

The role and business case for existing and emerging fibres in sustainable clothing

The Food and Environment Research Agency

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1 Executive summary

1.1 Rationale and objectives

Textile fibre production has more than doubled over the past 30 years, leading to increased demands for both natural and fossil resources. Consumption of these resources must be controlled in order to reduce our environmental impact. However, it is important that novel means of production and consumption are economically viable and do not compromise human health and welfare.

This project aims to evaluate the market potential, environmental impact, and social sustainability of established, niche, and emerging textile fibres to determine the business case for clothing fibres in light of their sustainability impacts. It will also identify key knowledge gaps and opportunities for further research. This information provides one part of the evidence base for the Sustainable Clothing Roadmap coordinated by Defra.

1.2 Approach

The project involved a literature review complemented by the expert advice and technical knowledge of a stakeholder group. It examined both existing fibres with an established market share and emerging fibres that have technical properties suitable for clothing fibre production.

The fibres of interest were divided into three major groups: natural, regenerated (derived from natural polymers but requiring treatment and processing), and synthetic. Regenerated and synthetic fibres are commonly grouped as “man-made” fibres.

Table 1. Fibres selected for inclusion in the study.

	Natural		Man-made		
			Regenerated		Synthetic
	Cellulose	Protein	Cellulose	Protein	
Existing	Cotton Flax (line)	Silk Wool	Viscose		Acrylic Nylon Polyester
Emerging	Flax (short fibre) Hemp Jute Nettle Ramie Spanish broom		Bamboo Lyocell Modal	Soybean	PLA PTT

For the purposes of the assessment of environmental impacts, textile fibre supply chains were divided into four processes from cradle to gate: raw material production, fibre preparation, fabric production, and dyeing and finishing. Literature and other sources of information were collated to identify the environmental impacts of each

fibre supply chain, from raw material production to factory gate for the above fibres. Data on energy use (indirect and direct) and water use for each phase of the chain was collated where available. Information on other impacts (greenhouse gas emissions, waste water emissions) was much more limited. Other impacts, such as land use demands for non-synthetic fibres, were calculated from the available data.

The environmental impacts of fibres during use and at end of life were also considered. However, Defra has commissioned separate evidence projects specifically focusing on these topics:

- Public Understanding of Sustainable Clothing (EV0405)
- Reducing the Environmental Impact of Clothes Cleaning (EV0419)
- Maximising Reuse and Recycling of UK Clothing and Textiles (EV0421)

This study draws on evidence from these reports where appropriate.

1.3 Market analysis

Clothing fibre production is dominated by cotton and polyester, which account for 35 and 40% of the global fibre market respectively. There has been a shift towards man-made fibres over the last 30 years, driven by growth in polyester production. Cotton and polyester are expected to increase in production and remain dominant for the foreseeable future. Other established fibres, such as wool and acrylic, have seen a decline in market share over the last 30 years and these trends are expected to continue. Regenerated cellulosic fibres show potential for further market growth if production facilities can be realised.

At present rates of growth, emerging fibres are unlikely to make significant market gains in the medium term. Hemp production has declined markedly. Although production of ramie and PLA is expected to increase, their role in the global fibre market is expected to remain small. High production costs and inferior technical qualities present a barrier to growth of emerging natural fibres such as jute, nettle, and Spanish broom.

1.4 Environmental impacts

With the exception of cotton, natural fibres are characterised by low energy demands during raw material production, fibre preparation, and fabric production phases. In contrast cotton has a moderate energy demand. Regenerated and synthetic fibres typically have moderate to high energy demands, with acrylic and nylon having very high energy demands. Dyeing and finishing represent the main energy demand for most natural fibres, while polymer production is the main energy demand for synthetic fibres.

Water use is low in natural fibre production, with the notable exception of irrigated cotton. Regenerated fibres have high water demands during pulping operations for fibre extraction. Wool and fibres blended with wool have high water requirements

during the scouring, dyeing and finishing stages, but overall water demands are similar to natural fibres (with the notable exception of cotton).

Regenerated cellulosic fibres exhibit similar energy demands to many synthetic fibres, but with increased water requirements.

Cotton production leads to moderate greenhouse gas emissions and waste water production. The energy requirement for polyester results in high greenhouse gas emissions, but polyester production generates little waste water. Chemical use in finishing is higher in cotton than in polyester. Data for other fibres on this aspect is scarce.

Direct land use requirements of natural and regenerated fibres are large, although yields vary widely according to geographical location and cultivation technique. However, the high energy use during production can lead to a much larger “ecological footprint” for synthetic fibres.

Organic cultivation and GM technologies may reduce the environmental impact of cotton cultivation through lower energy demands and pesticide use. However, organic farming can reduce yields and so increase demand for land area. Also, herbicide-resistant GM varieties may encourage increased use of broad-spectrum herbicides with potential negative consequences for biodiversity. The key advantage of certified organic production is the additional impact and environmental-compliance requirements that this places on downstream fibre processing operations.

Fibre blending can affect the environmental impact of a textile. In some cases, the different properties of the fibres that make up the blend means textiles must undergo two separate dyeing processes, thus increasing impacts. Blending also makes recycling more difficult. However, this may be offset by improved durability or laundering properties that can significantly reduce energy demands in the use phase.

The key fibre trends and indicative environmental impacts are summarised in Table 2.

1.5 Social impacts

There is a lack of quantifiable information on the social impacts of clothing fibre production and so only a qualitative assessment was possible. Cotton markets are currently distorted by subsidies paid to producers in industrialised nations, leading to lower incomes for farmers in developing countries. Low levels of safety awareness and lack of access to protective equipment also make pesticide use a major health concern in developing nations.

Initiatives such as Fairtrade encourage sustainable economic development for farmers in poorer nations, but currently only reach a minority of producers. Organic farming may increase product value and better access to GM varieties could increase yields and profits for developing countries.

Table 2. Summary of market potential and environmental impacts of textile fibre production.

Fibre	Current Volume (raw fibre)	Growth prospects in textiles	Fibre Cost \$/kg (typical and recent highs in brackets)	Relative impacts between fibres (+ = relatively low impacts, ++++ = relatively high impact)					
				Energy use	Water use	Greenhouse gas emissions	Waste water production	Chemical use in finishing	Land requirement
Acrylic	2.5m t	declining	2.7	+++	++	(+++)	+++	(++ - +++)	N/A
Bamboo	9000t	limited	ID	(++)	(+++)	(+)	(++)	(++ - +++)	(++)
Cotton	27.5m t	increasing	1.2-1.5 (c. 3.3 organic)	++	++++	++	++	+++	+++
Flax	0.45m t	limited	2.0-3.0 (up to 3.5)	+	+	(++)	(++)	(+++)	+++
Hemp	0.08m t	declining	0.5-1.5 (up to 2.0)	+	++	(++)	(++)	(+++)	++ - +++
Jute	3.3m t	limited	<0.5	ID	ID	(++)	(++)	(+++)	++
Lyocell	0.25m t	increasing	ID	++	++	+	(++)	(++ - +++)	+
Modal	Part of viscose share	increasing	ID	++	+++	(+)	(++)	(++ - +++)	++
Nettle	negligible	v.limited	(estimate - high)	(+)	+	(++)	(++)	(+++)	+++
Nylon	4.1m t of which 1.5 m t textiles	increase	2.84	+++	+++	++++	+	(+ - ++)	N/A
PLA	c. 0.01m t	increasing	1.5-2.4	++	(+)	++	ID	(+ - ++)	+
Polyester	30.7m t (17.1m t textile yarn)	increasing	1.1-1.65	++	+	+++	+	+ - ++	N/A
PTT	ID	ID	ID	++	+	+++	(+)	(+ - ++)	(+)
Ramie	0.29m t	limited	3.0-3.5	ID	ID	(++)	(++)	(+++)	++++
Silk	0.1m t	limited	15-26	ID	+++	ID	(++)	ID	ID
Soybean	3000t	limited	ID	ID	ID	ID	(+++)	(++ - +++)	ID
Spanish b.	negligible	v.limited	ID	ID	+	(++)	(++)	(+++)	ID
Viscose	2.92m t	increasing	2.95	++	+++	+	(++)	(++ - +++)	++
Wool	1.2m t	declining	2.8-6.6	+	+	ID	++++	++ - +++	++++

ID = insufficient data, NA = not applicable, Figures in brackets based on use of information from similar fibre types

1.6 Knowledge gaps

Clothing composition data is limited to primary fibre components and so further information is required to determine the market role of fibre blends. Production data for the emerging fibres ramie, Spanish broom, and regenerated bamboo are also lacking. Environmental data for niche and emerging fibres and alternative methods of cotton production, particularly to compare conventional, GM and organic production are currently lacking. In addition, more detailed information on the greenhouse gas emissions, waste-water production, and chemical pollution associated with the production of all fibres would allow a more complete environmental assessment to be made. The social implications of all stages of textile fibre production require significant further independent research using standardised methods in order to allow useful, quantifiable sustainability comparisons.

1.7 Conclusions and future prospects

This literature review has revealed significant gaps in our present understanding of textile fibre sustainability. It also highlights major trends and identifies future directions for research work. The market analysis shows the continuing dominance of cotton and polyester fibres in the clothing sector. The environmental assessment shows that, using typical processing methods, these fibres have relatively high environmental impacts when compared to other niche and emerging fibres. However, there are means of significantly reducing such impacts. Recycling polyester, via waste textiles or other polyester waste streams can significantly cut energy use, resource depletion and greenhouse gas emissions for polyester fibre production. Organic cotton production can reduce the toxicity, energy use and GHG emissions environmental impacts of both growing and processing cotton. However, the uptake of organic cotton needs to be elevated from current low levels to realise these benefits on a significant scale. Additionally, this may be at the cost of an increased land requirement where cotton yields are reduced. Development of more heat-resistant forms of PLA look promising as a less energy demanding alternative to cotton and polyester; current limited production hampers assessment of its real potential. Hemp and flax are well-established niche fibres with low environmental impact but are relatively costly. Further work is required to improve the suitability and yield of these, and other fibres with potentially favourable environmental production and technical properties, for wider use in apparel applications.

The summaries presented in this report (Table 2) identify the high-level key sustainability impacts of the fibres investigated. Further research is required to fill data gaps and verify these findings to a level that allows direct comparisons between fibres and to examine the wider environmental and social impacts of niche and emerging textile fibres. Consistency in methods, scope, data gathering, and analysis techniques will be key to providing a strong evidence base in accordance with best practice in life cycle assessment (LCA), that can be used by industry and consumer-focused applications to make informed choices about product sustainability.

2 Introduction

2.1 Rationale

Economic development and population growth have increased the demand for both natural and fossil resources. Combustion of fossil fuel leads to greenhouse gas emissions and the use of land for agricultural production reduces the habitat available for other species. Consumption of these resources must be controlled if we are to reduce our environmental impact. However, it is also critical that emerging production methods and consumption of resources are economically viable and uncompromising to human welfare and social development, particularly in countries where employee protection is less well regulated.

The UK strategy for sustainable development incorporates environmental, social, and economic objectives intended to accelerate the shift towards sustainable consumption and production (HM Government 2005). Defra is focusing on high-impact products, one of which is clothing (Defra 2009). Previous studies have assessed energy and raw material use in the production, washing, and disposal phase of textiles. However, these have mainly focused on established fibres rather than emerging fibres. These emerging fibres represent significant knowledge gaps and further research is required to assess the sustainability of the numerous emerging and existing textile fibres available.

2.2 Objectives

This report aims to evaluate the environmental and social sustainability and market potential of traditional and emerging fibres used in the textile industry. Specifically, the following key objectives are addressed.

1. Identify and classify existing and emerging textile fibres of market interest.
2. Determine current and near-future scales of production for the fibres identified and evaluate their market potential.
3. Identify the environmental and social impacts of the fibres of interest using existing evidence and expert guidance.
4. Identify knowledge gaps that prevent a thorough analysis of the environmental and social impacts.
5. Present a summary impact table of the sustainability information per fibre in a clear and consistent way.
6. Provide recommendations for policy and industry on the role for existing and emerging fibres in sustainable clothing.

The information and analyses presented in this report contributes to the evidence base for the Sustainable Clothing Roadmap (Defra 2009).

3 Methodology

3.1 Approach

The project comprises a literature review complemented by the contributions from expert advice and technical knowledge drawn from a stakeholder group. The members of the stakeholder group were chosen to provide expertise in all the stages of the clothing production supply chain. Individuals and organisations with both national and international experience were selected. The role of the stakeholders was to provide expert guidance and assistance in formal group meetings and communication on an individual basis. A complete list of stakeholders invited to comment on the work is given in Appendix A.

Data collected through the literature review process are used to assess the sustainability of each fibre of interest. In this report, the business case forms a qualitative evaluation of the current and near-future market potential, production capacity, and technical properties of the fibre, in light of environmental and social impacts across the lifecycle. The sustainability assessment includes various environmental impacts, including energy use, greenhouse gas emissions, water demand, and chemical use. Where possible, the key social impacts of the fibres are also discussed.

3.2 Identifying fibres of interest

Many hundreds of fibres, both natural and man-made, can be used in the production of clothing. However, the modern textile industry is dominated by a small number of fibres. This report examines these established fibres as well as less widely used fibres with the potential for an increased market share.

1. Existing fibres are defined as those with a current and established role as a raw material for the manufacture of clothing.
2. Emerging fibres are defined as those that do not yet have an established significant market share, but whose fundamental technical properties have been investigated and demonstrated to be appropriate for clothing manufacture.

The fibres considered in this study must be capable of being spun into a yarn and be suitable for use in clothing textiles.

3.3 Fibre classification

Fibres used in the manufacture of clothing have been divided into three distinct groups, depending on their means of production.

1. Natural fibres develop into a useable fibrous form in the natural environment, although subsequent separation and cleaning is usually required. There are three main types of natural fibre, which are categorised according to their

origin: plant fibres, animal fibres (both hair-like and filamentous), and mineral fibres (such as asbestos).

2. Regenerated fibres are derived from polymers produced in the natural environment, but need further treatment and processing (fibre forming) for use as a textile fibre.
3. Synthetic fibres are manufactured by converting a synthetic polymeric material, typically derived from fossil resources, to a useable textile fibre via a chemical change.

Regenerated and synthetic fibres are typically grouped as “man-made” fibres.

A complete list of the fibres fulfilling the criteria of being capable to be used in textile applications of can be found in Appendix B, along with an explanation of rationale for selection of the following fibres for evaluation in this study. Emerging fibres were identified as those that had technical potential for use in the textile sector, but had to date seen only limited or small scale production, or were currently at a small scale of use but had potential for significant expansion.

Table 3 Fibres selected for inclusion in the study

	Natural		Man-made		
			Regenerated		Synthetic
	Cellulose	Protein	Cellulose	Protein	
Existing	Cotton Flax (line)	Silk Wool	Viscose		Acrylic Nylon Polyester
Emerging	Flax (short fibre) Hemp Jute Nettle Ramie Spanish broom		Bamboo Lyocell Modal	Soybean	PLA PTT

3.4 Literature review

3.4.1 Data sources and scope

Market, environmental, and social impact data for each fibre of interest were obtained from a wide-ranging literature review, including, but not limited to, reported life cycle assessments (LCAs) and data. Market data were derived from a wide range of sources to identify current and potential future fibre production and use trends. Where data were lacking, expert technical knowledge and experience were sought to estimate the potential market opportunities, technical capabilities, and restrictions affecting the fibres of interest.

When assessing the life cycle environmental impact of a product, it is necessary determine where the boundaries of the assessment. For the purposes of this project, the supply chains for each textile fibre are divided into four processes.

1. Raw material production, including crop production.
2. Fibre preparation.
3. Fabric production and preparation.
4. Dyeing and finishing.

Laundering and maintenance are also likely to have significant environmental impacts. However, these processes are not examined in this report as they are covered in a parallel Defra project, “Reducing the Environmental Impact of Clothes Cleaning” (EV0419). Garment manufacture (post dyeing and finishing) and transport impacts have also been excluded from this study. Although these processes will contribute to the overall environmental impact of textile fibres, they are highly dependent on geographical location and garment type and are outside the scope of most of the LCA and other environmental impact literature reviewed during the study.

3.4.2 Derivation of environmental impact data for individual fibres

Data obtained from the literature review were collated for each of the above processes (where available). Data on all reported impacts in the literature (energy use, global warming potential, ecotoxicology, acidification potential, etc.) were examined. However, the only impacts where there was some consistency in coverage across fibre type was in energy and water use, though not for all processes involved in textile manufacture. As a result, the environmental assessment concentrated on energy and water use in textile production. Useful sources of reference comparing other environmental impacts across a more limited set of fibre comparisons were included as short reviews to compliment the work on energy and water use.

Data on energy and water use in fibre production were very limited for some well-established fibres. No relevant data were found for the emerging fibres ramie, Spanish broom and bamboo, in part due to low levels of commercialisation or confidentiality considerations by sole manufacturers. In such situations, reference to alternative, comparable and better-documented fibres was used where possible

In other cases, ranges were presented in the literature or data was grouped across a range of processes. Where appropriate, attempts were made to disaggregate such data by using other available reference values to deduce data values by difference, but in some cases this proved impossible and data is presented as an aggregate for one or more processes in the textile chain. Where disaggregated data was presented, this was typically used in preference, to enable a better understanding of the processes involved and to allow comparisons between, and to identify synergy between different sources of data.

Although there are basic ISO 14000 standards covering the undertaking of LCAs, it remains a relatively novel approach in the textile sector. It has been more widely used in polymer sectors of interest to the textile sector. Appropriate data from such studies are drawn upon for polymer raw feedstock production. Processes vary significantly between technologies, companies and geographical regions, so the outcomes of an LCA are generally restricted to a narrow range of assumptions. There are also few detailed LCA comparisons across a wide range of textile fibres, and supply chain stages utilising the same methodology and assumptions.

Any specific assumptions and estimates made in this analysis in association with water and energy use data for a particular fibre are indicated within the results for each fibre. The full data set collated for consideration of water and energy use in this study is presented in Appendix C.

Different studies often concentrate on different aspects of the garment production chain, and some only relate to specific processes, for example polymer production. For each reference source reviewed, derived data on energy and water use are allocated to the processes or range of processes identified in the source reference (where this can be ascertained) and are shown in Appendix C, to enable readers to review the processes covered by each reference source.

In Appendix C, data unique to a particular natural or man-made fibre was allocated to a specific activity in the production of the fibre, yarn and fabric. Generic data was generated for energy and water use to help fill gaps in data for individual fibres for the yarn and fabric production stages. These are reported separately under the heading of “generic data” in appendix c.

In the main body of this report, data on energy and water use are collated for the production, processing, dyeing and finishing stages of the textile supply chain and are expressed in common units for comparison. Energy data are expressed in MJ/kg of fibre or fabric and water data in litres/kg of fibre or fabric.

In most cases referenced data sources primarily collated information on direct energy use expended in producing raw materials, embedded in raw materials or expended in processing. A general definition of direct energy use in this study was that considered related to the energy requirement for material inputs and the operation of the textile supply chain. Direct energy consumption is relatively straightforward to quantify, while indirect effects are inherently more difficult to calculate. Indirect energy consumption is typically that which is used in activities that are not directly part of the fibre and textile fibre supply chain, relevant examples may include public works around manufacturing facilities, land use change from producing one crop to producing a fibre crop or supply inefficiencies in the delivery of energy to fibre and textile processors. The latter data was excluded from this study to ensure appropriate comparisons could be made between fibres.

In studies of natural fibre production, the energy required for growing a fibre crop, such as fuel or electricity, and embedded energy use (i.e. energy invested in fertiliser and pesticides) is more commonly included in reported data (though not necessarily itemised). Data on these aspects were included as energy or water use expended in raw fibre production in most data covering natural fibre production. In the case of synthetic or semi-synthetic polymers, data was selected from studies where the energy contained in the feedstock was included in the analysis, along with energy invested in polymer production to ensure a fairer comparison with energy invested in natural fibre crop production.

Several reviews were identified, and a number of studies use or quote data from other studies. Where possible, instances of duplication of results were identified and removed from the dataset where these failed to add novel values.

Due to the difficulty in locating data from fully referenced and peer-reviewed sources, data from trade associations and manufacturers presentations were also sourced. To help provide an indication of the quality and scale of evidence underpinning data presented in section 5.2, index categories were used. (The index letter is presented alongside data presented for energy and water use for each fibre in section 5.2.). The index categories used are as follows:

- A) Peer reviewed data source, primary data source and authoritative source of relevant information
- B) Peer review or review article, but more limited data sets than in A)
- C) Not peer reviewed and/or peer reviewed but very limited data for comparison
- D) Little novel data and draws on comparable fibre or generic textile or other data, or isolated estimates of impacts

After collation of basic data on each fibre, impacts associated with each process stage where possible were classified into three impacts groups “high, medium, and low” to help identify relative differences between fibre types (see section 5.3 for method adopted).

3.5 Limitations of the LCA data

Agronomic practices vary widely between centres of production. Attempts were made to source data for major supply chains where possible. However, there are limitations on the availability of reliable LCA studies. For example, LCA studies of cotton in the USA are more readily available than those from other cotton-producing nations.

Published data on outputs of chemicals from all stages of processing, the potential impacts of such chemicals and of mixtures of such chemicals are lacking, as is any review of any associated ecotoxicological impacts (Kalliala and Nousiainen 1999) on which to base broad comparisons of impacts between fibre types. As some information may be commercially sensitive, it can be difficult to determine exactly what chemicals are used in textile production to enable a full impact analysis (Kalliala and Nousiainen 1999).

Often little account is also taken of the by-products of fibre production in LCA assessments. If these have useful outlets, then they can bear a proportion of the environmental burdens, reducing the overall burden on fibre production alone. This can considerably complicate the LCA analysis. For example, cottonseed oil is produced as a by-product of cotton production, which has numerous industrial uses. In addition, the resulting seed meal after oil extraction is a valuable animal feed. Lint produced as a by-product of fibre production can also be used as a raw materials for viscose production. Wool production is also linked to meat production, the implications of this for wool fibre production are discussed where they arise. A further complication is that animals are also responsible for methane emissions (an important greenhouse gas), though this predominantly affects ruminant animals. No

account is taken of livestock methane emissions in any of the studies on wool fibre sourced for this review.

Kalliala and Nousiainen (1999) studying impacts of cotton production, identified that typically around one third of the estimated environmental impacts on water and energy use should be allocated to by-products, reducing the allocation to raw cotton fibre production. They further identified that water use per kg cotton material was significantly reduced by 33%, and energy use by 24% when allocating impacts to both fibre and by-products. Such impacts are rarely addressed consistently between studies. In the studies sourced for this review, impacts of cotton production on water and energy were applied only to raw cotton production. Where this occurs it is highlighted that part of the water and energy use should also be allocated to by-products and the implications of this are discussed.

