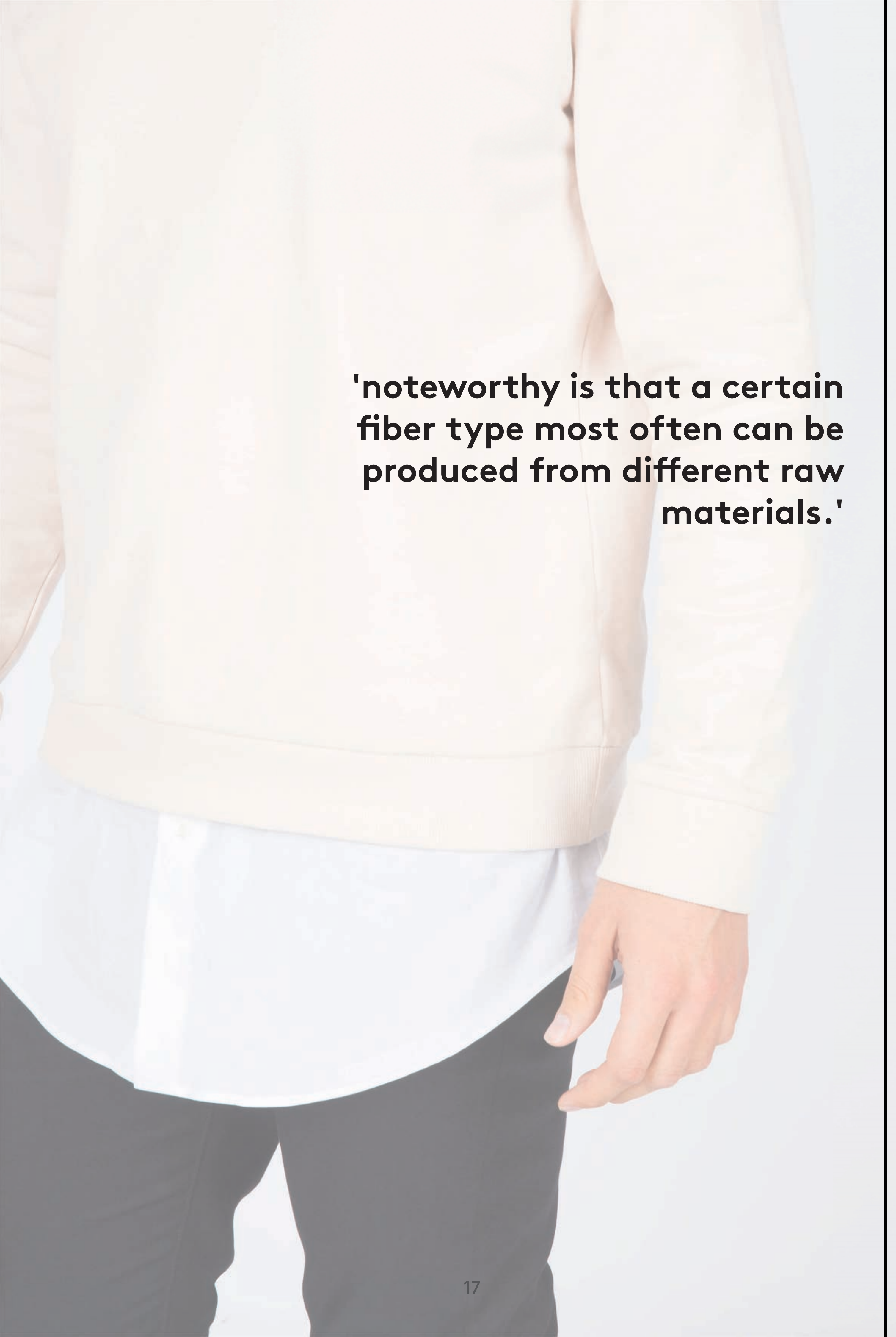
- animal fibers,
- plant fibers,
- regenerated fibers, and
- synthetic fibers.

Chapter 4 provides a discussion on, among others, what the available data tells us about the advantages and disadvantages of various fibers and the possibilities to compare fibers across and within fiber types, and where the information gaps are and how this put limitations on what can and cannot be said about the environmental performance of various fibers.

The main findings and conclusions are summarised in Chapter 4. In the end there is a reference list and appendices with further details.

1.7 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 is a study performed in the supply chain theme and complement as well as feed into parallel and subsequent deliverables, among others Part 1 of the Fiber Bibel, on the technical properties of textile fibers (Rex et al. 2019) and an updated version of Roos et al. (2015) to be relaesed in the summer of 2019, a report on the environmental impact of Swedish fashion consumption. Read more at www.mistrafuturefashion.com.



'noteworthy is that a certain fiber type most often can be produced from different raw materials.'

2. method

In this report, the framework used to provide quantitative environmental performance data is life cycle assessment (LCA). LCA is recognized as the most robust tool to provide the systems perspective required to accelerate the shift towards more sustainable consumption and production patterns (UNEP 2016). The benefits of LCA and life cycle thinking are described as:

> "It is natural for people to view any product or technology with respect to narrow sets of benefits and costs that impact them personally. However, that narrow focus can easily miss and often diminish a broader vision of the overall environmental and health footprint. LCA helps guard against this form of myopia and enables decision makers, the public, and other stakeholders to visualize and better understand the overall profile of a particular product or technology. The shared understanding that comes with a common vision is central to fostering informed dialogues and clear pathways toward decisions that involve the various parties who may benefit and/or be affected by a product or technology (UNEP 2016)"

The complexity of environmental assessment of fibers is introduced in Chapter 1.3. With raw materials from animals, plants and fossil resources, with fiber production technologies spanning from farming to advanced chemistry processes, the systems perspective is needed for comparing the environmental sustainability performance. The ambition has been to carry out the mapping and discussion in a transparent, structured and, as far as possible, unbiased manner in the sense that environmental performance is evaluated equally for all fibers and by an independent party.

2.1 initial method, and a change of direction

The work started with an aim to investigate the environmental performance of "new sustainable textile fibers" (relatively new fibers market-wise, associated with claims about greater sustainability), with the overall aim to identify the fibers with the greatest potential to mitigate the environmental impact of the fibers currently dominating the global fiber market.

To do this there was a need to (i) identify the fibers that, in a loose sense, can be considered new and (potentially) sustainable textile fibers, and (ii) select a subset of fibers that were deemed to be of sufficient interest for us to collect data on their environmental performance.

For step (i) all fibers encountered during the authors' work in Mistra Future Fashion (starting in 2011) and which are associated with claims of greater sustainability were included (Rex 2015). In addition, fibers identified in a master's thesis carried out in Mistra Future Fashion (Johannesson 2016) were included. Conventional fibers such as polyester, conventional cotton and elastane, that have already been covered in previous work from Mistra Future Fashion (Roos et al. 2015), were – at this time of the study – excluded.

For step (ii), criteria were developed to guarantee a certain level of commercial attractiveness and sustainability potential, in order not to consider fibers whose commercial future is still too uncertain or whose sustainability credentials are obviously doubtful. The criteria were, a subset of the criteria listed in the Preface of this report, feedstock availability, process scalability, technical quality, economic potential and environmental potential (for more information on the definition of the criteria and the process of developing them, see Preface).

Then the identified fibers were assessed based on these criteria (see Appendix 1 in Rex et al. 2018), which revealed very few fibers that did not have sufficient feasibility and sustainability potential. In other words, basically all fibers appear to – under the right conditions – have the potential to be part of a sustainable fiber future. Besides, when starting to collect data on the fibers, it was found that for most fibers data is scarce or non-existent, and when data is available, there are often tremendous variations between sources.

Apart from the fact that the criteria did not narrow down the list of fibers to consider, the work had so far shown three things:

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

2. There is no reason to restrict the study 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.

Based on these learnings, the direction of the work changed. We instead aimed at mapping all available data on the environmental impact of textile fibers, regardless of fiber type. The evaluation according to the criteria was still, however, used – albeit not for the original purpose of defining the included fibers (see Figure 2), but as input to the discussion section.

2.2 collecting and presenting data on the environmental impact of fibers

Publicly available quantitative data on the environmental sustainability of textile fibers were collected and interpreted. Below subsections describe the main decisions taken during this work.

2.2.1 inclusion and exclusion of data sources

In finding data, sources previously encountered by the authors were considered along with sources found in a literature search[7]. Following this, the identified sources and data were reviewed by an expert panel selected among the Mistra Future Fashion partners, to identify missing sources.

Publicly available and accessible data were included, which refer to data accessible in – for the authors – openly and freely available sources, such as public reports available online, data available in scientific journal articles (open access or not), life cycle inventory (LCI) databases such as Ecoinvent and GaBi Professional, and Sustainable Apparel Coalition's Higg Material Sustainability Index (Higg MSI) database. This means that confidential data and data behind pay-walls to which the authors do not have access were excluded. Among others, this excluded data from the World Apparel & Footwear Life Cycle Assessment (WALDB) (Quantis 2018) database.

There are many versions of Ecoinvent available – primarily Ecoinvent 3 was considered in the present study (more precisely, versions 3.3 and 3.4). Ecoinvent 3 datasets are available both as "production" and "market" datasets (i.e. production datasets with a default transport to the respective market added). It was decided to mainly consider the production datasets as the fiber production is the prime focus of this study. Market datasets were included in some instances just to show how they can differ compared to production datasets.

Some Ecoinvent 2 datasets were also included. This is because many of the LCA studies performed on textiles are based on version 2 datasets and it can be informative to see instances of when the results vary considerably between the two versions. For LCI datasets in databases, the LCA software SimaPro version 8.5.0.0 (PRé Consultants 2018) and GaBi version 8.5.0.79 (ThinkStep International 2018) were used to characterise the data, i.e. transform the LCI data into environmental impact data. Using both SimaPro and GaBi for the characterisation was done to enable the identification of potential discrepancies between the two, as such are of interest for those involved in generating environmental impact data. Within each software, there are many characterisation methods (also called impact assessment methods) available; here the methods recommended in the International Reference Life Cycle Data System (ILCD) handbook (European Commission 2011) were used – as implemented in SimaPro and GaBi, respectively – which at that point represented European consensus on characterisation methods to use in LCA[8] .

[7] The search phrases included names of fiber types, fiber brands and fiber producers, in combination with reference searches.
[8] Note that the ILCD method uses USEtox v1.0 since that was the available version in 2011.

Only sources in the English language were considered. Moreover, reports reproducing the data of others (i.e., secondary sources) were most often excluded. Some exceptions were done: data from LCI databases and Higg MSI were included although they often refer to some other primary data source, and some reports with secondary data were included if the original reference was not accessible online or not available in English (in these instances, the primary source is not listed in the present study but can be found through the given reference).

In a few cases, data was disregarded if it could not be found in the original reference; for example, Muthu et al. (2012) provides data on the water requirements of flax fibers, referring to Laursen et al. (1997) as the original reference, but as the data could not be found in Laursen et al., it was disregarded. Furthermore, only data on the fiber level was included, i.e. data of yarns, fabrics and final textile products was disregarded – unless data was available for fiber production expressed per amount of ready-made fibers (i.e. if results were specified for fiber production, but only per garment, they were disregarded as one would have to know e.g. the losses in each production phase to be able to translate the data into numbers per kg fibers[9]). Exceptions were made for synthetic oil-based fibers, for which data is also presented at the level of processes and granulates. The reason for this is explained in section 4.1.5.

2.2.2 reported impact categories

The categorization of different types of environmental impact in LCA – climate change, toxicity, ozone depletion, etc. – is made to ascertain that all relevant impacts are covered and to avoid overlaps. Today, there is a broad consensus and mature understanding both between different applications of LCA such as the European Product Environmental Footprint (European Commission 2017a) and the UN Environment Life Cycle Initiative (UNEP 2016) and between LCA and other environmental schemes such as the UN Sustainable Development Goals (United Nations 2015b) and the Planetary Boundaries (Rockström et al. 2009) regarding which environmental impact categories that are relevant to report. There is also consensus in that for a specific product or organisation, the most relevant impact categories should be reported.

Data on six environmental impact categories was collected: climate change, water use/depletion, toxicity, eutrophication, land-use and related indicators (e.g. land use change and biodiversity), and energy use. These cover the main environmental impacts of the textile industry for which fiber production can be a significant contributor (European Commission 2017b; Roos et al. 2015). Besides, other impact categories often included in LCAs of textile products frequently yield similar patterns as climate change results, as the burning of fossil fuels is an important driver also for these impacts – for example, see the similarities between results for climate change and acidification in Roos et al. (2015). Data on such impact categories is not reported here but can be found in some of the reported data sources.

It should be noted that although there is a relatively strong consensus in the LCA community regarding which impact categories to report, there is often no consensus regarding which characterisation methods to use (the methods with which the quantitative result is calculated). The recommendation of characterisation methods to use for each impact category varies both over time and to a certain extent also due to purpose (European Commission 2011; European Commission 2017a; UNEP 2016). The below Chapters 2.2.3 and 2.2.4 describe how this was handled in the report.

[9] This led to the exclusion of references such as Roos et al. (2015), Wang et al. (2015), Beton et al. (2014) and Steinberger et al. (2009).

2.2.3 reported meta data

For the selected impact categories, all data regardless of characterisation method was collected. For each collected data point, also important meta data was collected, such as the characterisation methods applied and other major methodological assumptions (e.g. the inclusion of sequestered carbon in climate impact assessments). However, it has not been practical to make a full description of the underlying method behind each data point, including system boundaries and other major assumptions. If the reader wants to fully understand a number, and use it in some other context, he/she is encouraged to go to the original reference for further information.

The present report is limited to providing a brief description of each data point, to enable general observations regarding the numerical values as well as data availability and data gaps. Hopefully, this can also function as a gateway for the interested reader in finding further information.

2.2.4 interpretation and presentation of data

To present environmental impact data from many different sources in a structured and coherent manner is challenging. Environmental impact data is, in different sources, presented in a multitude of ways, using different methods and units, with different specificity and representability, reflecting different spatial and temporal scopes. It has not been possible to be fully exhaustive and display all relevant meta data behind each presented datapoint, as emphasised above. Also, some of the identified data is clearly presented in the original reference, whereas others have required some interpretation, for example because information about methods or units are missing, or because data is only shown in bar charts without numerical values. Below is a clarification of how the data is presented along with explanations of some interpretations that had to be done. Some clarifications are also made as footnotes in the results section. The reader is urged to read the original reference to fully understand the meaning of the presented data.

Many methodological dimensions influence a quantification of environmental impact. For climate impact assessment, for instance, the most commonly used metric is global warming potential (GWP). Characterisation methods for GWP exist in several versions with different time horizons, which influence the relative contribution of different greenhouse gases. That is, using a 20-year time horizon (GWP20) yields different results compared to using a 500-year time horizon (GWP500), see the example of wool fibers in Chapter 4.1.1.

Even if two studies of identical product systems use, for example, GWP100, the results can differ, as GWPs of various greenhouse gases are updated regularly as we learn more about how they influence atmospheric temperatures. For example, the GWP100 of methane has increased from 21 kg CO2 equivalents per kg (IPCC 1995), to 25 (IPCC 2007), to 28 (IPCC 2013). The results presented below specifies if GWP and a specific time horizon has been used (although the time horizon is not always specified in the original reference), but not the original reference to the characterisation factors (e.g. IPCC 2007 or 2013). The same is true also for the other impact categories and indicators. Similarly, if an impact assessment framework has been used, such as ReCiPe (Huijbregts et al. 2016) or CML (CML 2013), this is specified, but not the specific version of the framework.

The environmental impact data is, in the present report, given in terms of a number and its unit. The method used to derive each number is stated in a parenthesis after the unit. Here the term "method" is used in a broad sense: it can refer to an impact assessment framework (such as "CML", if this has been specified in the original reference), an impact assessment method (such as "GWP100"), or a specification of an inventory indicator (such as "water consumption" or "water scarcity"). In some cases, indicators termed differently in fact refer to the same thing. For example, the terms water/energy use, water/energy consumption and water/energy requirements often have the same meaning, and sometimes they are even used alternately in the same report. In such cases, the present report displays the term most frequently used in the original reference.

Moreover, although methods of two studies are, in the present report, described in the same manner, and the data thus appears to be comparable, this may not be the case. For example, for an indicator such as "energy use", there are many potential discrepancies between studies using seemingly identical indicators – discrepancies not always clearly stated in the original reference. An energy use indicator can include fossil or non-fossil energy, or both; it can reflect primary or secondary energy use; it can reflect cumulative energy demand, the total extracted energy (energy content of raw materials plus cumulative energy demand) or net energy balance (energy content of product minus cumulative energy demand) (Arvidsson et al. 2012). The present report specifies some of these differences, if clearly stated in the original reference, but not all. For a full understanding of the indicators used for energy use and other impact categories, the reader is referred to the original reference.

Another influential aspect for climate impact data is whether biogenic CO2 emissions and CO2 sequestration during plant growth are included or not. As the default choice is exclusion, the present report only specifies if biogenic CO2 has been included (unless the same study also includes a scenario excluding biogenic CO2, then this is also specified). In cases in which a characterisation method has been used, but the method is unknown, it is described as "unknown method".

Sometimes inventory indicators have been used to present results also for impact categories. For example, climate impact results are sometimes given as kg CO2 and not as kg CO2 equivalents. If no characterisation method appears to have been applied, the present report does not specify any method, not even "unknown method". However, in some of these cases, it is obvious from the disclosed inventory data that the results have indeed been characterised and that the unit should have been stated in terms of equivalents (one example is Kalliala and Nousiainen (1999)). In such cases, the unit has been specified as an equivalent-unit in the present report. Similarly, in one case (Cherrett et al. 2005),the presented climate impact results were obviously a factor of 1000 wrong; this error has been corrected in the present report.

Besides impact assessment methodology, there are other key methodological assumptions influencing environmental impact data, such as how the impact of multifunctional systems is allocated between the functions. Multifunctionality is common in fiber production systems: cotton cultivation yields cotton lint and cotton seed, oil refineries yield a multitude of petroleum fractions whereof some enters polyester fiber production, sheep can provide both meat and wool, to name a few examples.

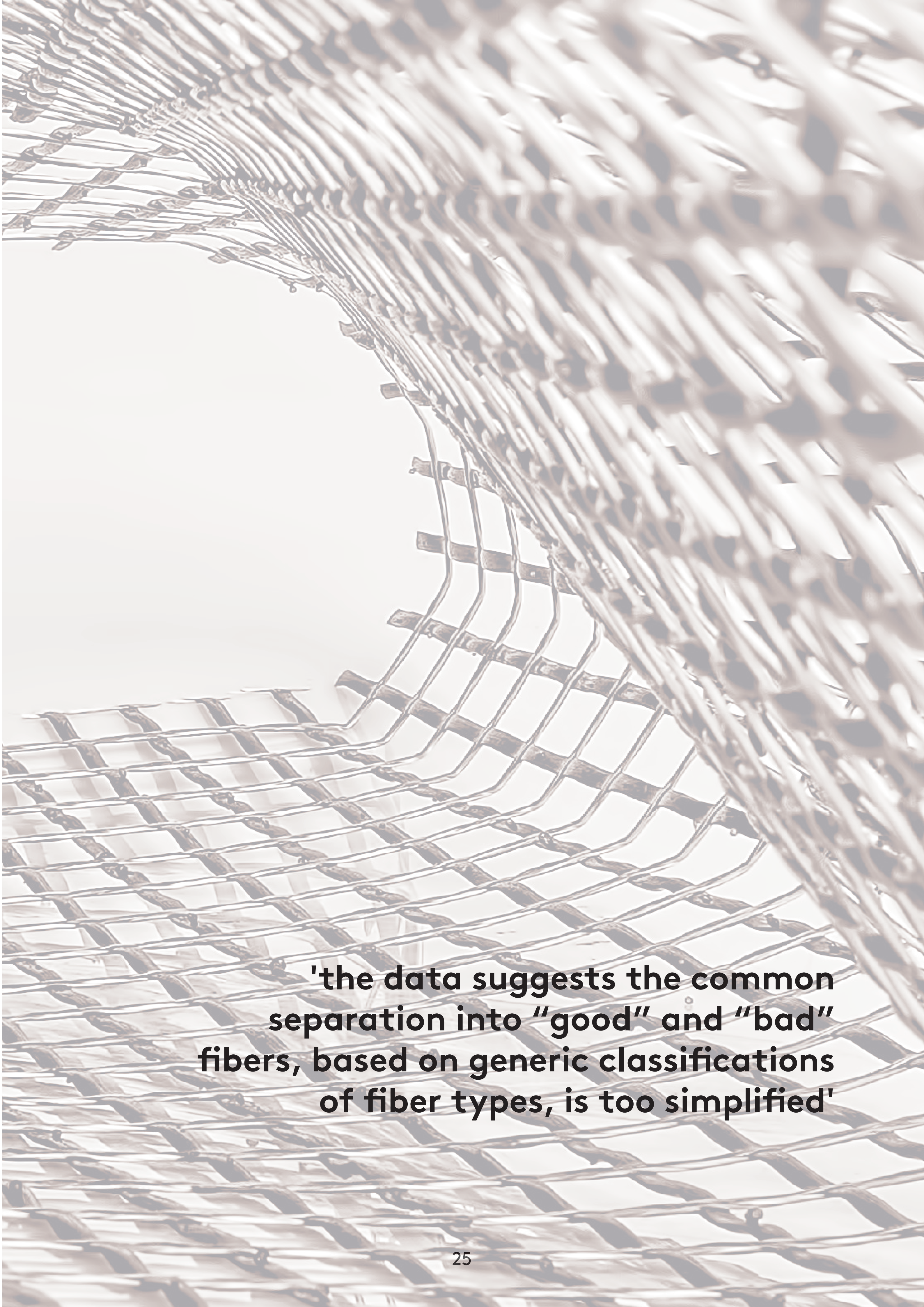
If the impact is divided based on mass, the heavy co-product is seen as responsible for most of the environmental impact; if the impact is divided based on market price, the most valuable co-product is held accountable for a larger share of the environmental impact. In the present study, the allocation methods behind the numbers are not presented (although in a few cases they are mentioned as a footnote), instead the reader is referred to the original reference. In a few cases, several allocation methods were tested, rendering several results; this is shown as a data range in the present report.

Often LCA software, such SimaPro, GaBi, Umberto or OpenLCA, has been used to calculate the environmental impact data. Choice of software has been shown to influence results (Roos et al. 2015) and is therefore a potentially important factor to consider when interpreting data. The used software is, however, often not stated in the original reference, so the present report does not specify it either.

Another type of meta data not given in the present report is statistical information about the data, such as standard deviations. As such information is important to account for when using data for decision making, the reader is urged to read the original reference before using any of the displayed data.

If data has been interpreted from a visual figure, such as a bar chart or a graph, "~" is inserted before the numerical value to indicate the uncertainty of the interpretation. Related, the present report displays as many significant digits as the original reference up to three significant digits (although sometimes it is doubtful whether this reflects the actual precision of the data).

Finally, all data shown has been recalculated to be expressed per kg fibers. To be concise, units are therefore most often expressed as being "per kg", implicitly meaning "per kg fibers", unless otherwise stated. Also, to be concise, abbreviations have been used for methods and other recurring terms, see Table 3 in Appendix 1.



'the data suggests the common separation into “good” and “bad” fibers, based on generic classifications of fiber types, is too simplified'

3 results

The identified data on environmental impact of fibres are presented in six tables, one for each of the following fibre groups: animal fibres, cotton fibres, other plant fibres, regenerated fibres, polyester fibres, and other synthetic fibres. The tables are found in Appendix 2.

3.1 overview of fibers and their feedstocks

Figure 2 shows a classification of the available textile fibers and the raw materials for the fiber feedstock. The figure also provides examples of fiber/yarn brands, and how they connect to one or several of the fiber groups. The focus has been on brands associated with some kind of sustainability profile, although also other brands are included. The listing of brands clarifies the difference between fiber types and brands, which helps to navigate the growing plethora of brands and how they connect to fiber groups and feedstock origin.

It should be noted that a given fiber type (as defined in the European Fiber Labelling Regulation (EU) No 1007/2011) may be derived from a multitude of raw materials, and a given raw material may end up in a multitude of fiber types and brands. Furthermore, it is important to stress that fiber production also relies on energy and materials other than the fiber feedstock, for production of heat, electricity, fertilizers, pesticides, feed, dissolution chemicals, catalysts, and more – these secondary flows are often larger, on a mass basis, than the raw materials used as fiber feedstock. Therefore, Figure 2 tells only part of the raw material story of textile fibers. Also note that the figure is a simplification – not all fibers, raw materials, brands and connections are shown. For more about the production of fibers and their technical properties, see Rex et al. (2019).

Appendix 2 includes six tables. Table 2.1 shows the identified environmental impact data on animal fibers. Table 2.2 and Table 2.3, shows the identified environmental impact data on cotton fibers and non-cotton plant fibers, respectively. Table 2.4 shows the identified environmental impact data on regenerated fibers. Table 2.5 and Table 2.6 shows the identified environmental impact data on polyester fibers and non-polyester synthetic fibers, respectively.