Impacts of transport were covered in very few of the sourced data, and even then in a limited capacity. Transport issues are rarely covered specifically and will vary considerably for different supply chain routes. All fibre, fabric and clothing supply chains are complex and international in nature with respect to supply to the UK. As such it is not possible to derive typical routes of supply for all fibres and account for all steps in the supply chain. As a result this aspect was not addressed in this review, but is expected to be common to all fibres studied. Therefore, this cannot be considered as a cradle to grave assessment, but as an indication of impacts at key stages in the apparel textile production chain.

None of the available LCAs sourced accounted for land use change impacts, or emission of greenhouse gases from soils. These are issues that have been brought to the fore by development of more recent LCAs attempting to assess the sustainability of biofuel production chains. If expansion of any fibre production is at the expense of loss of forest or grassland, there are likely to be significant impacts (i.e. impacts on greenhouse gas balance and emissions to water in particular). It is also difficult to find LCA studies that take into account the whole of life impacts (from raw material production, through use, to disposal) of textiles, a problem identified recently by others evaluating the environmental impacts of man-made cellulose textiles (Shen and Patel 2008a).

4 Current and future markets

4.1 Production trends

Global fibre output has more than doubled over the last 30 years, from 31 million tonnes in 1977 to 79 million tonnes in 2007 (Oerlikon 2008; Figure 1). There has also been a rise in the annual growth of fibre production. For example in the periods 1992 to 1997, 1997 to 2002, and 2002 to 2007 the average annual growth in global fibre production was 5.69%, 6.08%, and 6.49% respectively. This growth has been driven by a combination of human population growth and increased per capita fibre consumption (US Census Bureau 2008; Figure 2). In addition to an overall increase in fibre production, there has been a significant change in the types of fibres produced. Specifically, the market share of man-made fibres has increased from 40% in 1977 to 56% in 2007 (Oerlikon 2008). The total production of man-made fibres has exceeded that of natural fibres since the mid 1990s.

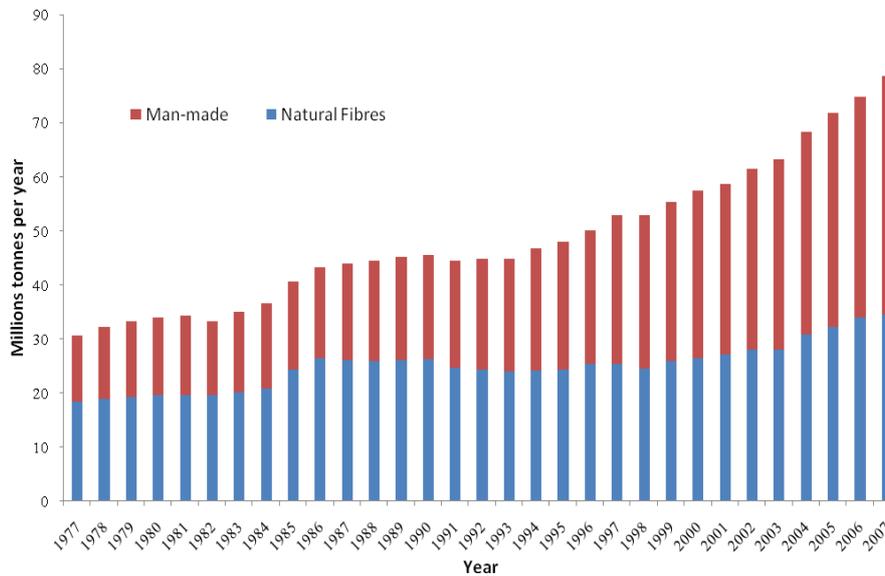


Figure 1. Global fibre production 1977–2007 (Oerlikon 2008).

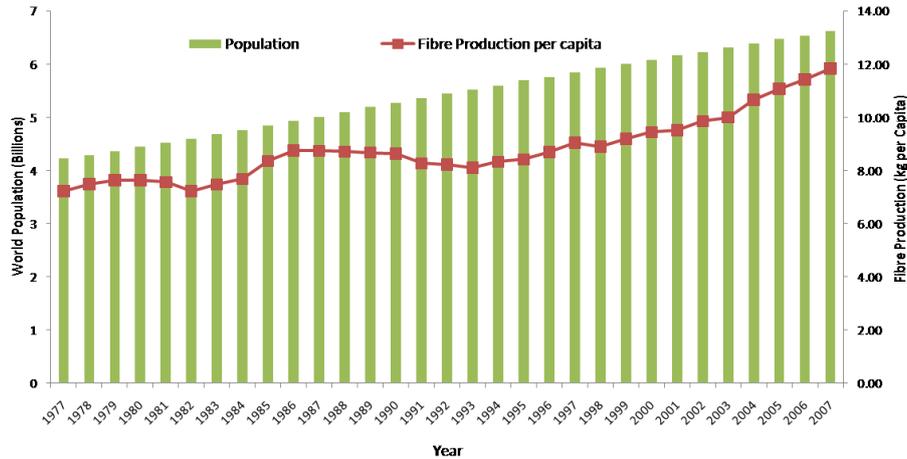


Figure 2. Global population and per capita fibre production 1977–2007 (US Census Bureau 2008).

4.1.1 Natural fibres

4.1.1.1 Cotton

Natural fibre production is dominated by cotton, the production of which has increased from 12.5 million tonnes in 1977 to 27.5 million tonnes in 2007 (FAO 2008; Figure 3 and Figure 4). Despite cotton's share of the natural fibre market increasing from 68% to 78% between 1977 and 2007, the growth in man-made fibres has meant that cotton's share of the total fibre market has fallen from 40% to 35% during this period (Figure 1). Though cotton remains one of the most important fibres used in clothing.

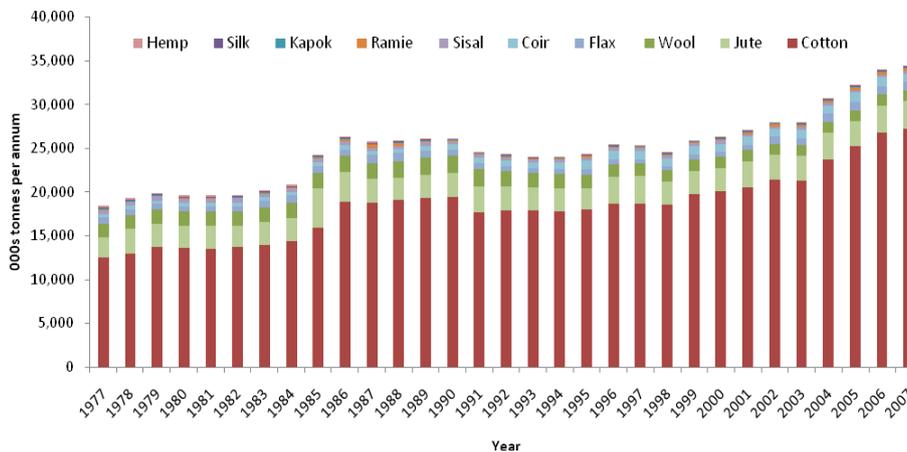


Figure 3. Global production of major natural fibres 1977–2007 (FAO 2008).

Approximately, 50% world's cotton production is used for the production of clothing. The global consumption of cotton has risen dramatically in recent years, increasing at a rate of approximately 3.5% per annum over the last decade, while the world trade in cotton has increased by approximately 4.3% per annum over this period. World cotton demand has risen significantly in the past decade in part because of increased economic efficiencies, due to the liberalisation of the textile trade with actions such as the elimination of the Multi-Fibre Agreement (MFA) quotas in 2005 and the

accession of China into the world trade organisation (WTO). Increased cotton consumption has also occurred because of the movement of cotton processing, mills to low-labour-cost economies where the domestic production is insufficient to meet the needs of rapidly growing textile sectors in countries such as China and Pakistan. Some countries have experienced a rise in cotton production and exports stimulated by trade policies. For example, China provides an export subsidy on finished textile products of 15-17.5%, while Turkey has had preferential access to EU markets and Mexico access to US and Canadian markets. In the case of the latter, this advantage has been eroded by the elimination of MFA, as access has increased to other low cost supplier countries.

Although the production of cotton has increased greatly, there has been no significant increase the area (hectares) of cotton harvested from 1977 to 2007. The area of harvested cotton has remained relatively constant at 30 million hectares. The increased production is due to an increase in yield from an average of 450 kg per ha in 1977 to 790 kg per ha in 2007 (USDA 2009; Figure 5).

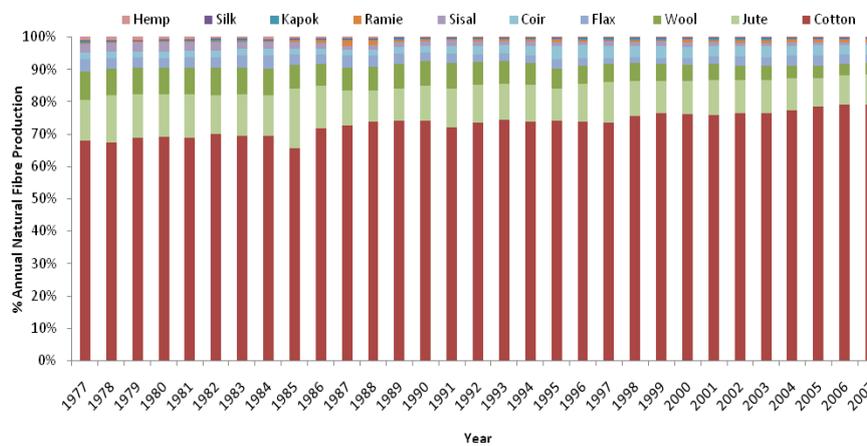


Figure 4. Share of total global major natural fibre production by fibre type 1977–2007 (FAO 2008).

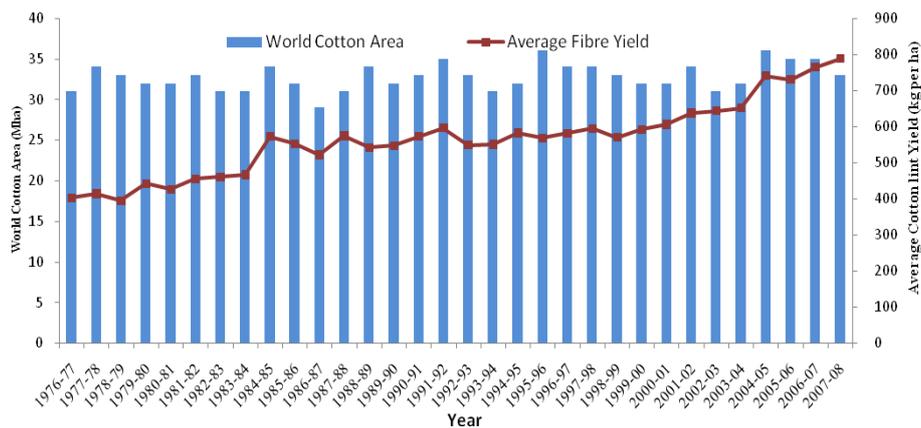


Figure 5. Global average cotton fibre yield and harvested area 1977–2007 (USDA 2009).

These increases in cotton crop yields are as a result of major advances in cotton growing technology. For example:

- Improved cotton cultivars with higher potential fibre yields.

- Biotechnological innovation, such as the commercial uptake of cotton cultivars genetically modified to be herbicide tolerant (glyphosate tolerant) and/or insect-protected (Bt cotton).
- Expansion and refinement of cotton irrigation systems, particularly in areas of expanding cotton production.
- Coordinated crop production programs, such as the boll weevil eradication program in the USA.

However, although average global cotton yields have increased significantly, there are large differences in the progress that has been achieved with cotton yields in the major cotton producing nations (Figure 6). In particular Brazilian cotton yields have increased very sharply over the last ten years, while Pakistani and Uzbekistani cotton yields have risen far less. In these major producer nations the area of harvested cotton has not changed significantly, although China has increased the area of cotton, while in the United States there has been a slight decline in cotton area (Figure 7).

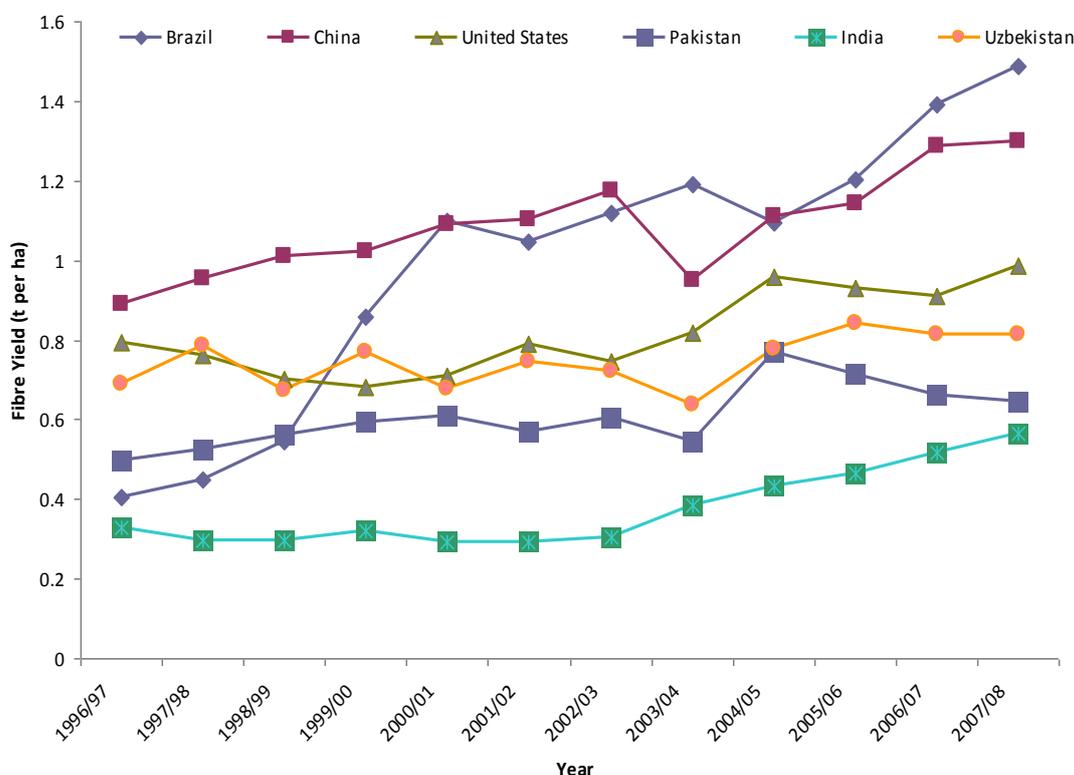


Figure 6. Average cotton fibre yield by country 1997–2007 (USDA 2009).

Cotton production in other countries tends to be small in comparison to the large producers, typically occupying less than 500,000 ha, although such nations may achieve very high cotton yields. For example, the highest yields per hectare are typically found in Australia (2.1 t per ha), while the lowest are found in Burma, Chad and Zimbabwe (less than 250 kg fibre per ha) (USDA 2009).

In addition to the growth in the total production of cotton (Figure 3), a major change in the pattern of production over the past 30 years has been the shift in production

from the USA to China and India, especially during the last 5 years (USDA 2009; Figure 8). Cotton production is, however, still very concentrated in just a few countries: India, China and the United States accounted for over two thirds of world cotton production as of 2007/08, and that rises to over three quarters when Brazil and Pakistan are included (Figure 8).

Exports of cotton from sub-Saharan Africa have declined significantly since 2006, as a result of low world prices. The planted area of cotton in the African countries using the CFA Franc has declined to the lowest level for 15 years, since just after the devaluation of the CFA Franc.

Cotton yields have improved significantly in India, as a result of the increasing use of genetically modified cotton. This has significantly raised production levels and enabled India to develop as a major cotton exporter.

Cotton prices have fluctuated significantly over the last 30 years, with a high price of 94.2 US cents per lb (\$2.07/kg) in 1980 and a low price 42.2 US cents per lb (\$0.93/kg) in 2001 (Figure 9). The average price during this period was 69.3 US cents per lb (\$1.53/kg), although the price has been lower than this for much of the time since the mid 1990s (Cotlook 2009).

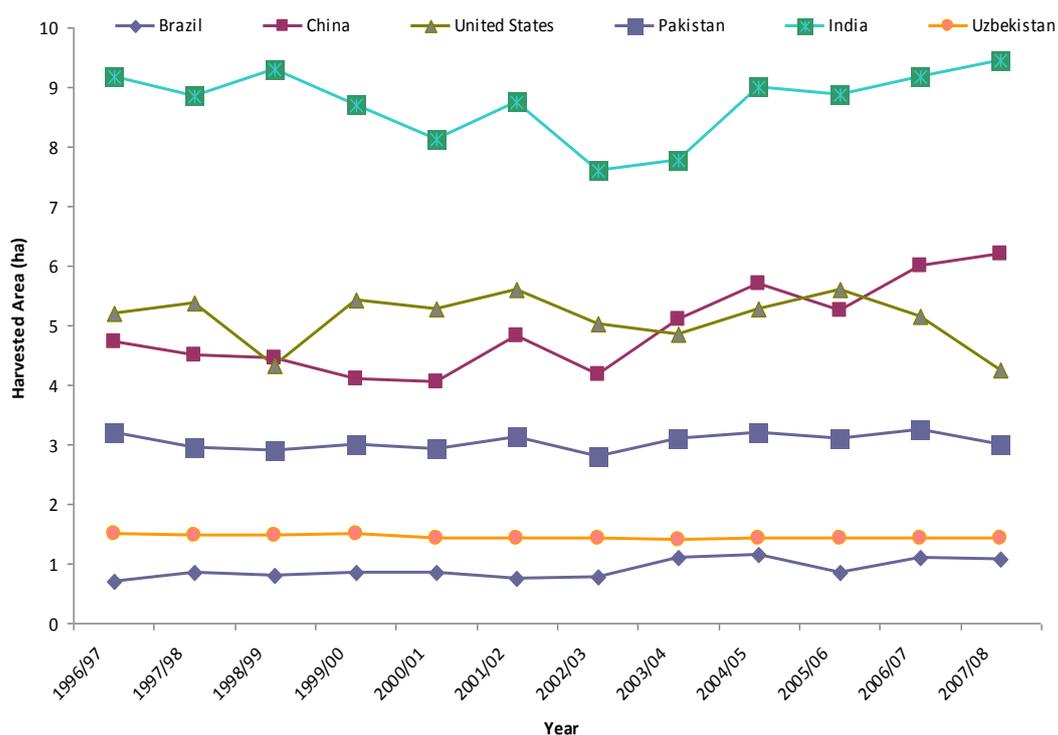


Figure 7. Area of harvested cotton fibre by country 1997–2007 (USDA 2009).

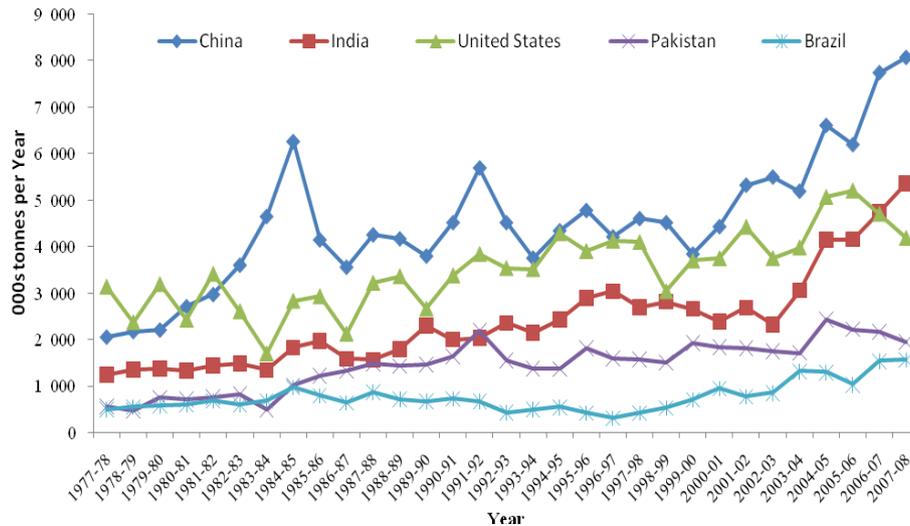


Figure 8. Major cotton fibre producers by country (USDA 2009).

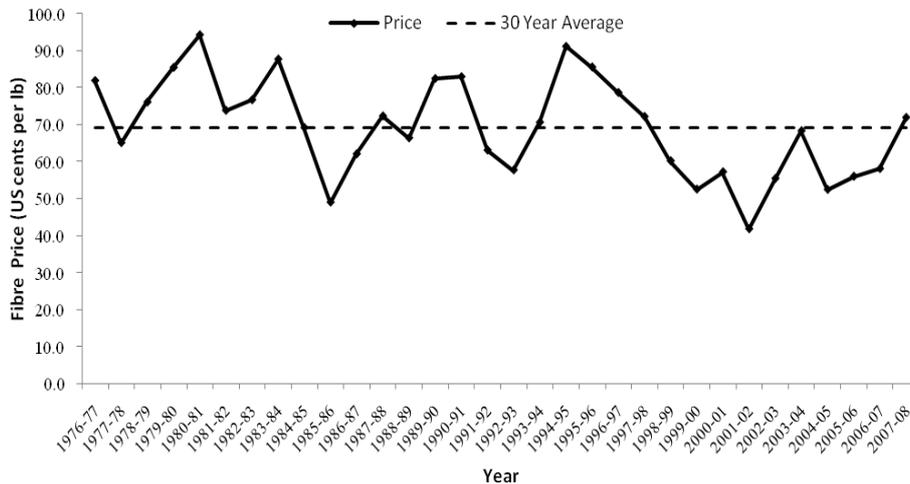


Figure 9. Cotton fibre price trends (Cotlook 2009).

4.1.2 Other natural plant fibres

Various other plant and animal fibres are produced for a very wide range of textile end uses, including clothing, non-wovens and industrial composites. Production of non-cotton natural fibres has increased from 5.9 million tonnes in 1977 to 7.3 million tonnes in 2007 (Oerlikon 2008), although their share of the natural fibre market has declined. Some fibres have shown a general decline in production. For example, hemp production has declined from 243,000 tonnes in 1977 to 85,000 tonnes in 2007 and, despite a recent increase in production from a low of 51,000 tonnes in 2000, its share of total natural fibre production has gradually fallen from 1.26% in 1977 to 0.25% in 2007. Similarly, sisal production has fallen from 523,000 tonnes to 330,000 tonnes over the same period, with a decline in share of total natural fibre production from 2.8% in 1977 to 1% in 2007.

Other natural fibres have generally been produced in increasing quantities each year, but often their share of total natural fibre production has fallen. The annual production

of jute, the most widely produced natural fibre after cotton, has expanded from 2.3 million tonnes in 1977 to 3.3 million tonnes in 2007. However, its share of natural fibre production has declined from 12.5% in 1977 to 9.5% in 2007. Annual world flax production has risen slightly from 727,000 tonnes in 1977 to 975,000 tonnes in 2007, but with significant year-to-year variation and an overall decline in share of natural fibre production from 3.93% to 2.8%. Silk production has increased from 51,000 tonnes in 1977 to 98,000 tonnes in 2007, maintaining its very small share of 0.28%. Similarly, kapok has maintained its small 0.4% share of total natural fibre production with an expansion in production from 74,000 tonnes fibre in 1977 to 123,000 tonnes in 2007.

The only fibres to have achieved an expansion in both production and natural fibre market share are coir and ramie, although both are produced in comparatively small quantities. Annual ramie production has expanded from 41,000 tonnes in 1977 to 285,000 tonnes in 2007, achieving a corresponding rise in share of natural fibre production from 0.2% to 0.8%. The share of annual natural fibre production occupied by coir fibre has risen from 1.92% in 1977 to 2.76% in 2007, as a result of an increase in production from 355,000 tonnes to 950,000 tonnes over this 30-year period.

In general many of these emerging non-cotton fibres have a very low value in comparison to the other natural fibres, such as cotton, wool or silk (Figure 10). This is foremost a reflection of their use in low-value, often non-woven, textiles for the manufacture of industrial products, where coarse fibres are acceptable. When these fibres are spun into yarns it is often either for the production of coarse twines or ropes, or for the production of yarns for manufacturing heavy fabrics such as those used in agricultural textiles, sacks, carpets and matting. Additionally, a number of end-uses have been developed for many of these fibres, most particularly their use in the manufacture of industrial composite materials. Generally, only flax and ramie fibres are suited to the production of clothing yarns and fabrics. Ramie is most often used in apparel as a cottonised fibre. As flax and ramie are used in the clothing industry, the prices of these fibres are higher than more coarse natural fibres.

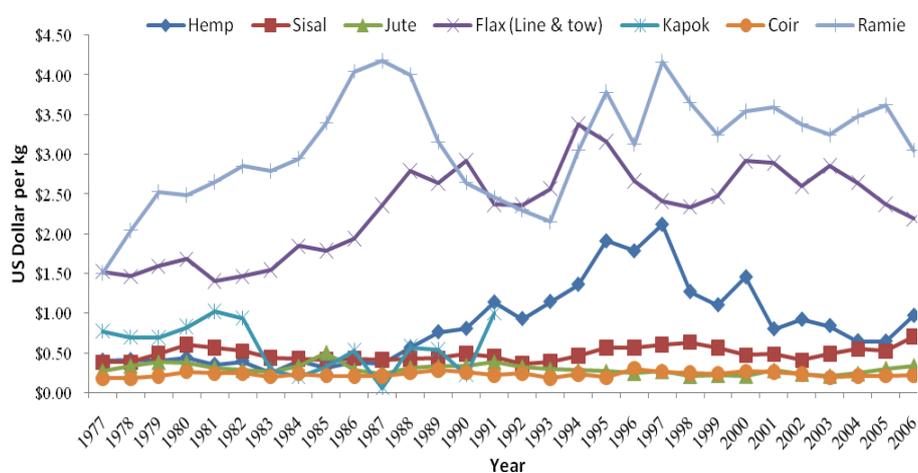


Figure 10. Non-cotton natural fibre price trends (FAO 2008; Oerlikon 2008).

4.1.2.1 *Flax*

Linen textiles are derived from flax-fibres extracted from the stems of fibre-flax. Processing of the straw to separate the fibres from the plant stem is achieved by mechanical 'scutching'. This process produces two types of fibre; the main end-product line flax, use for linen textiles (fibres 60-90cm in length) and by-product tow (fibres 10-25 cm in length). The ratio of line flax to tow is approximately 2:1, but it can vary according to crop quality. The shorter tow fibre can be cottonised, and blended with cotton.

Over 50% of world flax fibre production is currently found in the EU-27 (mainly France, Belgium and The Netherlands) occupying just 20% of the world's fibre-flax area. Approximately 150 scutching plants were operating in the EU-27 in 2008. This is partly as a result of the financial support given to EU fibre-flax growers and processors as part of the fibre marketing support arrangements under the Common Agricultural Policy (CAP). The production of linen fabrics was once concentrated in the EU-27, but now most (80%) of the line and tow fibre is exported to China for further processing and textile manufacture. Of total flax-fibre production just 350,000 to 450,000 tonnes of line flax are produced per annum for use in the production of linen textiles, a significant amount of which is used in the production of household and domestic textiles rather than clothing. However, flax tow fibres are suitable for cottonisation. This enables short-fibre flax to be blended with cotton, polyester, wool, acrylic, and silk, and to be spun on cotton spinning systems. There has been a strong demand for this in recent years, with a significant amount of the production of tow fibre from European scutchers (approx. 60,000t) being exported to China for cottonisation. The cottonisation of flax has been investigated and demonstrated as potentially viable in the UK (FAIR 2001; TEXFLAX 2001, Horne *et al*, 2008). At present, production volumes are small, but there is a growing demand as cottonised flax is more cost-effective than use of cotton alone in some applications, though not suited to all cotton applications.

4.1.2.2 *Hemp*

Hemp, like flax or jute, is a bast fibre. The fibres are extracted from the stems of the hemp plant with a 'decortication' process similar in principle intent to that used for flax. In the EU-27, which accounts for approximately 10 % of global fibre production, there are currently only 10 processors of hemp straw. In the EU, hemp is currently only used for short-fibre production, used as a source of cellulose for the paper industry, which accounts for 70% of EU hemp fibre production.

The production of hemp has fallen sharply in recent years to a world production of 85,000 tonnes in 2007, because of declining hemp fibre prices and a reduction in support for hemp cropping. The decline in the price for hemp is a reflection on its wider use in lower value, non-textile end-uses.

4.1.2.3 *Jute*

Jute is a bast fibre produced from two particular *Corchorus* plants: white jute (*Corchorus capsularis*) and tossa jute (*Corchorus olitorius*). The major producers of

jute are India and Bangladesh, but some is also produced in China, Nepal and Thailand on approximately 2.3 million hectares. Jute and its substitutes are mainly used in the manufacture of cheap low grade fabrics, such as hessian sacks for the packaging of crop products (coffee beans) and upholstery fabrics. More recently it has been developed as a fibre for use in performance technical textiles such as glass fibre replacements in composites. Traditionally, jute has not been suitable for use in apparel due to its coarse fibres being suited only to the production of coarse yarns. Consequently, it is largely used to produce ropes, sacking, carpet yarn, and fabrics for other industrial uses (Rahman 2008).

4.1.2.4 *Nettle*

Nettles (*Urtica dioica*) have been used as a source of fibre historically, (Bredemann 1959; Edom 2006) There have been a number of attempts to commercialise the production and development of a method of fibre extraction suitable for large scale use, particularly in the UK, Germany, and the Netherlands (Dreyer 1998; Hartl 2002; Bacci et al. 2009). However, the production of stinging nettle fibre is currently limited to opportunities in the high-value woollen fabric market for use in upholstery and furnishing fabrics. Currently, approximately 100-150 hectares are currently grown in the EU-27. Further work is required to establish greater levels of crop production and to restart fibre nettle breeding programmes, which ceased in the mid 20th century, to increase cost efficiencies and yields in the production of stinging nettle crops.

4.1.2.5 *Ramie*

Ramie (*Boehemeria nivea*) is a bast fibre that has been used as a source of textile fibre in eastern markets. However, up until the early 1980s the fibre was produced on a small scale (<60,000t) relatively little used in clothing and was still virtually unknown as an apparel fibre, when it was used as a substitute for cotton and linen. The fibres are finer and shorter than flax, and when blended with cotton, polyester or acrylic can be used to achieve a 'linen-like' look, but without the high cost. In the early 1980s there was a significant increase in the use of ramie fibre in knitwear and ladies outerwear, due to the fashion for a natural linen look. More importantly, until 1986 ramie was exempt from Multi Fibre Agreement regulations on imports into the United States. This meant that garments containing ramie could enter developed economy markets without the quota restrictions applied to garments made from other fibres, such as cotton, polyester or wool. However, after renegotiation of the MFA in 1986/87, ramie fibre products were subjected to restrictions similar to those imposed on other fibres and its popularity subsequently declined. At present, the world's largest producer of ramie fibre is China, most of which is used in upholstery and packaging materials.

4.1.2.6 *Silk*

Silkworm cultivation occurs predominantly in China (54%) and India (14%), with lower levels of production in Uzbekistan, Brazil, and Iran. Silk demand rose by 7.6% in 2007, following a 9.0% rise in 2006 (Textiles Intelligence Ltd 2008). Wild silk, also known as "vegetarian" or "peace" silk, is available from India and is collected

from discarded wild caterpillar cocoons of various moths. This method produces silk with shorter staple length and lower quality, but does not require killing of the silk worms to remove the silk. In general, silk production is an extremely intensive user of resources, such as water, energy and labour which makes silk fibres the most expensive per unit of natural fibre.

4.1.2.7 *Spanish broom*

Spanish broom (*Spartium junceum*) has historically been used for cordage and heavy cloth in France and Italy. It is native to the Mediterranean and the Canary Islands, and has also been introduced to North America. Considered the most drought resistant of the broom species, and can grow in poor, rocky soils. It is commonly found growing wild in disturbed areas, roadsides, and vacant building sites in California (Washington State 2009). Currently, controlled production for use in textiles is limited to a number of small-scale research projects that require further fundamental research to develop extraction and technical processing methods before Spanish broom can expand as a serious fibre in the textile industry. Trials have been completed at Bologna, Italy using mechanical cottonisation of Spanish broom. These have included trials of enzymatic maceration in collaboration with the University of Calabria, Italy. Yarns have been produced in conjunction with Filartex (ARTES 2009).

4.1.2.8 *Wool*

Wool production has declined steadily from a market share of 9% in 1977 to 6.5% in 2007. The tonnage of wool produced peaked at 1.99 million tonnes in 1990 (7.6% of natural fibre production in that year) before declining to 1.2 million tonnes in 2007. However, it remains a significant textile fibre and it is well recognised as a fibre for use in clothing. The world's principal producer of wool is Australia, but its annual clip has been declining over a number of years. Sheep numbers and wool production have reached their lowest level since the mid 1920s. Wool production has also declined in most of the significant wool producing nations, with the exception of China where annual wool production has increased by approximately 100,000 tonnes per year.

Of the clean wool (greasy wool after processing, such as scouring) produced from the raw greasy fibre, a significant part is too coarse to be suited to use in clothing textiles. Wool fibre with a mean fibre diameter exceeding 25 μm is generally too coarse to be used in clothing and is used primarily in furnishing, upholstery textiles and carpets. It has estimated by the International Wool Textile Organisation (IWTO) that 600,000 tonnes (50%) of the clean wool produced in 2006 was used in the production of apparel (Oerlikon, 2008). Australian wool generally comes from specialist wool breeds and has the finest fibres and, consequently, the highest price (Figure 11 and Figure 12). New Zealand and South African wool usually has a coarser fibre and a lower price (AWEX 2009).

The Australian Wool Exchange (AWEX) Eastern Market Indicator (EMI) showed that wool prices varied significantly during the 2007/2008 season, largely due to the effect of the Australian drought on sheep numbers and falls in the prices of other commodities. From the start of the 2007/2008 season, the EMI rose from AU\$9.29

per kilogram in July 2007 to a peak of AU\$10.29 in January 2008, then fell to AU\$7.64 in November 2008 (Textiles Intelligence Ltd 2008). Global demand for wool is heavily influenced by the world's largest consuming nation, China. However, the price fall after January 2008 was also prompted by concerns over falling demand in industrialised countries. Japan's demand is expected to be down as spinners cut back on wool yarn production and weavers reduce their output of wool fabrics. Wool consumption for the EU as a whole is expected to fall by a further 8.9% in 2008/2009, on top of an 8.2% decline in 2007/2008. Global demand is anticipated to fall by 2.1% in 2008/9 and is likely to fall even further in the future. As a result, wool may suffer a further loss in its percentage share of the global fibre market (Textiles Intelligence Ltd 2008).

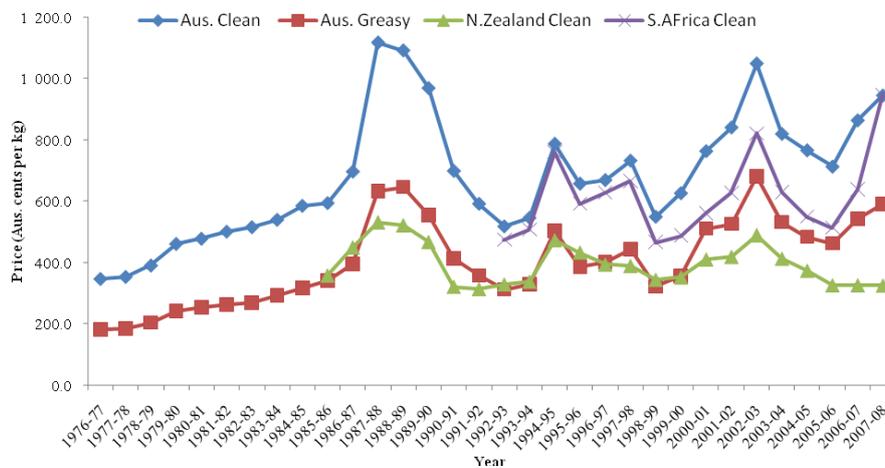


Figure 11. Australian, New Zealand, and South African wool price trends (AWEX 2008).

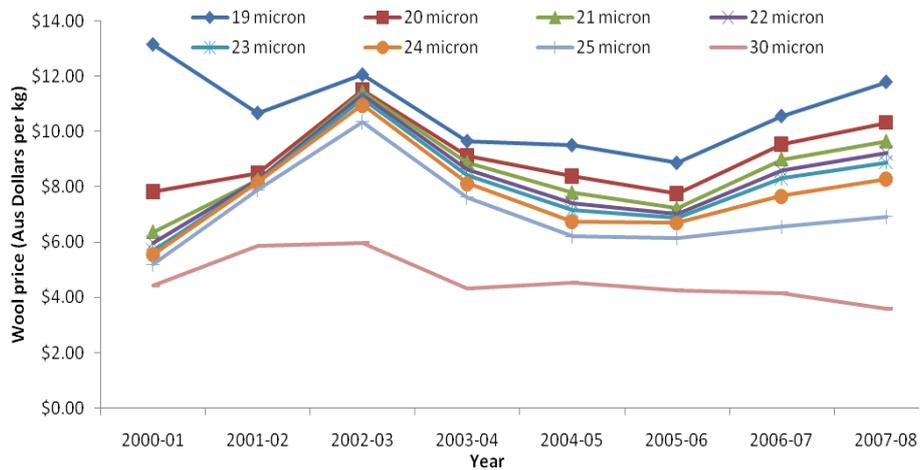


Figure 12. Australian 12–30 µm diameter clean wool prices (AWEX 2008).

4.1.3 Man-made fibres

The production of man-made fibres, both synthetic and regenerated, currently accounts for 56% of the world's total annual fibre production. Over the past 30 years there has been a significant increase in both the total amount and the market share of

man-made fibres (Figure 13). The tonnage production of man-made fibres has risen from 12.3 million tonnes in 1977 to 44.1 million tonnes in 2007, with a corresponding increase in market share from 40% to 56%.

The most significant feature of the production of man-made fibres over the previous 30 years has been the large increase in production of polyester, which has led to its current dominant position in the man-made fibre market (Figure 14). The world's annual production of polyester has risen nearly eightfold in the last 30 years, from 4.04 million tonnes in 1977 to 30.7 million tonnes in 2007, with a corresponding increase in the share of total world man-made fibre production from 33% to 70% over this period.

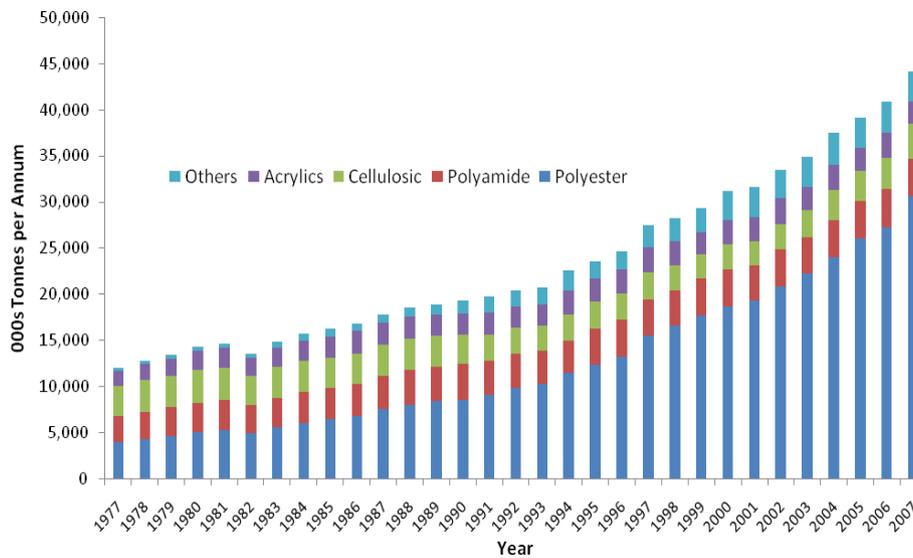


Figure 13. Global production of man-made fibres 1977–2007 (Oerlikon 2008).

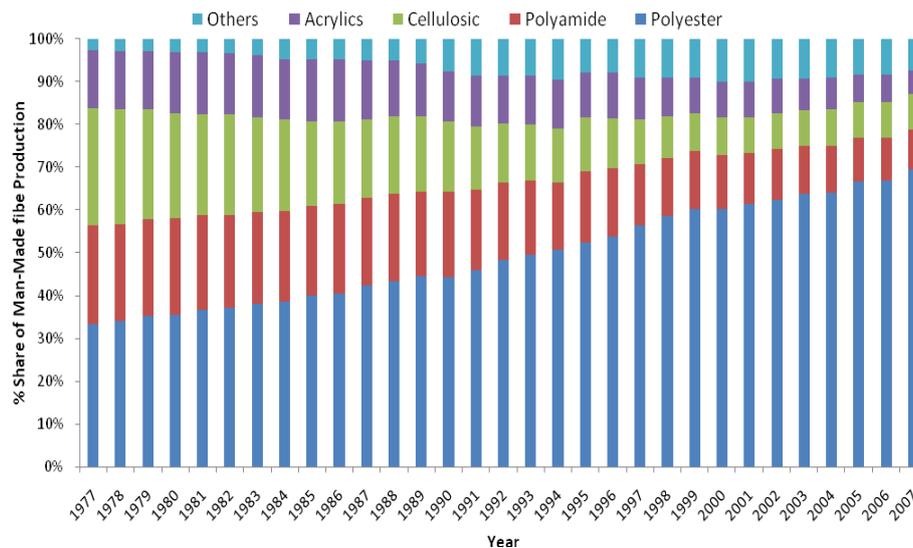


Figure 14. Share of global man-made fibre production by fibre type (Oerlikon 2008).

Man-made fibre production is concentrated in a small number of countries, with three quarters of world production occurring in just seven countries. Between 1998 and

2007, the production of man-made fibres has become particularly concentrated in China, where the annual production of man-made fibres increased from 18.4% to 51.6% of total world man-made fibre production. With the exception of India, most of the other major man-made fibre producing nations have witnessed a decline in production over the last 10 years. In 2007 China was the largest producer of all the individual types of man-made fibres. It is most dominant in the production of polyester fibre, producing 65% of total global output.

The price of many man-made fibres has fallen over the past 25 years, although production costs vary significantly between different countries (Figure 15). However, in general the cost of man-made fibres for use in clothing is significantly less than that of wool and many other non-cotton natural fibres. The cost of man-made fibres is close to the cost of cotton (Table 4).

Table 4. Man-made fibre prices.

Fibre	Price (\$/kg)	Source
Acrylic (staple fibre)	2.70	Yarns and Fibres Exchange (2006)
Nylon (filament yarn)	2.84	Emerging Textiles (2007)
PLA	1.5–2.4	Blackburn (2006)
Viscose (staple fibre)	2.95	Emerging Textiles (2007)

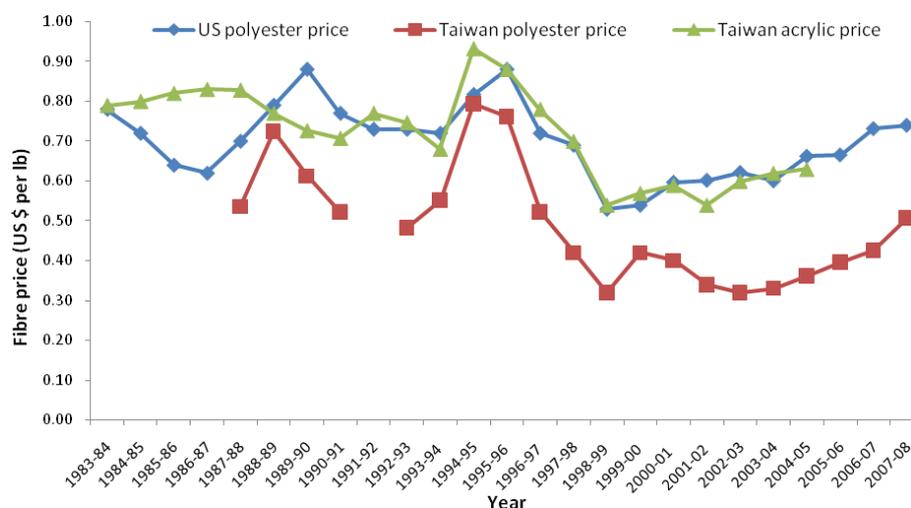


Figure 15. Global average prices of polyester and acrylic fibres (Meyer 2009; US Census Bureau 2008).

4.1.4 Regenerated fibres

4.1.4.1 Bamboo

Bamboo is a relatively recent addition as a textile fibre, although it has been grown for thousands of years for other uses such as furniture, food, and paper making. The majority of “bamboo” currently on the market is believed to be produced via the viscose process, using bamboo as a feedstock in place of wood pulp. Bamboo production is estimated at 9000 tonnes per year (Kirkwood 2007).