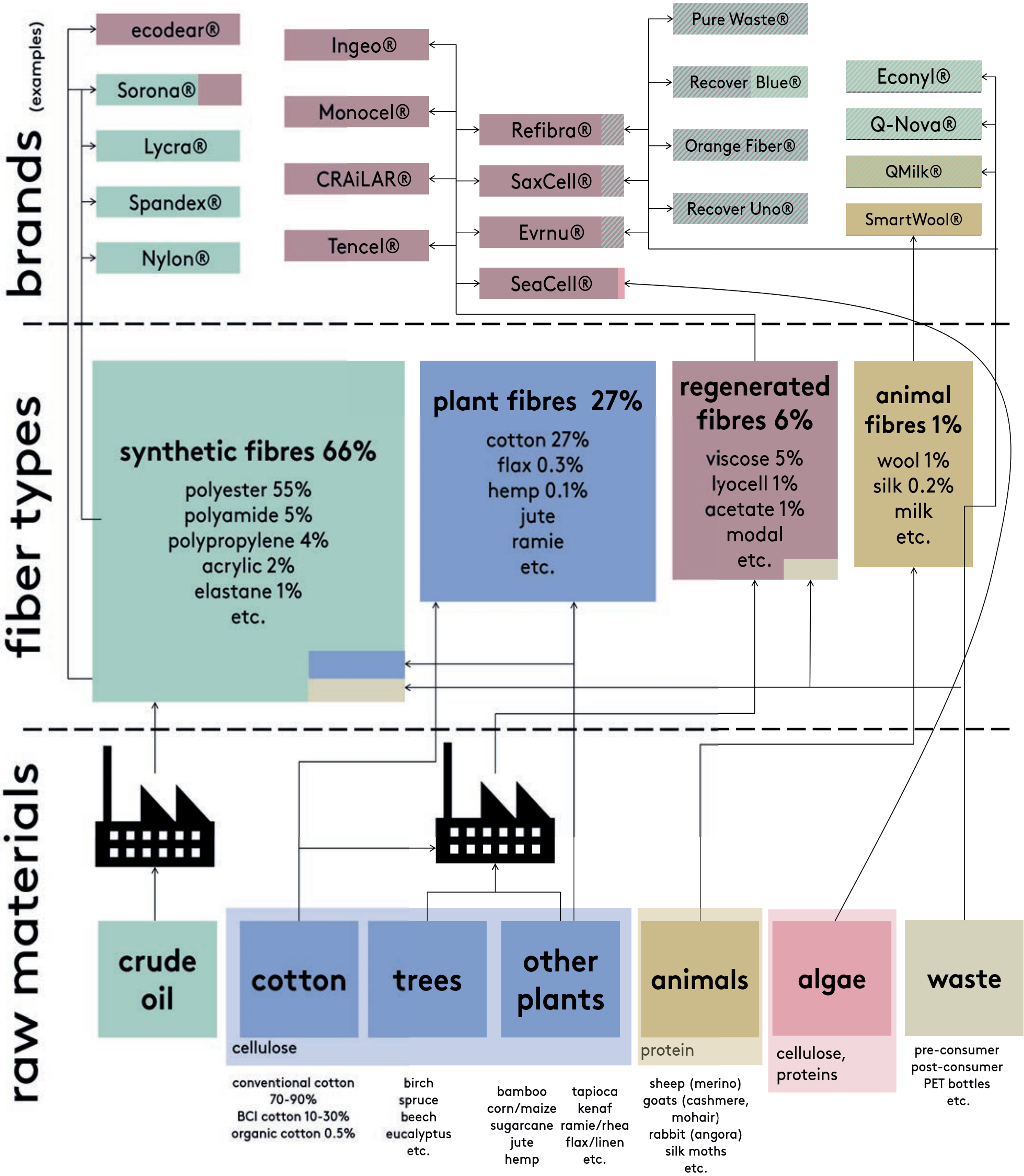


Figure 2 Overview of fiber types, raw materials, market shares[10] and examples of fiber/yarn brands. The sizes of the fiber group boxes indicate their relative market shares but are not directly proportional to the market shares.

[10] Market share data is from Carus (2013), Textile Exchange (2014), About Organic Cotton (2018), Better Cotton Initiative (2018), Fact Fish (2018), Global Market Insight (2018) and International Sericultural Commission (2018). Percentages do not always add up because several sources were used and different sources state different market shares for a given fiber (e.g. due to year-to-year variations, whether or not data is restricted to fibers used for textile applications, etc.), and percentages were rounded off (e.g., wool has a market share of 1.3% and animal-based fibers in total have 1.5%).

4. discussion

The data listed in Appendix 3 summarises the state of knowledge on the environmental impact of textile fibers. Apart from shedding light on the environmental preferability of some fibers compared to others, the data reveals great variations within fiber types and exposes a glaring lack of knowledge concerning some fibers and impacts. Interestingly, the data suggests the common separation into "good" and "bad" fibers, based on generic classifications of fiber types, is too simplified. A much more nuanced view is warranted, in which the separation rather is done between producers with or without appropriate environmental management, and poor or better uses of the fiber, accounting for the environmental performance throughout the life cycle of the final textile product. Below these findings are discussed in greater detail.

4. 1 environmental performance of fibers and influential factors

4.1.1 animal fibers

Wool from sheep is the animal fiber produced in the largest volume and also the one for which most LCA data was found. Sheep wool is also the only animal hair fiber for which LCA data was found. Climate impact of wool fibers range from 1.7 to 36.2 kg CO2 equivalents per kg fibers (excluding CO2 sequestered in the fiber). In a special case where the climate impact was highly allocated to meat production and the fiber production was regarded as a means of avoiding waste, the climate impact from wool fiber production was calculated to -26 kg CO2 equivalents per kg fibers. Silk fibers are very little studied, only two studies were found. The climate impact of silk fibers was calculated from 52.5 to 80.9 kg CO2 equivalents per kg fibers depending on the farm practices (dominated by emissions from composting waste). In the Higg MSI database, the difference between silk and wool in terms of climate impact is very small. The silk figures should be interpreted with care since so little data exists. The results on water use/depletion show a variation from 27 to 54 cubic metres of water per kg silk depending on farm practices.

The reported environmental performance of animal fibers is mainly influenced by direct emissions at site. For silk fibers it is the composting of waste that (in the only available study) stands for 45% of the relatively high climate impact. This impact could potentially be reduced and even turned to a negative number if the waste was instead incinerated with energy recovery, replacing other fuels. Wool usually turns out to be comparatively climate intensive due to the fact that sheep are ruminants that emit methane; about 75% of the climate impact of wool is due to these emissions. Moreover, the allocation of environmental impact between meat and fiber production has a large influence on LCA results of wool. The results on water use/depletion show a variation from 37 litres of water per kg wool fibers[11] to 1,210 litres of water per kg wool fibers[12].

It is worthwhile to elaborate on how the choice of method influences the fact that wool fibers "suffer" from the sheep's methane emissions. Methane is a more potent greenhouse gas than carbon dioxide and therefore is given a higher contribution to climate impact per kg of emission. However, the comparative importance of the contribution to global warming from different anthropogenic activities has been debated (Savory & Butterfield 1998; Johansson et al. 2008; Gillenwater 2010; Gillenwater 2008; Wynes & Nicholas 2017).

[11] Sheep wool at farm in US from Ecoinvent 2.2.
[12] Sheep fleece in the grease {RoW} from Ecoinvent 3.4.

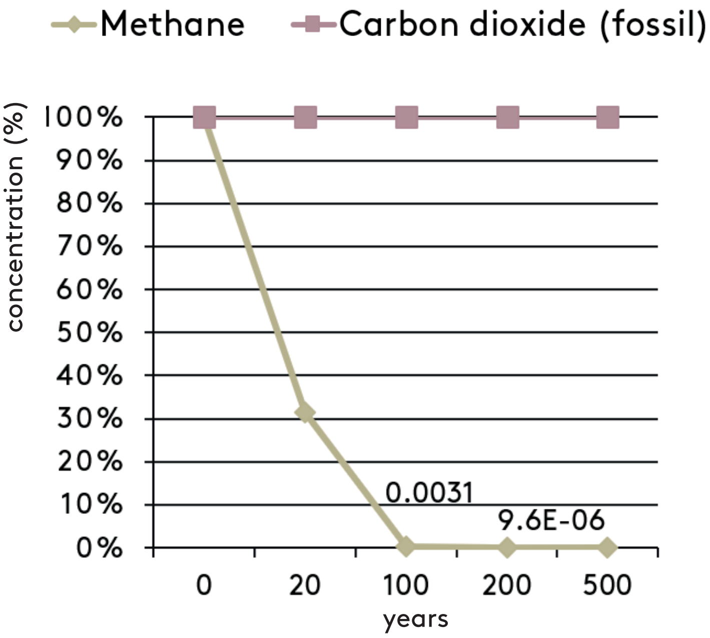


Figure 3. Concentration in the atmospheric over time for emissions of methane and carbon dioxide

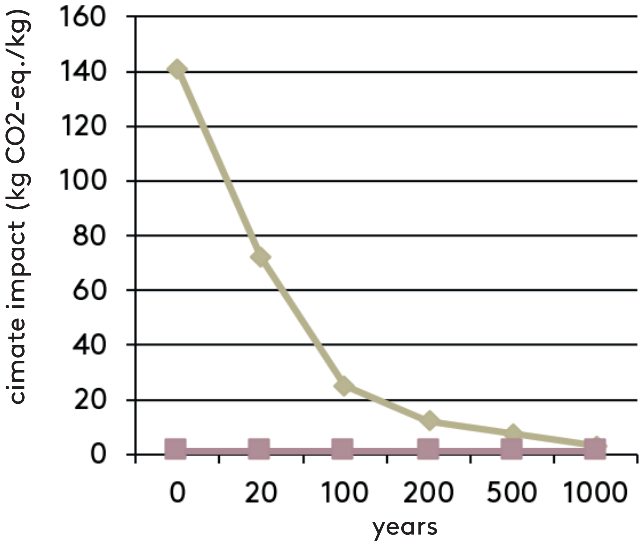


Figure 4. Climate impact expressed as CO2 equivalents of methane and carbon dioxide in relation to the time scale over which it is measured.

The fact that methane emissions from sheep farming are biogenic means that it matters greatly on what time scale the climate impact is calculated for. The half-life of methane is 12 years, so after 12 years half of the methane has been broken down to biogenic carbon dioxide, which is most often considered not to contribute to global warming (IPCC 2007). After 200 years, basically all methane has been broken down to biogenic carbon dioxide, see Figure 3. The implications of this removal of methane from the air are that the contribution to global warming is reduced correspondingly over time.

The current consensus for calculations of GWP is to use a 100-year time horizon (GWP100). On this time scale the GWP is 28 kg CO2-equivalents per kg methane. Some studies also report results using GWP20 or GWP500; calculated on 20 years basis the GWP of methane is 84 kg CO2-equivalents per kg (IPCC 2013) and calculated on 500 years basis the GWP is 7.6 kg CO2-equivalents per kg methane (IPCC 2007). Figure 4 shows how the potential contribution to global warming from the emission of 1 kg of biogenic methane will be similar to that of 1 kg fossil carbon dioxide when the time scale is longer. Which time scale that is selected can depend on, for example, whether the aim is to stabilize the anthropogenic temperature change (in the long term) or if focus is on early mitigation (Johansson et al. 2008).

On the other hand, one could argue that to stabilize the temperature in the long term, threshold effects must be avoided, and therefore early mitigation is necessary. Regardless of one’s view on the urgency of climate impact mitigation, one should be aware about the fact that the time perspective chosen has considerable influence on the climate impact of emissions of biogenic methane vis-à-vis fossil carbon dioxide, and thus influence on the climate viability of wool vs. other fibers. Having said this, it should be acknowledged that with the current consensus on climate impact assessment method, namely GWP100, methane emissions from sheep are seen as a significant contributor to climate change and thus wool most often yields a high climate impact in relation to other fibers.

4.1.2 cotton fibers

Cotton is the fiber for which most data were found: 14 studies cover 50 different production routes. In addition, data were found in databases and in Higg MSI. Studied production routes span different geographical scopes: global, national and regional averages, and different farming practices, in terms of irrigation, tillage, fertiliser rates, pesticide use and cotton varieties (e.g. GM and non-GM), reflecting various modes of conventional and certified (organic, REEL and CmiA cotton) farming. Climate impact and water use/depletion are the most studied impacts, considered in 11 studies (corresponding to 79% of studies), followed by eutrophication (7 studies, 50% of studies), energy use (6, 43%), toxicity (5, 38%) and land use and related impacts (4, 29%). Water, eutrophication and toxicity data is more commonly included in studies of cotton, compared to studies of other fibers, which probably is because cotton is viewed as a thirsty plant grown in arid regions, which requires large amounts of toxic pesticides and eutrophying fertilisers. So, overall, cotton is a relatively well-studied fiber. In terms of climate impact, water use/depletion and energy use, the methods used are quite similar, which makes it possible to get a relatively robust understanding of what a typical impact is for cotton. For other impact categories, the data is too sparse to get a similarly robust understanding.

Climate impact of cotton fibers is often calculated to be in the range 0.5 to 4 kg CO2 equivalents per kg fibers (excluding CO2 sequestered in the fiber), but it is not unusual with results up to about 6 kg CO2 equivalents – so the variations span about one order of magnitude. Moreover, organic cotton generally results in a bit lower climate impact compared to conventional cotton[13] , mainly due to less use of artificial fertilisers whose production is CO2 intensive (see, e.g., Kalliala and Nousiainen (1999)and Cherret et al. (2005)). But the data behind this observation is scarce and relatively old; to be more conclusive regarding the climate impact of organic vs. conventional cotton, there is a need of more and updated studies comparing the two farming practices, for example reflecting more updated organic and conventional practices. Other site-specific farming characteristics (beyond the more general differences between conventional farming and farming adhering to a certain certification scheme) also seem to considerably influence the climate impact (see, e.g., Khabbaz (2010)).

Other studied certifications (REEL and CmiA) are covered in too few studies to enable robust comparisons vis-à-vis conventional cotton or other certifications. Notably, BCI cotton has not been covered[14] in any of the studies, although it makes up 10-30% of the global cotton market. Thus, there is a need for studies of BCI cotton. As a basis for such a task one could use the available country-level data on the use of pesticides, synthetic fertilisers and water, which do indicate some potential benefits vs. "comparison farmers" (BCI 2014).

Site-specific characteristics, more so than regional ones, appear to be very influential for the water use of cotton farming, and even more influential for the impact of water use on water stress and water depletion (see Figure 5).

[12] When discussing the environmental impact data of cotton in Table 5, "conventional" is interpreted in a broad sense, including both the production practices explicitly described as being conventional (which are termed "conventional cotton" in the table), but also those without any description (simply termed "cotton"), as data on the latter most probably is derived from conventional farms, or at least from a set of farms dominated by conventional practices.
[13] Unless if BCI cotton is included in some of the datasets for which farming practices are not specified; but this is unknown.

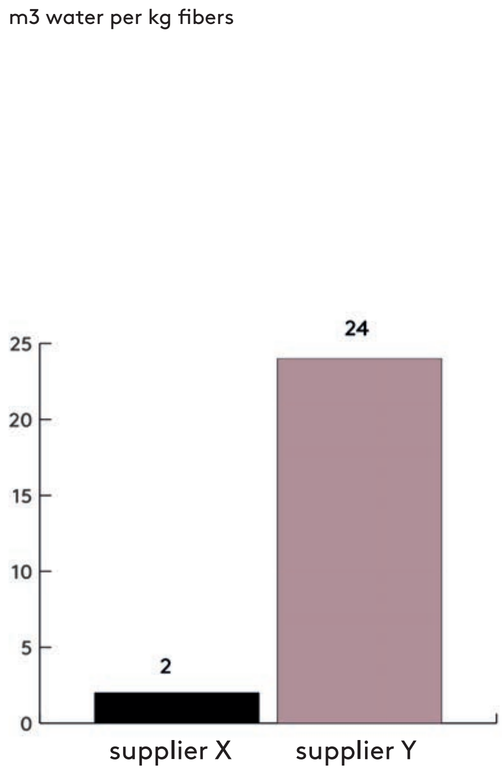


Figure 5. visualization of different site specific water usage, comparing the extremes.

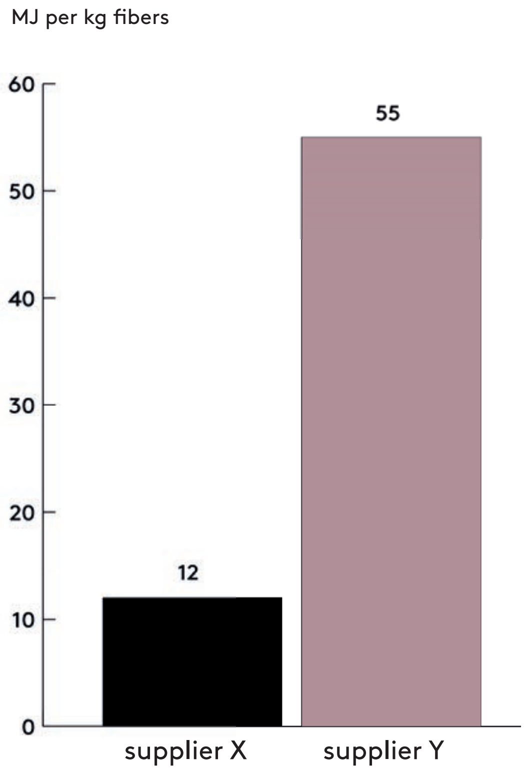


Figure 6. visualization of different site specific electricity usage, comparing the extremes.

Total water use ranges from a few up to 24 m3 per kg fibers, with blue water use[14] (mainly irrigation) constituting from none to all of that (note that database data generally yields lower numbers, but as this data is presented in m3 equivalents it is not directly comparable to the literature data in m3). Although organic cotton in general uses less blue water than conventional cotton, variations between regions and sites are larger than variations between the averages for conventional and organic cotton (Chapagain et al. 2006; Safaya et al. 2016).

Grey water use (a virtual metric accounting for direct water use as well as the water needed to dilute water emissions to a certain quality) can be up to several hundred m3/kg fibers, and is in several cases much higher for conventional than organic cotton; but once again, the differences between sites are enormous, and some conventional farms have lower grey water footprints than some organic farms (Chapagain et al. 2006; Safaya et al. 2016). As grey water footprint can be seen as a proxy for eutrophication as well, the same site-specific dependency is evident also for eutrophication.

Literature data on energy use suggests cotton fiber production require from 12 to 55 MJ per kg fibers (see Figure 6), whereas database data suggests numbers up to about 90 MJ/kg. We have not carried out an in-depth analysis of underlying factors behind these variations, but it is an expected consequence of the variations in tillage practices, rate of synthetic fertiliser use, harvesting equipment and similar.

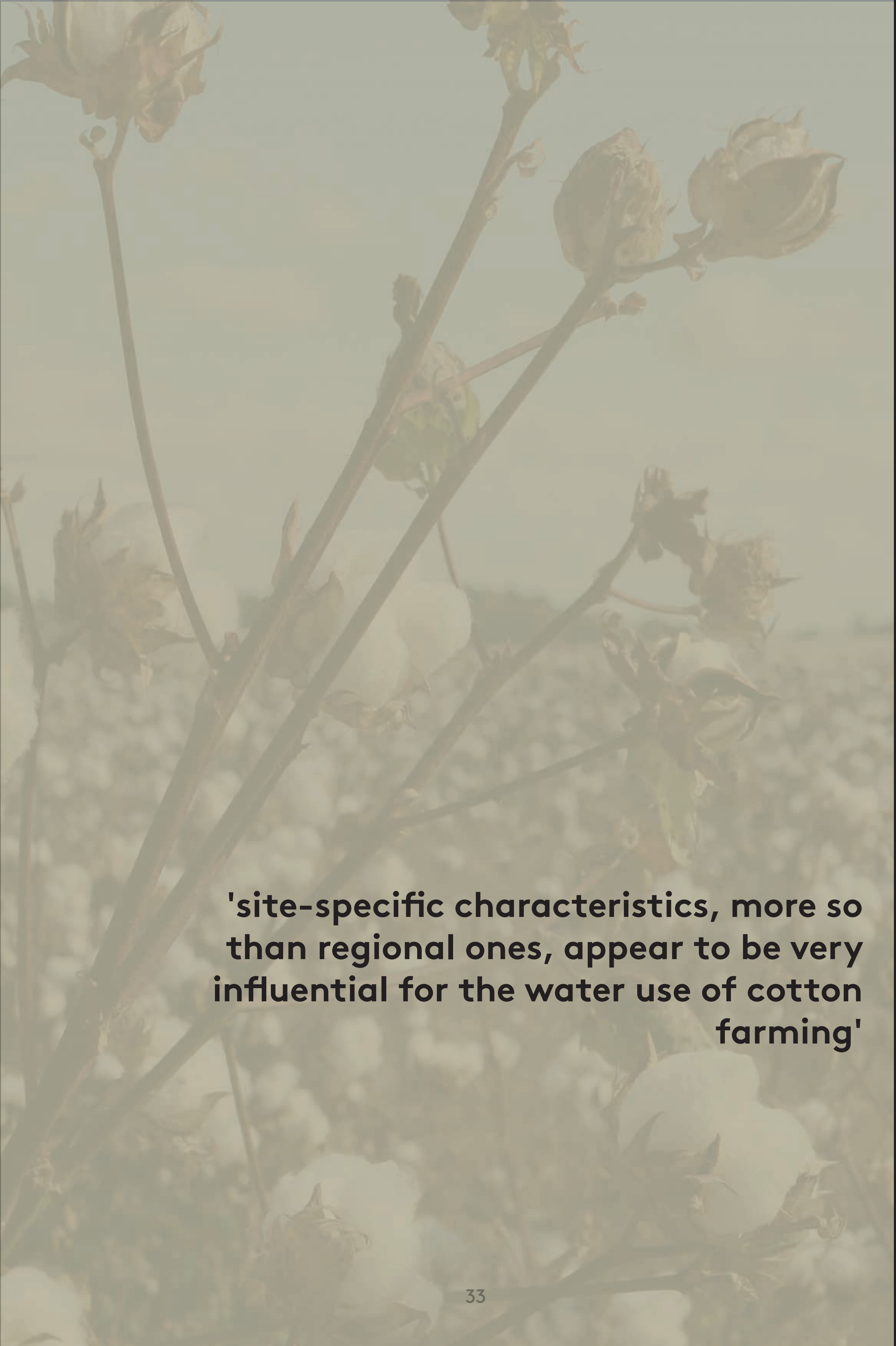
[14] Blue water use means use of water that has been sourced from surface or groundwater resources. This is distinguished from green water, which origins from precipitation that is stored in the root zone of the soil and evaporated, transpired or incorporated by plants. Sometimes also grey water use is reported, which is the amount of freshwater required to dilute pollutants to meet specific water quality standards.

For toxicity and land use impacts it is difficult to draw any general conclusions, as there are but a few studies which most often use different (non-comparable) characterisation methods (see Chapter 2.2.3). The lack of studies, and the great variety of methods used, is probably largely due to the challenges of measuring toxic and land use impacts in LCA.

There are reasons to believe that, for example, organic cotton farming has advantages in terms of these impacts, as it restricts the use of harmful pesticides and put requirements on soil management, such as crop rotation, that most likely enhances long-term soil quality (compared to non-organic farming, in general). On the other hand, these requirements – and the exclusion of genetically modified cotton varieties – may cause lower yields, at least in the short term, which may enhance some land-related pressures. Without quantitative evidence shedding light on this discussion, potential benefits (and risks) of non-conventional cotton farming may be overlooked and disregarded in decision-making in the textile industry. Methods that increasingly enable quantitative and fair comparisons of different farming practices are needed, so that environmentally preferable practices can be encouraged. Fortunately, there is ongoing development both in land use and toxicity impact assessment methods (De Baan et al. 2013; Koellner et al. 2013; Jolliet et al. 2018; Roos et al. 2017). There is also a need to build a consensus regarding what methods to use, to allow comparisons across studies, and then to adopt those methods in practice.

Noteworthy are the differences between the numbers reported by Cotton Inc (2012) and the numbers derived when characterising the Ecoinvent 3.3 datasets on cotton, which are based on Cotton Inc (2012), and the GaBi Professional dataset on global average conventional cotton, which is also based on Cotton Inc (2012). There are differences also in the Ecoinvent 3.4 datasets as implemented in SimaPro, which also is based on Cotton Inc (2012). For example, the climate impact, excluding carbon sequestration, reported by Cotton Inc (2012) for global average cotton is about 1.8 kg CO2 equivalents per kg cotton. Using the ILCD method to characterise the Ecoinvent 3.3 dataset in GaBi the result was about 3.4 kg CO2 equivalents and using the ILCD method to characterise the Ecoinvent 3.4 dataset in SimaPro it was about 2.4 kg CO2 equivalents. Instead using the dataset from the GaBi Professional database, and the GaBi software, the result (also with the ILCD method) was about 1.4 kg CO2 equivalents. So in four different sources, allegedly based on the same original source (the study underlying the Cotton Inc (2012) report) and the same impact assessment method, the climate impact results are very different.

The higher results for the Ecoinvent 3.3 dataset is known to be due to an error in the unit when energy use data was inserted: MJ was mixed up with kWh – this error has been confirmed in E-mail correspondence with ThinkStep (formerly known as PE International), the company which is behind the GaBi software and database, and also wrote the Cotton Inc (2012) report and implemented the data in Ecoinvent. This error was corrected in the Ecoinvent 3.4 version, which means that the difference between the calculated result in SimaPro and the original data from Cotton Inc is not explained by this error. Possibly, the remaining differences could be because of different allocation procedures and/or differences in the background processes (e.g. different data on the production of electricity or fertilisers). The conclusion is that there is a need to consider the influence of the software and different implementations of databases and impact assessment methods when interpreting LCA results. Some more examples of deviating results for seemingly identical datasets are given in Appendix 2.



'site-specific characteristics, more so than regional ones, appear to be very influential for the water use of cotton farming'

4.1.3 non-cotton plant fibers

Six studies and seven datasets were found that include environmental impact data on non-cotton plant fibers. Four of the studies include data on flax fibers, three on hemp fibers, and one on jute and kenaf fibers. The datasets include data on jute fibers (rainfed or irrigated cultivation) and kenaf fibers. Due to the scarcity of studies, one must be careful in drawing general conclusions regarding the environmental impact of these fibers and the most influential factors causing variations between product systems. Therefore, below discussion is restricted to climate impact, for which all six studies, and the characterisation of the datasets, provided data using similar methods.

According to three studies, flax has a carbon footprint of between 0 and 0.8 kg CO2 equivalents/kg fibers (excluding CO2 sequestration), which is relatively low compared to other fibers. But in one study, the results were much higher: 11.2 to 18.6 kg CO2 equivalents per kg fibers (Dissanayake et al. 2009). Likewise, climate impact of hemp varies greatly, from about 0.3 to 6 kg CO2 equivalents per kg fibers (excluding CO2 sequestration). An important reason for these variations is likely the selection of allocation method: both flax and hemp farming are associated with high-volume and low-value by-products, meaning that mass-based and economic allocation yield very different outcomes. So, based on the identified data, it is difficult to be conclusive regarding the climate impact of flax and hemp fibers. The same is true also for jute and kenaf fibers, as only one study and a few datasets were found for these fibers (giving data in the range of 0.4 to 1 kg CO2 equivalents per kg fibers). Finally, it can be noted that the only study covering all the four fibers found the climate impact to be from 0.6 to 0.8 kg CO2 equivalents per kg fibers regardless of fiber type (Barth & Carus 2015). As the study used comparable methods for all fibers, the small range indicates that climate impact is quite similar for these fibers and that the most influential factor for climate impact is the choice of allocation method.