4.1.4.2 *Lyocell*

World lyocell capacity in 2001 was around 100,000 tonnes per year, with pilot plant-scale filament fibre production of 500 tonnes (White et al. 2006). Production capacity is currently estimated at 150,000 tonnes per year. Overcapacity was noted in 2001, however, long term growth in requirements for lyocell is anticipated. Cellulosic fibres remain the material of choice for linings. Polyester is expected to take a larger share of the clothes lining business, leaving viscose and lyocell for higher quality garments.

4.1.4.3 *Soybean*

Regenerated soybean fibre is also known as azlon, vegetable cashmere, or soybean protein fibre (SPF). The countries with the largest volumes of soybean production are currently Argentina, Brazil, China, India, and the USA. Research into fibre production has primarily been undertaken in China and the USA. Soybean fibre production is estimated at 3000 tonnes per year (Kirkwood 2007). There is significant interest in use of soybean as a replacement for cashmere fibres, and China produces 80% of world's cashmere fibre (approximately 10,000 tonnes). Some soybean fibre is marketed with organic certification and costs approximately 30% more than organic cotton. Fibres are spun on cotton or worsted machinery and blended with cashmere (80% soya to 20% cashmere) or in 50% blends with wool, silk, and cotton. To date, the fabrics are used in very limited niche fashion markets, often in blends with cashmere, silk, cotton, wool, and bamboo (Brooks 2006).

4.1.4.4 *Viscose and modal*

By 2000, cellulosic fibre production (including viscose, rayon, and cupro) had declined from a peak in absolute tonnage of 3.5 million tonnes in 1975 to approximately 3 million tonnes. Since 2005, after a period of steady markets, markets have started to increase again, and the output for 2007 is documented at 2.92 million tonnes. Asian cellulosic fibre output in 2007 increased in China by 15.9%, India by 10.4%, Indonesia by 16.1%, and Taiwan by 3%. Conversely, USA and Western European output of cellulosic fibres continued to fall in 2007; US output dropped by 7% in 2007 following a dramatic 44.6% fall in 2006. These falls resulted from the decline of the textile manufacturing base in the US resulting from declining competitiveness with Asian producers. As a result US producers are no longer significant players in the world cellulosic fibres market.

The hydrophilic (moisture absorbing) property of viscose that it shares with cotton makes it a fibre of choice for garments in contact with the skin in preference to polyester. Demand for hydrophilic fibres could be met by either increased cotton production, by a new or variant hydrophilic fibre or an increase in viscose or lyocell capacity. However, consultation with industry experts suggested that pollution constraints (gaining operating licenses and cost-effectively managing effluent streams in the face of tightening environmental legislation) will prevent a significant increase in viscose or rayon capacity and that future generations will predominantly wear synthetic fibres (mostly polyester).

4.1.5 Synthetic fibres

There has been increasing use of synthetic fibres in technical and performance applications as trends in fashion have promoted such uses, particularly in the sportswear sector.

4.1.5.1 *Acrylic*

Acrylic is a synthetic fibre made from the polymer polyacrylonitrile. Most acrylic fibres incorporate copolymers of other monomers to improve subsequent wet processing. When the copolymer content exceeds 15%, the fibre is called modacrylic. The production process includes dissolving the polymer in a solvent such as sodium thiocyanate, extruding filaments through a spinneret, then wet or dry spinning, followed by washing, stretching and crimping. Lightweight, soft, and warm, acrylic is often used as a cheaper substitute for wool or cashmere. Acrylic production is approximately 2.5 million tonnes per year, but in long-term decline (Oerlikon 2008). Acrylic fibre production declined by 6.5% in 2006 and by a further 3% in 2007. As a result, the share of acrylic fibres in the total output of the main synthetic fibre types fell to 6.5%, one third of its share held in 1984. Acrylic is very durable but has a tendency to feel harsh and for this reason it is often blended with other fibres. Uses include knitwear such as jumpers, hats, scarves, sportswear, and socks as well as home furnishings, such as rugs and upholstery.

4.1.5.2 *Nylon*

Nylon is the generic name given to the group of synthetic polymers comprised of repeating units bridged by amide linkages. It is frequently referred to as a polyamide fibre. Invented in 1935, it was the first synthetic fibre produced. The most common forms of nylon for apparel are nylon 6 and nylon 6,6. As a clothing fabric, nylon is lightweight and possesses exceptional strength characteristics; it is very durable and has good laundering properties. It is used widely in apparel such as swimwear, active wear, and underwear. Although typically used to produce fabrics comprising 100% nylon, the fibre can be blended with a range of other fibres. Polyamide fibre output increased by 1.7% in 2006, achieving a volume of 4.05 million tonnes of staple fibre production, of which around 1.5m tonnes was used in textiles (Oerlikon 2008), but production fell by 0.4% in 2007. As a result the share of nylon fibres fell to 10.4% in 2007.

4.1.5.3 *Polyester*

Polyester production increased by 10.5% in 2007, up from the 6.3% growth rate observed in 2006. Polyester was also the only fibre among the main polymer types to register growth in output. As a result, it increased its dominance to command 83.1% of total production of the major synthetic fibre types. Within the total increase in polyester production of just under 3 million tonnes, during this same period, the largest increase was in polyester industrial filament yarn (up by 2.1 million tonnes) with the rise of polyester staple fibre for textiles (an increase of 900,000 tonnes) significantly less (Oerlikon, 2008)

4.1.5.4 *Polylactic acid (PLA)*

PLA is produced via fermentation of starch substrates by bacteria to produce lactic acid. Early versions of fibres derived from PLA suffered from low temperature melting points. However, more heat resistant variants have been developed. Biofront™ (TeiJin Ltd) a polymer based on PLA is intended for use in clothing applications. Its high melting point of 210°C is better than conventional PLA fibres, which melt at 170°C.

Teijin currently operate a pilot plant with an annual production capacity of 200 tonnes, and recently acquired Toyota's demonstration plant with 1000 tonne capacity. By 2010 annual capacity is anticipated to be around 10,000 tonnes.

Natureworks is scheduled to double the annual capacity of "Ingeo", another PLA-based polymer, at its plant in Blair, Nebraska to 140,000 tonnes. There are also plans to establish the first PLA facility in Europe. Pyramid Bioplastics Guben GmbH, a partnership between Pyramid Technologies of Zug in Switzerland and Bioplastics GmbH of Guben in Germany, plan to construct and operate a plant for the production of PLA biopolymer in Guben. The first project phase will see the installation of a plant, with a capacity of 60,000 tonnes per year by 2012 (Teijin. 2009) .

4.1.5.5 *Polytrimethylene terephthalate (PTT)*

Polytrimethylene terephthalate (PTT) is a synthetic fibre produced from a partially renewable feedstock. However the resulting fibre has similar properties to polyester and is not biodegradable. Sugar cane is the basis for production of dextrose, which is then fermented and purified to produce 1,3 propanediol (PDO). PDO is then melt spun with purified terephthalic acid (PTA) as in polyester production to form PTT. Production of PDO currently takes place in the USA through a joint venture between DuPont and Tate & Lyle announced in 2004. The process of melt spinning takes place predominantly in Asia.

4.2 Existing clothing market segmentation

The UK imported 1.02 million tonnes of clothing and manufactured a further 110,000 tonnes in 2008. Clothing is imported from a wide range of countries (Figure 16). However, the vast majority of imports come from Asia and Oceania (typically Australia, New Zealand, Malaysia), which accounted for 760,000 tonnes of UK clothing imports in 2007. China, Hong Kong, and Bangladesh produced more than a third of the clothing imported into the UK in that year. A further 83,000 tonnes were imported from Europe and 42,000 tonnes were imported from the Middle East and North America. Turkey, the Netherlands, and Italy are the largest European suppliers of clothing to the UK.

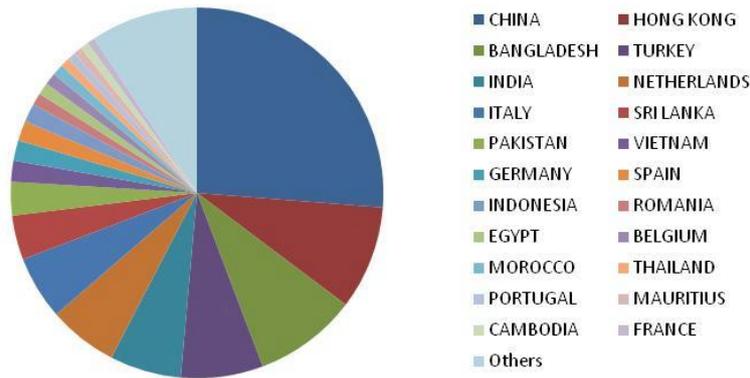


Figure 16. UK clothing imports in 2008 by mass (HMRC 2008).

The European Union (EU) Common Nomenclature System divides the clothing market into the following categories (Anon. 2008):

1. Accessories
2. Babies' garments
3. Jerseys
4. Nightwear and underwear
5. Overcoats
6. Shirts and blouses
7. Suits (including suits, jackets, trousers, dresses, skirts, and ensembles)
8. Tracksuits
9. T-shirts

The largest market sector in the UK is the suits category, which accounted for 317,000 tonnes (28%) of the UK clothing market in 2008 (Figure 17). More than 70% of this category is represented by trousers, with jackets, dresses, and skirts comprising the majority of the remainder (HMRC 2008; Figure 18).

Garments may be made of one or more natural and/or man-made fibres. For the purposes of this report, the term "other fibres" is applied to those situations where the textile fibre has not been specified or declared. Where a product is made up of two or more textiles, it is classified as if consisting wholly of that one textile material which predominates by weight over any other single textile material. Using these assumptions, it was found that more than 50% of UK clothing is made of cotton and that more than 30% is made of man-made fibres (Figure 19). However, there is significant variation in garment composition between clothing market sectors (HMRC 2008; Table 5).

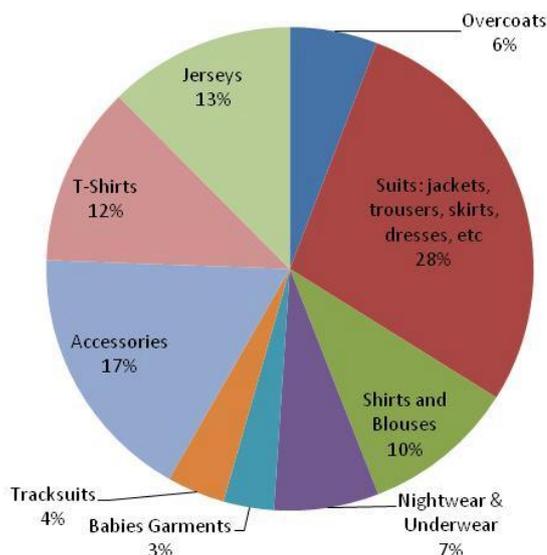


Figure 17. Relative size of UK clothing market sectors by mass (HMRC 2008).

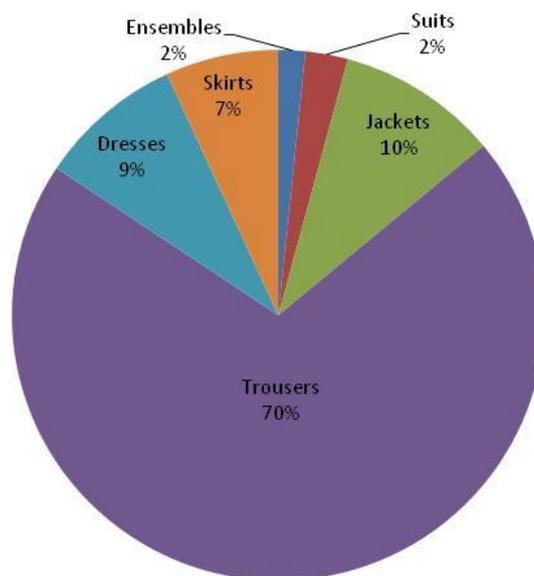


Figure 18. Sub-categories of the suits market sector in the UK by mass (HMRC 2008).

Man-made fibres predominate as constituents of tracksuits and overcoats, accounting for 73% and 59% of these market sectors respectively. Cotton is the major component of 21% of tracksuits and 30% of overcoats. Cotton and man-made fibres constitute approximately equal proportions of imported jerseys, with only a small quantity (7%) jerseys being made of wool. Cotton is also the most important fibre in men's shirts and women's blouses, suits, nightwear, and underwear. Man-made fibres comprise around one third of garments in each of these sectors. Babies' garments and T-shirts are overwhelmingly composed of cotton, which accounts for 86% and 87% of products respectively. While this provides useful information on broad fibre use, information on the prevalence of fibre blends within the above statistical summaries is not readily available, as component materials are categorised by the primary fibre component only.

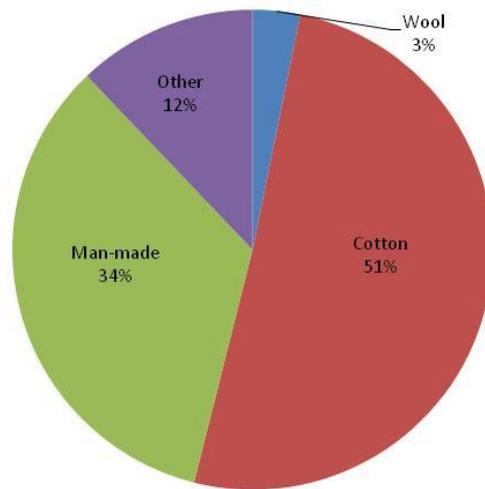


Figure 19. Constituents of total UK clothing imports by mass (HMRC 2008).

Table 5. Constituents of UK clothing by market sector (HMRC 2008).

Sector	Natural (%)		Man-made (%)	Other (%)
	Cotton	Wool		
Babies' garments	86	1	11	2
Jerseys	44	7	46	3
Nightwear and underwear	63	0	31	6
Overcoats	30	8	59	3
Shirts and blouses	53	0	35	12
Suits	57	3	31	9
Tracksuits	21	2	73	4
T-shirts	87	0	9	4
<i>All clothing</i>	<i>51</i>	<i>3</i>	<i>34</i>	<i>12</i>

4.3 Future market trends and potential

Global fibre production has increased consistently during the last 30 years. This period has also shown increased dominance of cotton and polyester fibres, which together account for more than 75% of the global clothing fibre market. This section extrapolates these trends to provide an assessment of future fibre markets. It is acknowledged that policy, trade initiatives, economic developments, technological innovations, tariffs, embargoes, oil production, energy prices, and consumer demand will all influence the global production and consumption of clothing textiles. However, the “business as usual” projections presented here are intended to demonstrate the logical results of current trends in order to inform policy on sustainable production and development.

4.3.1 Natural fibres

4.3.1.1 Cotton

Projections for the future of cotton production and consumption suggest a global increase in the production of cotton, as a result of the continued expansion of textile industries, especially in emerging economies such as Pakistan and China. Over the next 10 years this pattern is expected to continue, with the majority of the expansion of cotton imports accounted for by consumption in China and Pakistan.

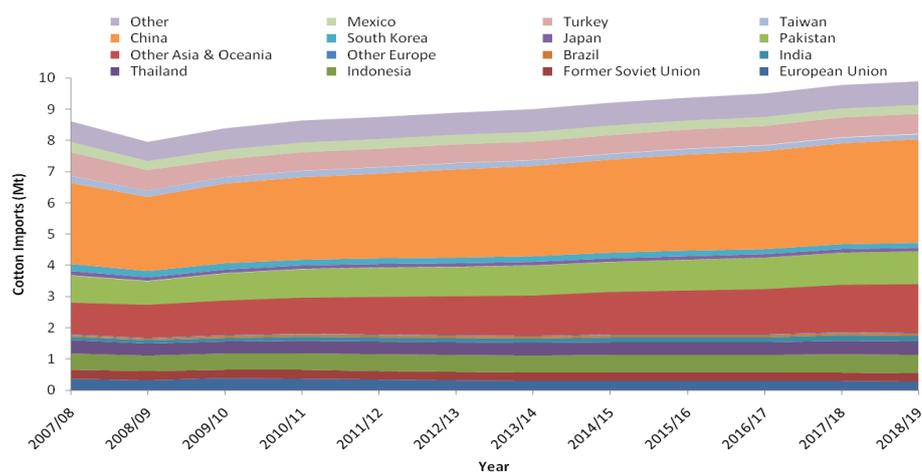


Figure 20. Projected Global Cotton Imports 2007/08 to 2018/19.

In general, the expansion of cotton imports is likely to occur mostly in Asian countries. The EU, Japan, Taiwan and South Korea are likely to see a small decline in cotton imports as the textile industry in these countries is driven to low cost economies and these developed textile industries specialise in low volume, high value clothing and textile production.

The major producers of cotton, including the world's major exporters, are likely to continue to gain from the globalisation of the cotton industry, increased availability of favourable cotton technology (genetic modification), and resource advantages such as large land bases. Over the next 10 years the United States is likely to continue as the world's largest major exporter, as a result of resurgent cotton exports, but United States' cotton exports are unlikely to occupy as great a share of total global cotton exports than at the beginning 2007/08 (USDA, 2009). Cotton exports from the Central Asian nations, formerly part of the Soviet Union, have been major competition for the cotton exports from the United States but many of these countries are expanding the production of textile products rather than raw materials. Additionally, this region's cotton production is expected to expand only slowly due to limited access to technology, capital investment and water.

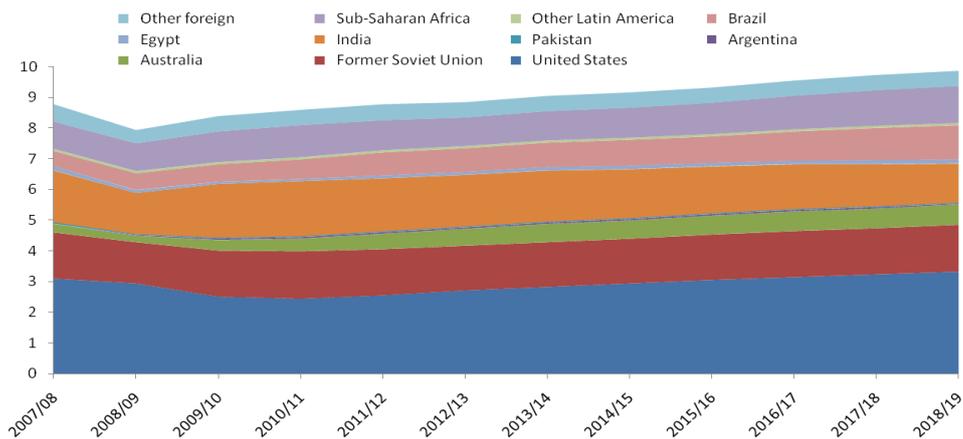


Figure 21. Projected Global Cotton Exports 2007/08 to 2018/19 (USDA, 2009s)

Some expansion of production in sub-Saharan Africa is likely to occur as a result of economic development of the economies involved and potentially through the adoption of genetically modified cotton. Exports from this region are expected to rise by 20% over the next decade (USDA, 2009).

Although the increase in cotton output from India is likely to continue as the use of genetically modified cotton continues to expand, over the next 10 years cotton exports are likely to contract as domestic demand for cotton increases. Those countries likely to see the greatest expansion of cotton exports are Brazil and Australia, with an expansion of 120% and 140% respectively over the next decade from 2007/08 levels.

4.3.1.2 Flax (line)

Linen clothing articles are renowned for their characteristics of high moisture absorbency and strength, but only the finest line-flax yarns are used in apparel. As a result of its unique characters, linen still commands some cachet in the market place. However, it is anticipated that it will struggle to expand significantly from its niche market status, in part because of the strong seasonality associated with its use in the clothing markets in developed economies.

4.3.1.3 Flax (short fibre)

Given that a significant quantity of short-fibre/tow-fibre is currently used for cottonisation and it has been demonstrated as technically and economically viable there is significant potential for flax fibre to be developed as an alternative to cotton fibre for use in textile yarns. However, the significance of the expansion of the crop and processing facilities will determine how much of the fibre will be available. With the development of short-fibre flax cropping and the continued production of tow-fibre as a by-product of the linen industry there is significant potential for the production of cottonised flax to expand to a level in excess of 100,000 tonnes per annum in the next 10 years.

4.3.1.4 *Hemp*

The fibres extracted from hemp tend to be coarse ($> 30 \mu\text{m}$), and abrasive (rough) unless excessive chemical, biological or mechanical processing are used to improve its properties for use in textile applications. As a result, most hemp fibre production is mainly aimed at low-grade industrial, non-woven end-uses and processing capacity is limited. Some development has been made with the use of hemp for the production of regenerated cellulosic fibres (viscose), but the production of pulp from hemp is unlikely to be competitive in comparison with conventional wood pulp. The technical limitations of the fibre for apparel markets make it unlikely that hemp will play a significant role in the production of fibres for use in clothing textiles in the near future.

4.3.1.5 *Jute*

Recent research has led to the production of finer jute yarns from both 100% jute and jute blends produced with cotton, wool, flax, acrylic, rayon, and silk. These have the potential to be used in high quality jute textiles (mainly knitted) including apparel, but jute containing yarns remain coarse compared to those produced from cotton. At present, there is no evidence to suggest that Jute will be cost effective as an apparel fibre in the near future and the fibres current low price reflects its development for use predominantly in low value end uses.

4.3.1.6 *Nettle*

Although levels of production of stinging nettle fibre are currently very low, it is likely that current production levels will increase from their current low base gradually, mainly driven by emerging interests in the upholstery sector. However, the cost of producing nettle fibre is likely to remain too high for it to be attractive as an apparel fibre in the short term.

4.3.1.7 *Ramie*

The prospects for ramie fibre garments are primarily in knitted jumpers and woven outerwear for a linen-like look. In Eastern markets, such as Japan, China or the Philippines where there is a familiarity with the fibre its prospects for use in clothing are attractive, but it is unlikely that ramie fibre will become a significant fibre in world terms in the next decade as the fibre lacks the cachet of linen which is widely available in garments, whether as blends with cotton or polyester, or as 100% linen fabrics. Additionally, the low-price advantage previously enjoyed by ramie has disappeared, making it less attractive.

4.3.1.8 *Silk*

Although the production of silk fibre has doubled in the previous 30 years, silk is still produced in very small quantities (approx. 100,000 tonnes in 2008 (pers comm. Dr. Jinsong Shen, Textiles Engineering and Materials Group, De Montfort University).

Silk is likely to remain a specialist high value fibre for use in high value textiles (Freddi et al. 2003).

4.3.1.9 *Spanish broom*

Although there is an interest in the production of Spanish broom for textile fibres, and future research and development is likely to be forthcoming, the limited volumes of usable fibre available to commercial processors at present, and likely into the near future, will result in very low levels of consumption (<10,000tonnes) of the fibre in clothing production over the next 10 years or so (ARTES, 2009).

4.3.1.10 *Wool*

Despite its importance in the textile market, there is an ongoing slow market decline for wool. In the medium term wool consumption is expected to decline significantly, particularly as the use of cotton in knitwear has developed as a cost effective alternative.

4.3.2 **Regenerated fibres**

4.3.2.1 *Bamboo*

Current production is limited. As bamboo is essentially just another viscose fibre, markets are anticipated to be 'niche' cashing in on its novelty value.

4.3.2.2 *Lyocell*

Despite recent over-capacity issues, long-term growth in requirements for both viscose and lyocell is anticipated for lining materials, particularly in higher quality garments.

4.3.2.3 *Soybean*

The significant interest from China in soybean as a replacement for cashmere is anticipated to stimulate growth in this fibre, though use is likely to remain limited to niche fashion markets, often in blends with other high value fibres such as cashmere, silk, wool, and bamboo (Brooks 2006).

4.3.2.4 *Viscose and modal*

The hydrophilic property of viscose that it shares with cotton makes it a fibre of choice for garments in contact with the skin in preference to polyester. However, gaining operating licenses and cost-effectively managing effluent streams in the face of tightening environmental legislation will hamper any moves to increase viscose or rayon capacity. It is anticipated that synthetic fibres (mostly polyester) will most likely be the main competitor to market growth of these fibres.

4.3.3 Synthetic fibres

4.3.3.1 Acrylic

Use of acrylic is in long-term decline and this trend is expected to continue due to cost differentials and the increasing use of other fibres, such as polyester, offering similar levels of performance but at lower price.

4.3.3.2 Nylon

Use of nylon is currently relatively static in textile markets, and is not anticipated to increase significantly in the near to mid-term. In part this is due to consumer perceptions about the ‘breathability’ of the textile, particularly in western countries.

4.3.3.3 Polyester

Polyester continues to show growth in output and share of the fibre market. Polyester is expected to continue to dominate both the synthetic apparel and overall apparel fibre market, along with cotton.

4.3.3.4 Polylactic acid (PLA)

Further work is required to demonstrate the viability of using PLA fibres in textile applications (due to initial problems with low melting temperature of current materials). In the interim, production capacity in the short-term is likely to be limited, though development of applications for PLA in other market sectors (disposable bioplastics) could help to ramp up production.

4.3.3.5 Polytrimethylene terephthalate (PTT)

The volumes of PTT produced at present are small and are not expected to rise significantly. Most demonstrated applications to date have been in the upholstery sector.

4.4 Summary conclusions

Global fibre output has more than doubled over the last 30 years. This growth has been driven by human population growth and increased per capita fibre consumption. At the same time there has been a significant shift in the types of fibres produced, with the proportion derived from man-made fibres increasing from 40% in 1977 to 56% in 2007. Total man-made fibre production exceeded that of natural fibres from the mid 1990s. The growth in use of synthetic fibres reflects their reducing cost and technical improvements to give them properties similar to those of cotton. Much of the growth can be attributed to the large increase in production of polyester, which dominates the man-made fibre market (accounts for 70% of man-made fibre

production). In contrast, the market shares for acrylic and nylon fibres have declined. Production of man-made textile fibres is dominated by Asian production. China is the largest producer of all types of man-made fibres (with a 52% market share) producing 65% of the total global output of polyester fibre. The price of most man-made fibres has fallen over the last 25 years, and these are typically lower in cost than wool and non-cotton fibres, and similar to prices for cotton. Long-term increases polyester production are expected to continue over the next ten years, with polyester retaining its dominant market position. Acrylic production is expected to continue its long-term decline and nylon production will likely remain relatively static.

Natural fibre production is dominated by cotton, which accounts for 78% of the natural fibre market. Cotton is the dominant natural fibre in UK textiles and is present in half of all UK clothing. Despite its falling market share against man-made fibres, cotton production has increased. However, the long-term average world price of cotton has remained relatively static and if inflation is taken into account, then this reflects a real drop in cotton prices. While technical advances have boosted the supply of cotton and additional value has been added to what was previously cotton waste, this has been countered by increasing financial pressure arising from competition with other fibres. As a result of falling returns, production of cotton is continuing to move away from the US to China and India.

Natural fibres other than cotton have generally shown either a static or declining market share. High cost (flax (see Figure 10), silk, ramie) and/or technical issues (hemp, Jute) limit market uptake to relatively niche segments. In other cases fibres have yet to be effectively commercialised (nettle, Spanish broom). However, short fibre flax and ramie show some prospects for increase, though again these will be niche relatively small volume markets. Wool use in apparel textiles is expected to continue its long-term decline.

Regenerated cellulosic fibres (viscose, lyocell and modal) have the largest share of the natural fibre apparel market after cotton. With specific opportunities in textiles worn next to the skin or higher-value clothes linings. Growth is anticipated, though may be production limited.

Polylactic acid (PLA) is still in development as a textile fibre, particularly more heat-resistant variants, but the technical properties show potential as an apparel fibre. The main issues affecting development are the current low levels of production capacity and the wide number of outlets that PLA is likely to be directed towards, including biodegradable packaging. Together, these are likely to restrain PLA availability in the textile sector in the near-term.

As a silky fibre, soybean fibre it is suited to apparel wear. Currently, production is constrained to development scale plants. Key questions relate to the availability of the raw material and cost of processing soybean to extract protein. Soy meal is a by-product of oil production, but the meal is also an important protein feed supplement, globally traded and widely used in ruminant and other animal feeds. Use for fibre production will have to compete with this market. Extraction of proteins is relatively simple for concentrates, but becomes increasingly expensive for purified isolates. It is currently not clear what type of protein is required, but it appears that fibres derived from soy are likely to be relatively expensive. Blending with expensive fibres like

cashmere can help defer such costs, but again this relegates soy protein fibre to niche uses

The main conclusions can be summarised as:

- The textile market is increasingly turning towards synthetic fibres, and polyester significantly dominates the sector.
- Cotton is the most important natural fibre and dominates natural fibre production. In general the growth in raw fibre production is moving to China and Asia, predominantly from the US.
- After cotton, all other natural plant fibres occupy niche roles with few prospects of taking significant market share in the apparel sector.
- Regenerated cellulose, in all forms, show prospects for growth, though production capacity may be limited by environmental concerns associated with the associated chemical pulping plants.
- PLA shows promise, but production for textile use may be limited in the near future until production capacity increases.
- The promise for soy-bean fibre is unclear until more is known about costs and potential future availability.

In terms of key issues for the environmental work in this study, the impacts associated with cotton and polyester production will have the greatest significance in terms of the size of the footprint of any impact. While many of the remaining natural fibres have relatively niche markets, they are worth examining to identify if they have any specific environmental benefits that could help promote wider use. The potential for growth in regenerated cellulosic fibres also warrants attention on their environmental credentials.

5 Sustainability assessment

Fibres used in textiles clearly separate into three distinct groups (see section 3.3)

1. Natural fibres
2. Regenerated cellulosic fibres
3. Synthetic fibres

Even through the simplest of explanations of the differences in production between the fibre types (see section 3.3), it is clear that there are likely to be very different environmental impacts associated with production of each for use in apparel products. Natural fibres require fertiliser, agrochemical and water inputs which then can pose a risk through ‘leakage’ to the natural environment, or in the case of irrigation can deplete water resources. Regenerated cellulose production requires significant energy, chemical and water inputs to produce pulps, and synthetic polymer production requires fossil oil inputs and chemical and energy inputs to generate appropriate polymers. There are also numerous variants in terms of types of crop plants involved, how they are managed and types of chemical modifications used for synthetic and regenerated fibres that result in generation of a wide range of fibre types.

Faced with such a wide range of possible fibre options and in trying to better understand the sustainability of fibres used in clothing textiles, a key question is how do the environmental impacts of these fibres compare? The following sections outline the environmental impacts of textile fibres by identifying key environmental issues associated with each stage of the fibre production process from raw material production to final dyeing and finishing.

The basic processes involved in each stage of the textile production chain are first described for reference. Following this, for each fibre, a brief description of the typical supply chain and areas of potential environmental concern are outlined. Detailed summaries of the impacts on energy and water use are presented, which draw on more detailed data gained from the literature review (presented in Appendix C). The methods adopted in deriving the environmental impact values are outlined in section 3.4.2. The impacts of individual fibres on energy and water use are categorised using a matrix table to allow relative comparison of effects of different fibres (following the method outlined in section 5.3). The final sub-section of the environmental review details other environmental impacts of textile fibre production, where they are reported in the literature.

5.1 Fibre chain steps and processes (fibre to fabric)

The supply chains and production methods for each textile fibre of interest were divided into four processes (see section 3.4) as outlined below. Figure 22 shows a simplified summary of the four key processes for each fibre type and the relationship between the processes. It can be seen that although the initial production and processing steps differ widely between fibre types, the final stages are similar across different textile fibres.

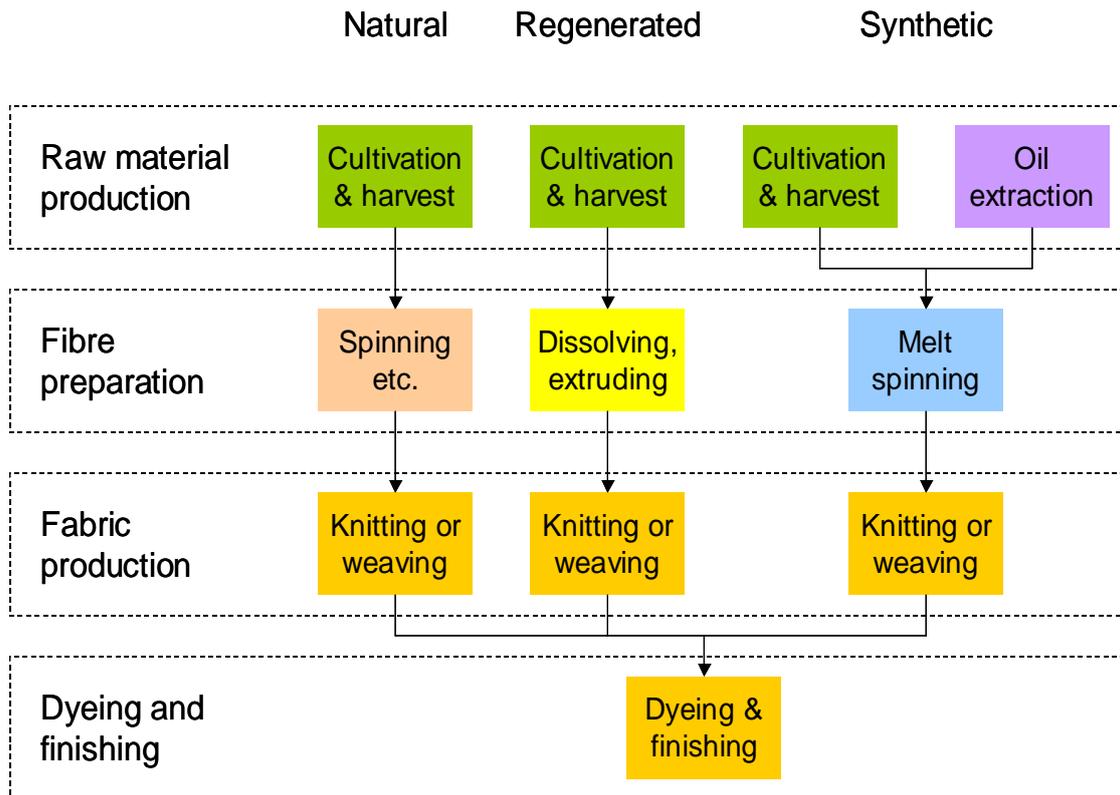


Figure 22. Graphical summary of the four key processes examined in the environmental assessment.

5.1.1 Raw material production

In the case of natural or regenerated fibres, the first phase of the supply chain is agricultural or arboricultural production. This phase can have a wide range of environmental impacts, depending on the location of production and the combination of crop type and farming system employed. This phase includes all impacts associated with energy and water use invested in growing crops, including energy involved in irrigation, fertiliser and pesticide manufacture, and though often mentioned, data is not always itemised in studies (see Appendix C).

After raw material production, fibre is extracted, cleaned and prepared for use as a textile fibre. For silk production, cultivation typically refers to the production of silkworms. Synthetic fibre production begins with crude oil extraction and refining, followed by the production of the respective polymer. This applies to polyester, acrylic, nylon, and part of the feedstock for PTT. This stage usually involves a relatively high-energy demand.

5.1.2 Fibre preparation

Fibres must undergo a number of processes before a textile-quality fibre is produced. For natural fibres, extraction and cleaning may include mechanical, enzymatic, chemical, or a combination of all three treatments. Regenerated fibre preparation involves chemical dissolution of cellulose. Synthetic fibre preparation involves polymerisation, then extrusion into a filament and cutting and crimping.

5.1.3 Fabric production

The production of a filament or staple fibre is followed by spinning and the production of a yarn to enable weaving or knitting. Prior to spinning, several preparatory stages are necessary. For natural fibres, this may include opening, blending and carding, and formation into a sliver - which is an assemblage of fibres in a continuous form without twist. The sliver is then “drafted” or drawn out into a roving prior to spinning. Various methods of spinning exist; the term refers to the drafting and insertion of twist into natural and manmade fibres, but equally alludes to the extrusion of filaments by silkworms, and the production of filaments from fibre forming polymers.

Ring spinning is responsible for 80% of the world’s yarn production and a significant proportion of the yarn used in UK garments is spun in China. Open end rotor spinning systems are much less common, with most found in China, followed by Russia and Turkey. Spinning lubricants and oils are commonly used in this process and are responsible for ecological loads in wastewater in finishing processes (Schönberger and Schäfer 2003).

Weaving involves the interlacing of yarns. Sizing, the application of a gelatinous film-forming substance, is normally carried out before weaving to protect the yarn during the weaving process from damage or break. Machine weaving predominantly takes place in China or India. Approximately 40% of the world’s cotton-type weaving capacity is located in China. China also has the largest number of wool and filament weaving looms. However, India has by far the largest hand-loom weaving capacity of any country. Knitted textiles are fabrics made of yarns or yarn systems by stitch formation.

5.1.4 Dyeing and finishing

During and following the production of a yarn or fabric, there are many stages of ‘finishing’ carried out to improve the properties of the textile, to provide a specific colour, durability and functionality. Finishes may be mechanical, chemical or enzymatic, and often involve significant amounts of water and energy, as well as chemicals. The impacts of these processes vary considerably depending on the technologies employed as well as the presence, and use of, waste-water treatments. Finishing can be carried out at any step in the textile chain, but fabric finishing dominates. Typical processes include de-sizing, bleaching, scouring (removal of oils and grease), dyeing, washing, mercerising (to improve strength, lustre and dye uptake), softening, and singeing (burning to remove loose fibres).

Washing prior to finishing removes spinning oils and preparation agents that may be difficult to biodegrade. Typical chemical oxygen demand (COD) loads of effluent waters are 40-80 g COD/kg fibre. Washing water from desizing of cotton and cotton-blend fabrics may account for up to 70% of the total COD loads in final effluent (with emission factors of up to 95g COD/kg fabric (EC, 2003)).

Wool scouring leads to effluent discharge with a high organic content (which leads to COD and variable amounts of pesticide pollutants (organophosphates, pyrethroids and even organophosphates from some source countries (EC, 2003))).

Bleaching is carried out on almost all natural and man-made fibres prior to dyeing, with use of different bleaching methods typically matched to different fibre types (Table 6). Bleaching with hydrogen peroxide produces waste-water with a high alkali content, and other agents and materials removed from cellulose that results in a waste-water with a high COD (Schönberger and Schäfer 2003). Chlorite bleaching can result in release of chlorine dioxide if pH is not well controlled. This process is banned in some countries, such as Germany (Schönberger and Schäfer 2003). Sodium hypochlorite bleaching of fibres leads to formation of organic halogen compounds (such as trichloromethane) and low concentrations can still be found in the following spent hydrogen peroxide bath (EC, 2003). Reductive bleaching uses sodium dithionite and formaldehyde sulfoxylates, which again lead to contaminated waste problems. The peroxide approach is viewed as the least damaging preferred option (EC, 2003), and is used in preference with most natural and protein based fibres, while the regenerated cellulosic fibres tend to be bleached using the chlorite treatment.

Table 6. Most common approaches to bleaching for different base fibre types (Schönberger and Schäfer 2003) '+' denotes common areas of use for each bleaching method

Textile fibre composition	Peroxide	Sodium chloride	Reductive
Acrylic		+	
Cellulose	+	+	
Cellulose esters		+	
Cellulose/Polyester	+		
Nylon			+
Polyester		+	
Viscose		+	
Wool and other Protein fibres	+		+

Dyeing is typically carried out using reactive, disperse, metallic, or acid dyes, using a wide range of techniques, and each of these has their own specific environmental issues (Table 7). The liquor ratio (ratio of water to textile substrate used in the dyeing process) tends to decrease (from highest to lowest water consumption) in the following order: winch, beam dyeing, jigger, jet, and airflow techniques (Schönberger and Schäfer 2003). The lower the water to textile ratio, the less waste-water is generated, which is typically loaded with non-exhausted dyes, dyeing auxiliaries, salts, alkalis, and acids. The methods used are influenced by product make up (i.e. fabric type, yarn, hank or rope etc), weight of fabric, dye type and therefore textile fibre. The use of jet dyeing for cotton is therefore representative of one of the better available technologies, though not all cotton is dyed this way. Following most wet processes, and as a last step in finishing, fabrics are dried, a process consuming significant amounts of energy.

A key environmental concern in the textile industry is the amount of water discharged and its chemical loading. Other important considerations are energy use and air emissions (EC, 2003). Emissions to water from textile operations are not well characterised and waste waters contain a mixture of chemicals reflecting both the various processes involved and origin of textile feedstocks (EC, 2003).

Table 7. Main dye types and key associated environmental impacts (derived from information in Schönberger and Schäfer, 2003 and EC, 2003)

Dyesuff class	Environmental aspects	Fibre types where typically used
Acid/metal complex	Heavy metal contaminants in waste	Wool, silk ,nylon
Azoic	Cleavage of azo-dyes (under anoxic or anaerobic conditions) can produce carcinogenic aromatic amines affecting routes of disposal	Used on cellulosics and polyester
Basic (cationic)	Quaternary ammonium compounds used to control dye process	Acrylic, also nylon
Direct	High salt levels, after treatment contains many cationic agents with high toxicity to water environments	Primarily cellulosics also some nylon and silk
Disperse	Used with carriers – so spent carrier materials, and residues of sulphur-containing after treatments	Primarily used with polyester also acrylic and nylon
Reactive	Low fixation to textiles, low absorbency in waste water sludges, high salt levels	Primarily cellulosics, also some silk and wool
Sulphur	Sulphur contaminants, reducing agents and halogene-containing oxidising agents	Cellulosics
Vat	Contains sulphur based reducing agents and halogene-containing oxidising agents	Cellulosics

5.2 Environmental impacts of individual fibres

Data in the following sections draw on results of the full literature review, presented in full in Appendix C. The choice of data or data ranges used was based on expert consultation and opinion based on methodology outlined in section 3.4.

5.2.1 Natural fibres

5.2.1.1 Cotton

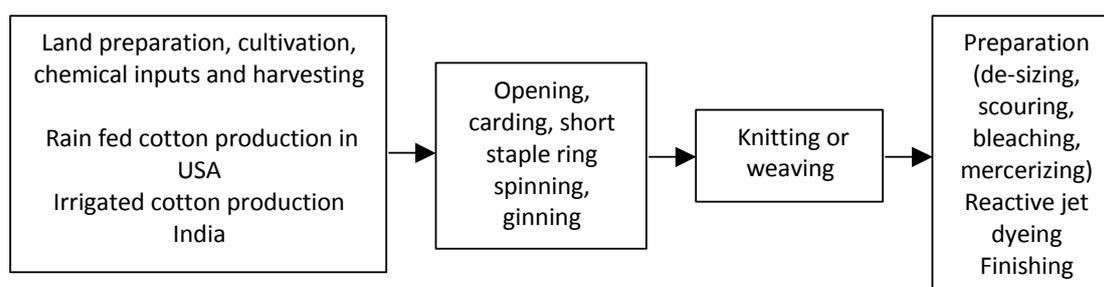


Figure 23. Typical steps and procedures in production chain for UK-sourced cotton fibre

Cotton uses very large quantities of water in growing and processing; the most of any fibre in the study. The crop is irrigated in many parts of the world, significantly adding to the water demand. However, there is no clear distinction between irrigated and non-irrigated cotton as the extent of irrigation varies depending on local growing conditions and annual variations in climate (Chapagain et al. 2005). Furthermore, irrigation is necessary to maintain yields or to allow production in some parts of the world. Around 53% of the global cotton area receives some form of irrigation and this area accounts for 73% of cotton production (Cherrett et al. 2005). Of the top five cotton producing nations, the USA has a relatively low proportion of irrigated cotton. Approximately 52% of US cotton is irrigated, with an average water requirement of 576 L/kg fibre. This is in contrast with Uzbekistan, where all cotton is irrigated and the average water demand is 4377 L/kg fibre. Table 8 shows the maximum and minimum irrigation water use of the top five cotton producers (China, USA, India, Pakistan, and Uzbekistan) as well as the global average (Chapagain et al. 2005) for raw fibre production. These figures, assume all is allocated to cotton production, but as discussed earlier (Section 3.5) typically up to one third of the estimated environmental impacts on water use should be allocated to cotton fibre by-products. But, even allowing for such reductions, in the vast majority of case, water use in cotton still remains significantly higher than for all other fibres.

The relatively high use of pesticides in cotton production and fertiliser practices are associated with an increased risk to water in terms of ecotoxicological and eutrophication risks. However for comparison, typical nitrogen (106 to 218 kg N/ha) and phosphate (63 to 70 kg P₂O₅/ha) use for cotton, is comparable to cereal crop cultivation (EDIPTX 2007; Yilmaz et al. 2005). It is difficult to find reliable data on actual chemical inputs to cotton production to assess against widespread claims of ‘high’ pesticide use for cotton.

Cotton is also commonly bleached. Chlorine-based bleaches are less desirable than hydrogen peroxide treatments on environmental grounds. Formaldehyde may also be used as a dye fixing agent.

The variability in fibre quality in raw cotton fibres and contamination with other materials during harvesting (seed, lint, stem materials etc) mean that cotton requires cleaning, combing and ginning resulting in loss of up to 20-30% of the harvested fibre yield. Carding alone results in losses of up to 15%, compared to 9% for carded synthetic fibres (though this discarded fibre may be used for lower quality yarns).