4.1.4 regenerated fibers

Four studies were found with environmental impact data of regenerated fibers[15] :

- Shen et al. (2010), which assessed several scenarios of viscose, lyocell and modal produced by the Austrian manufacturer Lenzing;

- Sandin et al. (2013), which assessed the environmental impact of a hypothetical future production system for a generic regenerated cellulose fiber; and

- Schultz and Suresh (2017), which assessed one lyocell and eight viscose production scenarios located in different places all around the world using different feedstocks.

- Laursen et al. (1997), which assessed one scenario of viscose production without specified geographical location.

All in all, these four studies cover 18 different production paths. In addition, an Ecoinvent dataset on viscose was found, which is also based on data provided by Lenzing, but from an earlier date compared to the data in Shen et al. (2010). The Idemat database also has a dataset on viscose, based on Shen et al. (2010). Finally, the Higg MSI database covers acetate, lyocell, modal and viscose fibers. The latter three datasets were provided by Lenzing, although modified to represent a general manufacturer.

[15] There are several more publications by Shen and colleagues which include data on regenerated fibers, but they are all based on the same original study.

Two drawbacks of the identified data are that much of it is derived from one manufacturer, Lenzing, and that the recent studies not using data from Lenzing (Sandin et al. 2013; Schultz & Suresh 2017) use unconventional impact assessment methods, making it difficult to compare results across the studies. Despite the drawbacks, the multitude and diversity of production routes covered by the data still enables some conclusions regarding influential factors.

Climate impact[16] spans from about -2 to 13 kg CO2 equivalents per kg fibers according to Schultz and Suresh (2017) (not using GWP100, but GCC, see original report for further clarification) and from about 1.7 to 5.5 kg CO2 equivalents per kg fibers according to Shen et al. (2010), excluding CO2 sequestration. In a sensitivity analysis, Schultz and Suresh (2017) also shows results for GWP100 using the CML method, which yields results from 1.6 to 8.3 kg CO2 equivalents per kg fibers (Table 2.4 shows the identified environmental impact data on regenerated fibers). Thus, climate-wise, regenerated cellulose fibers can be among the best in class, or among the worst in class, depending on the characteristics of the specific production path. Influential factors, for climate impact as well as for several other studied environmental impacts, are: (i) where the wood feedstock is sourced from (e.g. whether it causes deforestation or not), (ii) whether or not fiber production is integrated in the pulp mill[17], (iii) whether renewable or non-renewable energy is used as input in fiber and pulp production (which in turn often depends on geographic location), and (iv) under what conditions key input chemicals are produced (for viscose, primarily sodium hydroxide and sulphuric acid).

Water use ranges from 0.290 to 0.740 m3 per kg fibers according to Schultz and Suresh (2017), and from 0.263 to 0.472 m2 per kg according to Shen et al. (2010). The water use is 0.64 m3 according to Laursen et al. (1997). These numbers include industrial water use only (i.e. blue water), so water used by the tree during growth is excluded, probably because this is not seen as a consequence of the fiber production system (tree growth would occur anyway) and/or because water stress is not a major issue in (most of) the regions from which wood is sourced. That is, the numbers in the present report suggest regenerated fibers use much less water than, for example, cotton (about one to two orders of magnitude less), but due to the different scopes of the data, one should be cautious in drawing conclusions solely based on these numbers. Nonetheless, cotton in general uses more blue water in cultivation, and cotton cultivation in general takes place in more arid regions where water use contributes to water deprivation – but not all cotton cultivation relies on irrigation water and/or is located in arid regions, and not all feedstock cultivated for subsequent pulping and fiber production are without effects on local water systems. The latter point was shown by Sandin et al. (2013), who found that land use practices can influence the water deprivation impact of regenerated (and cotton) fibers.

So once again, the reviewed environmental impact data suggests that one should be careful in comparing data of different studies of different fibers and based on such comparisons make too general judgements or ratings about a specific fiber type. Instead one should consider the nuances within each fiber type, and encourage the best in class, both in terms of its direct environmental impact as well as the fiber's influence on the subsequent product life cycle, as will be discussed further on in this report.

[16] This refers to global climate impact; Schultz and Suresh (2017) also assessed regional climate impact, in terms of aerosol loading.
[17] So-called dissolving pulp is the input to regenerated fiber production.

4.1.5 polyester fibers

Polyester fibers are the second most studied fiber type after cotton. The polyester polymer is also used in other products (water bottles, electronics, vehicles etc.) and data for polyester granulate is therefore relatively abundant though mostly originating from the PlasticsEurope's Ecoprofiles (Boustead 2005). Therefore, some granulate datasets are shown in the present study as well. Ten studies treating polyester in textile applications were found in addition to data in databases and in Higg MSI. It is important to differentiate between when the figures describe polymer granulate production, melt spinning or fiber production (polymer granulate production and melt spinning). It can also be highlighted that different types of crystallization (bottle grade or amorphous) can give different results and that polyester used for textiles is best represented by the amorphous grade (low degree of polymer chain orientation).

Some of the studies found compare petroleum-based polyester fibers with bio-based or recycled fibers. The latter fibers are generally shown to be environmentally favourable. Energy consumption is the most common environmental aspect that is covered in the studies. The energy figures can describe both direct consumption of energy and the primary energy use, including the energy available in the feedstock (gross calorific value)[18]. In several studies it is not clearly documented what the figures contain. The primary energy use figures for the production of virgin polyester granulate span from 67 to 96 MJ/kg whereas the figures for recycled granulates span from 8.5 to 48 MJ/kg. Figures for bio-based polyester span from 51 to 59 MJ/kg.

The fiber spinning that creates fibers is not easily separated from the filament yarn spinning. Polyester fibers are melt spun into filaments, after which they are drawn and textured into filament yarns or cut into staple fibers (usually 38 mm) to produce spun yarn, depending on the application (Roos 2016). The figures for energy use in the spinning fibers often originally from Brown et al. (1985), with 0.64 kWh/kg direct electricity use and 5 MJ/kg in terms of steam, but it is unclear whether this is on ready-made filament fibers or on fibers before the drawing. For spinning to staple fibers, figures between 3.2 and 11.7 MJ/kg (electricity + heat) are given, for partially drawn and not textured filament the energy figures span from 0.3 kWh (1.1 MJ)/kg to 13.6 MJ/kg (the latter figure is probably primary energy use though this is not stated).

For the total fiber production (staple or filament) the energy use is between 96 and 125 MJ/kg. The calculated climate impact of polyester fibers ranges from 1.7 to 4.5 kg CO2 equivalents per kg fiber. Data about other impact categories than energy use and climate change is scarcely reported for synthetic fibers, and the figures on for example toxicity and eutrophication in databases are expected to origin from background processes rather than direct emissions (Roos et al. 2015). One source gives data for water use during production of polyester fiber: 62 liters per kg fiber (Muthu et al. 2012). Main influential factors for climate impact results are: (i) the energy system with which the fibers are produced, and (ii) the choice of database data used to represent the production of fossil granulate materials.

None of the LCA studies describe the issue with microplastics shedding from synthetic polymers which has recently come up as a major important aspect of synthetic fibers, regardless of the material origin (fossil, bio-based, recycled) (Roos et al. 2017).

[18] The gross calorific value is 23.1 MJ/kg for PET, 19 MJ/kg for PLA and ~15 MJ/kg for regenerated fibers according to Shen et al. 2012.

4.1.6 non-polyester synthetic fibers

Synthetic fibers other than polyester are less well studied. Just as with polyester, the different polymers are also used in other products (packaging, electronics, vehicles etc.) and data for the granulates are relatively abundant, especially those covered by the PlasticsEurope's Ecoprofiles (Boustead 2005), while data for fibers is scarce. Also here it is important to note when the figures describe polymer granulate production, melt spinning or fiber production (polymer granulate production and spinning (melt spinning, dry spinning and sometimes wet spinning)). In most studies, spinning is assumed to be the same for different polymers; in one case it is assumed that the fiber extrusion process costs half the energy for PLA as for polyester (Shen et al. 2012). Fiber spinning is therefore covered in Table 8 for polyester fibers and not repeated in Table 9 for non-polyester synthetic fibers.

The found climate impact results of all the fibers and granulate processes range from 1.94 kg CO2 equivalents per kg granulate (PE) to 324 kg CO2 equivalents per kg granulate (PTFE). The figure for polytetrafluoroethylene (PTFE), common in outdoor garments, is a special case where the production of tetrafluoroethylene monomers has a calculated climate impact of 324 kg CO2 equivalents per kg. This is due to plausibly erroneously modelled emissions of small amounts of extremely potent greenhouse gases (Althaus et al. 2007), which does not represent the reality very well; in contrast, the newer data in the Idemat database gives a value of 8.01 CO2 equivalents per kg granulate (Idemat 2018). For polyamides (PA6, PA66, EVO) which is the second most produced synthetic fiber after polyester, the calculated climate impact of polyamide granulate range from 8.0 to 9.4 kg CO2 equivalents per kg fiber. In recent years the production of PA66 has been improved from a climate point of view as the abatement of emissions of N2O (a potent greenhouse gas) for the adipic acid route has been developed (Shimizu et al. 2000). The main influential factors for climate impact results are the same as for polyester fibers: (i) the energy system with which the fibers are produced and (ii) the database data used to represent the production of fossil granulate materials.

The primary energy consumption for fibers and granulate processes range from 35 to 250 MJ/kg; the first figure is for PLA and the latter for nylon (unspecified which kind). The large range and lack of details indicate a large uncertainty in these figures.

'there is a risk that new and better fibers are, in decision-making, undervalued and unappreciated in relation to established fibers for which environmental impact data is available.'

4. 2 the performance of many fibers is unknown due to data gaps

Above subsections have focused on what was found in the search for data. It is also interesting to talk about what was not found. As noted in the method section, initially the intent was to map data of "new sustainable textile fibers", but due to the lack of such data, the scope changed.

In Section 4.1.1, the lack of data of certified cotton was noted, but there is also a glaring lack of data of more or less all new and potentially more sustainable fibers: synthetic fibers made by bio-based or recycled feedstock, artificial protein fibers, regenerated fibers made via new production routes or from new bio-based or recycled feedstock, plant fibers still only grown in small amounts, etc. These data gaps encompass talked-about fiber/brand names like Sorona, Econyl, Recyclon, Orange Fiber, Qmilk, Evrnu, Ioncell-F and Infinited fiber, to name a few (more information is found in Rex et al. (2019)). These are fibers which are associated with claims of greater sustainability – and there are strong reasons to believe several of them indeed can be environmentally preferable – but without publicly available (and transparent) data backing up such claims, their environmental claims can be questioned.

Using some kind of "waste" or by-product that would otherwise be burned or landfilled, or using a process that does not rely on toxic carbon disulphide (viscose) or explosive NMMO (lyocell) for dissolving cellulose prior to regenerating new fibers, are solid starting points. But the final fiber may still not be an environmentally sound option, for example without sufficiently efficient processes in terms of energy, water and chemical use, without or lacking appropriate waste management, if some problematic by-product is produced, if the fiber quality is poor, or if there is no suitable end application. So LCA studies are needed to ensure the environmental performance of new fibers, and the data coming out of such studies should preferably be openly and freely available. Without such data, there is a risk that investments in new fiber technologies are not made where there are greatest potential gains. There is also a risk that new and better fibers are, in decision-making, undervalued and unappreciated in relation to established fibers for which environmental impact data is available.

Having said this, there are of course reasonable explanations for why data is scarce for new fibers, especially those not yet existing in commercial scale: producers and brands are understandable restrictive in disclosing data until large commercial scale has been realised – because they simply don't yet know the data, or because smaller scale operations, or even newly built large scale operations, are not as efficient as large-scale operations that have been fine-tuned for years. Exposing data too early can constitute a business risk.

It should be stressed that there is also scarcity of environmental impact data of established fibers produced in large scale. Previously we have noted BCI cotton as one example, and only one or a few studies were found on fibers such as organic cotton and Cotton made in Africa (CmiA). It should be noted that CmiA is sometimes sold as BCI cotton since they have benchmarked against BCI and meet the BCI requirements.

Noteworthy is that not much data was found for fibers from recycled feedstock. More data is, however, available on textile recycling if the scope is expanded beyond fiber production. Recently, 41 studies of the environmental impact of textile recycling (and reuse) were reviewed by Sandin and Peters (2019), who found that there are potential environmental gains of textile recycling in general, but that there are cases in which the gains are questionable, for example if the replacement rate is too low – that is, if production from virgin resources is only replaced to a low degree – or if the environmental impact of the replaced existing production process is low.

To conclude, fiber producers are urged to publish data of the environmental impact of their fibers, whether they are novel or established. Preferably the studies behind those data should have undergone third-party review as recommended by the ISO 14040/44 standards (ISO 2006a; ISO 2006b), be openly and freely available, and written in a transparent manner. Here, Lenzing can be mentioned as a good example of a fiber manufacturing disclosing data, as they have provided much of the data available on regenerated fibers.

4. 3 environmental performance depends on in which product the fiber is used – the life cycle perspective

The possibilities for fibers to be used in different types of textiles will depend on the quality of the fiber in terms of mechanical and comfort properties, which are described in Rex et al. (2019). In a life cycle perspective, the garment life length is a crucial aspect for reducing the environmental load also from the fibers, so it is essential that the fibers do not negatively influence the garment life length, see Figure 7.

Synthetic fibers have superior mechanical properties in terms of strength, abrasion resistance, etc., compared to all other fiber types (Rex et al. 2019). Therefore, for garments with high demands on technical strength, synthetic fibers are often the superior sustainable choice also if they are based on fossil resources. How many times a garment is used does not only depend on the technical performance however, but also on the consumer's needs (real or perceived needs) (Haeggblom 2017). For garments that are designed to be short-lived (e.g. garments with a high fashion grade, or t-shirts printed with an event logo on) there is a much higher variety of fibers that can be suitable to use.

For the environmental performance, the ideal would be to use the "best-in-class" fibers for each application – not oversize the fiber quality at the cost of a higher environmental burden from production, but neither undersize it at the cost of a higher environmental burden due to shorter life span of the end product. One way of achieving this can be to put more emphasis on the "speed" of the material in the design of textile products, e.g. to use durable fibers for slow fashion and more brittle (and easily recyclable) fibers for fast fashion. How to consider material speeds in design processes has been explored in other projects of Mistra Future Fashion (Early & Goldsworthy 2016; Goldsworthy 2017).

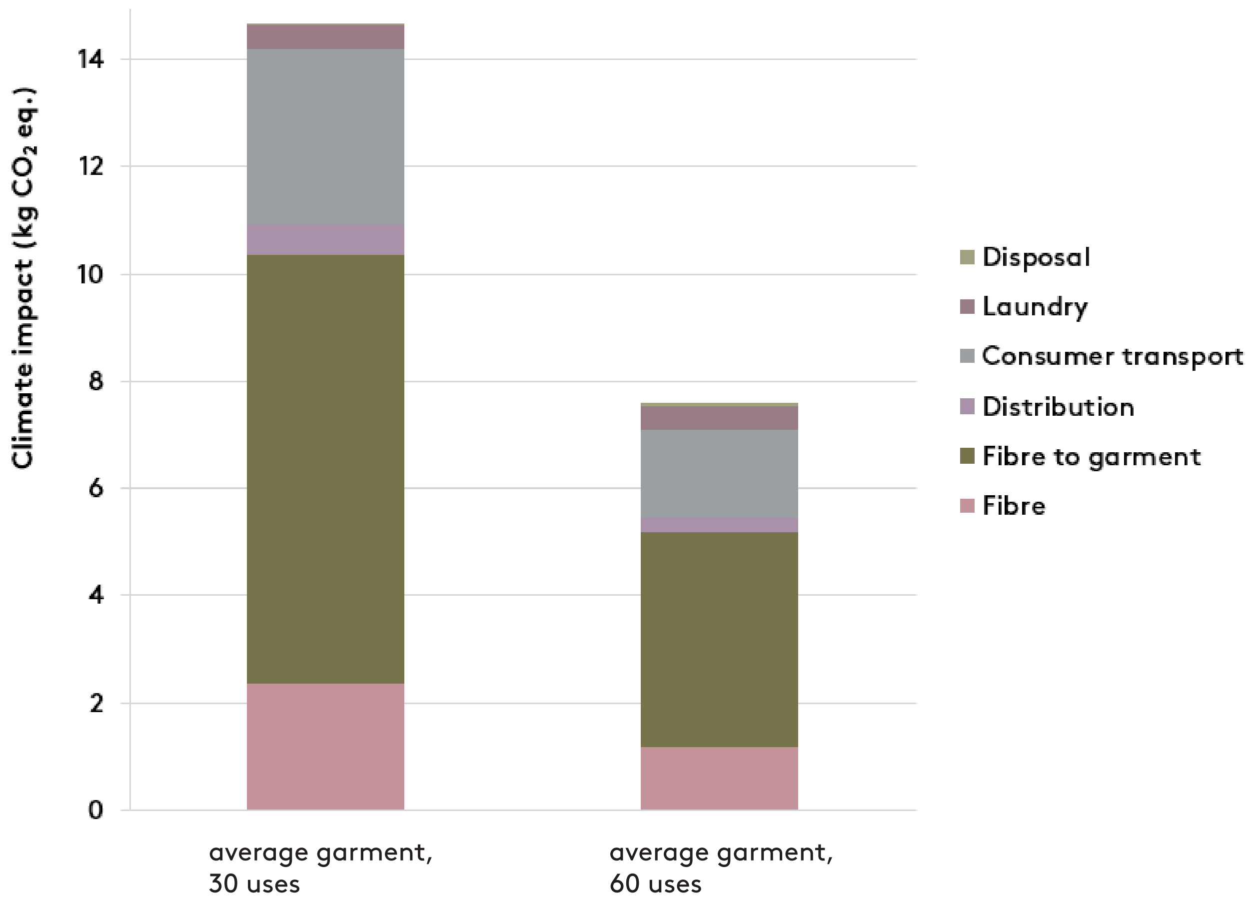


Figure 7. Climate impact expressed as kg CO2 equivalents and calculated for a hypothetical average garment of 0.5 kg. A doubled life length, from 30 uses of the garment (left) to 60 uses of the garment (right), decreases the climate impact by 52% - from 14.7 to 7.6 kg CO2-equivalents. Modified from Roos et al. (2015).

4. 4 key environmental aspects depend on the time perspective

Over time, what are considered key environmental aspects of the textile industry may change, as may the performance of different fibers. Below is a discussion of two examples on what can be future challenges – or problems that will be solved.

1. Energy system changes to more renewable energy resources

Today, the major part of the climate impact generated under the textile life cycle is caused by the use of electricity and heat during the textile production processes – from fiber to garment, see Figure 8.

In the future, the use of renewable energy resources (wind, solar, etc.) is predicted to increase and the use of fossil energy resources (petroleum, coal, natural gas, etc.) is predicted to be phased out. This transition is foreseen although it has not yet happened: in 2017 the global use of fossil energy resources increased instead and carbon emissions rose for the first time since 2014 (IEA 2018). More than 70% of the global energy demand growth was met by fossil fuels. Despite uncertainty in the time horizon for a predicted transition to renewables, as well as sustainability concerns of e.g. conflict minerals used in the production of solar panels, the vision of the future is that energy will be produced at a much lower environmental cost. The contribution of various life cycle phases, as depicted in Figure 8, may then change considerably, and perhaps climate impact from land use and land use change – in other words, climate impact associated with the production of natural fiber feedstock and bioenergy used throughout the garment life cycle – may become more important in relative terms (Godfray et al. 2010.

2. By-products from regenerated fibers become hard to handle at a larger scale

In the production of viscose and similar types of regenerated fibers, one of the key environmental aspects is the large consumption of sodium hydroxide and sulphuric acid. These chemicals are needed for the process and will generally leave the process as a by-product: sodium sulphate. For each tonne of viscose fibers produced, about 1.3 tonnes of sodium sulphate will be generated; the amount of by-product is larger than the target product (Shen & Patel 2010). Today this by-product can be a valuable resource for the cosmetics industry that uses sodium sulphate to produce soap and similar products. However, the market is today close to saturated and a large scale-up of this type of regenerated fibers likely means that much of these by-products will become waste. There are also other types of regenerated fibers, for example lyocell which is spun in the solvent NMMO which is recycled in the process (Shen & Patel 2010). Here the problem with large amounts of by-products is not a hinder for scale-up.

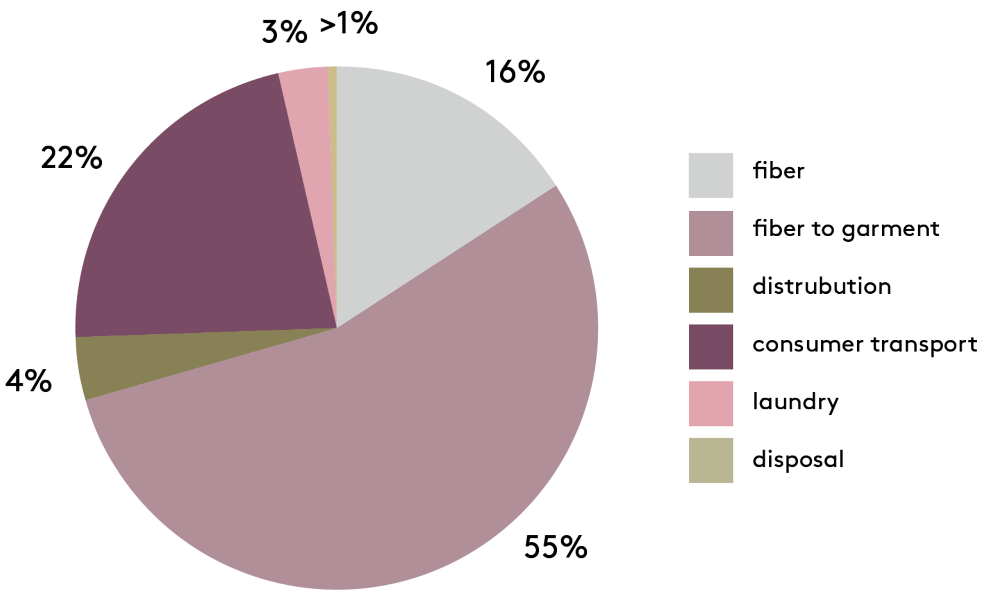


Figure 8, Climate impact from the different life cycles of a garment (Roos et al. 2015).

4. 5 some environmental impacts are better covered than others

There are more data available for some impact categories than others. Data of climate impact, water use and energy use is more common than data of toxicity and eutrophication impact, which in turn is more common than data on land use and (especially) its subsequent effects on ecosystems, such as impact on soil quality, soil erosion and biodiversity. Further, there is generally no or little information about the uncertainty of data, and comparing two datasets without information about uncertainty doesn't make scientific sense.

The land use impact is a particularly problematic data gap when assessing bio-based fibers relying on either forestry or agriculture, especially if one wants to compare different forestry/farming practices, for which soil quality or biodiversity benefits are often the expected prime difference between practices and perhaps even the prime driver behind the introduction of non-conventional practices in the first place. This data gap is potentially a road block in the development and diffusion of better land-use practices, because the better practices are at risk of being undervalued or even disregarded in decision-making if the benefits cannot be quantified, especially as they are often – at least initially – more expensive.

A higher resolution of land use and farming practices is also necessary to be able to answer questions on which fibers compete with food cultivation about land resources, and if there is a risk for deforestation of rainforests or other sensitive habitats. In the end this can favour non-bio-based fibers and conventionally farmed (and, at least in the short term, less land-intensive) plant fibers.

The lack of data for toxicity and land-use impacts is probably largely due to the difficulties in collecting inventory data for such impact and translating these data into quantified environmental impact – well-known shortcomings of LCA methodology. The reason for these difficulties is chiefly that toxicity and land-use impacts are local in nature. In other words, the impact is highly dependent on where the environmental pressure – a toxic emission or a land occupation – occurs. A given pressure may be harmless in one place, but utterly devastating elsewhere. Besides, it is far from straightforward to define which quality of an ecosystem that is important and relevant to consider. Take a concept such as biodiversity as an example, which can refer to the diversity of ecosystems, species or genes. Even if it is decided that species is the relevant biodiversity aspect to consider, and that a certain group of species, such as vascular plants, is a suitable proxy for biodiversity in a certain ecosystem or region, it can be a completely irrelevant proxy in another ecosystem or region.

It is a great challenge to find a metric that is sufficiently broad in relevance and applicability to enable assessments of, and comparisons between, different kinds of bio-based production systems. And once a metric has been agreed upon, data must be collected and made available for the type of land and the type of disturbance that occurs in the product system one wants to study. For the moment, the existing metrics are easily misinterpreted, and expert knowledge is needed to be able to use the collected environmental impact data correctly based on how and for what purpose the underlying inventory data was originally collected and based on which methods were used to transform the inventory data into environmental impact data.

Despite these difficulties, great progress has been made in recent year in impact assessment methods for toxicity and land use (Jolliet et al. 2018; Roos et al. 2017), and the study by Schultz and Suresh (2017) of regenerated fibers proves there is a willingness to adopt new and non-established impact assessment methods in studies of textile fibers. To sum up, there are reasons to be optimistic that the environmental impact data of textile fibers eventually will become more complete in terms of the coverage of various impact categories.

4. 6 sustainability requires fiber diversity

As emphasised above, to use the full potential of each fiber is essential to tackle the sustainability challenges of the textile industry. This entails using durable fibers such as polyester for long-lasting products – or for several products in subsequent use phases – and using fibers that more easily worn out for short-lasting products, while developing recycling systems for managing such rapid material loops (Early & Goldsworthy 2016; Goldsworthy 2017). Phrased differently, this entails using fibers that answer to the diversity of user needs, not only the needs (perceived or "real" ones) of fast and slow fashion and different cultural expressions, but also needs in terms of the very different functions of a basic white T-shirt, a pair of regular blue jeans, the everyday underwear, your dream wedding dress (or suit), the frequently washed home textiles, that tough blue collar workwear or your favourite weather-proof jacket for the trekking adventure.