Table 8 impacts of cotton fibre production on energy and water use

Stage	Energy (MJ/kg)	Water (L/kg)
Raw material production	48.7 (A)	576.0–4377.0 (B) (global average 1818.0)
Fibre preparation	18.4 (A)	nil
Fabric production	5-30 (C)	nil
Dyeing and finishing	17.9-60.9 (B)	105-145 (B)

For explanation of the role of index letters accompanying each data entry see section 3.4.2

In relation to energy and water use in cotton production, the only data amended to those drawn from sources in Appendix C, or from interpolation between data values in Appendix C were; use of a typical energy value for dyeing and finishing of 5-30

MJ/kg, drawn from Shen and Patel (2008a). This represents a generalised energy value for dyeing and finishing in cotton and polyester operations (knitted or woven) that compares favourably with other sources of data or data ranges in the literature.

The above data assume all inputs into raw cotton fibre production are allocated to cotton fibre production, rather than be divided between the fibre and any by products such as cotton seed. Cotton raw fibre production has a very high water demand compared to all other fibres. The values for water use in raw fibre production draw on studies of irrigation use (Chapagain et al., 2005). Water use in finishing draws on data on common cotton dyeing treatment processes by Blackburn and Burkinshaw (2002).

The energy data values are drawn predominantly from the review by Laursen et al. (1997) where the data is more clearly itemised and includes embedded energy and also compares favourably with other data sources for cotton in Appendix C.

As a major cellulosic fibre where LCA assessments are more readily available than for other cellulosic fibres, appropriate energy and water use figures for cotton were used as surrogate sources of data for other cellulosic fibres.

5.2.1.2 Flax (line) (linen)

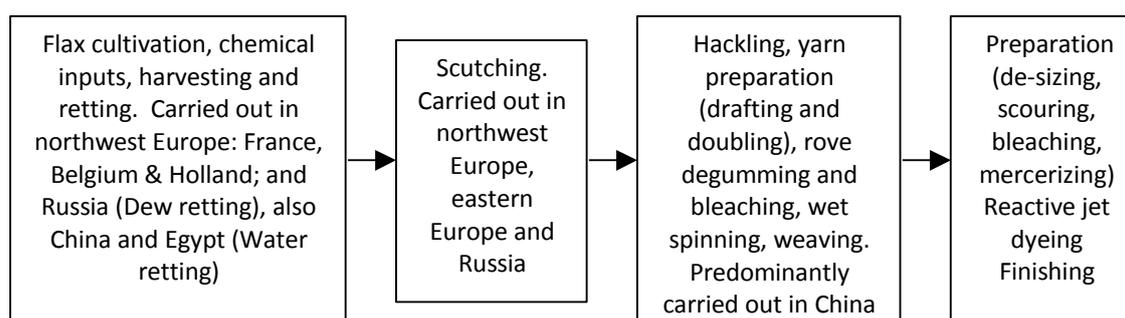


Figure 24. Typical steps and procedures in processing for UK-sourced line flax fibre

Flax has a greater reliance on use of pesticides than hemp, but use is still relatively low for an agricultural crop, as a result it should pose a relatively low ecotoxicological risk to water. Flax crops tends to require lower inputs than hemp and both less than cotton. This is typically reflected in a lower eutrophication potential for flax than hemp (26g v 30 g PO₄ eq/kg fibre) van der Werf and Turunen, 2008). However, these figures are higher than eutrophication potentials reported for synthetic and semi-synthetic fibre production (van der Werf and Turunen, 2008). This arises primarily due to fertiliser use in crop production (accounts for 90% of impact of natural fibre material production). Overall, impacts on greenhouse gas emissions, use of fossil fuel resources and acidification risks are very similar for hemp and flax and effects are primarily associated with impacts of yarn production (van der Werf and Turunen, 2008). Water use in flax fibre production is primarily associated with bleaching operations. Where water retting is carried out this will increase the water demand and eutrophication risk.

Table 9. Impacts of line flax fibre production on energy and water use

Stage	Energy (MJ/kg)	Water (L/kg)
Raw material production	5.5-11.7 (B)	rain fed
Fibre preparation	2.7 (C)	72.3 (C)
Fabric production	as cotton	Nil
Dyeing and finishing		as cotton

Apart from data drawn from the relevant table in Appendix C, energy and water use in dyeing and finishing operations were assumed to be the same as those for cotton.

There was only one novel source of data on water use in fibre preparation. Energy values for raw material production represent the range across the available data sources in Appendix C, which are relatively similar. Energy use in fibre production was drawn from Shen and Patel (2008a) as more representative of textile applications.

5.2.1.3 Flax (short fibre)

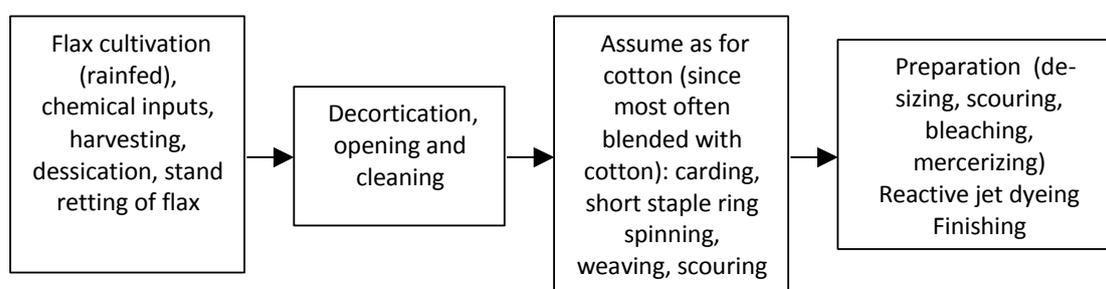


Figure 25. Typical steps and procedures in production chain for UK-sourced short fibre flax

The issues affecting line flax also relate to short-fibre flax production. Short fibre flax is produced as a by-product of line flax, 0.7 tonnes short-fibre flax per tonne of line flax. No additional energy or water use per kg of product is incurred in its production.

5.2.1.4 Hemp

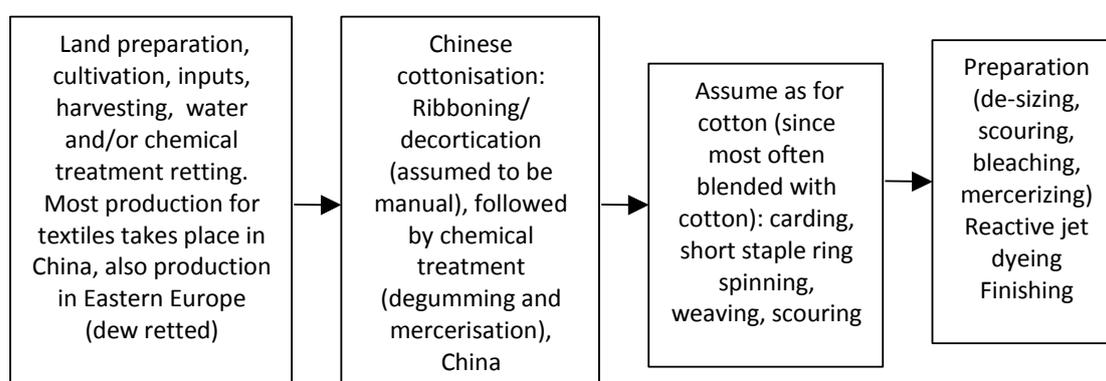


Figure 26. Typical steps and procedures in production chain for UK-sourced hemp fibre

Less than 30% of the fibre recovered from hemp is long fibre (van der Werf and Turunen, 2008), which represents a target for crop improvement as well as total fibre

yield. Energy use in hemp yarn production (a key area of energy use) is reported to be typically three times that of cotton spinning, due to differences in cotton and bast fibre spinning technologies (Turunen and van der Werf, 2006). However, this was not evident in the data collated for this study. Further energy is expended in the water retting process (where used – this involves use of a warm water bath for up to 72 hours) and in drying fibres. Water retting uses significant quantities of water, though alternative dew-retting and mechanical decortification processes are used to varying degrees of success.

The crop production phase contributes to water eutrophication risk, but inputs to hemp are relatively low in an agricultural context. As little or no pesticide is used in hemp production, ecotoxicological risks to water are very low.

The resulting effluent from hemp processing and particularly water retting operations is commonly considered to be detrimental for the environment. However, studies by van der Werf and Turunen (2008) found that the contribution of waste waters to eutrophication risk were lower than risks associated with the crop production phase, though a key aim remains to reduce water use in processing.

Overall impacts on greenhouse gas emissions, use of fossil fuel resources and acidification risks are very similar for hemp and flax production (van der Werf & Turunen, 2008). However, significantly more water is used in hemp processing, due to retting (0.19 v 0.07 m³/kg fibre).

Table 10. Impacts of hemp fibre production on energy and water use

Stage	Energy (MJ/kg)	Water (L/kg)
Raw material production	13-32.6 (C)	rain fed
Fibre preparation		199-221 (C)
Fabric production	as cotton	nil
Dyeing and finishing		as cotton

Apart from data drawn from the relevant table in Appendix C, energy and water use in dyeing and finishing operations were assumed to be the same as those for cotton.

Data on water use was limited to one reference for use in raw material and fibre preparation (Appendix C). Data for energy use in raw material production represents a typical range for values found in the literature. (Two very high values in Appendix C (van der Werf and Turunen, 2008) were excluded on the basis that the values represented significant extremes and the method of calculation was not entirely clear).

5.2.1.5 Jute

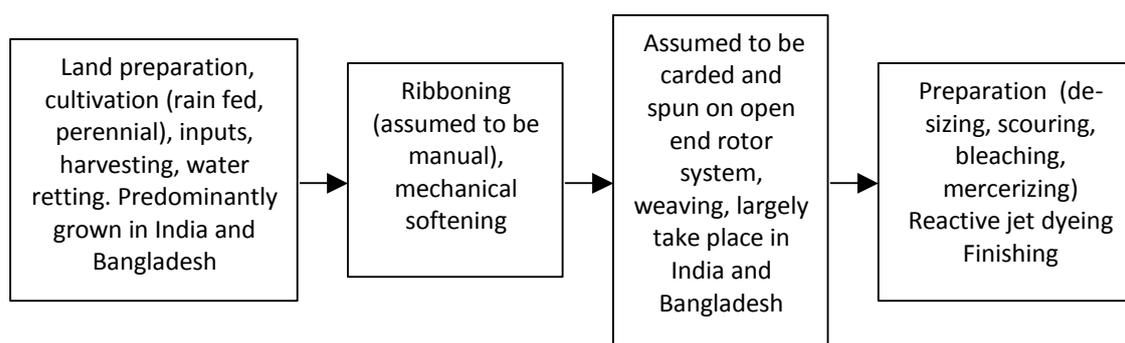


Figure 27. Typical steps and procedures in production chain for UK-sourced jute fibre

Fine jute fibres are needed for spinning into applications suitable for apparel, which requires significant chemical modification of the fibres. Recently finer jute yarns have been produced from 100% jute and jute blends produced with cotton, wool, flax, acrylic, rayon, and silk. A small number of industries are producing finer yarns of jute and union fabrics (cotton warp and jute weft). As a relatively novel apparel fibre, very little data on its environmental performance was available in the literature. In the absence of any specific data on jute fibre production itself, it is assumed that energy use in fabric production would be the same as the generic values proposed by Shen and Patel (2008a) for a range of fibre types, and that water and energy use in dyeing was assumed to be the same as that for cotton fabrics.

Table 11. Impacts of jute fibre production on energy and water use

Stage	Energy (MJ/kg)	Water (L/kg)
Raw material production	no data	rain fed
Fibre preparation	no data	no data
Fabric production	5-30 (D)	nil
Dyeing and finishing	as cotton	as cotton

5.2.1.6 Nettle

Nettle is a crop that has yet to be fully commercialised as a fibre crop but shows potential. As a rain-fed crop of temperate areas, water demand is low and inputs are likely to be similar to those of hemp, with some demand for nitrogen required. Mechanical decortification means water demands during the fibre extraction phase are low, reducing effluent output. In apparel it is most likely to be blended with cotton. Impacts of production are thought to most closely match those of flax fibre.

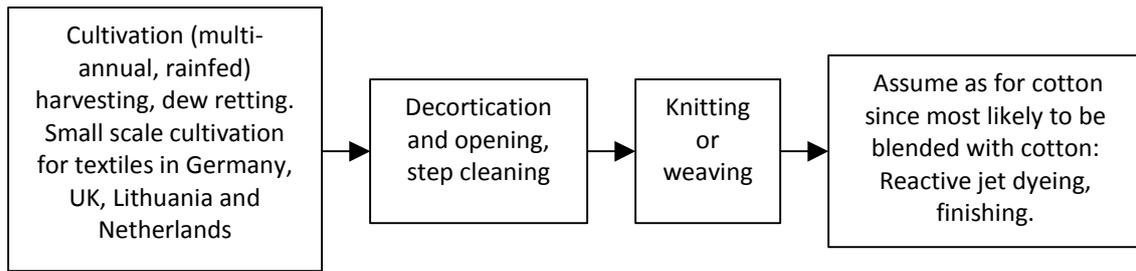


Figure 28. Typical steps and procedures in production chain for UK-sourced nettle fibre

As a novel fibre, data on energy use was very limited and draws on one source of information (Huxtable and Turley, 2008).

Table 12. Impacts of nettle fibre production on energy and water use

Stage	Energy (MJ/kg)	Water (L/kg)
Raw material production	25.8 (C)	rain fed
Fibre preparation	as line flax	nil
Fabric production		nil
Dyeing and finishing	as cotton	as cotton

5.2.1.7 Ramie

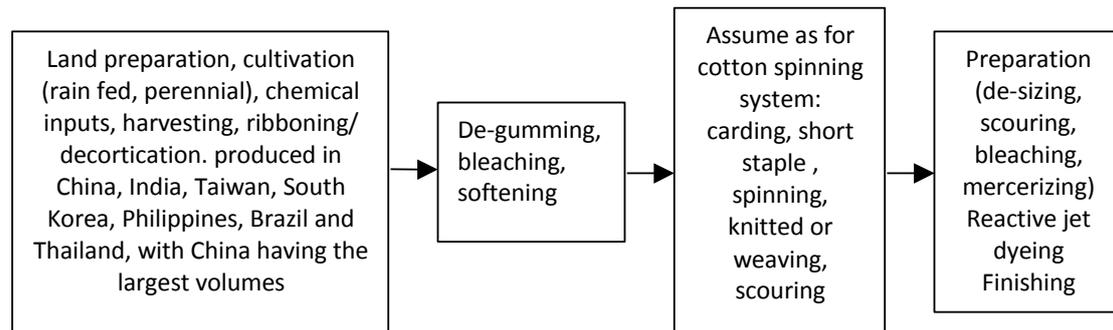


Figure 29 . Typical steps and procedures in production chain for UK-sourced ramie fibre

A novel apparel fibre often blended with cotton, and available in woven and knit fabrics. Typically it is currently hand harvested. Bark fibres are degummed by alkaline boiling, followed by washing, neutralizing and bleaching steps. This poses an environmental threat if not well controlled and contained. Alternatives include microbial degumming (retting). Bleaching and softening with oil or wax is also usually required. There is little information available on the environmental impacts of ramie production.

Table 13. Impacts of ramie fibre production on energy and water use

Stage	Energy (MJ/kg)	Water (L/kg)
Raw material production	no data	rain fed
Fibre preparation	no data	no data
Fabric production	5-30 (D)	nil
Dyeing and finishing	as cotton	as cotton

In the absence of data specifically for ramie, energy in fabric production was assumed to be within the typical range proposed by Shen and Patel (2008a), and energy and water use in dyeing and finishing was assumed to be the same at that for cotton (with which it is typically blended).

5.2.1.8 *Silk*

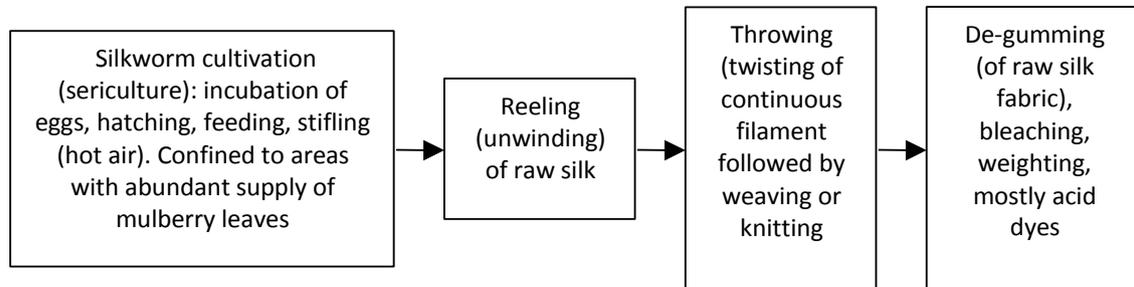


Figure 30. Typical steps and procedures in production chain for UK-sourced silk

Despite its widespread use, there is very little documented assessment of the environmental impacts associated with silk production. As a protein-based fibre, it is assumed that impacts are similar to those associated with wool, though without the need for washing and scouring treatments. Silk has a very high water requirement in fibre production/preparation, though data on this was limited to one reference (Lee, 1999)

Table 14. Impacts of silk production on energy and water use

Stage	Energy (MJ/kg)	Water (L/kg)
Raw material production	no data	no data
Fibre preparation	no data	800-1000 (C)
Fabric production	no data	nil
Dyeing and finishing	as wool	as wool

5.2.1.9 *Spanish broom*

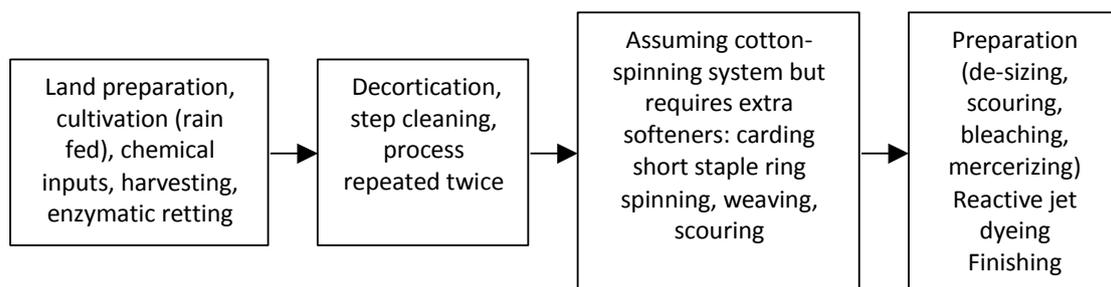


Figure 31. Typical steps and procedures in production chain for UK-sourced Spanish broom fibres

As a Mediterranean native, Spanish broom is relatively drought tolerant and water requirements will reflect this. Mechanical cottonisation of Spanish broom and enzymatic maceration options show promise (ARTES 2009), and in the former case will help to keep water demands down. As it is not commercialised, there is no

information on the environmental impacts of Spanish broom fibre production, so it was assumed that impacts would be similar to those for processing cotton.

Table 15. Impacts of Spanish broom fibre production on energy and water use

Stage	Energy (MJ/kg)	Water (L/kg)
Raw material production	no data	no data
Fibre preparation	no data	no data
Fabric production	5-30	nil
Dyeing and finishing	as cotton	as cotton

In the absence of other data, it was assumed that energy and water use in dyeing and finishing operations were the same as those for cotton. In addition, energy use in fabric production was assumed to be within the typical range proposed by Shen and Patel (2008a).

5.2.1.10 Wool

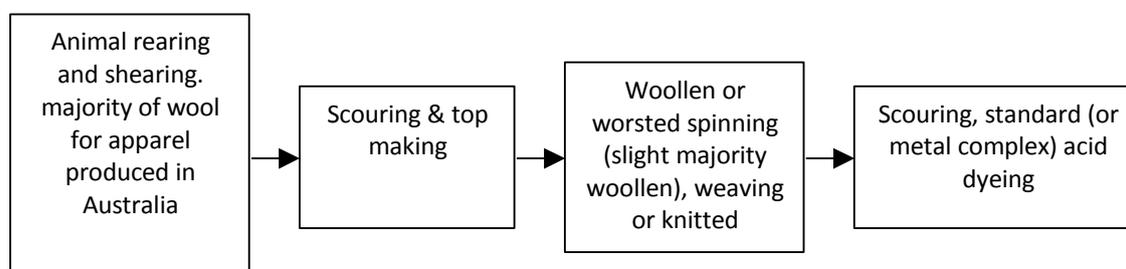


Figure 32. Typical steps and procedures in production chain for UK-sourced wool fibres

Energy use in wool production tends to be relatively low, similar to other natural fibres. Scouring (cleaning and de-waxing) of wool accounts for a significant part of the energy input, but also a very high waste-water output. Harsh alkaline scouring agents (mostly sodium hydroxide) are also used, and chlorine bleaches are also often used. Finishing treatments are similar to those used for cotton and cotton-like materials.

Table 16. Impacts of wool fibre production on energy and water use

Stage	Energy (MJ/kg)	Water (L/kg)
Raw material production	8*-13.9 (B)	rain fed
Fibre preparation	4.3-20 (B)	5-14 (C)
Fabric production	39.6-75.6 (C)	70-314 (C)
Dyeing and finishing		

*8 MJ/kg figure takes account of part of energy use being allocated to meat production

The above data were drawn from sources in Appendix C, excluding those of Berber and Pellow (2006), where primary energy was also accounted for. Energy inputs for raw material and fibre preparation reflect the range of data in the reviewed information sources. Accounting for allocation of part of the energy demand to meat production, had little impact on energy demand for raw wool production, which is relatively low. Data on water use in fibre preparation represents a common range for

fine and coarse wool. Data on water use in wool dyeing and finishing is quite variable in the literature. The range chosen in Table 16 draws on primary data from an EC Best Available Technology for Textiles review (EC, 2003) which details a case study of waste water output for a number of wool-finishing textile mills.