The importance of fit-for-purpose and the wide range of user needs imply that a sustainable fiber future will require a great diversity of fibers, in terms of raw material input, production paths and fiber properties. Fiber diversity is also important for maintaining healthy ecosystems and building resilient fiber supply. For example, growing a diversity of crops – that is, diversity in terms of feedstock for plant fibers, regenerated fibers and bio-based synthetic fibers – for instance through crop rotation or mixed cropping, can sustain or enhance soil services and promote pollinators (Bommarco et al. 2013) and make ecosystems and ecosystem services, such as supply of raw material, less sensitivity to disturbances (Elmqvist et al. 2003; Lin 2011). This will be particularly important in case the market share of bio-based fibers increases.

To conclude, it is unlikely that one or a few fiber types alone can constitute a future sustainable fiber supply. In contrast, fiber diversity enhances sustainability. This underlines the importance of being careful in exaggerating or simplifying sustainability claims of certain fiber types while rejecting others. The large differences between different manufacturers of the same fiber type must be acknowledged – through better systems for traceability, closer supply chain collaboration and more conscious sourcing – and the best manufacturers of each fiber type should be rewarded, and the worst rejected. And in the end, one must seek to use each fiber that is produced according to its full potential.

4. 7 technical substitution vs. market substitution

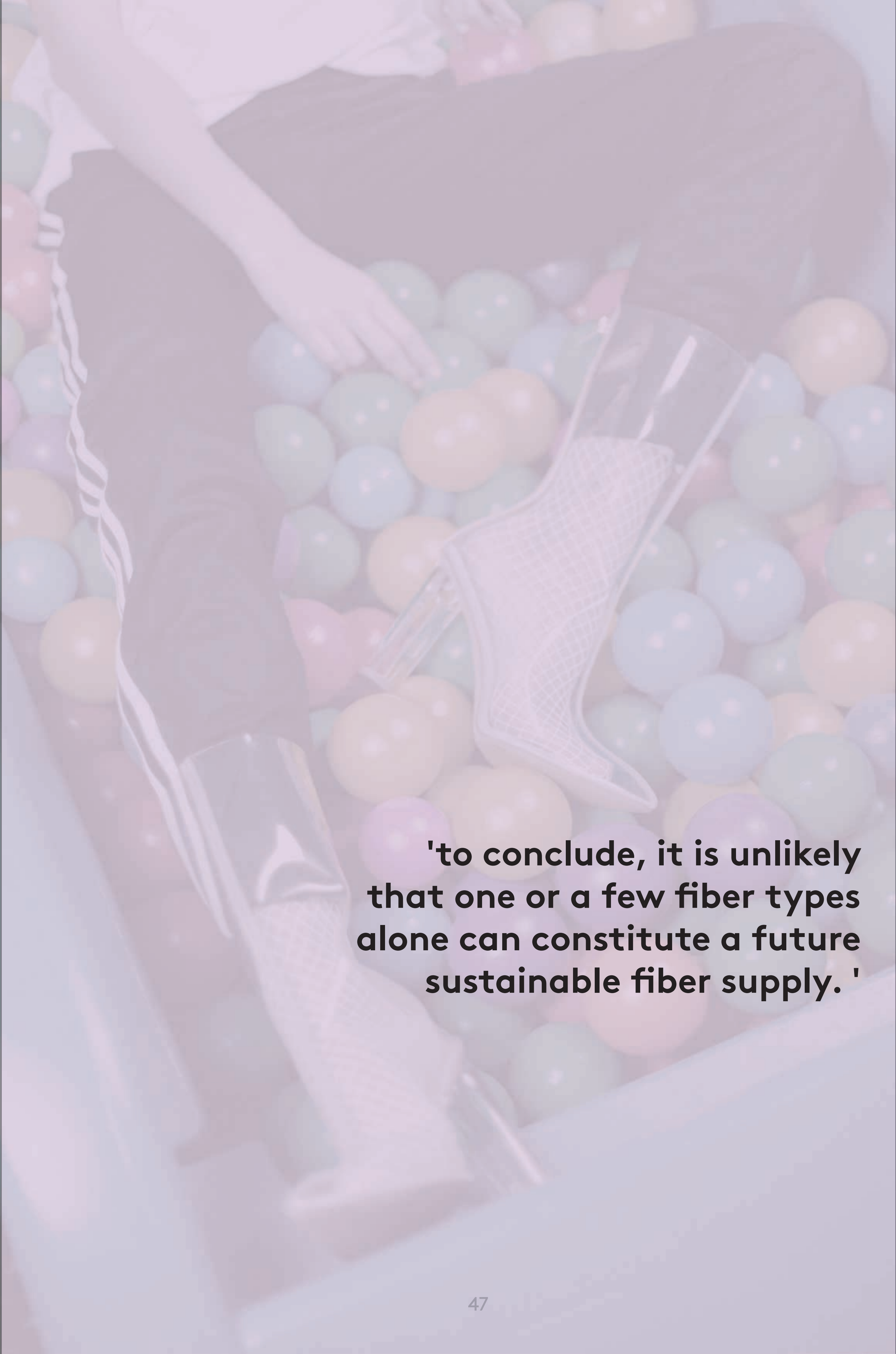
Are there any sustainable substitutes to conventional cotton today? The viewpoint that we must find new sustainable fiber alternatives to cotton is commonly advocated. To bring further clarity to the discussion we propose that the discussion about cotton substitutes is divided into:

1. Technical substitution. It is sometimes a discussion about producing fibers that behave exactly as cotton, for good and for bad (e.g. cotton needs much energy to dry).

2. Market substitution. It is sometimes a discussion about producing fibers that can be used in the same applications as cotton (e.g. wood-based regenerated fibers or polyester taslan fibers).

The high price of cotton and uncertainties in its supply historically has led to the development of alternatives. There are already many companies that have replaced cotton with wood-based regenerated fibers such as viscose and lyocell, and sometimes also polyester. With the right texturization, not even trained people can feel the difference between cotton and taslan polyester fibers. However, the properties of these substitutes are not identical to virgin conventional cotton, and the substitution is then market-based. Thus, to enable this kind of substitution the market demands may need to be altered.

If the market demands that new fibers substituting cotton must have identical properties to virgin conventional cotton, instead a technical substitution needs to be made. Today, there are no alternatives on the market that enable a technical substitution of cotton.



'to conclude, it is unlikely that one or a few fiber types alone can constitute a future sustainable fiber supply. '

5. conclusions

This report maps and discusses the available quantitative data on the environmental impact of textile fibers. LCA was used as framework since it is recognized as the most robust environmental assessment tool to provide the systems perspective required to accelerate the shift towards more sustainable consumption and production patterns. The ambition was to carry out the mapping and discussion in a transparent, structured and unbiased manner. Both conventional and newer, potentially more sustainable textile fibers were included since - under the right conditions - all fiber types appear to have the potential to be part of a sustainable fiber future. Below, key conclusions of the mapping and discussion are outlined.

The environmental impact of fibers depends not only on the fiber type but also on where and how the fibers are manufactured. The context in terms of scale, geography, energy sources, chemical suppliers and waste management can matter greatly, as will the final use of the fibers in different types of garments and the possibilities for reuse and recycling at end-of-life. Also, it is important to stress that a certain fiber type most often can be produced from different raw materials which influence the environmental performance. Likewise, a certain raw material is often found in different fiber types. Related to this, there is confusion around some terminology used for textile fibers, for example the term “cellulose fibers” is often used to describe regenerated cellulose fibers, although for example cotton is also a fiber consisting of cellulose.

Overall, there is glaring lack of data on the environmental impact of fibers – in several instances just a few studies were found, and often only one or a few environmental impacts are covered. For example, climate change and water use are relatively well-studied, whereas toxicity and eutrophication are scarcely studied. This means that there is a great potential for improving the knowledge about the environmental impact of textile fibers, both in terms of the number of fibers studied and in terms of a more comprehensive set of impact categories. The lack of data also means that some claims made about the environmental performance of fiber types or broad groups of fibers are based on rather few data points, and considering the large variations found between producers of a single fiber type, this constitute a weak basis for generalisations. Therefore, there is a need to scrutinise overly general claims about the environmental sustainability of textile fibers, and increasingly consider the circumstances of individual producers and how a specific use of a fiber influences its environmental performance, accounting for the environmental impact throughout the life cycle of the final textile product.

Early on when working with the report, a screening was made of so called “new sustainable fibers” (newly developed, non-conventional fibers associated with claims of greater sustainability; see Chapter 2.1 for further information about this screening). The screening led to the following conclusions:

1. First – even more so than for conventional fibers – data is often lacking for “new sustainable fibers” – producers and brands are (understandable) restrictive in disclosing data until large commercial scale has been realised, and even at that time data is scarce.

2. Secondly, there is no reason to restrict a study to “new” fibers – established fibers produced in new and better ways, or traditional fibers long undervalued, may be the sustainability winners of tomorrow.

3. Thirdly, there are great variations within each fiber type (as turned out to be consistent with later findings of the report): viscose produced with nearly closed chemical loops and renewable energy can be among the best alternatives, while viscose produced with irresponsible chemical management and coal power can be among the worst.

Because of these conclusions, the scope of the report expanded to a mapping of all available data on the environmental impact of all types of textile fibers. This mapping served two purposes: to reveal the data gaps and to showcase the variations between and within fiber types. Revealing the data gaps hopefully pushes the generation and disclosing of new data, which is fundamental for increasing the transparency of fashion, backing up sustainability claims, and building trust along the textile supply chain and among end users. Showcasing the variations between and within fiber types provides a more nuanced picture of the environmental performance of fibers, which can hopefully push and encourage the production and use of the better alternatives of each fiber type, rather than condemning entire groups of fibers. Thus, the report sends a strong recommendation to actors in the textile sector to request data on environmental performance and not just accept claims which have nothing backing them up – to minimize the risk for "greenwashing"[19] .

The report highlights some methodological concerns when calculating the environmental impact of fibers. There is a broad consensus and mature understanding regarding which environmental impacts (impact categories) that are relevant to assess in LCA as well as in schemes such as the Product Environmental Footprint (PEF), the UN Sustainable Development Goals (SDGs) and the Planetary Boundaries framework. The impact categories considered in the present study – climate change, water use/depletion, toxicity, eutrophication, land use and energy use – are important in all these schemes.

To some extent there is also consensus and ongoing harmonisation efforts regarding which methods to use for quantifying environmental impacts in LCA for each impact category (so called characterisation or impact assessment methods). However, some of the impact assessment methods are still under development and the LCA community is recurrently creating new recommendations for which methods to use when progress has been made. This makes comparison between older and newer studies difficult as these may use the recommended methods at two different occasions – or they may only use a subset of recommended methods due to a narrow scope or lack of data. There are also other methodological elements of LCA that influence results, such as the choice of allocation method. The present report highlights several examples of when different choices of LCA methodology have led to different results, which of course adds to the difficulty of attaining a consistent and unambiguous view of the environmental impact of a certain fiber type (or even a fiber produced at a specific site).

The variations within fiber types are exemplified by Figures 9 and 10, which show the span of climate impact and water use/depletion, respectively, in the collected data for each fiber type and for a selection of granulate types. For the fiber types not included in the figures, no data for climate or water use/depletion was found. The figures also illustrate the minor differences between granulates of different origin for some impact categories – compare the climate impact of PET granulates of fossil, bio-based and recycled origin. This indicates that changing to recycled or bio-based feedstock will not automatically and substantially improve the environmental performance of PES fibers – also the environmental performance of background systems (e.g. the electricity used) and subsequent production steps (e.g. melt spinning) must be considered.

[19] https://en.wikipedia.org/wiki/Greenwashing

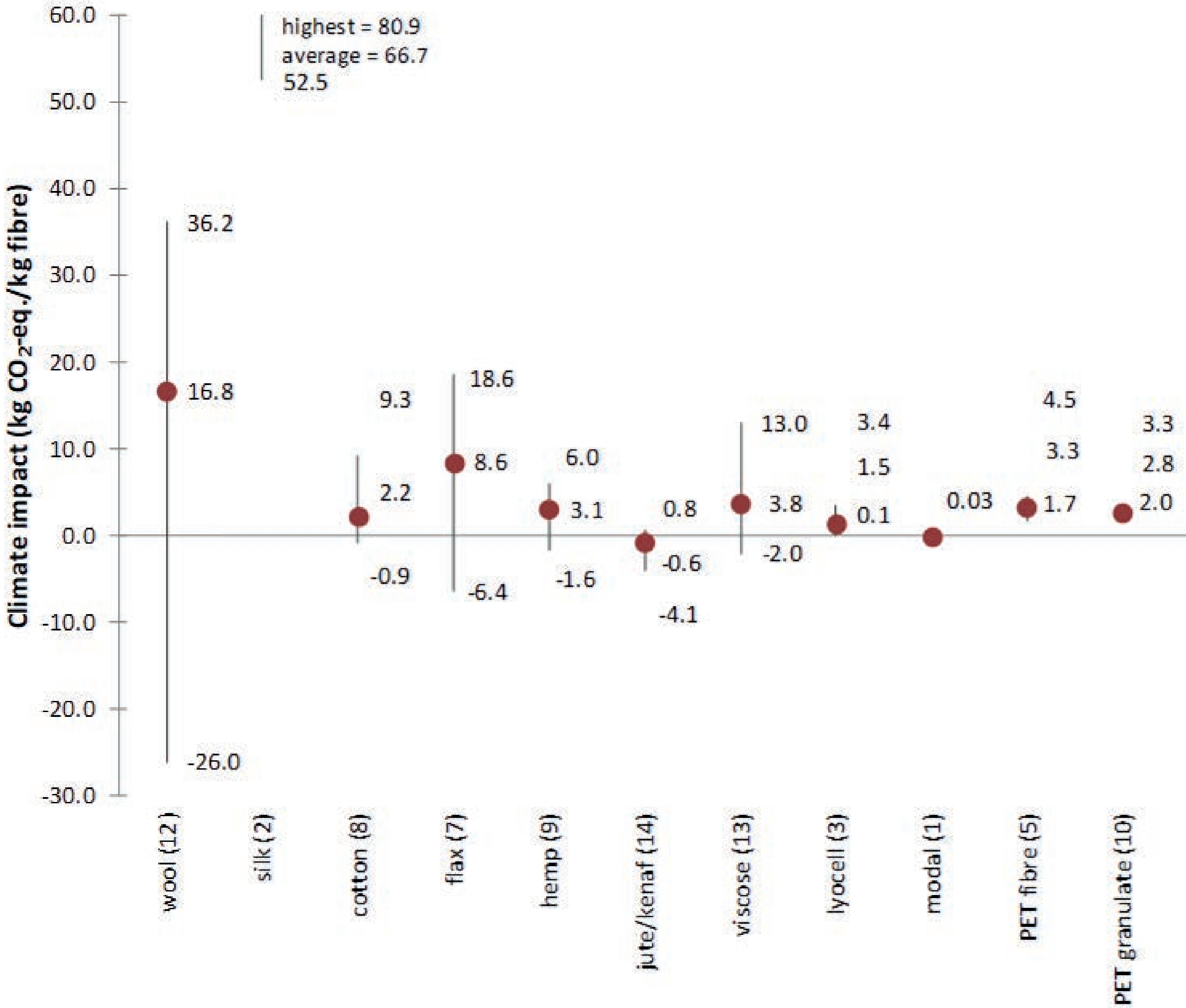
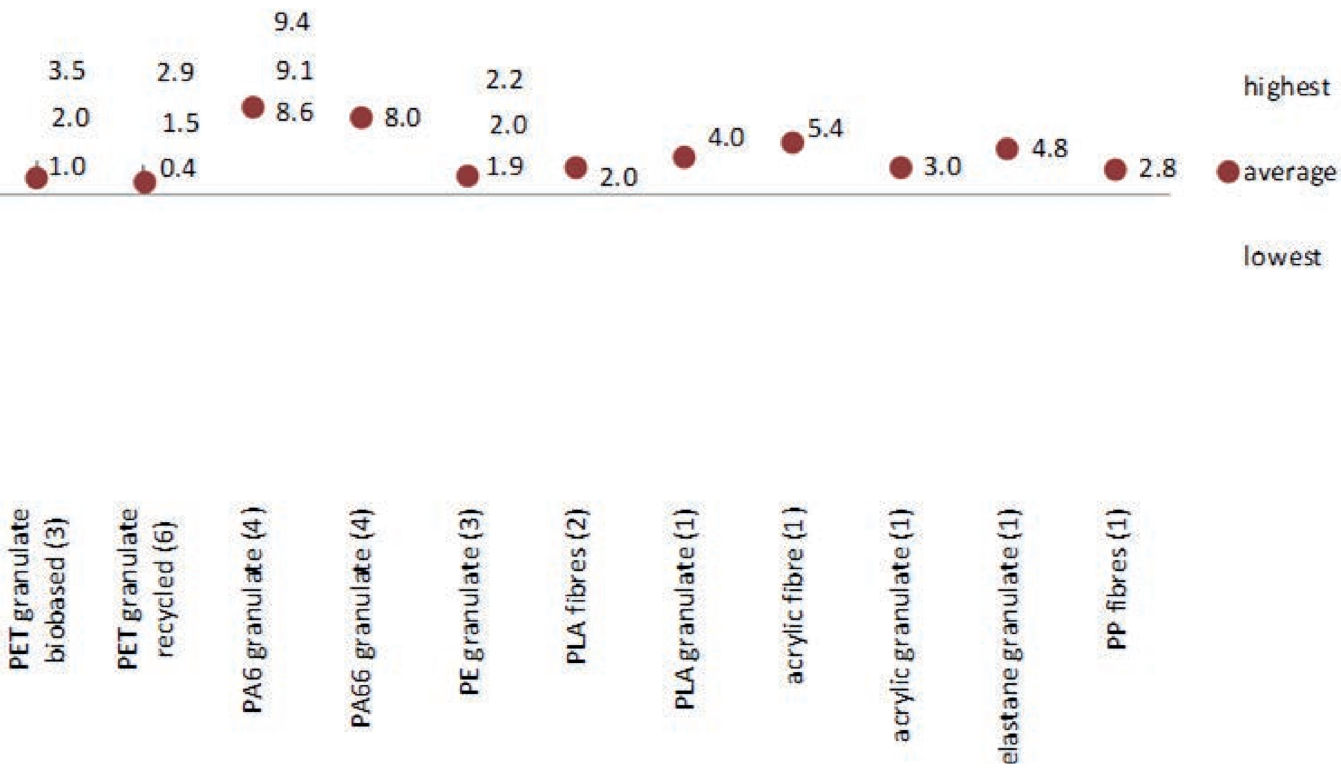


Figure 9. Climate impact of textile fiber types and a selection of granulate types. The number of data points included are given in parenthesis after the fiber name. The numbers are collected from different LCA studies with different methods and are not necessarily directly comparable; the figure merely illustrates the variations existing within each fiber type.


9.4
3.5
2.9
9.1
2.2
highest
2.0
1.5
8.6
8.0
2.0
4.0
5.4
1.0
0.4
1.9
2.0
3.0
4.8
2.8
average
lowest
PET granulate biobased (3)
PET granulate recycled (6)
PA6 granulate (4)
PA66 granulate (4)
PE granulate (3)
PLA fibres (2)
PLA granulate (1)
acrylic fibre (1)
acrylic granulate (1)
elastane granulate (1)
PP fibres (1)

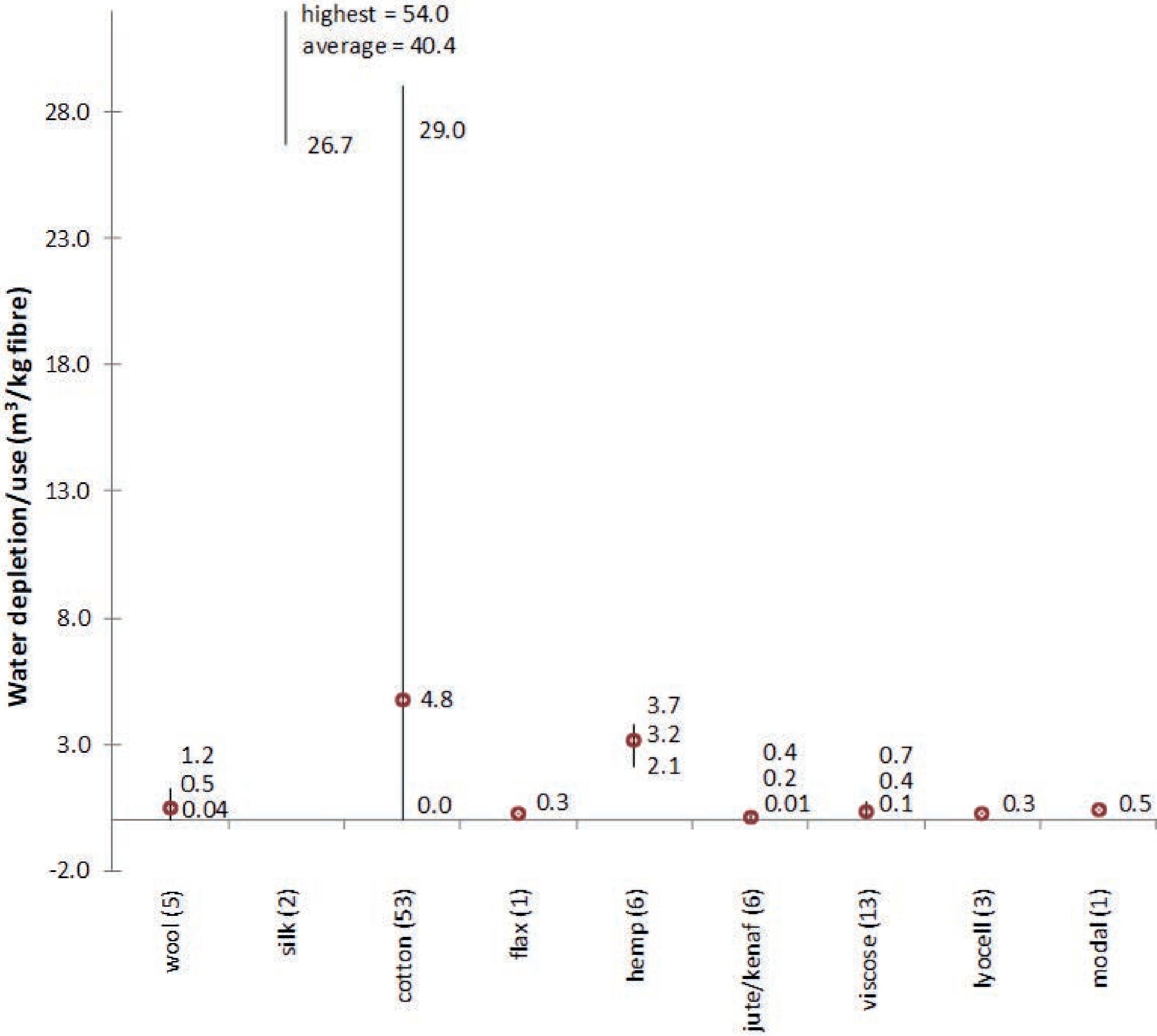
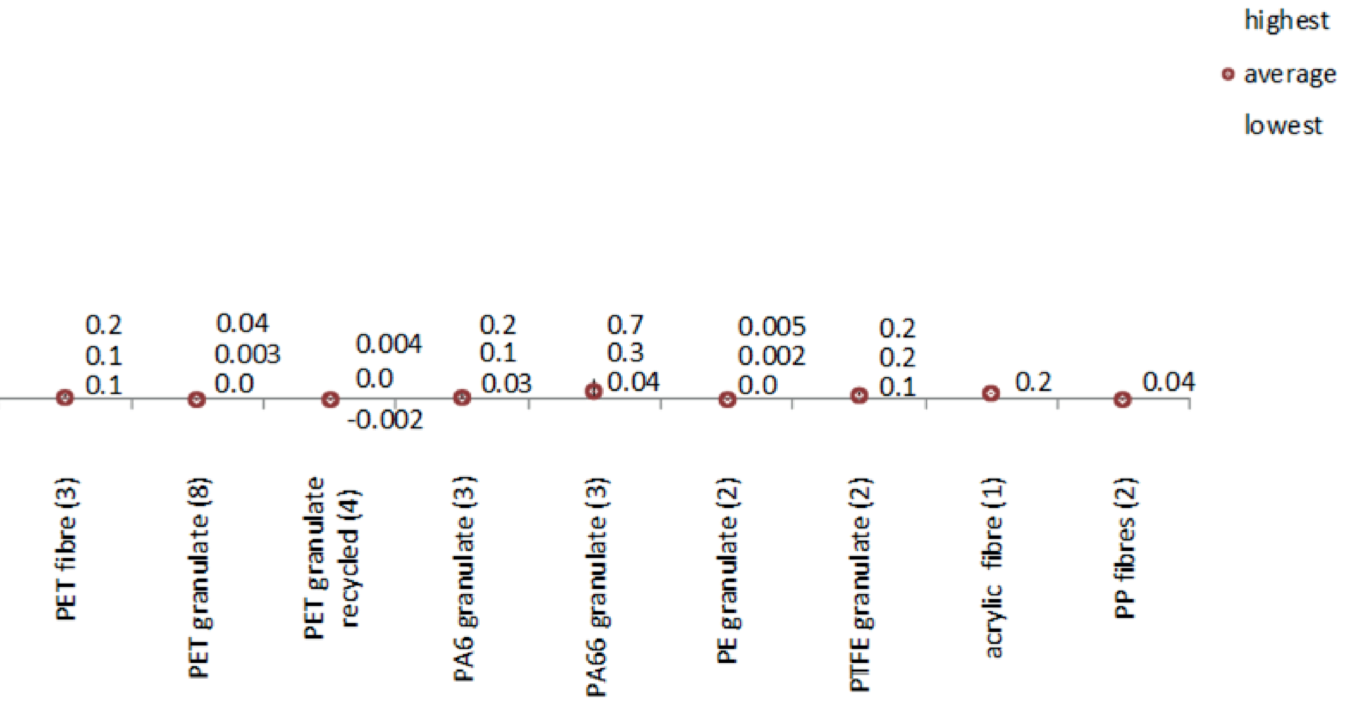


Figure 10. Water use/depletion of textile fiber types and a selection of granulate types. The number of data points included are given in parenthesis after the fiber name. The numbers are collected from different LCA studies with different methods and are not necessarily directly comparable; the figure merely illustrates the variations existing within each fiber type. In cases where figures for both green and blue water use are given, the blue water figure was used for this graph as it is the most common metric for water use.

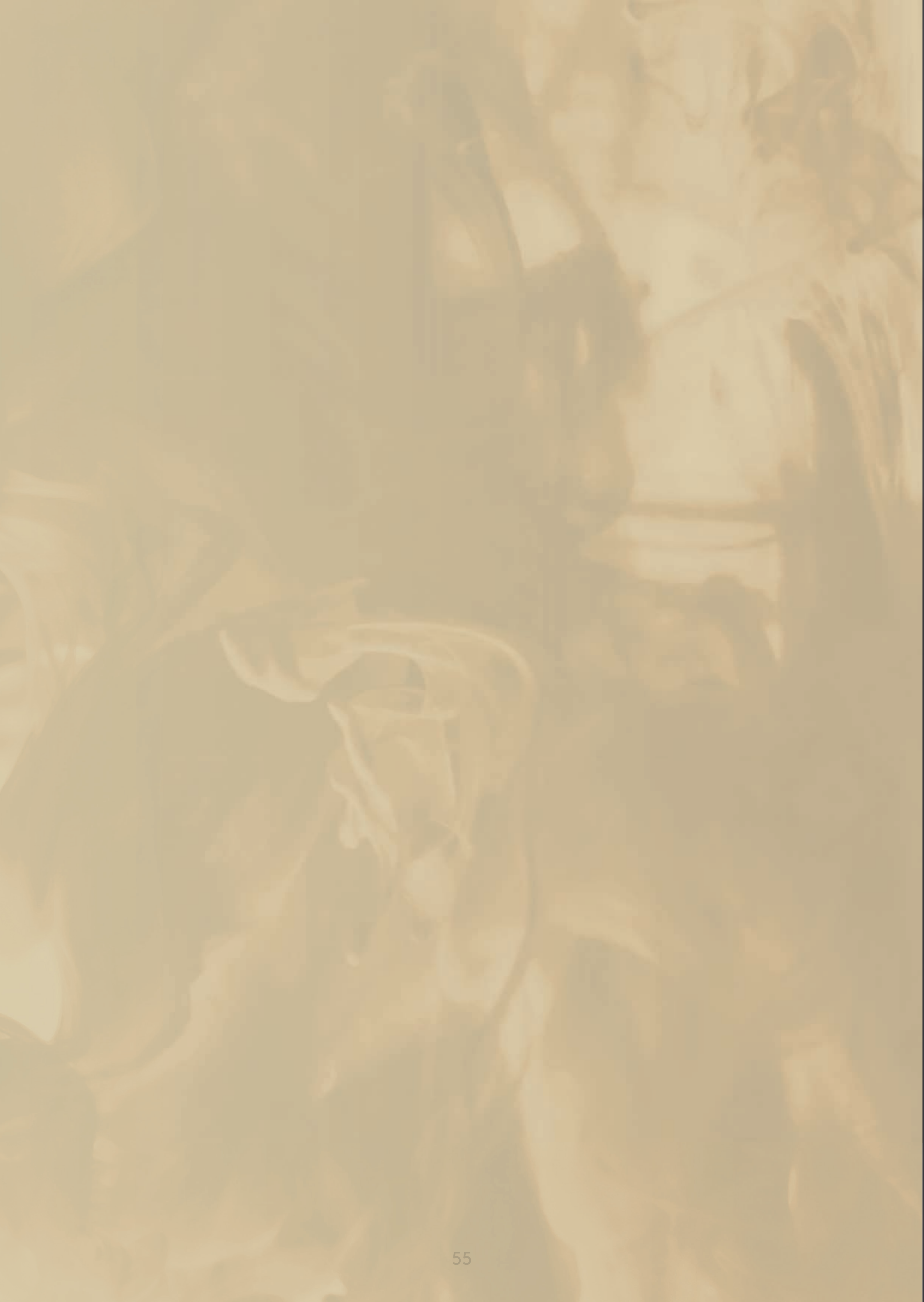

highest
average
lowest
0.2
0.1
0.1
0.04
0.003
0.0
0.004
0.0
-0.002
0.2
0.1
0.03
0.7
0.3
0.04
0.005
0.002
0.0
0.2
0.2
0.1
0.2
0.04
PET fibre (3)
PET granulate (8)
PET granulate recycled (4)
PA6 granulate (3)
PA66 granulate (3)
PE granulate (2)
PTFE granulate (2)
acrylic fibre (1)
PP fibres (2)

To summarise, by the mapping and discussion done in the present study we hope to contribute to:

- Fiber diversity, in terms of reduced dependency on a few feedstocks and technologies.
- More conscious and fact-based fiber selection by designers and buyers.
- Fiber selection that considers a wider array of available fibers and sets the fibers' life-cycle performance at centre stage – including their fit-for-purpose and effects on subsequent production, user behaviour and end-of-life options.
- Fiber selection that comprise and inspire conscious sourcing, which rewards the best in class and – if possible without compromising life-cycle performance – moves on to better classes, when there is data available supporting such a transition.
- Better resolution in environmental labels and indexes showing the variations between and within fiber types, which thereby have the capability to reward the best in class.
- Harmonization in the methods for data collection and impact assessment to enable communication of environmental impact data not only to LCA experts but also to consumers.

Different actors hopefully find these contributions valuable and useful in in their work for creating a more sustainable textile future. Here are some examples of implications for specific actors:

- Industry can improve their understanding of the art of assessing the environmental impact of fibers, get a more nuanced view of fibers and their environmental performances and thereby improve design, selection and sourcing, contribute to greater knowledge by improving transparency and knowledge-sharing, and improve communication around the environmental advantages and disadvantages of fibers while being more vigilant for attempts of greenwashing.
- Policy developers can, for example, expand their understanding about the environmental impact of fibers, and how this – and the fiber properties – connect and relate to the life-cycle impact of the end product. They can also see the general lack of openly available data and the diversity and inconsistencies of methods as an inspiration for standardisation of metrics and methods as well as regulation including data collection.
- LCA practitioners and researchers can see the identified data gaps, become aware of methodological differences between case studies and the current methodological shortcomings of LCA, as opportunities for future research on how to improve the environmental assessment of textile fibers.



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Appendix 1. terminology and abbreviations

Table 1 Definitions of terminology related to fibers and textiles.

Terminology	Definition
Amorphous	Low degree of polymer chain orientation.
Monomer	A relatively small and simple molecule that can be linked together to form a larger molecule (a polymer).
Polymer (chain)	A compound made of many (up to millions) linked simpler molecules (monomers).
Polymerisation	The process of linking monomers into polymers.
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).
Textile fibers	Fibers used for textile applications (in this report, the term "fibers" always refers to textile fibers).
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).
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.
Staple fibers	Fibers of discrete length (natural fibers e.g. cotton, wool, but also synthetic fibers can be cut to staple fibers).
Filament fibers	Fibers of continuous or near continuous length produced by industrial spinning (melt, dry or wet spinning) or natural processes e.g. silk.
Staple yarn (or spun yarn)	A yarn made by staple fibers.

Filament yarn	A yarn made by filament fibers. A long, continuous strand of interlocked 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).
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).
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).

Table 2 Abbreviations

Abbreviation	Explanation
CO2	Carbon dioxide
EVO	Bio-based polyamide (Nylon 10,10), commonly from castor oil
GWP	Global Warming Potential
Higg MSI	Higg Material Sustainability Index (from SAC)
ISO	International Organization of Standardization
LCA	Life cycle assessment
NMMO	N-Methylmorpholine N-oxide (a solvent)
N2O	Nitrogen oxide (laughing gas)
PE	Polyethylene
PET	Polyethylene terephthalate (one polyester type)
PA6	Polyamide 6 (Nylon 6) – polymer consisting of repeated blocks of caprolactame
PA66	Polyamide 66 (Nylon 66) – polymer built from adipic acid and hexamethylenediamine
PED	Primary Energy Demand
PLA	Polylactic acid

PP	Polypropylene
PTFE	Polytetrafluoroethylene
REEL	Responsible Environment Enhanced Livelihoods (cotton certification)
SAC	Sustainable Apparel Coalition

Table 3 Abbreviations used in the environmental impact data tables in Appendix 2

General	
Av	Average
BCI	Better Cotton Initiative (a cotton certification scheme)
CML	CML 2001 (an impact assessment method framework)
CmiA	Cotton made in Africa (a cotton certification scheme)
EI99	Eco Indicator 99 (an impact assessment method framework)
Eq	Equivalents
GM	Genetically modified
ILCD	ILCD-recommended impact assessment methods according to the used software (GaBi or SimaPro)
MSI	Higg Material Sustainability Index
REEL	Responsible Livelihood Enhanced Environment (a cotton certification scheme)
UM	Unknown method
DMT	Dimethyl terephthalate
EG	Ethylene glycol
EVA	Ethylene vinyl acetate
PTA	Purified terephthalic acid
PTFE	Teflon, polytetrafluoroethylene
PU	Polyurethane
RoW	Rest of World
TPA	Terephthalic acid
Climate change	
excl seq	Excluding CO2 sequestration/biogenic CO2 emissions
GCC	Global climate change with 20-year time horizon
GGP	Greenhouse gas protocol
GWP	Global warming potential (without time horizon specified)
GWP20	Global warming potential with 20-year time horizon
GWP100	Global warming potential with 100-year time horizon
GWP500	Global warming potential with 500-year time horizon

incl seq	Including CO2 sequestration/biogenic CO2 emissions
RCHI	Regional climate hotspot impacts
Water use/depletion	
aWD	Attributional water deprivation
BW	Blue water (water footprint methodology)
BWC	Blue water consumption
BWU	Blue water use
cWD	Consequential water deprivation
GreyW	Grey water (water footprint methodology)
GW	Green water (water footprint methodology)
NFC	Net freshwater consumption
RD-W	Resource depletion, water
VWRDN	Volume of water required to dilute nitrogen leached to water bodies
WC	Water consumption
WF	Water footprint (blue water and green water, water footprint methodology)
WR	Water requirement
WS	Water scarcity
WU	Water use
Eutrophication	
EP	Eutrophication potential
EP-F	Eutrophication potential, freshwater
EP-M	Eutrophication potential, marine
EP-M	Eutrophication potential, terrestrial
FE	Freshwater eutrophication
Toxicity	
CTU	Comparative toxic unit, environmental
ET	Ecotoxicity
EQ-ET	Ecosystem quality, ecotoxicity
EQ-SET	Ecosystem quality, stored ecotoxicity
FAETP	Freshwater aquatic ecotoxicity potential
FSETP	Freshwater sedimental ecotoxicity potential
HAACER	Hazardous ambient air contaminant exposure risks, respiratory non-cancer health effects
HHI-NC	Human health impact, non-cancer
HH-C	Human health, carcinogenics
HH-SC	Human health, stored carcinogenics
HTC	Human toxicity, carcinogenics
HTNC	Human toxicity, non-carcinogenics
HTTP	Human toxicity potential
TETP	Terrestrial ecotoxicity potential
UT	Usetox

Land use and related impact	
LU	Land use
LUC	Land use change
Al	Agricultural land
ALO	Agricultural land occupation
BI	Biodiversity impact
C deficit	Carbon deficit
Dist	Disturbed
EQ-LO	Ecosystem quality, land occupation
Fl	Forest land
ILUC	Indirect land use change
LC	Land competition
LOI	Land occupation indicator
SOM	Soil Organic Matter
TD	Terrestrial disturbance
TSHD	Threatened species habitat disturbance
WRD	Wood resource depletion
Energy use	
CED	Cumulative energy demand (i)
EC	Energy consumption
ER	Energy requirement
NRERD	Non-renewable energy resource depletion
NREU	Non-renewable energy use
PE	Primary energy
PED	Primary energy demand (ii)
REU	Renewable energy use

(i) For the LCI datasets characterised in GaBi, the PED indicator of the net calorific value of renewable and non-renewable resources was chosen.

(ii) For the LCI datasets characterised in SimaPro, the CED single issue indicator for renewable and non-renewable resources were chosen and reported separately.

Appendix 2. Table of identified environmental impact data on animal fibers, plant fibers, regenerated fibers and synthetic fibers

2.1 Environmental impact data of animal fibers.

Source	Fibre type/ process	Further description	Production location	Climate change		Water depletion/use		Toxicity		Eutrophication		Land use and related indicators		Energy use	
				number	unit (method)	number	unit (method)	number	unit (method)	number	unit (method)	number	unit (method)	number	unit (method)
Peer-reviewed journal articles															
Astudillo et al. 2014	Silk	Silk, farm practices	India	80.9	kg CO_2 eq/kg (GWP100)	54.0	m^3 eq/kg (BWF)	1040	CTUe/kg (ILCD, USEtox, ET)	7.0	kg P eq/kg (ILCD, EP-F)	35.6	m2a/kg (ALO)	244 1610	MJ/kg (NREU CED) MJ/kg (REU CED)
Astudillo et al. 2014	Silk	Silk, recommended practices	India	52.5	kg CO_2 eq/kg (GWP100)	26.7	m^3 eq/kg (BWF)	523	CTUe/kg (ILCD, USEtox, ET)	4.8	kg P eq/kg (ILCD, EP-F)	19.8	m2a/kg (ALO)	117 1350	MJ/kg (NREU CED) MJ/kg (REU CED)
Bevilacqua et al. 2011	Wool	Scoured merino wool	South Africa	1.70	kg CO_2 eq/kg (GWP100)										
Eady et al. 2012	Wool	Greasy merino wool, biophysical allocation	Australia	36.2	kg CO_2 eq/kg (GWP100)										
Eady et al. 2012	Wool	Greasy merino wool, economic allocation	Australia	28.7	kg CO_2 eq/kg (GWP100)										
Brock et al. 2013	Wool	Greasy merino wool, biophysical allocation	Australia	24.9	kg CO_2 eq/kg (GWP100)										
Brock et al. 2013	Wool	Greasy merino wool, economic allocation	Australia	14.8	kg CO_2 eq/kg (GWP100)										
Wiedemann et al. 2015	Wool	Greasy broad wool, by-product allocation meat	UK	-26	kg CO_2 eq/kg (GWP100)										
Wiedemann et al. 2015	Wool	Greasy UK broad wool, by-product allocation wool	UK	37	kg CO_2 eq/kg (GWP100)										
Other reports															
Barber & Pellow 2006	Wool	Greasy merino wool, average farming	New Zealand	0.99	kg CO_2 eq/kg (GWP100)									13.4	MJ/kg
Barber & Pellow 2006	Wool	Merino dry wool top, average farming	New Zealand	1.66	kg CO_2 eq/kg (GWP100)									22.6	MJ/kg
Laursen et al. 1997	Wool		New Zealand											8.0	MJ/kg
Laursen et al. 1997	Wool		Not specified			0.125	m^3/kg (WC)								
Databases															
Ecoinvent 3.4 as implemented in SimaPro	Wool	Sheep fleece in the grease	USA	21.3 33.5	kg CO_2 eq/kg (ILCD, GWP100 incl seq) kg CO_2 eq/kg (ILCD, GWP100 excl	1.08	m^3 eq/kg (ILCD, RD-W)	89.8 4.88E-7	CTUe/kg (ILCD, USEtox, ET) CTUh/kg (ILCD, USEtox, HTC)	5.22 1.22E-3	Mole of N eq/kg (ILCD, EP-T) kg P eq/kg (ILCD, EP-F)	677.1	kg C deficit eq/kg (ILCD, LU)	89.0 167	MJ/kg (NREU CED) MJ/kg (REU CED)

					seq)			-7.45E-7	CTUh/kg (ILCD, USEtox, HTNC)	0.196	kg N eq/kg (ILCD, EP-M)				
Ecoinvent 3.4 as implemented in SimaPro	Wool	Sheep fleece in the grease	RoW av	21.3	kg CO_2 eq/kg (ILCD, GWP100 incl seq)	1.21	m^3 eq/kg (ILCD, RD-W)	89.7	CTUe/kg (ILCD, USEtox, ET)	5.22	Mole of N eq/kg (ILCD, EP-T)	677	kg C deficit eq/kg (ILCD, LU)	88.9	MJ/kg (NREU CED)
				33.5	kg CO_2 eq/kg (ILCD, GWP100 excl seq)			4.88E-7	CTUh/kg (ILCD, USEtox, HTC)	1.22E-3	kg P eq/kg (ILCD, EP-F)			167	MJ/kg (REU CED)
								-7.49E-7	CTUh/kg (ILCD, USEtox, HTNC)	0-196	kg N eq/kg (ILCD, EP-M)				
Ecoinvent 2.2 as implemented in SimaPro	Wool	Sheep wool at farm	USA		kg CO_2 eq/kg (ILCD, GWP100 incl seq)	0.037	m^3 eq/kg (ILCD, RD-W)	19.1	CTUe/kg (ILCD, USEtox, ET)	2.69	Mole of N eq/kg (ILCD, EP-T)	349	kg C deficit eq/kg (ILCD, LU)	35.9	MJ/kg (NREU CED)
				11.9	kg CO_2 eq/kg (ILCD, GWP100 excl seq)			2.62E-7	CTUh/kg (ILCD, USEtox, HTC)	6.56E-3	kg P eq/kg (ILCD, EP-F)			81.7	MJ/kg (REU CED)
								1.07E-7	CTUh/kg (ILCD, USEtox, HTNC)	0.12	kg N eq/kg (ILCD, EP-M)				
Ecoinvent 3.3 as implemented in GaBi	Wool	Sheep fleece in the grease	USA	23.7	kg CO_2 eq/kg (ILCD, GWP100 incl seq)	0.184	m^3 eq/kg (ILCD, RD-W)	57.5	CTUe/kg (ILCD, USEtox, ET)	3.41	Mole of N eq/kg (ILCD, EP-T)	681	kg C deficit eq/kg (ILCD, LU)	166	MJ/kg (PED)
				21.9	kg CO_2 eq/kg (ILCD, GWP100 excl seq)			3.2E-7	CTUh/kg (ILCD, USEtox, HTC)	8.04E-3	kg P eq/kg (ILCD, EP-F)				
								-5.8E-7	CTUh/kg (ILCD, USEtox, HTNC)	0.128	kg N eq/kg (ILCD, EP-M)				
Higg MSI															
Higg MSI	Wool	Sheep wool type (coarse, medium, fine wool)	Global	34.1	points	1.3	points (WS)			9.9	points				
Higg MSI	Silk	Silk, raw, from silkworm	Global	35.6	points	9.1	points (WS)			18.2	points				
Higg MSI	Process	Reeling and throwing	Global	5.6	points	0.5	points (WS)			2.5	points				

2.3 Environmental impact data of cotton fibers.

Source	Fibre type	Further description	Production location	Climate change number	Climate change unit (method)	Water depletion/use number	Water depletion/use unit (method)	Toxicity number	Toxicity unit (method)	Eutrophication number	Eutrophication unit (method)	Land use and related indicators number	Land use and related indicators unit (method)	Energy use number	Energy use unit (method)
Peer-reviewed journal articles															
Shen et al. 2010	Cotton		China/USA av	2.0	kg CO_2 eq/kg (CML, GWP100 incl seq)	0.573	m^3/kg (WU)[1]	1.7	kg 1,4 DB eq/kg (CML, HTP)	2.2E-3	kg PO_4^{3-} eq/kg (CML, EP)	~8E-4	ha/kg-yr (al)	~55	MJ/kg (CED)
								17.3	kg 1,4 DB eq/kg (CML, FAETP)					36	MJ/kg (NREU)
								1.6	kg 1,4 DB eq/kg (CML, TETP)					~19	MJ/kg (REU)
Sandin et al. 2013[2]	Cotton		Northwestern China			0.848	m^3/kg (cWD, without LUC)					3.4E-3-5.2E-3	wS_{100}/kg (BI of LU)		
						0.311	m^3/kg (cWD, with LUC)					0	wS_{100}/kg (BI of LUC without LUC)		
						2.251	m^3/kg (aWD)					2.15-3.34	wS_{100}/kg (BI of LUC with LUC[3])		
												0.017-0.027	wS_{100}/kg (BI of LUC with LUC[4])		
Bevilacqua et al. 2014	Cotton		Northern Egypt	0.63	kg CO_2 eq/kg (GWP20)			1.84E-3	EI points (EI99, EQ-ET)			0.29	EI points (EI99, EQ-LO)		
								2.61E-6	EI points (EI99, EQ-SET)						
				0.63	kg CO_2 eq/kg (GWP100)			1.04E-3	EI points (EI99, HH-C)						
				0.52	kg CO_2 eq/kg (GWP500)			1.36E-7	EI points (EI99, HH-SC)						
Bevilacqua et al. 2014	Cotton		Xinjiang, China	0.73	kg CO_2 eq/kg (GWP20)			1.77E-3	EI points (EI99, EQ-ET)			0.73	EI points (EI99, EQ-LO)		
				0.72	kg CO_2 eq/kg (GWP100)			1.98E-6	EI points (EI99, EQ-SET)						
								1.66E-3	points (EI99, HH-C)						
				0.57	kg CO_2 eq/kg			1.63E-7	EI points						

[1] Includes process water, cooling water and irrigation water.
[2] Water use and land use (biodiversity) impact results also given on an EI end-point level in terms of impact on human health, ecosystem quality, resources and aggregated. For this data, the reader is referred to the original reference.
[3] Impact of LUC allocated to 1st harvest.
[4] Impact of LUC allocated to all harvests in 62.5 years,

					(GWP500)				(EI99, HH-SC)						
Bevilacqua et al. 2014	Cotton		Northern India	0.89	kg CO_2 eq/kg (GWP20)			2.71E-3	points (EI99, EQ-ET)			1.43	EI points (EI99, EQ-LO)		
								1.27E-6	EI points (EI99, EQ-SET)						
				0.89	kg CO_2 eq/kg (GWP100)			1.52E-3	EI points (EI99, HH-C)						
				0.77	kg CO_2 eq/kg (GWP500)			8.73E-8	EI points (EI99, HH-SC)						
Bevilacqua et al. 2014	Cotton		Missouri, USA	0.63	kg CO_2 eq/kg (GWP20)			2.05E-3	EI points (EI99, EQ-ET)			0.84	EI points (EI99, EQ-LO)		
				0.62	kg CO_2 eq/kg (GWP100)			1.52E-6	EI points (EI99, EQ-SET)						
								1.74E-3	EI points (EI99, HH-C)						
				0.56	kg CO_2 eq/kg (GWP500)			8.7E-8	EI points (EI99, HH-SC)						
Kalliala & Nousiainen 1999	Cotton	Conventional cotton	Not specified	4.7	kg CO_2 eq/kg (UM)	22.2[5]	m³/kg (WU)								
				3	kg CO_2 eq/kg (incl seq, UM)										
Kalliala & Nousiainen 1999	Cotton	Organic cotton	Not specified	~10% lower than conventional cotton	kg CO_2 eq/kg (UM)	24.0	m³/kg (WU)								
Chapagain et al. 2006	Cotton		Argentina			5.39	m³/kg (BW)			0.351	m³/kg (VWRDN)				
						12.6	m³/kg (GW)								
Chapagain et al. 2006	Cotton		Australia			3.28	m³/kg (BW)			0.327	m³/kg (VWRDN)				
						2.03	m³/kg (GW)								
Chapagain et al. 2006	Cotton		Brazil			0.107	m³/kg (BW)			0.190	m³/kg (VWRDN)				
						6.01	m3/kg (GW)								
Chapagain et al. 2006	Cotton		China			1.78	m³/kg (BW)			0.380	m³/kg (VWRDN)				
						2.93	m³/kg (GW)								
Chapagain et al. 2006	Cotton		Egypt			9.88	m³/kg (BW)			0.226	m³/kg (VWRDN)				

[5] This paper also specifies irrigation for cotton cultivation as 7-29 m³/kg fibres, a number appearing in many papers and reports, other with a reference to Kaillala and Nouisainen (1999); here it has been listed under the reference Laursen et al. (1997), although the data is originally from Marini et al. (1996), which is a conference contribution written in German and thus excluded from this report.

						0	m^3/kg (GW)								
Chapagain et al. 2006	Cotton		Greece			4.22	m^3/kg (BW)			0.420	m^3/kg (VWRDN)				
						1.24	m^3/kg (GW)								
Chapagain et al. 2006	Cotton		India			5.02	m^3/kg (BW)			1.60	m^3/kg (VWRDN)				
						15.2	m^3/kg (GW)								
Chapagain et al. 2006	Cotton		Mali			3.43	m^3/kg (BW)			0.339	m^3/kg (VWRDN)				
						8.75	m^3/kg (GW)								
Chapagain et al. 2006	Cotton		Mexico			3.86	m^3/kg (BW)			0.404	m^3/kg (VWRDN)				
						1.99	m^3/kg (GW)								
Chapagain et al. 2006	Cotton		Pakistan			9.01	m^3/kg (BW)			1.04	m^3/kg (VWRDN)				
						2.46	m^3/kg (GW)								
Chapagain et al. 2006	Cotton		Syria			7.59	m^3/kg (BW)			0.128	m^3/kg (VWRDN)				
						0.204	m^3/kg (GW)								
Chapagain et al. 2006	Cotton		Turkey			6.56	m^3/kg (BW)			0.409	m^3/kg (VWRDN)				
						0.672	m^3/kg (GW)								
Chapagain et al. 2006	Cotton		Turkmenistan			13.1	m^3/kg (BW)			1.23	m^3/kg (VWRDN)				
						0.951	m^3/kg (GW)								
Chapagain et al. 2006	Cotton		USA			1.35	m^3/kg (BW)			0.645	m^3/kg (VWRDN)				
						3.91	m^3/kg (GW)								
Chapagain et al. 2006	Cotton		Uzbekistan			10.2	m^3/kg (BW)			0.937	m^3/kg (VWRDN)				
						0.195	m^3/kg (GW)								
Chapagain et al. 2006	Cotton		Global av			4.24	m^3/kg (BW)			0.622	m^3/kg (VWRDN)				
						4.26	m^3/kg (GW)								
Murugesh &	Cotton	Conventional seed cotton	India	1.33	kg CO_2 eq/kg seed			1.12	kg 1,4-DB eq/kg	2.9E-3	kg PO_4^{3-} eq/kg	0.147	m^2a/kg seed		

Salvadess 2013		fibres			cotton (CML, GWP500)			 0.48 0.010 1.03	seed cotton (CML, HTP) kg 1,4-DB eq/kg seed cotton (FAETP) kg 1,4-DB eq/kg seed cotton (TETP) kg 1,4-DB eq/kg seed cotton (FSETP)		seed cotton (CML)		cotton (LC)		
Murugesh & Salvadess 2013	Cotton	Conventional seed cotton fibres	India	1.08	kg CO_2 eq/kg seed cotton (CML, GWP500)			0.93 0.38 9.5E-3 0.83	kg 1,4-DB eq/kg seed cotton (CML, HTP) kg 1,4-DB eq/kg seed cotton (FAETP) kg 1,4-DB eq/kg seed cotton (TETP) kg 1,4-DB eq/kg seed cotton (FSETP)	2.0E-3	kg PO_4^{3-} eq/kg seed cotton (CML)	0.147	m^2a/kg seed cotton (LC)		
Murugesh & Salvadess 2013	Cotton	Conventional seed cotton fibres	Kutch, Gujarat, India (literature data)	0.75	kg CO_2 eq/kg seed cotton (CML 2001, GWP500)			0.67 0.25 6.2E-3 0.53	kg 1,4-DB eq/kg seed cotton CML, HTP) kg 1,4-DB eq/kg seed cotton (FAETP) kg 1,4-DB eq/kg seed cotton (TETP) kg 1,4-DB eq/kg seed cotton (FSETP)	1.4E-3	kg PO4 eq/kg seed cotton (CML)	0.104	m^2a/kg seed cotton (LC)		
Other reports															
Cotton Inc 2012	Cotton		Global av	0.268 1.81	kg CO_2 eq/kg (CML, GWP incl seq) kg CO_2 eq/kg (CML, GWP excl seq)	2.47 2.12	m^3/kg (WU) m^3/kg (WC)	Footnote: [6]		3.84E-3	kg PO_4^{3-}eq/kg (CML, EP)			15.0	MJ/kg (PED non-renewable)
Cotton Inc 2016	Cotton		Global av	-0.113	kg CO_2 eq/kg (CML, GWP incl seq)	1.56	m^3/kg (BWC)	3.89	CTUe/kg (CML, ET)	7.8E-3	kg PO_4^{3-}eq/kg (CML, EP)	10.6	m^2a (LOI)	13.7	MJ/kg (PED non-

[6] No quantitative results, but a comment: "Uncertainties around the USEtox™ model notwithstanding, the impact results of the present study showed that certain pesticides outweighed all other life cycle".