5.2.2 Regenerated fibres

5.2.2.1 Bamboo

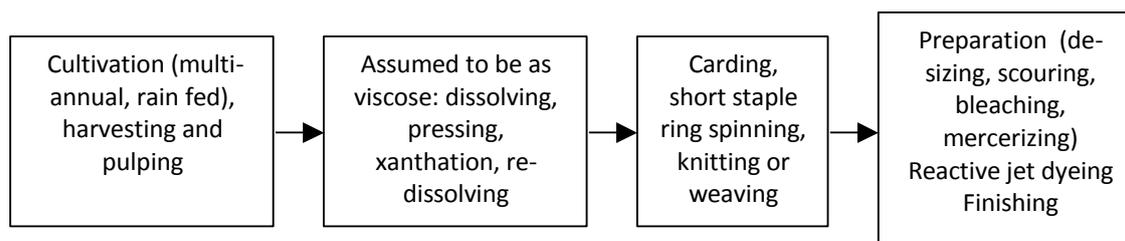


Figure 33. Typical steps and procedures in production chain for UK-sourced bamboo fibres

Bamboo grows very quickly in its native habitats, but requires very few agrochemical inputs or fertilisers. It also requires relatively little water in its natural rain-fed habitats. This is counter-balanced by the chemicals and energy used in pulping the stems. Bamboo fibre production is subject to the same problems associated with viscose production. Care is required in effluent treatment from such processes. In the absence of any assessment of the environmental impacts of bamboo fibre production in the literature, it is assumed that impacts will be identical to those associated with viscose fibre production.

5.2.2.2 Lyocell

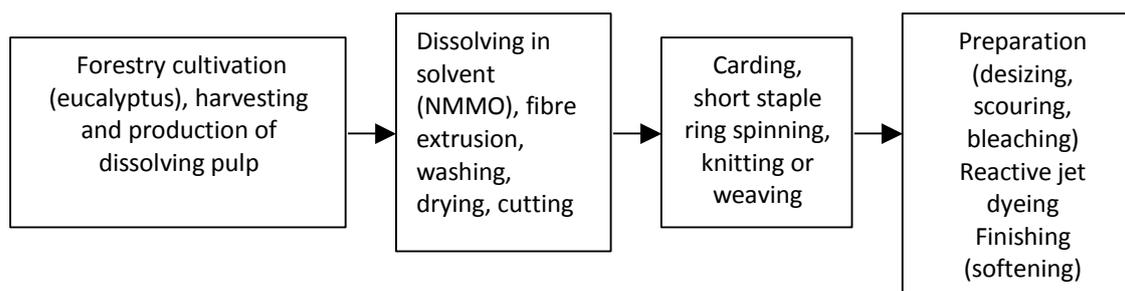


Figure 34. Typical steps and procedures in production chain for UK-sourced lyocell fibres

Compared to the viscose process, on which lyocell production is based, the lyocell process requires substantially less chemicals in fibre processing, and uses less water than the viscose process due to lower cooling water requirement (243 v 403 m³ per tonne of fibre) (Shen and Patel 2008b). The lyocell process uses NMMO (N-methylmorpholine-N-oxide) to dissolve wood pulp and regenerate cellulose in a closed solvent cycle, which avoids the use of the solvent carbon disulphide (CS₂), thereby reducing processing steps and energy use.

Table 17. Impacts of lyocell fibre production on energy and water use

Stage	Energy (MJ/kg)	Water (L/kg)
Raw material production	66-102 (C)	263.0 (C)
Fibre preparation		
Fabric production	5-30 (D)	nil
Dyeing and finishing	as cotton	as cotton

In relation to energy and water use in lyocell fibre production, the only data added to that drawn from ranges presented in very limited data in Appendix C, were that energy inputs to dyeing and finishing were assumed to be similar to those of cotton.

5.2.2.3 Modal

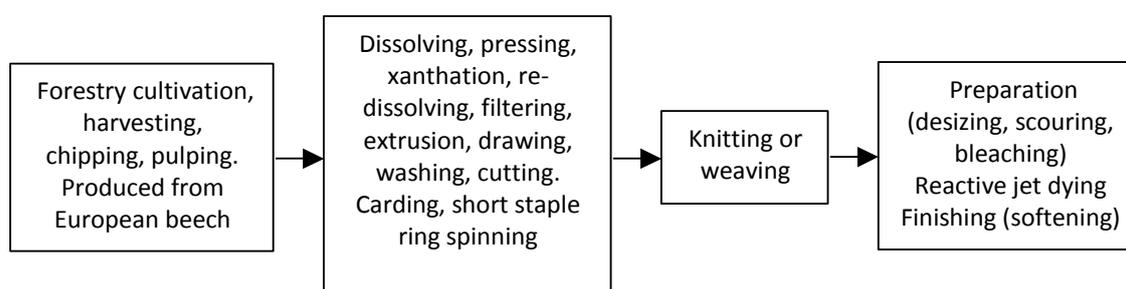


Figure 35. Typical steps and procedures in production chain for UK-sourced Modal fibre

Modal is derived from a viscose-based process, but in this case through the chemical pulping of beech wood. A modified spinning process is used to produce a fine fibre, but in all other respects its production (and environmental impact) mirrors that of viscose. In use in blends it helps prevent cotton shrinking and reduces ‘pilling’, so extending the life of garments.

Table 18 . Impacts of Modal fibre production on energy and water use

Stage	Energy (MJ/kg)	Water (L/kg)
Raw material production	78.0 (C)	472.0 (C)
Fibre preparation		
Fabric production	5-30 (D)	nil
Dyeing and finishing	as cotton	as cotton

In relation to energy and water use, the only data added to those drawn from very limited data in Appendix C, were that energy inputs to fabric production, dyeing and finishing were assumed to be similar to those of viscose and cotton.

5.2.2.4 Soybean

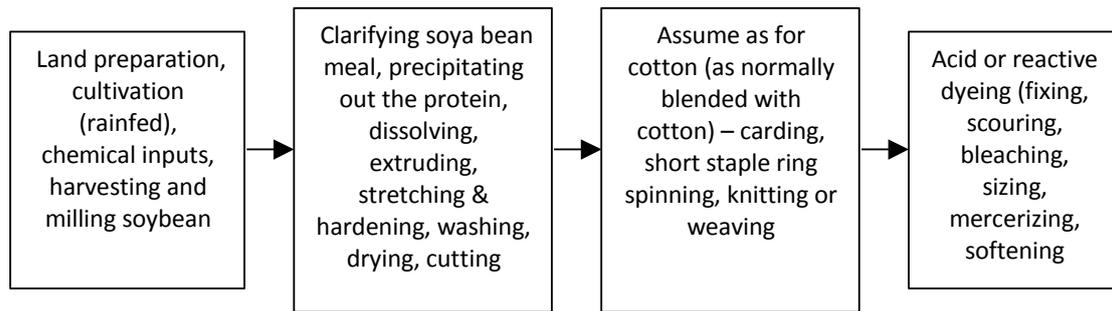


Figure 36. Typical steps and procedures in soy bean protein fibre production

Stage	Energy (MJ/kg)	Water (L/kg)
Raw material production	0.9	rain fed
Fibre preparation	as wool	as wool
Fabric production		
Dyeing and finishing		

In the absence of any published data, a figure of 0.9 MJ/kg was derived (from Huo et al. (2008)) as an indication of energy inputs to soybean production. For fabric production and finishing, it is assumed that energy and water use would be as for wool, with which most soybean fibre will be blended.

5.2.2.5 Viscose

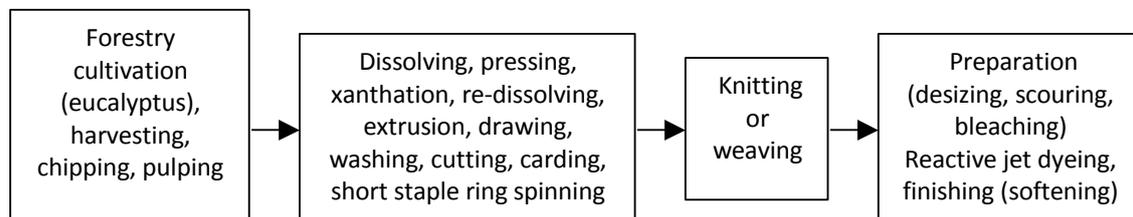


Figure 37. Typical steps and procedures in production chain for UK-sourced viscose fibre

Key environmental impacts of viscose production are associated with production of sulphur dioxide for use in pulping, use of large amounts of caustic soda, use of energy intensive pulping operations and from associated CS₂ emissions (a toxic solvent). However, up to 70% of CS₂ emissions are recycled and much of the rest is converted to sulphuric acid and recycled to the process (Shen and Patel 2008c). The pulping operation also uses large amounts of water, similar to that used in silk production.

In the viscose process, the acid sulfite process is used to dissolve resins, lignin and hemi-cellulose from wood feedstock to leave cellulose xanthate dissolved in caustic soda. This process produces xylose, furfural and acetic acid as by-products, along with a thick liquor and bio-sludge from waste-water treatment. The latter are retained and burned for energy production in advanced pulp and fibre integrated plants, reducing the overall fossil energy demand. In other cases, pulping may be performed in isolation from viscose production, but energy efficiency is reduced. The cellulose xanthate is then precipitated out using a bath containing sulphuric acid, sodium

sulphate and zinc sulphate, and spun into viscose fibres. After this stage impacts are similar to those of natural cellulosic materials.

Table 19. Impacts of viscose fibre production on energy and water use

Stage	Energy (MJ/kg)	Water (L/kg)
Raw material production	37-74* (C)	55.0 (C)
Fibre preparation	33.3	319-750 (C)
Fabric production	5-30 (D)	nil
Dyeing and finishing	as cotton	as cotton

*Calculated by difference from totals presented in literature (Appendix C) for raw material plus fibre preparation and specific figure for fibre preparation (Shen and Patel 2008a)

The above data were drawn from the limited sources available in Appendix C. (with energy figures for raw material production derived as described in the footnote above). In the absence of specific data for viscose, energy use in fabric production was estimated to be within the typical generic range proposed by Shen and Patel (2008a), and water and energy use in dyeing is assumed to be similar to that for cotton fabrics.

5.2.3 Synthetic fibres

5.2.3.1 Acrylic

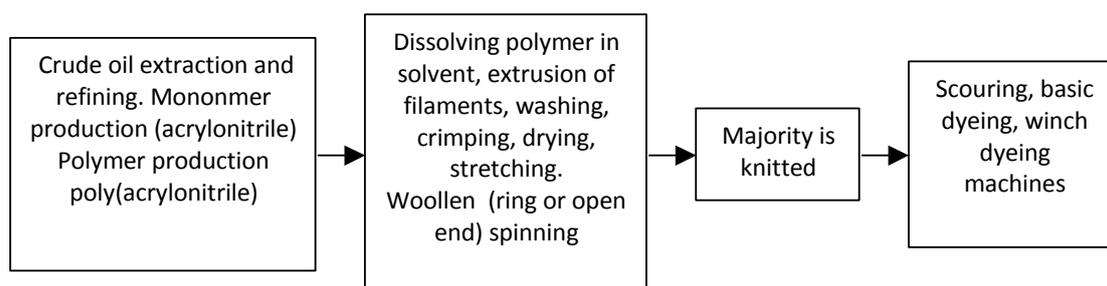


Figure 38. Typical steps and procedures in production chain for UK-sourced acrylic fibre

It is assumed that most acrylic fabric production is in association with wool/acrylic blends, as acrylic is generally too harsh to be used as a clothing fibre on its own. High energy use is associated with reliance on fossil fuel feedstock and for refining of synthetic polymers. To spin fibres, the polymer is dissolved in sodium thiocyanate and extruded, and spun using wet or dry spinning processes. As with any fibre, numerous finishing options are possible. In contrast to cellulosic and wool fibres, water use in production of base fibres is relatively low.

Table 20. Impacts of acrylic production on energy and water use

Stage	Energy (MJ/kg)	Water (L/kg)
Raw material production	112 (C)	210 (D)
Fibre preparation	46 (C)	
Fabric production	5-30 (D)	50-66.8 (C)
Dyeing and finishing	as polyester	62-278 (C)

Data on energy use in raw material production were taken from Shen and Patel (2008a) as this figure specifically includes energy in the polymer feedstock. Energy use in fibre production represents a common value used in the sourced literature. Generic figures for energy use in fabric production were taken from Shen and Patel (2008a), dyeing and finishing energy requirements were assumed to be similar to those of polyester.

The figure for water use in acrylic fibre production is an estimate made by Laursen et al. (2006) based on waste water treatment emissions, after difficulties were encountered in deriving definitive values from industry or other sources. It should therefore be treated with caution until further information is available in the public domain. Other water use values are drawn from a review by Laursen et al. (1997).

5.2.3.2 Nylon

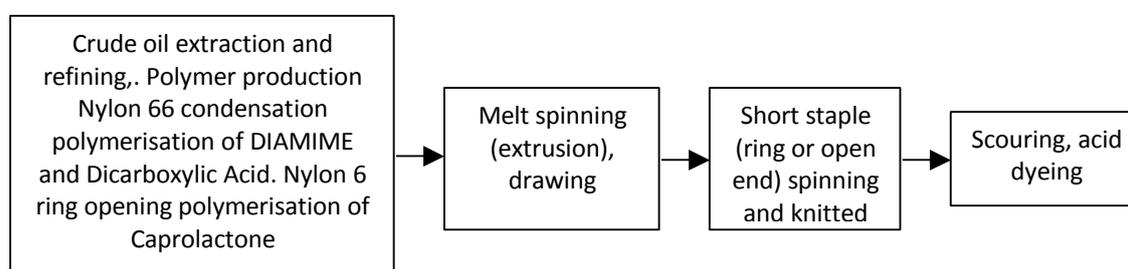


Figure 39. Typical steps and procedures in production chain for UK-sourced nylon fibres

High energy use is associated with reliance on fossil fuel feedstock and for refining of synthetic polymers. As with any fibre, numerous finishing options are possible. In contrast to cellulosic and wool fibres, water use in production of base fibres is low.

Table 21. Impacts of nylon fibre production on energy and water use

Stage	Energy (MJ/kg)	Water (L/kg)
Raw material production	116 -119 (C)	663 (C)
Fibre preparation	no data	110 (C)
Fabric production	as polyester	
Dyeing and finishing		

Energy inputs for raw material production (including feedstock energy) represent the data range in the limited reference sources available. In the absence of suitable data for nylon, energy inputs into fabric production, dyeing, and finishing were assumed to be similar to those for polyester. Data for water use draws on separate single sources of information for each of the stages indicated above.

5.2.3.3 Polyester

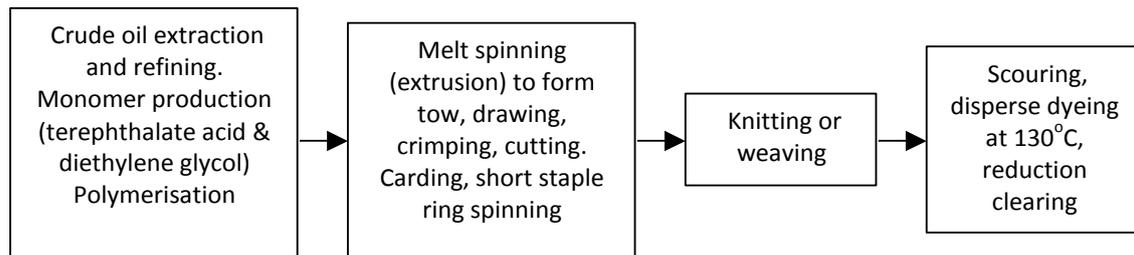


Figure 40. Typical steps and procedures in production chain for UK-sourced polyester fibre

Polyester has a high energy demand, both in terms of raw fossil-derived feedstock material and in production of the polymer fibre itself. However, there can be compensations for this in the use phase through reduced drying times in laundering (see section 5.5). As with any fibre, numerous finishing options are possible. In contrast to cellulosic and wool fibres, water use in production of base fibres is low

Table 22. Impacts of polyester fibre production on energy and water use

Stage	Energy (MJ/kg)	Water (L/kg)
Raw material production	77.3-112 (C)	17.2 (C)
Fibre preparation	13.6 (C)	
Fabric production	5-30 (C)	nil
Dyeing and finishing	40.0 (D)	65.0-148.0 (B)

Most of the figures for energy and water inputs to polyester were drawn from data in Appendix C. The data range for energy use in polymer production reflects the range of data available in the sources reviewed, and includes energy in the raw feedstock. Energy used in polyester fibre production is drawn from a single source that itemises energy use in this phase (Shen and Patel, 2008a). The very limited number of usable values presented in the literature for energy use in dyeing, were viewed as low. As a compromise, a standard figure for energy use in dyeing was used (EC, 2003). The same source was used for information on water use in dyeing and finishing (EC (2003) where data is presented on an actual case study of waste water outputs for eight mills dyeing and finishing polyester, the results of which are comparable to other data sources in Appendix C.

5.2.3.4 Polylactic acid (PLA)

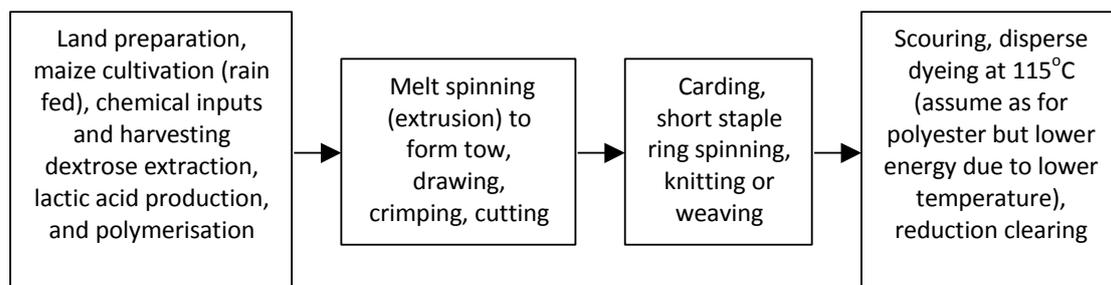


Figure 41. Typical steps and procedures in production chain for UK-sourced polylactic acid fibres

Currently most PLA is produced from wet-milled corn (other sugar and starch crops are feasible alternatives). Starch is extracted and converted to dextrose, which is then fermented to lactic acid. This is then further chemically processed via a lactide intermediate (avoiding use of solvents and need for solvent recycling), which is then purified by distillation and polymerised to form pellets.

Despite the energy demands of fermentation and for producing the polymerised PLA from lactide (73% of total energy requirement) PLA has a relatively moderate raw material energy requirement, similar to that of raw cotton production, and much lower than that of acrylic, nylon and polyester. Improvements in fermentation and PLA production are possible in the future as the relatively new methodology is refined, which could reduce energy demands. PLA can also be recycled with appropriate recovery and processing infrastructure, allowing the potential to sequester carbon into further products.

With the use of irrigation water for corn production, and in fermentation of lactic acid, water use in PLA production (c. 50 kg water/kg fibre (Vink et al., 2003)) is higher than that of PET, but it is considerably lower than that of nylon production chains.

Table 23 Impacts of polylactic acid fibre production on energy and water use

Stage	Energy (MJ/kg)	Water (L/kg)
Raw material production	54.2 (C)*	69.0 (C)
Fibre preparation	as polyester	as polyester
Fabric production		
Dyeing and finishing	34.6	

* excludes energy in corn feedstock, but assumes current production technologies

In relation to energy and water use in PLA fibre production, figures were drawn from the limited source available in Appendix C. In the absence of any specific data sources covering energy and water use in PLA fibre preparation, fabric production and dyeing and finishing, these were assumed to be similar to those of polyester. However, dyeing temp is around 15°C lower for PLA, so energy use was reduced accordingly (86.5% lower energy demand).

5.2.3.5 Polytrimethylene terephthalate (PTT)

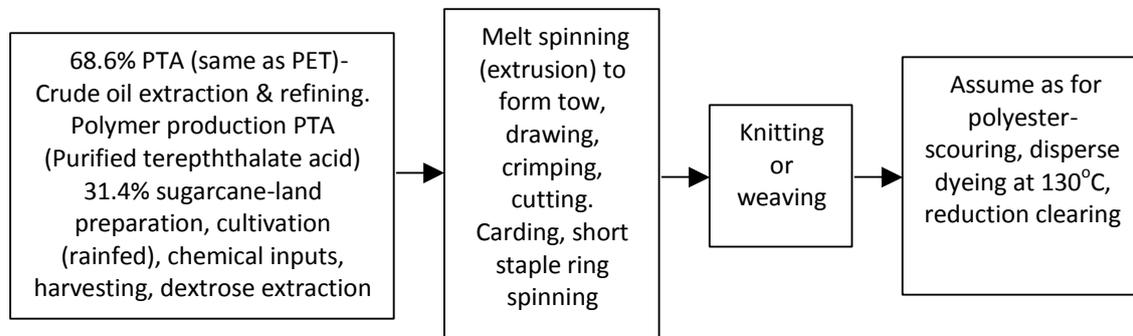


Figure 42. Typical steps and procedures in production chain for UK-sourced PTT fibre

PTT is synthesised from the condensation polymerisation of petrochemical-derived terephthalic acid and 1,3-propanediol, which in the case of the commercialised Sorona polymer is derived from fermented sugar. So the fibre is semi-synthetic in nature. As there is little data available on PTT, it is assumed that water use in raw polymer production would be higher than that of pure polyester due to the fermentation process for bio-propanediol production. Energy in raw material production draws on limited data sources from Du Pont and Shell, which in at least the high data value presented, includes the energy in the oil feedstock.

Table 24. Impacts of PTT fibre production on energy and water use

Stage	Energy (MJ/kg)	Water (L/kg)
Raw material production	83.8-94.6 (C)	> polyester
Fibre preparation	as polyester	
Fabric production		
Dyeing and finishing		as polyester

5.3 Energy and water use comparisons

Using the information from the individual fibre impact tables, presented throughout the previous section, to enable indicative relative comparisons of the impacts of individual fibres, summary tables were produced for water and energy use for each fibre, and for each stage of processing. A set of indicative bandings were derived for each stage of fibre production. These took account of the full range of data available across all fibres at each stage of production. The effects of each fibre were compared against this range to provide a relative ranking – high, medium or low impact. However, given the significant gaps in data for many fibres, this provides only a high level indication of impacts for comparison between fibres.

The ranges for each band category were established by first calculating the difference between the maximum and minimum value across all fibres for energy and water use. Individual minimum and maximum values (where a range was presented in tables) were included within the ranges in assessing the range end points. The only exception to this was where data ranges were highly skewed, as was the case for water use in cotton production. For water use, the maximum value was taken as the lower limit for water use in cotton.

The ranges of individual impact band boundaries were calculated as shown in Table 25. Band ranges were re-calculated for each of the four stages of processing, and repeated for a final cumulative score to rank across all stages of production. In assigning individual fibres to categories, where a range was presented in tables in section 5.2, the mid point or mean of the range was used to allocate the fibre to the appropriate band.

Table 25. Approach used to calculate band ranges for energy and water use for each fibre.