				1.33	kg CO_2 eq/kg (CML, GWP excl seq)	2.24	m^3/kg (BWU)	9.90E-10 8.08E-8	CTUh/kg (CML, HTC) CTUh/kg (CML, HTNC)						renewable)
Textile exchange 2014	Cotton	Organic cotton	Global av	0.98	kg CO_2 eq/kg (GWP)	~14-15 ~0.5 0.18	m^3/kg (WU/WC) m^3/kg (BWU) m^3/kg (BWC)	Footnote: [7]		2.8E-3	kg PO_4^{3-}eq/kg (CML, EP)			5.80	MJ/kg (PED non-renewable)
Safaya et al. 2016	Cotton	Conventional cotton	Madhya Pradesh, India			4.02 0.252 334	m^3/kg (GW) m^3/kg (BW) m^3/kg (GreyW))	See GreyW footprint		See GreyW footprint					
Safaya et al. 2016	Cotton	Conventional cotton	Gujarat, India			2.35 0.174 3.96	m^3/kg (GW) m^3/kg (BW) m^3/kg (GreyW))	See GreyW footprint		See GreyW footprint					
Safaya et al. 2016	Cotton	Conventional cotton	Maharashtra, India			2.59 0.007 44.2	m^3/kg (GW) m^3/kg (BW) m^3/kg (GreyW))	See GreyW footprint		See GreyW footprint					
Safaya et al. 2016	Cotton	Organic cotton	Gujarat, India			4.65 0.320 0.178	m^3/kg (GW) m^3/kg (BW) m^3/kg (GreyW))	See GreyW footprint		See GreyW footprint					
Safaya et al. 2016	Cotton	Organic cotton	Maharashtra, India			5.57 0.257 0.361	m^3/kg (GW) m^3/kg (BW) m^3/kg (GreyW))	See GreyW footprint		See GreyW footprint					
Safaya et al. 2016	Cotton	REEL cotton	Gujarat, India			1.76 0.381	m^3/kg (GW) m^3/kg	See GreyW footprint		See GreyW footprint					

[7] No quantitative results, but a comment: "Given the findings that pesticide use typically dominates USEtox profiles of agricultural category products (Berthoud et al 2011, Cotton Inc. 2012), it is expected that the USEtox profile of organic cotton would well withstand comparison with other cultivation systems in this impact category."

						 1.20	(BW) m^3/kg (GreyW))								
Safaya et al. 2016	Cotton	REEL cotton	Maharashtra, India			1.53 0 8.43	m^3/kg (GW) m^3/kg (BW) m^3/kg (GreyW))	See GreyW footprint		See GreyW footprint					
PE International 2014	Cotton	CmiA cotton	Zambia /Ivory Coast av	1.037	kg CO_2 eq/kg (CML)	3.4 0.001	m^3/kg (WU) m^3/kg (BWU)			20.4	kg PO_4^{3-}eq/kg (CML, EP)				-
Nill & Wick 2013	Cotton	CmiA cotton	CmiA av[8]	1.92	kg CO_2 eq/kg (GWP100)	14.2	m^3/kg (WF)								-
Nill & Wick 2013	Cotton	Conventional cotton	Global av[9]	4.64	kg CO_2 eq/kg (GWP100)	13.1	m^3/kg (WF)								-
Cherrett et al. 2005	Cotton	Conventional cotton	USA	5.89[10]	kg CO_2/kg (UM)	9.8-10	m^3/kg (WR)							25.6	MJ/kg (ER)
Cherrett et al. 2005	Cotton	Conventional cotton	Punjab, India	4.5-5	kg CO_2/kg (UM)	9.8-10	m^3/kg (WR)							~15	MJ/kg (ER)
Cherrett et al. 2005	Cotton	Organic cotton	USA	2.35	kg CO_2/kg (UM)	9.8-10	m^3/kg (WR)							~12	MJ/kg (ER)
Cherrett et al. 2005	Cotton	Organic cotton	Punjab, India	3-4	kg CO_2/kg (UM)	9.8-10	m^3/kg (WR)							11.7	MJ/kg (ER)
Khabbaz 2010	Cotton	Conventional, non-GM cotton	Australia	3.8	kg CO_2 eq/kg (UM)									54.2	MJ/kg (EC)
Khabbaz 2010	Cotton	GM cotton	Australia	3.84	kg CO_2 eq/kg (UM)									45.8	MJ/kg (EC)
Khabbaz 2010	Cotton	GM cotton, furrow irrigation and zero tillage	Australia	1.75	kg CO_2 eq/kg (UM)									20	MJ/kg (EC)
Khabbaz 2010	Cotton	GM cotton furrow irrigation and minimum tillage	Australia	1.8	kg CO_2 eq/kg (UM)									21	MJ/kg (EC)
Khabbaz 2010	Cotton	GM cotton, conventional cultivation	Australia	1.83	kg CO_2 eq/kg (UM)									22	MJ/kg (EC)
Khabbaz 2010	Cotton	GM cotton, lateral move irrigation, zero tillage, low fertiliser rate, machinery reflecting a bigger farm ("all new technologies combined")	Australia	1.75	kg CO_2 eq/kg (UM)									20	MJ/kg (EC)
Laursen et al.	Cotton		Not specified			7-29	m^3/kg							48.7	MJ/kg

[8] Average of Benin, Burkina Faso, Ivory Coast, Malawi, Mozambique, Zambia, Cameroon
[9] Average of China, India, USA, Pakistan, Brazil, Uzbekistan, Turkey, Australia (data based on Ecoinvent 3.3 on US and Chinese cultivation, which in turn is based on Cotton Inc (2012), but adjusted to account for cultivation techniques in respective countries)
[10] The carbon footprints of fibres stated in Cherrett et al. (2005) are in the range 2-10 kg CO_2/*tonne* fibres. We have interpreted this as an error, as similar numbers are usually per kg, and multiplied the numbers by a factor of 1000.

1997							(WC)								(ER)
Databases															
Ecoinvent 3.4 as implemented in SimaPro	Cotton	Market dataset	Global av	-0.848	kg CO_2 eq/kg (ILCD, GWP100 incl seq)	1.204	m^3 eq//kg (ILCD, WS)	52.5	CTUe/kg (ILCD, USEtox, ET)	0.133	Mole of N eq/kg (ILCD, EP-T)	80.6	kg C deficit eq/kg (ILCD, LU)	27.3	MJ/kg (NREU CED)
				2.46	kg CO_2 eq/kg (ILCD, GWP100 excl seq)			1.69E-7	CTUh/kg (ILCD, USEtox, HTC)	1.14E-3	kg P eq/kg (ILCD, EP-F)			40.3	MJ/kg (REU CED)
								9.14E-7	CTUh/kg (ILCD, USEtox, HTNC)	0.012	kg N eq/kg (ILCD, EP-M)				
Ecoinvent 3.4 as implemented in SimaPro	Cotton		Chinese av	-0.709	kg CO_2 eq/kg (ILCD, GWP100 incl seq)	1.487	m^3 eq//kg (ILCD, WS)	51.3	CTUe/kg (ILCD, USEtox, ET)	0.135	Mole of N eq/kg (ILCD, EP-T)	80.5	kg C deficit eq/kg (ILCD, LU)	25.8	MJ/kg (NREU CED)
				2.61	kg CO_2 eq/kg (ILCD, GWP100 excl seq)			1.60E-7	CTUh/kg (ILCD, USEtox, HTC)	8.98E-4	kg P eq/kg (ILCD, EP-F)			40.4	MJ/kg (REU CED)
								8.83E-7	CTUh/kg (ILCD, USEtox, HTNC)	0.012	kg N eq/kg (ILCD, EP-M)				
Ecoinvent 3.4 as implemented in SimaPro	Cotton		USA av	-1.058	kg CO_2 eq/kg (ILCD, GWP100 incl seq)	0.744	m^3 eq//kg (ILCD, WS)	53.0	CTUe/kg (ILCD, USEtox, ET)	0.128	Mole of N eq/kg (ILCD, EP-T)	80.3	kg C deficit eq/kg (ILCD, LU)	26.4	MJ/kg (NREU CED)
				2.42	kg CO_2 eq/kg (ILCD, GWP100 excl seq)			1.75E-7	CTUh/kg (ILCD, USEtox, HTC)	1.35E-3	kg P eq/kg (ILCD, EP-F)			40.0	MJ/kg (REU CED)
								9.26E-7	CTUh/kg (ILCD, USEtox, HTNC)	0.012	kg N eq/kg (ILCD, EP-M)				
Ecoinvent 3.4 as implemented in SimaPro	Cotton		RoW av	-0.886	kg CO_2 eq/kg (ILCD, GWP100 incl seq)	1.272	m^3 eq//kg (ILCD, WS)	52.5	CTUe/kg (ILCD, USEtox, ET)	0.132	Mole of N eq/kg (ILCD, EP-T)	80.5	kg C deficit eq/kg (ILCD, LU)	27.3	MJ/kg (NREU CED)
				2.42	kg CO_2 eq/kg (ILCD, GWP100 excl seq)			1.69E-7	CTUh/kg (ILCD, USEtox, HTC)	1.16E-3	kg P eq/kg (ILCD, EP-F)			40.4	MJ/kg (REU CED)
								9.11E-7	CTUh/kg (ILCD, USEtox, HTNC)	0.012	kg N eq/kg (ILCD, EP-M)				
Ecoinvent 2.2 as implemented in SimaPro	Cotton		US	1.52	kg CO_2 eq/kg (ILCD, GWP100 incl seq)	0.246	m^3 eq//kg (ILCD, WS)	40.0	CTUe/kg (ILCD, USEtox, ET)	0.147	Mole of N eq/kg (ILCD, EP-T)	116	kg C deficit eq/kg (ILCD, LU)	36.1	MJ/kg (NREU CED)
				3.06	kg CO_2 eq/kg (ILCD, GWP100 excl seq)			4.05E-7	CTUh/kg (ILCD, USEtox, HTC)	4.85E-3	kg P eq/kg (ILCD, EP-F)			18.9	MJ/kg (REU CED)
								6.41E-7	CTUh/kg (ILCD, USEtox, HTNC)	0.012	kg N eq/kg (ILCD, EP-M)				

Ecoinvent 3.3 as implemented in GaBi	Cotton	Market dataset	Global av	-0.271	kg CO_2 eq/kg (ILCD, GWP100 incl seq)	0.346	m³ eq//kg (ILCD, RD-W)	65.1	CTUe/kg (ILCD, USEtox, ET)	0.145	Mole of N eq/kg (ILCD, EP-T)	86.6	kg C deficit eq/kg (ILCD, LU)	79.1	MJ/kg (PED)
				3.39	kg CO_2 eq/kg (ILCD, GWP100 excl seq)			1.95E-7	CTUh/kg (ILCD, USEtox, HTC)	1.58E-3	kg P eq/kg (ILCD, EP-F)				
								1.09E-6	CTUh/kg (ILCD, USEtox, HTNC)	0.018	kg N eq/kg (ILCD, EP-M)				
Ecoinvent 3.3 as implemented in GaBi	Cotton		Chinese av	0.206	kg CO_2 eq/kg (ILCD, GWP100 incl seq)	0.344	m³ eq/kg (ILCD, RD-W)	63.1	CTUe/kg (ILCD, USEtox, ET)	0.152	Mole of N eq/kg (ILCD, EP-T)	86.6	kg C deficit eq/kg (ILCD, LU)	78.3	MJ/kg (PED)
				3.88	kg CO_2 eq/kg (ILCD, GWP100 excl seq)			1.80E-7	CTUh/kg (ILCD, USEtox, HTC)	1.06E-3	kg P eq/kg (ILCD, EP-F)				
								1.04E-6	CTUh/kg (ILCD, USEtox, HTNC)	0.019	kg N eq/kg (ILCD, EP-M)				
Ecoinvent 3.3 as implemented in GaBi	Cotton		USA av	-0.659	kg CO_2 eq/kg (ILCD, GWP100 incl seq)	0.343	m³ eq/kg (ILCD, RD-W)	66.8	CTUe/kg (ILCD, USEtox, ET)	0.136	Mole of N eq/kg (ILCD, EP-T)	86.2	kg C deficit eq/kg (ILCD, LU)	78.3	MJ/kg (PED)
				3.00	kg CO_2 eq/kg (ILCD, GWP100 excl seq)			2.11E-7	CTUh/kg (ILCD, USEtox, HTC)	2.06E-3	kg P eq/kg (ILCD, EP-F)				
								1.13E-6	CTUh/kg (ILCD, USEtox, HTNC)	0.0175	kg N eq/kg (ILCD, EP-M)				
GaBi Professional database 8.7 as implemented in GaBi	Cotton		Global av	-0.112	kg CO_2 eq/kg (ILCD, GWP100 incl seq)	0.363	m³ eq/kg (ILCD, RD-W)	4.37	CTUe/kg (ILCD, USEtox, ET)	0.199	Mole of N eq/kg (ILCD, EP-T)	163	kg C deficit eq/kg (ILCD, LU)	57.6	MJ/kg (PED)
				1.43	kg CO_2 eq/kg (ILCD, GWP100 excl seq)			4.29E-8	CTUh/kg (ILCD, USEtox, HTC)	3.06E-4	kg P eq/kg (ILCD, EP-F)				
								8.08E-8	CTUh/kg (ILCD, USEtox, HTNC)	5.82E-3	kg N eq/kg (ILCD, EP-M)				
GaBi Professional database 8.7 as implemented in GaBi	Cotton	Organic cotton	Global av	-0.554	kg CO_2 eq/kg (ILCD, GWP100 incl seq)	0.116	m³ eq/kg (ILCD, RD-W)	0.173	CTUe/kg (ILCD, USEtox, ET)	3.36E-3	Mole of N eq/kg (ILCD, EP-T)	206	kg C deficit eq/kg (ILCD, LU)	50.8	MJ/kg (PED)
				0.987	kg CO_2 eq/kg (ILCD, GWP100 excl seq)			2.54E-9	CTUh/kg (ILCD, USEtox, HTC)	1.03E-4	kg P eq/kg (ILCD, EP-F)				
								1.15E-7	CTUh/kg (ILCD, USEtox, HTNC)	4.78E-3	kg N eq/kg (ILCD, EP-M)				
GaBi Professional	Cotton	Conventional cotton, raw fibres (including fibres and	EU-28 av	-0.777	kg CO_2 eq/kg (ILCD, GWP100 incl	0.149	m³ eq/kg (ILCD, RD-W)	0.829	CTUe/kg (ILCD, USEtox,	0.044	Mole of N eq/kg (ILCD, EP-T)	94.4	kg C deficit eq/kg	30.1	MJ/kg (PED)

database 8.7 as implemented in GaBi		grains, excluding ginning)			seq)				ET)				(ILCD, LU)		
				1.06	kg CO_2 eq/kg (ILCD, GWP100 excl seq)			2.10E-8	CTUh/kg (ILCD, USEtox, HTC)	8.27E-4	kg P eq/kg (ILCD, EP-F)				
								-1.43E-6	CTUh/kg (ILCD, USEtox, HTNC)	0.016	kg N eq/kg (ILCD, EP-M)				
GaBi Professional database 8.7 as implemented in GaBi	Cotton	Organic cotton	EU-28 av	-0.826	kg CO_2 eq/kg (ILCD, GWP100 incl seq)	0.116	m^3 eq/kg (ILCD, RD-W)	0.176	CTUe/kg (ILCD, USEtox, ET)	0.037	Mole of N eq/kg (ILCD, EP-T)	206	kg C deficit eq/kg (ILCD, LU)	26.6	MJ/kg (PED)
				1.01	kg CO_2 eq/kg (ILCD, GWP100 excl seq)			2.71E-9	CTUh/kg (ILCD, USEtox, HTC)	1.03E-4	kg P eq/kg (ILCD, EP-F)				
								1.16E-7	CTUh/kg (ILCD, USEtox, HTNC)	5.04E-3	kg N eq/kg (ILCD, EP-M)				
Idemat 2018	Cotton		China	3.59	kg CO_2 eq/kg (ReCiPe)			6.06E-6	species.year/kg (ReCiPe, ET)					11.0	MJ/kg (CED)
								1.00E-3	DALY/kg (ReCiPe, H)						
Idemat 2018	Cotton		USA	6.62	kg CO_2 eq/kg (ReCiPe)			7.48E-6	species.year/kg (ReCiPe, ET)					54.4	MJ/kg (CED)
								1.24E-3	DALY/kg (ReCiPe, H)						
Idemat 2018	Cotton		China	7.02	kg CO_2 eq/kg (ReCiPe)			1.67E-5	species.year/kg (ReCiPe, ET)					62.2	MJ/kg (CED)
								2.76E-3	DALY/kg (ReCiPe, H)						
Idemat 2018	Cotton		Market mix	7.47	kg CO_2 eq/kg (ReCiPe)			1.68E-5	species.year/kg (ReCiPe, ET)					68.9	MJ/kg (CED)
								2.77E-3	DALY/kg (ReCiPe, H)						
Idemat 2018	Cotton		RoW	7.02	kg CO_2 eq/kg (ReCiPe)			1.68E-5	species.year/kg (ReCiPe, ET)					62.6	MJ/kg (CED)
								2.78E-3	DALY/kg (ReCiPe, H)						
Idemat 2018	Cotton		USA	9.30	kg CO_2 eq/kg (ReCiPe)			1.67E-5	species.year/kg (ReCiPe, ET)					94.2	MJ/kg (CED)
								2.76E-3	DALY/kg (ReCiPe, H)						
Higg MSI															
Higg MSI	Cotton	Conventional cotton	China, India, Australia, USA av	2.2	points	47.6	points (WS)			9.1	points				

2.2 Environmental impact data of non cotton plant fibers.

Source	Fibre type	Further description	Production location	Climate change		Water depletion/use		Toxicity		Eutrophication		Land use and related indicators		Energy use	
				number	unit (method)	number	unit (method)	number	unit (method)	number	unit (method)	number	unit (method)	number	unit (method)
Peer-reviewed journal articles															
Zampori et al. 2013	Hemp	Technical fibres	Italy	-1.64-(-1.73)	kg CO_2 eq/kg (GGP, GWP100 incl seq)									~20-22	MJ (CED)
				0.1-0.2	kg CO_2 eq/kg (GGP, GWP100 excl seq)										
Le Duigou et al. 2011	Flax	Hackled flax fibres (final state prior to, e.g., wet spinning of yarn)	Normandy, France	-6.4-(-1.4)	kg CO_2 eq/kg (CML, GWP100 incl seq)			0.77-0.215	kg 1,4 DB eq/kg (CML, HTP)	1.4E-3-6.3E-3	kg PO_4^{3-} eq/kg (CML, EP)	0.84-3.8	m²/yr/ha (IMPACT2002+, LU)		
				0.3	kg CO_2 eq/kg (CML, GWP100 excl seq)			0.059-0.24	kg 1,4 DB eq/kg (CML, FAETP)						
								8.7E-3-0.22	kg 1,4 DB eq/kg (CML, TETP)						
Other reports															
Cherrett et al. 2005[1]	Hemp	Experimental process	UK	~5-6	kg CO_2/kg (UM)	2.123-3.483	m³/kg (WR)							~30	MJ (ER)
Cherrett et al. 2005	Hemp	Semi-experimental process	UK	~5-6	kg CO_2/kg (UM)	2.123-3.483	m³/kg (WR)							~30	MJ (ER)
Cherrett et al. 2005	Hemp	Traditional process	UK	~4	kg CO_2/kg (UM)	2.384-3.744	m³/kg (WR)							~25	MJ (ER)
Cherrett et al. 2005	Hemp	Organic, experimental process	UK	~5	kg CO_2/kg (UM)	2.123-3.483	m³/kg (WR)							~25	MJ (ER)
Cherrett et al. 2005	Hemp	Organic, semi-experimental process	UK	~5	kg CO_2/kg (UM)	2.123-3.483	m³/kg (WR)							~25	MJ (ER)
Cherrett et al. 2005	Hemp	Organic, traditional process	UK	~3.5-4	kg CO_2/kg (UM)	2.384-3.744	m³/kg (WR)	-		-		-		~15	MJ (ER)

[1] The carbon footprints of fibres stated in Cherrett et al. (2005) are in the range 2-10 kg CO_2/*tonne* fibres. We have interpreted this as an error, as similar numbers are usually per kg, and therefore multiplied the numbers by a factor of 1000.

Barth & Carus 2017[2]	Hemp	Mineral fertilizers	The Netherlands	0.768	kg CO_2 eq/kg (GWP100)										
Barth & Carus 2017	Hemp	Organic fertilizers	The Netherlands	0.615	kg CO_2 eq/kg (GWP100)									~5[3]	MJ (ER)
Barth & Carus 2017	Flax		Middle Europe	0.731	kg CO_2 eq/kg (GWP100)										
Barth & Carus 2017	Jute		India and Bangladesh	0.766	kg CO_2 eq/kg (GWP100)										
Barth & Carus 2017	Kenaf		India and Bangladesh	0.767	kg CO_2 eq/kg (GWP100)										
Schultz & Suresh 2017	Flax	Made by-products from linen industry (e.g. combings and card waste)	Belgium	-0.63 0	kg CO_2 eq/kg (GCC) kg CO_2 eq/kg (GCC)	0.263	m^3/kg (NFC)	4.3E-3 0.3E-6	kg acrolein eq/kg (HAACER) kg Cr VI eq (HHI-CR)	ND	kg NO_3 eq/kg (FE)	4E-5 6E-6 0	eq ha dist*yr/kg (TD) species/kg (TSHD) m^3 (WRD)	9	MJ/kg (NRERD)
Dissanayake et al. 2009[4]	Flax	No-tillage and water retting (sliver, same as hackled flax)	Not specified	11.2	kg CO_2 eq/kg (CML, GWP100)			0.022 1.03	kg 1,4 DB eq/kg (CML, HTP) kg 1,4 DB eq/kg (CML, FAETP)	0.102	kg PO_4^{3-} eq/kg (CML, EP)				
Dissanayake et al. 2009	Flax	Conservation tillage and dew retting (sliver, same as hackled flax)	Not specified	17.9	kg CO_2 eq/kg (CML, GWP100)			0.034 1.99	kg 1,4 DB eq/kg (CML, HTP) kg 1,4 DB eq/kg (CML, FAETP)	0.195	kg PO_4^{3-} eq/kg (CML, EP)				
Dissanayake et al. 2009	Flax	Conservation tillage and bio-retting (sliver, same as hackled flax)	Not specified	18.6	kg CO_2 eq/kg (CML, GWP100)			0.015 0.905	kg 1,4 DB eq/kg (CML, HTP) kg 1,4 DB eq/kg (CML, FAETP)	0.089	kg PO_4^{3-} eq/kg (CML, EP)				
Dissanayake et al. 2009	Flax	No-tillage and bio-retting (sliver, same as hackled flax)	Not specified	18.5	kg CO_2 eq/kg (CML, GWP100)			0.015 0.905	kg 1,4 DB eq/kg (CML, HTP) kg 1,4 DB eq/kg (CML, FAETP)	0.099	kg PO_4^{3-} eq/kg (CML, EP)				
Databases															
Ecoinvent 3.4 as implemented in SimaPro	Jute	Rainfed cultivation	India	-1.033	kg CO_2 eq/kg (ILCD, GWP100 incl seq)	0.049	m^3 eq/kg (ILCD, WS)	6.042 2.79E-8	CTUe/kg (ILCD, USEtox, ET) CTUh/kg (ILCD, USEtox,	0.048 2.46E-4	Mole of N eq/kg (ILCD, EP-T) kg P eq/kg (ILCD, EP-F)	11.6	kg C deficit eq/kg (ILCD, LU)	1.7 28.5	MJ/kg (NREU CED) MJ/kg (REU CED)

[2] Impact data listed here from Barth and Carus (2017) exclude distribution transport to Germany, which are included in the original data. Moreover, it should be noted that impact data were calculated using mass-based allocation, which (in contrast to economic allocation) is beneficial for long hemp fibres (as these are) due to the many lower quality by-products of hemp cultivation.
[3] The stated source for this number in turns refers to a primary source only available in German, thus the first encountered source is stated here (i.e. Barth & Carus 2017).
[4] Units and methods not explicitly specified, but we interpret the reference as using the CML framework.

									HTC)						
				0.302	kg CO_2 eq/kg (ILCD, GWP100 excl seq)			-1.13E-7	CTUh/kg (ILCD, USEtox, HTNC)	0.003	kg N eq/kg (ILCD, EP-M)				
Ecoinvent 3.4 as implemented in SimaPro	Jute	Irrigated cultivation	India	-0.823	kg CO_2 eq/kg (ILCD, GWP100 incl seq)	0.405	m^3 eq/kg (ILCD, WS)	8.079	CTUe/kg (ILCD, USEtox, ET)	0.047	Mole of N eq/kg (ILCD, EP-T)	12.0	kg C deficit eq/kg (ILCD, LU)	4.1	MJ/kg (NREU CED)
								9.05E-8	CTUh/kg (ILCD, USEtox, HTC)	3.37E-4	kg P eq/kg (ILCD, EP-F)			30.9	MJ/kg (REU CED)
				0.517	kg CO_2 eq/kg (ILCD, GWP100 excl seq)			-7.77E-7	CTUh/kg (ILCD, USEtox, HTNC)	0.003	kg N eq/kg (ILCD, EP-M)				
Ecoinvent 3.4 as implemented in SimaPro	Kenaf		India	-0.877	kg CO_2 eq/kg (ILCD, GWP100 incl seq)	0.331	m^3 eq/kg (ILCD, WS)	6.756	CTUe/kg (ILCD, USEtox, ET)	0.044	Mole of N eq/kg (ILCD, EP-T)	10.4	kg C deficit eq/kg (ILCD, LU)	3.8	MJ/kg (NREU CED)
								5.52E-8	CTUh/kg (ILCD, USEtox, HTC)	2.85E-4	kg P eq/kg (ILCD, EP-F)			30.7	MJ/kg (REU CED)
				0.461	kg CO_2 eq/kg (ILCD, GWP100 excl seq)			-5.56E-7	CTUh/kg (ILCD, USEtox, HTNC)	0.044	kg N eq/kg (ILCD, EP-M)				
Ecoinvent 3.3 as implemented in GaBi	Jute	Rainfed cultivation	India	-4.05	kg CO_2 eq/kg (ILCD, GWP100 incl seq)	0.0100	m^3 eq/kg (ILCD, RD-W)	10	CTUe/kg (ILCD, USEtox, ET)	0.0674	Mole of N eq/kg (ILCD, EP-T)	19.8	kg C deficit eq/kg (ILCD, LU)	49	MJ/kg (PED)
								3.75E-8	CTUh/kg (ILCD, USEtox, HTC)	4.11E-4	kg P eq/kg (ILCD, EP-F)				
				0.561	kg CO_2 eq/kg (ILCD, GWP100 excl seq)			-3.69E-7	CTUh/kg (ILCD, USEtox, HTNC)	3.79E-3	kg N eq/kg (ILCD, EP-M)				
Ecoinvent 3.3 as implemented in GaBi	Jute	Irrigated cultivation	India	-3.70	kg CO_2 eq/kg (ILCD, GWP100 incl seq)	0.107	m^3 eq/kg (ILCD, RD-W)	13.5	CTUe/kg (ILCD, USEtox, ET)	0.0651	Mole of N eq/kg (ILCD, EP-T)	20.4	kg C deficit eq/kg (ILCD, LU)	52.7	MJ/kg (PED)
								1.46E-7	CTUh/kg (ILCD, USEtox, HTC)	6.00E-4	kg P eq/kg (ILCD, EP-F)				
				0.911	kg CO_2 eq/kg (ILCD, GWP100 excl seq)			-1.52E-6	CTUh/kg (ILCD, USEtox, HTNC)	4.57E-3	kg N eq/kg (ILCD, EP-M)				
Ecoinvent 3.3 as implemented in GaBi	Kenaf		India	-3.80	kg CO_2 eq/kg (ILCD, GWP100 incl seq)	0.0857	m^3 eq/kg (ILCD, RD-W)	11.3	CTUe/kg (ILCD, USEtox, ET)	0.0604	Mole of N eq/kg (ILCD, EP-T)	17.7	kg C deficit eq/kg (ILCD, LU)	52.4	MJ/kg (PED)
								8.52E-8	CTUh/kg (ILCD, USEtox, HTC)	5.06E-4	kg P eq/kg (ILCD, EP-F)				
				0.82	kg CO_2 eq/kg (ILCD, GWP100 excl seq)			-1.13E-6	CTUh/kg (ILCD, USEtox, HTNC)	3.85E-3	kg N eq/kg (ILCD, EP-M)				
Idemat 2018	Jute	Rainfed cultivation	Bangladesh	0.96	kg CO_2 eq/kg (ReCiPe)			4.89E-7	species.year/kg (ReCiPe, ET)					3.66	MJ/kg (CED)

								8.10e-5	DALY/kg (ReCiPe, H)						
Idemat 2018	Jute	Rainfed cultivation	India	0.96	kg CO_2 eq/kg (ReCiPe)			4.89E-7 8.10e-5	species.year/kg (ReCiPe, ET) DALY/kg (ReCiPe, H)					3.66	MJ/kg (CED)
Idemat 2018	Jute	Rainfed cultivation	Market mix	0.96	kg CO_2 eq/kg (ReCiPe)			4.90E-7 8.12e-5	species.year/kg (ReCiPe, ET) DALY/kg (ReCiPe, H)					3.66	MJ/kg (CED)
Idemat 2018	Kenaf		India	0.38	kg CO_2 eq/kg (ReCiPe)			5.85E-6 9.63E-4	species.year/kg (ReCiPe, ET) DALY/kg (ReCiPe, H)					5.57	MJ/kg (CED)
Idemat 2018	Kenaf		Italy	0.38	kg CO_2 eq/kg (ReCiPe)			5.85E-6 9.63E-4	species.year/kg (ReCiPe, ET) DALY/kg (ReCiPe, H)					5.57	MJ/kg (CED)
Higg MSI															
Higg MSI	Flax		Global	5.5	points	2.1	points (WS)			22.2	points				

2.4 Environmental impact data of regenerated fibers.

Source	Fibre type	Further description	Production location	Climate change		Water depletion/use		Toxicity		Eutrophication		Land use and related indicators		Energy use	
				number	unit (method)	number	unit (method)	number	unit (method)	number	unit (method)	number	unit (method)	number	unit (method)
Peer-reviewed journal articles															
Sandin et al. 2013[1]	Generic regenerated fibre	Hypothetical future production. Spruce pulp.	Pulp and fibre production in Southern Sweden.			(-0.022)-0.044	m^3/kg (cWD)					3.9E-3-7.3E-3	wS_{100}/kg (BI of LU)		
						0.135	m^3/kg (aWD)					0	wS_{100}/kg (BI of LUC without LUC)		
												0.039-0.071	wS_{100}/kg (BI of LUC with LUC)		
Sandin et al. 2013	Generic regenerated fibre	Hypothetical future production. Spruce pulp.	Pulp and fibre production in China. Wood from Eastern Russia.			0.035-0.217	m^3/kg (cWD)					3.9E-3-7.2E-3	wS_{100}/kg (BI of LU)		
						0.516	m^3/kg (aWD)					0	wS_{100}/kg (BI of LUC without LUC)		
												0.039-0.071	wS_{100}/kg (BI of LUC with LUC)		
Sandin et al. 2013	Generic regenerated fibre	Hypothetical future production. Eucalyptus pulp.	Pulp and fibre production in China. Wood from Indonesia (Borneo).			0.049-0.202	m^3/kg (cWD)					4.2E-3-7.1E-3	wS_{100}/kg (BI of LU)		
						0.948	m^3/kg (aWD)					0.157-0.267	wS_{100}/kg (BI of LUC[2])		
												0.023-0.038	wS_{100}/kg (BI of LUC[3])		
Shen et al. 2010a	Lyocell	Production in 2010. Eucalyptus and beech pulp.	Fibre production in Austria. Pulp production partly in Austria, partly elsewhere. Wood of unspecified origin	~1.1	kg CO_2 eq/kg (CML GWP100 incl seq)	0.263	m^3/kg (WU)[4]	0.470	kg 1,4 DB eq/kg (CML, HTP)	1.8E-3	kg PO_4^{3-} eq/kg (CML, EP)	~0.25E-3	ha/t-yr (fl)	~65	MJ/kg (CED)
				~2.3	kg CO_2 eq/kg (CML GWP100 excl seq)			85	kg 1,4 DB eq/kg (CML, FAETP)					42	MJ/kg (NREU)
								5.0	kg 1,4 DB eq/kg (CML, TETP)					~23	MJ/kg (REU)
Shen et al. 2010a	Lyocell	Future scenario for production in 2012.	Fibre production in Austria. Pulp	~0.05	kg CO_2 eq/kg (CML GWP100	0.263	m^3/kg (WU)	660	kg 1,4 DB eq/kg (CML, HTP)	1.9	kg PO_4^{3-} eq/kg	~0.22E-3	ha/t-yr (fl)	~103	MJ/kg (CED)

[1] Scenarios were created to reflect potential future production of a new kind of regenerated fibre under development, but data used rather reflect generic production of regenerated fibres. Water use and land use (biodiversity) impact results also given on an EI end-point level in terms of impact on human health, ecosystem quality, resources and aggregated. For this data, the reader is referred to the original reference.
[2] Impact allocated to first harvest after LUC.
[3] Impact allocated to all harvests in 62.5 years after LUC.
[4] Includes process water, cooling water and irrigation water (same for below water use data from Shen et al. 2010).

		Eucalyptus and beech pulp.	production partly in Austria, partly elsewhere. Wood of unspecified origin		incl seq)						(CML, EP)				
				~1.7	kg CO_2 eq/kg (CML GWP100 excl seq)			75	kg 1,4 DB eq/kg (CML, FAETP)					21	MJ/kg (NREU)
								5.0	kg 1,4 DB eq/kg (CML, TETP)					~82	MJ/kg (REU)
Shen et al. 2010a	Viscose	Fibre and pulp production separate. Eucalyptus pulp.	Fibre production in Asia. Pulp of unspecified origin. Wood from Southern hemisphere.	~3.8	kg CO_2 eq/kg (CML GWP100 incl seq)	0.319	m^3/kg (WU)	1490	kg 1,4 DB eq/kg (CML, HTP)	2.3	kg PO_4^{3-} eq/kg (CML, EP)	~0.3E-3	ha/t-yr (fl)	~107	MJ/kg (CED)
				~5.5	kg CO_2 eq/kg (CML GWP100 excl seq)			160	kg 1,4 DB eq/kg (CML, FAETP)					61	MJ/kg (NREU)
								16	kg 1,4 DB eq/kg (CML, TETP)					~46	MJ/kg (REU)
Shen et al. 2010a	Viscose	Fibre and pulp production integrated. Beech pulp.	Fibre and pulp production in Austria. Wood from Europe.	~ -0.25	kg CO_2 eq/kg (CML GWP100 incl seq)	0.445	m^3/kg (WU)	630	kg 1,4 DB eq/kg (CML, HTP)	1.2	kg PO_4^{3-} eq/kg (CML, EP)	~0.7E-3	ha/t-yr (fl)	~107	MJ/kg (CED)
				~1.75	kg CO_2 eq/kg (CML GWP100 excl seq)			74	kg 1,4 DB eq/kg (CML, FAETP)					19	MJ/kg (NREU)
								11	kg 1,4 DB eq/kg (CML, TETP)					~88	MJ/kg (REU)
Shen et al. 2010a	Modal	Fibre and pulp production integrated. Beech pulp.	Fibre and pulp production in Austria. Pulp from Europe.	~0.03	kg CO_2 eq/kg (CML GWP100 incl seq)	0.472	m^3/kg (WU)	765	kg 1,4 DB eq/kg (CML, HTP)	1.3	kg PO_4^{3-} eq/kg (CML, EP)	~0.8E-3	ha/t-yr (fl)	~79	MJ/kg (CED)
				~2.2	kg CO_2 eq/kg (CML GWP100 excl seq)			93	kg 1,4 DB eq/kg (CML, FAETP)					42	MJ/kg (NREU)
								16	kg 1,4 DB eq/kg (CML, TETP)					~37	MJ/kg (REU)
Other reports															
Schultz & Suresh 2017[5]	Lyocell	Eucalyptus and beech pulp	Fibre production in Austria. Pulp from South Africa and Austria.	3.4	kg CO_2 eq/kg (GCC)	0.290	m^3/kg (NFC)	3.7E-6	kg acrolein eq/kg (HAACER)	ND[6]	kg NO_3 eq/kg (FE)	158E-6	eq ha dist*yr/kg (TD)	25	MJ/kg (NRERD)
				0	kg aerosol loading/kg (RCHI)			0.7E-6	kg Cr VI eq (HHI-CR)			25E-6	species/kg (TSHD)		
												0	m^3 (WRD)		
Schultz & Suresh 2017	Viscose	Softwood pulp	Fibre production in Germany. Pulp from Sweden.	5.2	kg CO_2 eq/kg (GCC)	0.327	m^3/kg (NFC)	5.5E-6	kg acrolein eq/kg (HAACER)	ND	kg NO_3 eq/kg (FE)	250E-6	eq ha dist*yr/kg (TD)	22	MJ/kg (NRERD)
				0	kg aerosol loading/kg (RCHI)			0.9E-6	kg Cr VI eq (HHI-CR)			7E-6	species/kg (TSHD)		
												0	m^3 (WRD)		

[5] In a sensitivity analysis, Schultz and Suresh (2017) also provide results using the CML impact categories and characterisation methods. These are not shown here for brevity.
[6] Instead of leaving the cell blank, ND (no data) is specified and the unit and method are kept, in cases where the original authors attempted to find data.

Schultz & Suresh 2017	Viscose	Softwood pulp	Fibre production in Asia. Pulp from Canada.	12	kg CO_2 eq/kg (GCC)	0.422	m^3/kg (NFC)	6.6E-6	kg acrolein eq/kg (HAACER)	ND	kg NO_3 eq/kg (FE)	435E-6	eq ha dist*yr/kg (TD)	33	MJ/kg (NRERD)
				0.015	kg aerosol loading/kg (RCHI)			0.8E-6	kg Cr VI eq (HHI-CR)			7E-6	species/kg (TSHD)		
												5.5E-6	m^3 (WRD)		
Schultz & Suresh 2017	Viscose	Tropical hardwood pulp	Fibre production in China. Pulp from Indonesia.	13	kg CO_2 eq/kg (GCC)	0.310	m^3/kg (NFC)	5.6E-6	kg acrolein eq/kg (HAACER)	ND	kg NO_3 eq/kg (FE)	787E-6	eq ha dist*yr/kg (TD)	37	MJ/kg (NRERD)
				0.028	kg aerosol loading/kg (RCHI)			0.9E-6	kg Cr VI eq (HHI-CR)			55E-6	species/kg (TSHD)		
												5.2E-6	m^3 (WRD)		
Schultz & Suresh 2017	Viscose	Eucalyptus pulp	Fibre production in China. Pulp from Indonesia.	6.3	kg CO_2 eq/kg (GCC)	0.310	m^3/kg (NFC)	5.6E-6	kg acrolein eq/kg (HAACER)	ND	kg NO_3 eq/kg (FE)	304E-6	eq ha dist*yr/kg (TD)	37	MJ/kg (NRERD)
				0.028	kg aerosol loading/kg (RCHI)			0.9E-6	kg Cr VI eq (HHI-CR)			55E-6	species/kg (TSHD)		
												0	m^3 (WRD)		
Schultz & Suresh 2017	Viscose	Pulp made from recycled clothing	Fibre production in Germany	-2.0	kg CO_2 eq/kg (GCC)	0.377	m^3/kg (NFC)	5.3E-6	kg acrolein eq/kg (HAACER)	ND	kg NO_3 eq/kg (FE)	0	eq ha dist*yr/kg (TD)	21	MJ/kg (NRERD)
				0	kg aerosol loading/kg (RCHI)			0.7E-6	kg Cr VI eq (HHI-CR)			0	species/kg (TSHD)		
												0	m^3 (WRD)		
Schultz & Suresh 2017	Viscose	Bamboo pulp	Fibre production in China. Pulp from China.	4.4	kg CO_2 eq/kg (GCC)	0.738	m^3/kg (NFC)	6.6E-6	kg acrolein eq/kg (HAACER)	ND	kg NO_3 eq/kg (FE)	89E-6	eq ha dist*yr/kg (TD)	26	MJ/kg (NRERD)
				0.020	kg aerosol loading/kg (RCHI)			0.8E-6	kg Cr VI eq (HHI-CR)			0	species/kg (TSHD)		
												0	m^3 (WRD)		
Schultz & Suresh 2017	Viscose	Cotton linter pulp	Fibre production in China. Indian cotton linter pulped in China.	2.3	kg CO_2 eq/kg (GCC)	0.740	m^3/kg (NFC)	8.3E-6	kg acrolein eq/kg (HAACER)	ND	kg NO_3 eq/kg (FE)	116E-6	eq ha dist*yr/kg (TD)	34	MJ/kg (NRERD)
				0.020	kg aerosol loading/kg (RCHI)			0.7E-6	kg Cr VI eq (HHI-CR)			0	species/kg (TSHD)		
												0	m^3 (WRD)		
Schultz & Suresh 2017	Viscose	Eucalyptus pulp	Fibre production in China. Pulp from South Africa.	0.072	kg CO_2 eq/kg (GCC)	0.432	m^3/kg (NFC)	5.1E-6	kg acrolein eq/kg (HAACER)	ND	kg NO_3 eq/kg (FE)	41E-6	eq ha dist*yr/kg (TD)	28	MJ/kg (NRERD)
				0.015	kg aerosol loading/kg (RCHI)			0.7E-6	kg Cr VI eq (HHI-CR)			14E-6	species/kg (TSHD)		
												0	m^3 (WRD)		
Laursen et al. 1997	Viscose		Not specified			0.64	m^3/kg (WC)							35.3	MJ/kg (EC)

Databases															
Ecoinvent 3.4 as implemented in SimaPro	Viscose		Global av	1.43	kg CO_2 eq/kg (ILCD, GWP100 incl seq)	0.088	m^3 eq/kg (ILCD, WS)	37.3	CTUe/kg (ILCD, USEtox, ET)	0.620	Mole of N eq/kg (ILCD, EP-T)	29.4	kg C deficit eq/kg (ILCD, LU)	80.2	MJ/kg (NREU CED)
				4.78	kg CO_2 eq/kg (ILCD, GWP100 excl seq)			3.54E-7	CTUh/kg (ILCD, USEtox, HTC)	2.87E-3	kg P eq/kg (ILCD, EP-F)			88.9	MJ/kg (REU CED)
								3.44E-6	CTUh/kg (ILCD, USEtox, HTNC)	7.4E-3	kg N eq/kg (ILCD, EP-M)				
Ecoinvent 3.3 as implemented in in GaBi	Viscose		Global av	2.12	kg CO_2 eq/kg (ILCD, GWP100 incl seq)	0.069	m^3 eq/kg (ILCD, RD-W)	29.8	CTUe/kg (ILCD, USEtox, ET)	0.0393	Mole of N eq/kg (ILCD, EP-T)	13.1	kg C deficit eq/kg (ILCD, LU)	78.6	MJ/kg (PED)
				3.53	kg CO_2 eq/kg (ILCD, GWP100 excl seq)			1.96E-7	CTUh/kg (ILCD, USEtox, HTC)	1.49E-3	kg P eq/kg (ILCD, EP-F)				
								1.91E-6	CTUh/kg (ILCD, USEtox, HTNC)	4.03E-3	kg N eq/kg (ILCD, EP-M)				
Idemat 2018	Viscose without pulp[7]	Viscose production	Austria	1.50	kg CO_2 eq/kg (ReCiPe)			6.89E-9	species.year/kg (ReCiPe, ET)					20.6	MJ/kg (CED)
								3.67E-6	DALY/kg (ReCiPe, H)						
Higg MSI															
Higg MSI	Modal	Non-integrated fibre and pulp production. Pulp from eucalyptus, spruce, beech, birch and other hardwoods.	Global	10.6	points	3.9	points (WS)			5.9	points				
Higg MSI	Viscose	Non-integrated fibre and pulp production. Pulp from eucalyptus, spruce, beech, birch and other hardwoods	Global	7.6	points	4.1	points (WS)			5.4	points				
Higg MSI	Lyocell	Non-integrated fibre and pulp production. Pulp from eucalyptus, spruce, beech, birch and other hardwoods.	Global	6.9	points	2.5	points (WS)			4.8	points				
Higg MSI	Acetate	Pulp from pine, spruce and cotton linters.	Global	7.6	points	4.1	points (WS)			5.5	points				

[7] Pulp assumed not to be included. Another dataset is called "Idematapp2018. spinning viscose fibres (80-500 dtex)", which is assumed to be spinning of viscose staple fibre into yarn since the viscose production includes wet spinning to filaments.

2.5 Environmental impact data of polyester fibers.

Source	Fibre type /polymer /process	Further description	Production location	Climate change		Water depletion/use		Toxicity		Eutrophication		Land use and related indicators		Energy use	
				number	unit (method)	number	unit (method)	number	unit (method)	number	unit (method)	number	unit (method)	number	unit (method)
Peer-reviewed journal articles															
van der Velden et al. 2014	Granulate	PET granulates, bottle grade, fossil	Not specified	2.0	kg CO_2 eq/kg (GWP100)									68.4	MJ/kg (NREU)
van der Velden et al. 2014	Granulate	PET granulates, amorphous, fossil	Not specified	3.3	kg CO_2 eq/kg (GWP100)									80.5	MJ/kg (NREU)
Shen et al. 2012	Granulate	Petrochemical PET (amorphous), cradle-to-factory gate	Western Europe	2.05	kg CO_2 eq/kg (GWP100)									67	MJ/kg (NREU)
Shen et al. 2012	Granulate	Bio-based PET from maize, amorphous	Feedstock from USA. Production in Europe:	1.36	kg CO_2 eq/kg (GWP100)									59	MJ/kg (NREU)
				1.65	kg CO_2 eq/kg (GWP100 incl. ILUC)										
Shen et al. 2012	Granulate	Bio-based PET from sugar cane, amorphous	Feedstock from Brazil. Production in Europe.	1.03	kg CO_2 eq/kg (GWP100)									51	MJ/kg (NREU)
				1.47	kg CO_2 eq/kg (GWP100 incl. ILUC)										
Shen et al. 2012	Granulate	Recycled PET, amorphous, from bottles	Europe	1.01	kg CO_2 eq/kg (GWP100)									9.5	MJ/kg (NREU)
van der Velden et al. 2014	Process	Granulate to staple fibre	Not specified											0.31-0.89	kWh (direct electricity use)
														0.48-10.6	MJ/kg (direct energy use)
van der Velden et al. 2014	Process	Granulate to filament (POY)	Not specified											0.30-1.70	kWh (direct electricity use)
														0.48-5.00	MJ/kg (direct energy use)
Shen et al. 2012	Process	Granulate to filament fibre	Not specified											0.64	kWh/kg (direct electricity use)
														5.0	MJ/kg (NREU)
Shen et al. 2010b	Polyester fibre	Fossil PET staple fibres	Western Europe	4.1	kg CO_2 eq/kg (GWP100)									95	MJ/kg (NREU)
														1-2	MJ/kg (REU)

Shen et al. 2012	Polyester fibre	Recycled PET fibres	Europe	1.7	kg CO_2 eq/kg (GWP100)									22	MJ/kg (NREU)
Muthu et al. 2012	Polyester fibre		Not specified			0.062	m^3/kg (WU)								
Kalliala & Nousiainen 1999	Polyester fibre		Not specified	2.31	kg CO_2/kg									15.2	kWh/kg (direct electricity use)
														82.2	MJ/kg (direct energy use)
Other reports															
Laursen et al. 1997	Granulate	Fossil polyester	Not specified											50.0	MJ/kg (process energy use)
														45.8	MJ/kg (energy of material resources)
Laursen et al. 1997	Process	Granulate to filament fibre	Not specified											13.5	MJ/kg (process energy use)
														0.19	MJ/kg (energy of material resources)
Laursen et al. 1997	Polyester fibre		Not specified											109	MJ/kg (energy use)
Cherrett et al. 2005[1]	Polyester fibre	Fossil polyester staple fibres	Europe											105	MJ/kg (energy incl. feedstock)
Cherrett et al. 2005	Polyester fibre	Fossil polyester staple fibres	US											127	MJ/kg (energy incl. feedstock)
Databases															
Ecoinvent 2 as implemented in SimaPro	Granulate	Fossil PET granulate amorphous	Europe	2.70	kg CO_2 eq/kg (GWP100)	0.0149	m^3 eq/kg (WS)	15.14	CTUe/kg (ILCD, USEtox, ET)	8.27E-4	kg P eq/kg (ILCD, EP-F)	1.53	kg C deficit/kg (ILCD, SOM))	74.2	MJ/kg (NREU)
								1.67E-07	CTUh/kg (ILCD, USEtox, HTC)					1.23	MJ/kg (REU)
								5.29E-07	CTUh/kg (ILCD, USEtox, HTNC)						
Ecoinvent 2 as implemented in SimaPro	Granulate	Fossil PET, granulate, bottle grade	Europe	2.89	kg CO_2 eq/kg (GWP100)	0.0163	m^3 eq/kg (WS)	18.67	CTUe/kg (ILCD, USEtox, ET)	1.00E-5	kg P eq/kg (ILCD, EP-F)	1.70	kg C deficit/kg (ILCD, SOM))	77.7	MJ/kg (NREU)
								2.03E-07	CTUh/kg (ILCD, USEtox, HTC)					1.46	MJ/kg (REU)

[1] Note that the energy use (for this row and the next) includes the feedstock (raw material). If the feedstock is not included, the energy use drops by approximately 36% (Cherrett et al. 2005).

								6.63E-07	CTUh/kg (ILCD, USEtox, HTNC)						
Ecoinvent 3.4 as implemented in SimaPro	Granulate	Fossil PET granulate, amorphous, market dataset	Global av	3.12	kg CO_2 eq/kg (GWP100)	3.38E-3	m^3 eq/kg (WS)	20.9	CTUe/kg (ILCD, USEtox, ET)	8.40E-4	kg P eq/kg (ILCD, EP-F)	2.53	kg C deficit/kg (ILCD, SOM))	74.3	MJ/kg (NREU)
								1.82E-07	CTUh/kg (ILCD, USEtox, HTC)					2.10	MJ/kg (REU)
								7.23E-07	CTUh/kg (ILCD, USEtox, HTNC)						
Ecoinvent 3.4 as implemented in SimaPro	Granulate	PET granulate, amorphous	European av	2.96	kg CO_2 eq/kg (GWP100)	4.92E-3	m^3 eq/kg (WS)	20.2	CTUe/kg (ILCD, USEtox, ET)	8.24E-4	kg P eq/kg (ILCD, EP-F)	2.23	kg C deficit/kg (ILCD, SOM))	73.1	MJ/kg (NREU)
								1.76E-07	CTUh/kg (ILCD, USEtox, HTC)					2.22	MJ/kg (REU)
								6.99E-07	CTUh/kg (ILCD, USEtox, HTNC)						
Ecoinvent 3.4 as implemented in SimaPro	Granulate	Recycled PET, granulate, amorphous, market dataset	Switzerland	0.44	kg CO_2 eq/kg (GWP100)	1.53E-3	m^3 eq/kg (WS)	17.27	CTUe/kg (ILCD, USEtox, ET)	1.54E-4	kg P eq/kg (ILCD, EP-F)	2.53	kg C deficit/kg (ILCD, SOM))	6.48	MJ/kg (NREU)
								6.34E-08	CTUh/kg (ILCD, USEtox, HTC)					2.02	MJ/kg (REU)
								3.43E-07	CTUh/kg (ILCD, USEtox, HTNC)						
Ecoinvent 3.4 as implemented in SimaPro	Granulate	Recycled PET granulate, amorphous, market dataset	European av	1.05	kg CO_2 eq/kg (GWP100)	3.53E-3	m^3 eq/kg (WS)	48.89	CTUe/kg (ILCD, USEtox, ET)	5.25E-4	kg P eq/kg (ILCD, EP-F)	2.53	kg C deficit/kg (ILCD, SOM))	14.8	MJ/kg (NREU)
								8.67E-08	CTUh/kg (ILCD, USEtox, HTC)					1.66	MJ/kg (REU)
								7.20E-07	CTUh/kg (ILCD, USEtox, HTNC)						
Ecoinvent 3.4 as implemented in SimaPro	Granulate	Recycled PET granulate, amorphous, market dataset	RoW av (non-Europe, Switzerland or US)	1.49	kg CO_2 eq/kg (GWP100)	-1.77E-3	m^3 eq/kg (WS)	52.18	CTUe/kg (ILCD, USEtox, ET)	4.80E-4	kg P eq/kg (ILCD, EP-F)	2.53	kg C deficit/kg (ILCD, SOM))	17.1	MJ/kg (NREU)
								9.45E-08	CTUh/kg (ILCD, USEtox, HTC)					1.15	MJ/kg (REU)
								7.88E-07	CTUh/kg (ILCD, USEtox, HTNC)						
Ecoinvent 3.4 as implemented in SimaPro	Granulate	Recycled PET granulate, amorphous, market dataset	USA	1.20	kg CO_2 eq/kg (GWP100)	-2.42E-3	m^3 eq./kg (WS)	50.48	CTUe/kg (ILCD, USEtox, ET)	8.00E-4	kg P eq/kg (ILCD, EP-F)	2.53	kg C deficit/kg (ILCD, SOM))	15.3	MJ/kg (NREU)
								1.07E-07	CTUh/kg (ILCD, USEtox, HTC)					0.726	MJ/kg (REU)
								7.76E-07	CTUh/kg (ILCD, USEtox, HTNC)						
Ecoinvent 3.3 as implemented in GaBi	Granulate	PET granulate, amorphous	Global av	2.90	kg CO_2 eq/kg (ILCD, GWP100 incl seq)	0.0263	m^3 eq/kg (ILCD, RD-W)	20.4	CTUe/kg (ILCD, USEtox, ET)	0.024	Mole of N eq/kg (ILCD, EP-T)	2.37	kg C deficit eq/kg (ILCD, LU)	71.3	MJ/kg (PED)
				2.90	kg CO_2 eq/kg (ILCD, GWP100 excl seq)			1.78E-7	CTUh/kg (ILCD, USEtox, HTC)	8.34E-4	kg P eq/kg (ILCD, EP-F)				
								7.05E-7	CTUh/kg (ILCD, USEtox, HTNC)	2.35E-3	kg N eq/kg (ILCD, EP-M)				

Ecoinvent 3.3 as implemented in in GaBi	Granulate	PET granulate, amorphous	European av	2.73	kg CO_2 eq/kg (ILCD, GWP100 incl seq)	0.0267	m^3 eq/kg (ILCD, RD-W)	19.7	CTUe/kg (ILCD, USEtox, ET)	0.021	Mole of N eq/kg (ILCD, EP-T)	2.04	kg C deficit eq/kg (ILCD, LU)	69.8	MJ/kg (PED)
				2.73	kg CO_2 eq/kg (ILCD, GWP100 excl seq)			1.71E-8	CTUh/kg (ILCD, USEtox, HTC)	8.13E-4	kg P eq/kg (ILCD, EP-F)				
								6.87E-7	CTUh/kg (ILCD, USEtox, HTNC)	2.07E-3	kg N eq/kg (ILCD, EP-M)				
Professional GaBi database 8.7 as implemented in GaBi	Granulate	PET granulate, amorphous, from DMT and EG	German av	2.92	kg CO_2 eq/kg (ILCD, GWP100 incl seq)	0.0398	m^3 eq/kg (ILCD, RD-W)	0.475	CTUe/kg (ILCD, USEtox, ET)	0.012	Mole of N eq/kg (ILCD, EP-T)	0.267	kg C deficit eq/kg (ILCD, LU)	79.2	MJ/kg (PED)
				2.91	kg CO_2 eq/kg (ILCD, GWP100 excl seq)			4.35E-8	CTUh/kg (ILCD, USEtox, HTC)	1.05E-5	kg P eq/kg (ILCD, EP-F)				
								2.76E-6	CTUh/kg (ILCD, USEtox, HTNC)	1.13E-3	kg N eq/kg (ILCD, EP-M)				
Professional GaBi database 8.7 as implemented in GaBi	Granulate	PET granulate, amorphous, from TPA and EG	European av	3.27	kg CO_2 eq/kg (ILCD, GWP100 incl seq)	8.80E-3	m^3 eq/kg (ILCD, RD-W)	0.124	CTUe/kg (ILCD, USEtox, ET)	0.032	Mole of N eq/kg (ILCD, EP-T)	0	kg C deficit eq/kg (ILCD, LU)	75.7	MJ/kg (PED)
				3.27	kg CO_2 eq/kg (ILCD, GWP100 excl seq)			8.41E-9	CTUh/kg (ILCD, USEtox, HTC)	1.13E-7	kg P eq/kg (ILCD, EP-F)				
								2.54E-9	CTUh/kg (ILCD, USEtox, HTNC)	2.88E-3	kg N eq/kg (ILCD, EP-M)				
Professional GaBi database 8.7 as implemented in GaBi	Polyester fibre		German av	4.52	kg CO_2 eq/kg (ILCD, GWP100 incl seq)	0.163	m^3 eq/kg (ILCD, RD-W)	0.513	CTUe/kg (ILCD, USEtox, ET)	0.019	Mole of N eq/kg (ILCD, EP-T)	1.17	kg C deficit eq/kg (ILCD, LU)	108	MJ/kg (PED)
				4.51	kg CO_2 eq/kg (ILCD, GWP100 excl seq)			4.75E-8	CTUh/kg (ILCD, USEtox, HTC)	1.67E-5	kg P eq/kg (ILCD, EP-F)				
								2.93E-6	CTUh/kg (ILCD, USEtox, HTNC)	1.85E-3	kg N eq/kg (ILCD, EP-M)				
Professional GaBi database 8.7 as implemented in GaBi	Polyester fibre		EU-28 av	4.09	kg CO_2 eq/kg (ILCD, GWP100 incl seq)	0.0836	m^3 eq/kg (ILCD, RD-W)	0.539	CTUe/kg (ILCD, USEtox, ET)	0.020	Mole of N eq/kg (ILCD, EP-T)	0.615	kg C deficit eq/kg (ILCD, LU)	108	MJ/kg (PED)
				4.08	kg CO_2 eq/kg (ILCD, GWP100 excl seq)			4.71E-8	CTUh/kg (ILCD, USEtox, HTC)	1.3E-5	kg P eq/kg (ILCD, EP-F)				
								2.97E-6	CTUh/kg (ILCD, USEtox, HTNC)	1.93E-3	kg N eq/kg (ILCD, EP-M)				
Idemat 2018	Process	Granulate to filament fibre (80–500 dtex)	Not specified	0.90	kg CO_2 eq/kg (GWP100)									19.2	MJ/kg (CED)
Idemat 2018	Granulate	PET granulate, amorphous	Europe	3.38	kg CO_2 eq/kg (GWP100)			1.87E-8	species.year/kg (ReCiPe, ET)					71.55	MJ/kg (CED)
								6.53E-6	DALY/kg (ReCiPe, H)						

Idemat 2018	Granulate	Bio-PET, bottle grade (not bio-degradable)	Europe	3.50	kg CO_2 eq/kg (GWP100)			1.92E-8 6.71E-6	species.year/kg (ReCiPe, ET) DALY/kg (ReCiPe, H)					73.08	MJ/kg (CED)
Idemat 2018	Granulate	PET/bio-PET recycled (estimate)	Europe	2.94	kg CO_2 eq/kg (GWP100)			1.16E-7 2.10E-5	species.year/kg (ReCiPe, ET) DALY/kg (ReCiPe, H)					48.09	MJ/kg (CED)
Higg MSI															
Higg MSI	Granulate	Fossil PET, continuous process	Global	3.2	points	0.7	points (WS)			1.5	points				
Higg MSI	Granulate	Partially bio-based PET (EG from sugarcane molasses)	Global	3.2	points	3.2	points (WS)			4.9	points				
Higg MSI	Granulate	Mechanically recycled PET flakes	Global	2.8	points	0.093	points (WS)			1.4	points				
Higg MSI	Granulate	PET, semi-chemically (BHET) recycled	Global	2.1	points	1.8	points (WS)			2.2	points				
Higg MSI	Process	Melt-spinning of continuous filament (80-500 dtex) and drawing, crimping, texturing, cutting	Global	2.4	points	0.2	points (WS)			1.8	points				

2.6 Environmental impact data of non-polyester synthetic fibres.

Source	Fibre type /polymer	Further description	Production location	Climate change		Water depletion/use		Toxicity		Eutrophication		Land use and related indicators		Energy use	
				number	unit (method)	number	unit (method)	number	unit (method)	number	unit (method)	number	unit (method)	number	unit (method)
Peer-reviewed journal articles															
van der Velden et al. 2014	Granulate	Acetonitrile (for acrylic fibre production)	European av	3.04	kg CO_2 eq/kg (GWP100)									86.7	MJ/kg (CED)
van der Velden et al. 2014	Granulate	PU, flexible foam	European av	4.83	kg CO_2 eq/kg (GWP100)									103	MJ/kg (CED)
van der Velden et al. 2014	Granulate	PA 6 50%, PA 66 50%	European av	8.64	kg CO_2 eq/kg (GWP100)									130	MJ/kg (CED)
Barber & Pellow 2006	Acrylic fibres		Not specified											175	MJ/kg (EC)
Yacout et al. 2016	Acrylic fibres		Egypt	5.4	kg CO_2 eq/kg (GWP100)					7E-3	kg NO_2			133	MJ/kg (CED)
Barber & Pellow 2006	Nylon fibres		Not specified											250	MJ/kg (EC)
Muthu et al. 2012	Nylon 66 fibres		Not specified			0.663	m^3/kg (WR)							139	MJ/kg
Muthu et al. 2012	Nylon 6 fibres		Not specified			0.185	m^3/kg (WR)							121	MJ/kg
Shen et al. 2010b	PLA fibres	PLA staple fibres	Not specified	2.0	kg CO_2 eq/kg (GWP100)									55	MJ/kg (NREU)
Shen et al. 2012	PLA fibres	PLA staple fibres. Feedstock from maize (50%) and sugarcane (50%).	USA and Thailand	~2.5	kg CO_2 eq/kg (GWP100)									~35	MJ/kg (NREU)
Barber & Pellow 2006	PP fibres		Not specified											115	MJ/kg (EC)
Muthu et al. 2012	PP fibres		Not specified			0.043	m^3/kg (WR)								
Other reports															
Laursen et al. 1997	Granulate	Acrylic, granulate, fossil-based	Not specified											42.5	MJ/kg
Laursen et al. 1997	Acrylic fibres		Not specified			0.210	m^3/kg (WC)							157	MJ/kg (EC)

Databases															
Ecoinvent 2 as implemented in SimaPro	Granulate	PA 6	European av	9.2	kg CO_2 eq/kg (ILCD, GWP100)	0.03	m^3 eq./kg (WS)	12.3	CTUe/kg (ILCD, USEtox, ET)	0.082	Mole of N eq/kg (ILCD, EP-T)	0.063	kg C deficit eq/kg (ILCD, SOM)	122	MJ/kg (NREU)
				14.5	kg CO_2 eq/kg (ILCD, GWP100 incl. biogenic)			2.2E-7	CTUh/kg (ILCD, USEtox, HTC)	2.1E-4	kg P eq/kg (ILCD, EP-F)			0.56	MJ/kg (REU)
								1.1E-7	CTUh/kg (ILCD, USEtox, HTNC)	10.0E-3	kg N eq/kg (ILCD, EP-M)				
Ecoinvent 2 as implemented in SimaPro	Granulate	PA 66	European av	8.0	kg CO_2 eq/kg (ILCD, GWP100)	0.11	m^3 eq./kg (WS)	13.2	CTUe/kg (ILCD, USEtox, ET)	0.067	Mole of N eq/kg (ILCD, EP-T)	0.040	kg C deficit eq/kg (ILCD, SOM)	136	MJ/kg (NREU)
				31.0	kg CO_2 eq/kg (ILCD, GWP100 incl. biogenic)			2.3E-7	CTUh/kg (ILCD, USEtox, HTC)	4.4E-4	kg P eq/kg (ILCD, EP-F)			1.33	MJ/kg (REU)
								1.0E-7	CTUh/kg (ILCD, USEtox, HTNC)	13.8E-3	kg N eq/kg (ILCD, EP-M)				
Ecoinvent 3.4 as implemented in SimaPro	Granulate	PA 66	European av	8.0	kg CO_2 eq/kg (ILCD, GWP100)	0.04	m^3 eq./kg (WS)	13.2	CTUe/kg (ILCD, USEtox, ET)	0.067	Mole of N eq/kg (ILCD, EP-T)	0.045	kg C deficit eq/kg (ILCD, SOM)	136	MJ/kg (NREU)
				31.4	kg CO_2 eq/kg (ILCD, GWP100 incl. biogenic)			2.3E-7	CTUh/kg (ILCD, USEtox, HTC)	4.4E-4	kg P eq/kg (ILCD, EP-F)			1.33	MJ/kg (REU)
								1.1E-7	CTUh/kg (ILCD, USEtox, HTNC)	13.6E-3	kg N eq/kg (ILCD, EP-M)				
Ecoinvent 3.4 as implemented in SimaPro	Granulate	PA 66, market dataset	Global av	8.1	kg CO_2 eq/kg (ILCD, GWP100)	0.04	m^3 eq./kg (WS)	13.7	CTUe/kg (ILCD, USEtox, ET)	0.069	Mole of N eq/kg (ILCD, EP-T)	0.34	kg C deficit eq/kg (ILCD, SOM)	137.1	MJ/kg (NREU)
				31.1	kg CO_2 eq/kg (ILCD, GWP100 incl. biogenic)			2.3E-7	CTUh/kg (ILCD, USEtox, HTC)	4.5E-4	kg P eq/kg (ILCD, EP-F)			1.37	MJ/kg (REU)
								1.3E-7	CTUh/kg (ILCD, USEtox, HTNC)	13.8E-3	kg N eq/kg (ILCD, EP-M)				
Ecoinvent 3.4 as implemented in SimaPro	Granulate	PA 6, market dataset	Global av	9.4	kg CO_2 eq/kg (ILCD, GWP100)	0.11	m^3 eq./kg (WS)	13.0	CTUe/kg (ILCD, USEtox, ET)	0.084	Mole of N eq/kg (ILCD, EP-T)	0.36	kg C deficit eq/kg (ILCD, SOM)	122.8	MJ/kg (NREU)
				14.7	kg CO_2 eq/kg (ILCD, GWP100 incl. biogenic)			2.2E-7	CTUh/kg (ILCD, USEtox, HTC)	2.2E-4	kg P eq/kg (ILCD, EP-F)			0.60	MJ/kg (REU)
								1.3E-7	CTUh/kg (ILCD, USEtox, HTNC)	8.5E-3	kg N eq/kg (ILCD, EP-M)				
Ecoinvent 3.3 as implemented in GaBi	Granulate	PA 6	European av	9.29	kg CO_2 eq/kg (ILCD, GWP100 incl seq)	0.0301	m^3 eq/kg (ILCD, RD-W)	12.4	CTUe/kg (ILCD, USEtox, ET)	0.0820	Mole of N eq/kg (ILCD, EP-T)	0.067	kg C deficit eq/kg (ILCD, LU)	116	MJ/kg (PED)
				9.27	kg CO_2 eq/kg (ILCD, GWP100 excl seq)			2.19E-7	CTUh/kg (ILCD, USEtox, HTC)	2.11E-4	kg P eq/kg (ILCD, EP-F)				
								1.11E-7	CTUh/kg (ILCD, USEtox, HTNC)	9.99E-3	kg N eq/kg (ILCD, EP-M)				

Ecoinvent 3.3 as implemented in iGaBi	Granulate	PA 66	European av	8.04	kg CO_2 eq/kg (ILCD, GWP100 incl seq)	0.107	m³ eq/kg (ILCD, RD-W)	13.2	CTUe/kg (ILCD, USEtox, ET)	0.0671	Mole of N eq/kg (ILCD, EP-T)	0.046	kg C deficit eq/kg (ILCD, LU)	128	MJ/kg (PED)
				8.01	kg CO_2 eq/kg (ILCD, GWP100 excl seq)			2.26E-7	CTUh/kg (ILCD, USEtox, HTC)	4.43E-4	kg P eq/kg (ILCD, EP-F)				
								1.05E-7	CTUh/kg (ILCD, USEtox, HTNC)	0.0138	kg N eq/kg (ILCD, EP-M)				
Ecoinvent 3.4 as implemented in SimaPro	Granulate	PE, high density, granulate, market dataset	Global av	2.0	kg CO_2 eq/kg (ILCD, GWP100)	0.002	m³ eq./kg (WS)	4.1	CTUe/kg (ILCD, USEtox, ET)	0.016	Mole of N eq/kg (ILCD, EP-T)	0.31	kg C deficit eq/kg (ILCD, SOM)	77.6	MJ/kg (NREU)
				15.3	kg CO_2 eq/kg (ILCD, GWP100 incl. biogenic)			6.7E-8	CTUh/kg (ILCD, USEtox, HTC)	3.8E-5	kg P eq/kg (ILCD, EP-F)			0.93	MJ/kg (REU)
								5.0E-8	CTUh/kg (ILCD, USEtox, HTNC)	1.5E-3	kg N eq/kg (ILCD, EP-M)				
Ecoinvent 3.3 as implemented in in GaBi	Granulate	PE, high density, granulate	European av	1.94	kg CO_2 eq/kg (ILCD, GWP100 incl seq)	5.26E-3	m³ eq/kg (ILCD, RD-W)	3.56	CTUe/kg (ILCD, USEtox, ET)	0.0138	Mole of N eq/kg (ILCD, EP-T)	0.016	kg C deficit eq/kg (ILCD, LU)	72.1	MJ/kg (PED)
				1.93	kg CO_2 eq/kg (ILCD, GWP100 excl seq)			6.23E-8	CTUh/kg (ILCD, USEtox, HTC)	2.73E-5	kg P eq/kg (ILCD, EP-F)				
								3.1E-8	CTUh/kg (ILCD, USEtox, HTNC)	1.27E-3	kg N eq/kg (ILCD, EP-M)				
Ecoinvent 2 as implemented in SimaPro	Granulate	PP, granulate	European av	2.0	kg CO_2 eq/kg (ILCD, GWP100)	0.007	m³ eq./kg (WS)	3.0	CTUe/kg (ILCD, USEtox, ET)	0.014	Mole of N eq/kg (ILCD, EP-T)	0.012	kg C deficit eq/kg (ILCD, SOM)	74.6	MJ/kg (NREU)
				10.4	kg CO_2 eq/kg (ILCD, GWP100 incl. biogenic)			5.2E-8	CTUh/kg (ILCD, USEtox, HTC)	6.43E-5	kg P eq/kg (ILCD, EP-F)			0.48	MJ/kg (REU)
								2.5E-8	CTUh/kg (ILCD, USEtox, HTNC)	1.3E-3	kg N eq/kg (ILCD, EP-M)				
Ecoinvent 2 as implemented in SimaPro	Granulate	Tetrafluoroethylene	European av	324	kg CO_2 eq/kg (ILCD, GWP100)	0.12	m³ eq./kg (WS)	95.5	CTUe/kg (ILCD, USEtox, ET)	0.087	Mole of N eq/kg (ILCD, EP-T)	8.23	kg C deficit eq/kg (ILCD, SOM)	208	MJ/kg (NREU)
				-3.9	kg CO_2 eq/kg (ILCD, GWP100 incl. biogenic)			9.1E-7	CTUh/kg (ILCD, USEtox, HTC)	6.3E-3	kg P eq/kg (ILCD, EP-F)			8.7	MJ/kg (REU)
								5.3E-6	CTUh/kg (ILCD, USEtox, HTNC)	9.1E-3	kg N eq/kg (ILCD, EP-M)				
Ecoinvent 3.3 as implemented in GaBi	Granulate	Tetrafluoroethylene monomers	European av	324	kg CO_2 eq/kg (ILCD, GWP100 incl seq)	0.201	m³ eq/kg (ILCD, RD-W)	149	CTUe/kg (ILCD, USEtox, ET)	0.115	Mole of N eq/kg (ILCD, EP-T)	17.2	kg C deficit eq/kg (ILCD, LU)	193	MJ/kg (PED)
				324	kg CO_2 eq/kg (ILCD, GWP100 excl seq)			9.13E-7	CTUh/kg (ILCD, USEtox, HTC)	6.18E-3	kg P eq/kg (ILCD, EP-F)				
								7.02E-6	CTUh/kg (ILCD, USEtox, HTNC)	0.011	kg N eq/kg (ILCD, EP-M)				
Idemat 2018	Granulate	Bio-PE (not bio-degradable)	Not specfied	2.19	kg CO_2 eq/kg (GWP100)			1.36E-8	species.year/kg (ReCiPe, ET)					68.9	MJ/kg (CED)
								4.22E-6	DALY/kg (ReCiPe, H)						

Idemat 2018	Granulate	PA-11, bio-based (not biodegradable), estimate	Not specified	8.01	kg CO_2 eq/kg (GWP100)			2.44E-8 5.95E-6	species.year/kg (ReCiPe, ET) DALY/kg (ReCiPe, H)					131	MJ/kg (CED)
Idemat 2018	Granulate	PLA, biodegradable	USA	3.95	kg CO_2 eq/kg (GWP100)			1.55E-8 7.40E-6	species.year/kg (ReCiPe, ET) DALY/kg (ReCiPe, H)					54.1	MJ/kg (CED)
Idemat 2018	Granulate	EVA rubber, estimate	Not specified	2.86	kg CO_2 eq/kg (GWP100)			8.73E-9 3.27E-6	species.year/kg (ReCiPe, ET) DALY/kg (ReCiPe, H)					80.8	MJ/kg (CED)
Idemat 2018	Granulate	PU rubber for shoe soles	the Netherlands	4.90	kg CO_2 eq/kg (GWP100)			9.54E-5 1.57E-2	species.year/kg (ReCiPe, ET) DALY/kg (ReCiPe, H)					97.8	MJ/kg (CED)
Idemat 2018	Granulate	PU polymer pellet production	Not specified	3.52	kg CO_2 eq/kg (GWP100)			1.08E-5 1.77E-3	species.year/kg (ReCiPe, ET) DALY/kg (ReCiPe, H)					85.7	MJ/kg (CED)
Idemat 2018	Granulate	PA polymer pellet production	Not specified	8.71	kg CO_2 eq/kg (GWP100)			4.13E-8 1.44E-5	species.year/kg (ReCiPe, ET) DALY/kg (ReCiPe, H)					118	MJ/kg (CED)
Idemat 2018	Granulate	PTFE, estimate	Not specified	8.01	kg CO_2 eq/kg (GWP100)			2.44E-8 9.14E-6	species.year/kg (ReCiPe, ET) DALY/kg (ReCiPe, H)					161	MJ/kg (CED)
Higg MSI															
Higg MSI	Granulate	Acrylonitrile, fossil-based	Global	3.3	points	0.9	points (WS)			7.8	points				
Higg MSI	Granulate	Elastane fibre	Global	9.9	points	2.9	points (WS)			5.9	points				
Higg MSI	Granulate	PA 6, fossil-based	Global	9.8	points	1.3	points (WS)			6.9	points				
Higg MSI	Granulate	PA 4.10, bio-based	Global	8.2	points	144.8	points (WS)			33.9	points				
Higg MSI	Granulate	PA 66, fossil-based	Global	8.8	points	4.1	points (WS)			7.9	points				
Higg MSI	Granulate	PA 66, recycled	Global	2.0	points	0.7	points (WS)			0.1	points				
Higg MSI	Granulate	PLA, bio-based	Global	3.8	points	6.7	points (WS)			6.9	points				
Higg MSI	Granulate	PP, fossil-based	Global	2.5	points	0.3	points (WS)			0.8	points				

Appendix 3. data differences due to software and their implementation of databases and impact assessment methods

Below are some examples of calculated environmental impact results for a number of fibers where the data differed between the LCA software GaBi and SimaPro . Some reasons behind these differences are discussed in the final paragraph of Chapter 5.1.2

Table 3.1. Calculated environmental impact results in GaBi resepctive SimaPro.

Datasets	GaBi		SimaPro	
	GWP100 (kg CO2 eq/kg)	PED (MJ)	GWP100 (kg CO2 eq/kg)	PED (MJ)
PET granulate amorphous (RER)	2.72	69.8	2.7	75.4
Nylon 6 (RER)	9.27	116	9.37	125
Nylon 66 (RER)	8.01	128	8.11	137
Viscose production (GLO)	3.53	78.6	1.43	169

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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