Band	Band lower limit	Band upper limit
Green		$(D/3) + (MI)$
Amber	$(D/3) + (MI)$	$2(D/3) + (MI)$
Red	$2(D/3) + (MI)$	

. D = difference between maximum and minimum (MI) value in range

The result of this was a set of high level indicative summary impact tables for both energy use (Table 27) and water use (Table 26). These provide a simplified indication of impacts only. However, given the gaps in data highlighted in the previous section, differences should be treated with caution and only considered indicative until more detailed and complete information is available. Fibres were omitted where there was deemed to be insufficient information to draw even indicative comparisons, and where impacts were primarily based on use of data for comparable fibres.

Within the tables, bands coloured red have the highest relative impact within the given production or processing stage, green bands the lowest relative impact with amber falling in the mid range.

5.3.1 Impacts on water use

Table 26. Indicative rankings of the impact of different fibres on water use in the production and processing chain.

	Raw Material Production	Fibre Production	Fabric Production	Preparation, Dyeing and Finishing	Cumulative
Acrylic	LOW	LOW	HIGH	LOW	MEDIUM
Cotton	HIGH	LOW	LOW	LOW	HIGH
Hemp	RAIN	LOW	LOW	LOW	MEDIUM
Line Flax	RAIN	LOW	LOW	LOW	LOW
Lyocell (Tencel)	LOW	LOW	LOW	LOW	MEDIUM
Modal	LOW	LOW	LOW	LOW	HIGH
Nylon	HIGH	LOW	LOW	LOW	HIGH
PLA (Ingeo)	LOW		LOW	LOW	
Polyester (PET)	LOW	LOW	LOW	LOW	LOW
Silk		HIGH	LOW		HIGH
Viscose	LOW	HIGH	LOW	LOW	HIGH
Wool	RAIN	LOW	MEDIUM		LOW

Cotton is the most water demanding fibre, far outstripping the water demands of all other fibres. Silk also uses very high volumes of water in the fibre spinning process (high enough to put it in the high impact category based on water use in this phase alone). The synthetic fibre nylon also uses relatively high volumes of water, in polymer production and spinning operations, leading to a high overall impact on water use. The pulping operations involved in regenerated cellulosic fibre production result in overall, relative high water use for viscose and modal textile production. By comparison, water use for lyocell is moderate by comparison, which reflects appropriately on the modified ‘closed’ viscose process used for Lyocell, which reduces steps in processing.

In contrast, Acrylic has moderate water demands overall and polyester and PLA have relatively low water demands for most stages of production, but gaps in available published data for PLA fibre and fabric production mean that it is not possible to confidently allocate PLA to an overall relative impact category for water use in the absence of such data.

Excluding cotton, natural plant-based fibres all have relatively low water demands, with the exception of hemp production (medium impact), where water is used in

retting processes to separate the fibres from the plant stems. Though a lot of water is used in wool production in cleaning and scouring operations, overall this has only a low impact on overall water use in wool textile production.

Soybean protein fibres are anticipated to be processed in a similar fashion to wool, though without the need for washing and scouring, but otherwise are anticipated to have similar water demands in final dyeing and finishing operations. However more information is required on water use in fibre preparation before any overall impact on water use can be assessed.

Where fibres have a relatively high impact on water use, most of this impact is associated with raw material and fibre production, rather than in fabric preparation and finishing operations.

5.3.2 Impacts on energy use

Table 27. Indicative rankings of the impact of different fibres on energy use in the production and processing chain

	Raw Material Production	Fibre Production	Fabric Production	Preparation, Dyeing and Finishing	Cumulative energy use
Acrylic	HIGH	HIGH	MEDIUM	MEDIUM	HIGH
Cotton	MEDIUM	MEDIUM	MEDIUM	MEDIUM	MEDIUM
Hemp	LOW		MEDIUM	MEDIUM	LOW
Line Flax	LOW	LOW	MEDIUM	MEDIUM	LOW
Lyocell (Tencel)	MEDIUM		MEDIUM	MEDIUM	MEDIUM
Modal	MEDIUM		MEDIUM	MEDIUM	MEDIUM
Nettle	LOW	LOW	MEDIUM	MEDIUM	LOW
Nylon	HIGH		MEDIUM	MEDIUM	HIGH
PLA (Ingeo)	MEDIUM	LOW	MEDIUM	MEDIUM	MEDIUM
Polyester (PET)	HIGH	LOW	MEDIUM	MEDIUM	MEDIUM
PTT (Sorona)	HIGH	LOW	MEDIUM	MEDIUM	MEDIUM
Viscose	MEDIUM	HIGH	MEDIUM	MEDIUM	MEDIUM
Wool	LOW	LOW	MEDIUM		LOW

Overall the lack of available data covering energy use for production and finishing operations for specific fibres (where a lot of generic data is used in tables in the previous section) means that the ranking of the effects of fibres on energy use reflects on differences in energy use in raw material and fibre production phases. However, energy use in fabric production, dyeing and finishing can be of a similar magnitude to that used in preceding operations.

Overall, the synthetic fibres acrylic and nylon are the most energy intensive, reflecting high inputs in terms of energy use and embodied energy in resources for polymer production. Pulping operations for regenerated cellulosic fibre production (viscose, lyocell and Modal) are energy intensive, but less so than for nylon and acrylic production, as a result, regenerated cellulosic fibres fall into the ‘moderate’ category for energy use in fibre production and processing.

Polyester, PLA and PTT have moderate energy use demands in comparison to acrylic and nylon. Cotton also has a moderate energy demand, due to higher crop inputs than the other natural fibres studied.

Natural fibres and wool have relatively low energy use demands, with flax and hemp having the lowest overall demand on energy use. In the absence of sufficient available data, it is assumed that natural fibres such as Spanish broom, jute and Ramie would have an impact on energy use that would be similar to other non-cotton natural plant fibres, and the impacts of soy bean, and silk (protein-based fibres) on energy use are most likely to be similar to those of wool, where for example dye bath temperatures are lower.

5.3.3 Fossil fuel depletion

Energy use typically reflects fossil fuel use and so can be seen as a proxy measure of depletion of fossil fuel reserves. Different end of life options for textile fabrics, including opportunities for use in energy production, can help to offset impacts on processing energy demands in the fibre production phase.

However, Shen and Patel (2008a; 2008b) compared the LCAs of regenerated cellulosic with other textile fibres. When taking account of both 'cradle to farm gate' and end of life energy recovery on incineration, they found that this made little difference to fibre energy use rankings in terms of depletion of fossil fuels (energy recovery ranged from 16.3 to 22.0 MJ/kg for the fibres in Table 27).

5.3.4 Greenhouse gas emissions

Taking account of the balance of impacts on net greenhouse gas (GHG) emissions (i.e. balance of CO₂ equivalent emissions from use of fossil energy expended in fibre production and processing (energy in feedstock or in growing feedstock and expended in processing operations), along with estimates of carbon sequestered in the final textile product). Shen and Patel (2008b) found that regenerated cellulosic materials (viscose, modal and lyocell) resulted in the lowest net greenhouse gas emissions per tonne of fibre, compared to synthetic fibres such as polyester, the highest, and cotton and PLA had intermediate effects. This arises from the relatively low use of fertiliser and pesticide inputs in forest production and the high fraction of biomass feedstock/unit area that ends up in the final textile product. Elliott and Cisneros (2005) reported similar net GHG emissions for PET and PTT, and that these were significantly lower than those for nylon production (by 35-45% versus nylon 6 with the highest GHG emissions).

Taking land use impacts also into consideration (i.e. fibre productivity/ha) for fibres derived from natural resources adds a further dimension in terms of impacts on net GHG emissions per unit area of fibre crop (see Figure 43).

Table 28. Net non-renewable energy requirement associated with fibre production and processing after accounting for energy recovery at end of life through incineration.¹

Fibre	Net fossil fuel requirement (MJ/kg fabric)	
	Low* processing energy demand	High* processing energy demand
Shen and Patel (2008a)		
Wool	27.5	103.5
Viscose	59.0	135.0
Cotton	72.7	148.7
Polyester	128.0	204.0
Shen and Patel (2008b)		
Viscose	10 - 53 ²	
Modal	16	
Cotton	26	
Tencel	34	
PLA	55	
Polyester (PET)	79	

* 'low' and 'high' cases account for high and low energy requirements respectively for fabric production and finishing used in Shen and Patel 2008a.

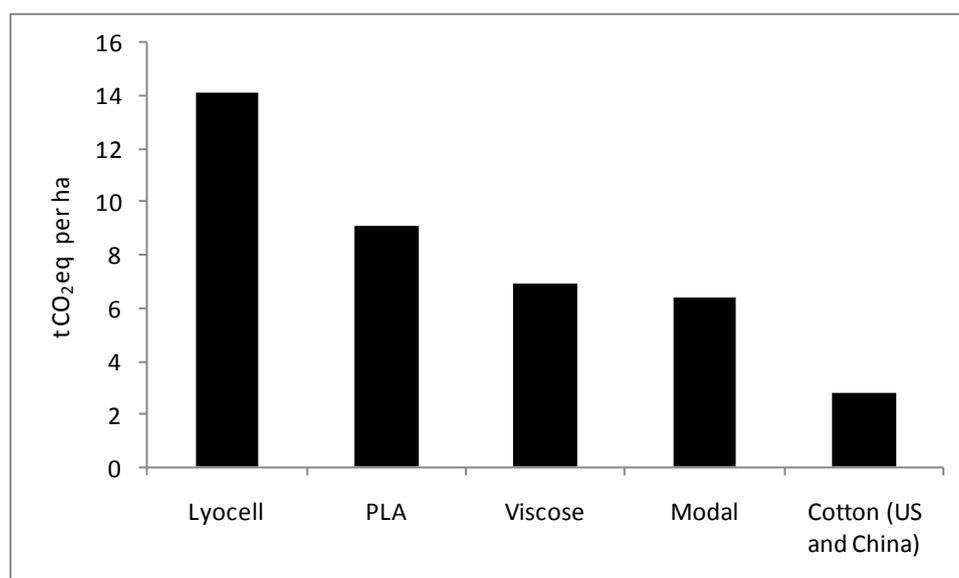


Figure 43. CO₂ equivalent savings (expressed per hectare of fibre production) for natural and cellulosic fibre production chains relative to polyester production chain. (Shen and Patel 2008c)

¹ Note data between the two referenced sources cannot be compared directly due to lack of full transparency in published data, methods and assumptions used.

² Lower value is for Austrian data, higher value for Asian data (Shen and Patel, 2008b)

5.4 Other environmental impacts

5.4.1 Waste-water

Textile processing uses a number of wet processing techniques, generating waste-water that requires treatment before discharge. Such waste-water contains dyes, dyeing auxiliaries, salts, alkali and acids, heavy metals, oils and halogenated organic compounds. Many of the additives in waste-water may be non-biodegradable and have to be filtered or sedimented out of water and disposed of as waste materials.

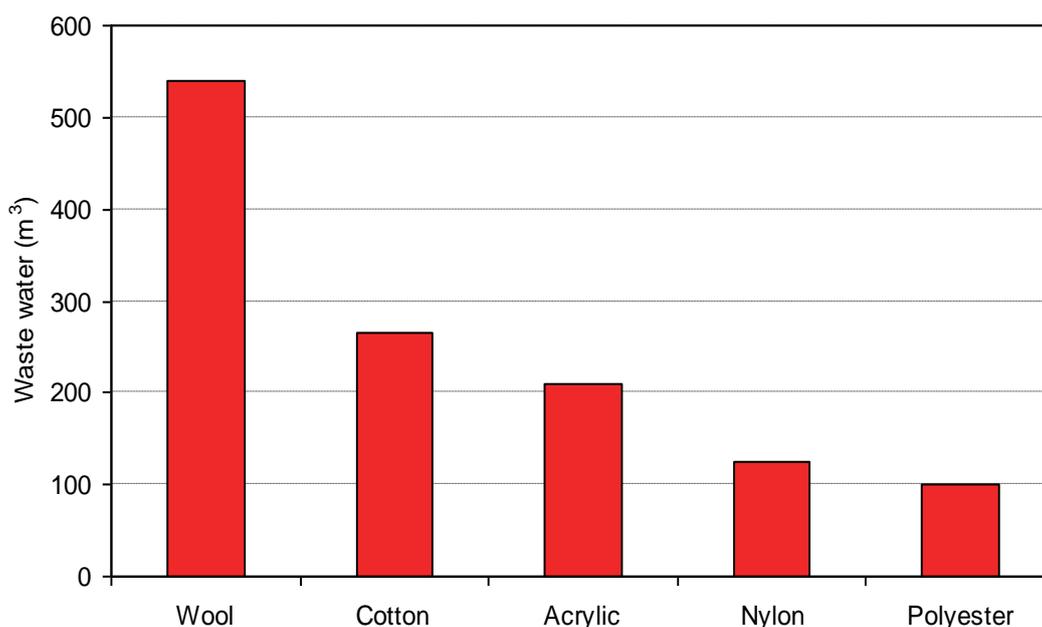


Figure 44. Waste water production per tonne fibre during fibre processing (World Bank Group 1998).

Pesticides may also arise in waste-water from processing of natural fibres, which often use relatively large volumes of treatment and wash waters. The World Bank Group (1998) recommended that wastewater loads should be less than 100 m³/tonnes textile produced, though up to 150 m³/tonnes is acceptable. Clearly, many textile production systems exceed this target, particularly with respect to natural fibre processing (Figure 44), in part this is due to increased need for washing (oil and grease removal) and bleaching to facilitate even dyeing and achievement of desired colour grades.

Wastewater from dye baths or rinsing baths are loaded with non exhausted dyes. A dye-formulation only contains approximately 30-60% pure dyestuff, the major part of the formulation consists – depending on dyestuff class and application field – of other chemicals and treatments to aid the dyeing process.

Sludges derived from settlement and wastewater treatment are disposed of in landfill, though those containing organic toxic materials and metals, at least in the UK, are incinerated in waste-regulation compliant facilities. The World Bank Group requires compliance with target effluent limits, volatile organic carbon emissions and

prescribes use of certain materials in return for assistance with textile-based ventures (World Bank Group, 1998).

5.4.2 Waste generation

In targeting measures to reduce potential pollution impacts, reducing wastewater output and the waste that requires flushing operations is a key area of focus. The World Bank Group (1998) identified a number of possible improvements to consider including:

- Better matching of processes to type and weight of fabrics produced
- Using biodegradable surfactants, reducing use of alkylphenol ethoxylates and organic solvents
- Use transfer printing for synthetic fabrics (reduces water use from 250 l/kg to 2 l/kg material), and use water-based printing pastes where feasible
- For non-knitted materials use pad-batch dyeing (reduces energy use by 80% and water consumption by 90%, and reduces dye and salt use)
- Use jet-dyers rather than winch dyers, ideally with a liquid to fabric ration of 4:1, rather than 8:1
- Avoid the use of benzidine-based azo dyes, those containing cadmium and other heavy metals and chlorine based dyes
- Use less toxic dye carriers and finishing agents
- Replace dichromate oxidation of vat dyes with peroxide oxidation
- Reuse dye solutions
- Use peroxide-based bleaches rather than sulphur and chlorine based bleaches
- Recover and re-use caustic and sizing treatments
- Preferentially use permethrin for mothproofing (wide range of organic pesticides and heavy metals used in other treatments)

In addition a number of other working practices were identified that could be improved to reduce wasteful use of finishing chemicals. Generic de-sizing methods maybe used by contract finishers who do not know which sizing method was used by spinning/weaving mill supplying yarn or textiles (Schönberger and Schäfer 2003). Most cotton dye houses will desize, scour and bleach all incoming raw fabric, even if dark/dull shades are required (Bide 2007).

5.4.3 Chemical and energy use in finishing treatments

While there may be differences in the class of dyes used on different fibres (Table 7), there is not much difference in the total amounts of dyestuffs and auxiliary chemicals used on different fibre types, though slightly lower volumes of dye tend to be used on wool. Polyester tends to use lower levels of other basic chemicals in the finishing process, while cotton typically uses considerable quantities in finishing processes. The environmental impacts of these effects depend on the levels of escape and the

ecotoxicology of the chemical species involved. More information is required in this area to enable meaningful comparisons to be drawn. Energy use in finishing systems is very similar between natural, wool and polyester finishing systems.

Table 29. Chemical and energy use in textile finishing operations reported for textile mills finishing yarn in specific textile sectors (EC, 2003)

	Cotton	Polyester	Wool, wool/viscose. Wool/acrylic blends
Basic chemicals (g/kg)	c. 400	95-125	85-325
Dyestuffs (g/kg)	c. 25	18-36	13-18
Energy use (kWh/kg)	11	11-18	4-17
Textile auxiliaries (g/kg)	c. 70	80-130	36-90

An important environmental implication of blending during the manufacturing phase is the impact on dyeing. Different fibres often have quite different dyeing requirements. Therefore, in some cases a blended textile will require two dyeing processes, thus increasing the demands on time, labour, energy, and water. Despite these disadvantages, dyeing tends to take place at the end of the finishing process when the fibres have been fully integrated into a single fabric.

5.4.4 Land use

There is increasing pressure on demand for land and concerns that development of renewables from plant-derived biomass could affect food production, pushing up food costs and/or bring more land into agricultural production, resulting in a loss of biodiversity and other environmental impacts. Removal of biomass combined with the drainage, aeration, and disturbance of soils can lead to reduction in soil quality and increased soil respiration, resulting in a net increase in carbon dioxide emissions (Schlesinger 1997). Both impacts are particularly severe during deforestation due to the large above- and below-ground biomass stocks (Bradley et al. 2005).

In the absence of swapping/substitution of fibre crop areas, unless yields can be significantly increased, then raising the demand for natural fibres will increase the land requirement. Regenerated cellulosic fibres utilise beech and eucalyptus woodland and plantations, and PLA and PTT rely on supplies of maize and sugar crops to supply raw feedstocks. In all cases increasing demand for these fibres will increase pressure on the demand for land.

Until recently, LCAs for biomass-based commodities have not taken sufficient account of the environmental impacts of land use change. Estimating the scale of such impacts is already very difficult, particularly when dealing with globally-traded commodities, but this is further complicated by lack of reliable published data on land use and natural fibre production. Differences in agricultural practices and climatic conditions and lack of associated data for yields and processing losses make assessment of land use demands difficult. For example, cotton yields average 713 kg/ha globally, but range from 133 kg/ha in Uganda to 2154 kg/ha in Brazil (USDA 2009). However, a range of land use figures were obtained or calculated, primarily for European climatic conditions (Figure 45).

Cotton is a land-demanding crop, compared to both alternative natural fibres and regenerated cellulosic fibres. PLA has a relatively low land requirement. Clearly, with the exception of Ramie and wool, replacing cotton with any of the fibres in Figure 45 would reduce the land area required for fibre production. The high biomass productivity associated with forest production and the high utilisation of biomass in the pulping process results in regenerated cellulosic fibres having a relatively low land requirement, particularly for the Tencel process. However, increasing eucalyptus plantations is not without problems as such plantations commonly have little other biodiversity value, and the leaf litter can be a potential fire hazard in dry climates.

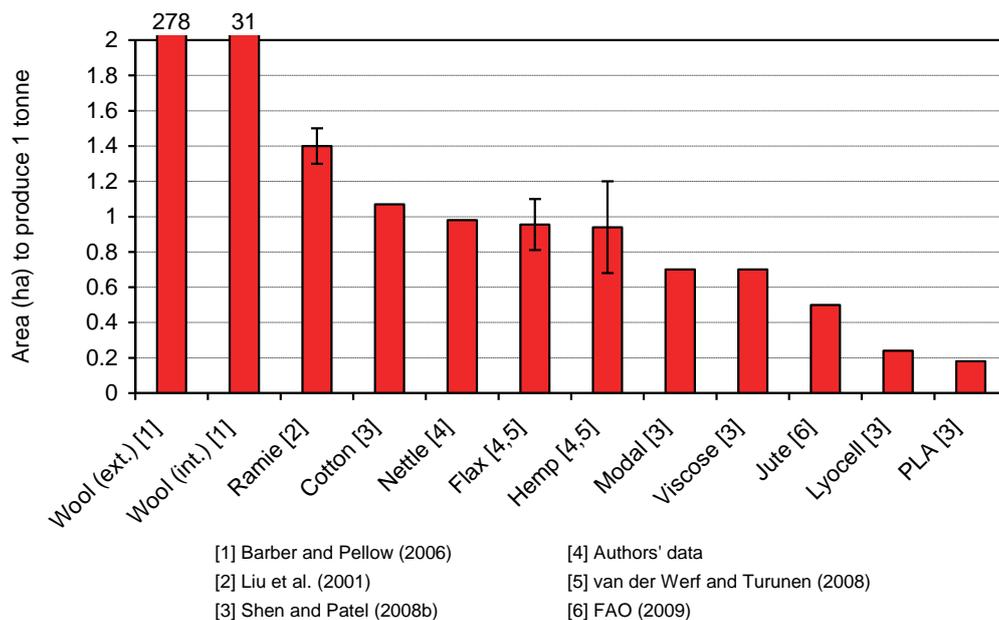


Figure 45. Land requirement for 1 tonne fibre production.

Wool has a very high land demand, but wool is also a by-product of meat production and utilises land that is unsuited to crop production, particularly in extensively grazed systems. Studies reviewed by Barber and Pellow (2006) suggest that up to 60% of the energy inputs to wool production could be allocated to meat production, this could be equally applied to the land demand, reducing the proportion allocated to wool production. However, the land demand for wool would still be significantly higher than that for plant-derived fibre sources.

Taking into account their high fibre productivity per hectare, and low to moderate energy demands, and assuming replacement of polyester on a like for like basis, then Lyocell and PLA are capable of delivering the highest savings in CO₂ emissions/ha, followed by other regenerated cellulosic fibres and cotton (Figure 43).

The global area of cotton has remained relatively static in recent years (see section 4.1.1) and increased production has been achieved through improved pest management, irrigation, fertiliser use, and pesticide applications. All of the natural, regenerated cellulose and PLA fibres should provide a reduction in global warming impacts when substituting for polyester (Shen and Patel 2008b), though impacts arising during the product use phase also need to be taken into consideration (see 5.5)

Care needs to be exercised in sourcing regenerated cellulosic materials to ensure safeguards are in place to avoid direct destruction of high biodiversity value forest, such as old growth forests for wood pulp. Lenzing, responsible for up to a fifth of the world's viscose production, state that the majority of their eucalyptus pulp for lyocell comes from Forest Stewardship Council (FSC) certified plantations, but this is unlikely to be the case for the majority of viscose pulp.

Although produced in very small volumes at present, increased demand for PLA, PTT (sugar crops – cane and beet) and soy protein fibre all have the potential to conflict with food production, unless this growth substitutes for reductions in other plant-derived fibres. There is little evidence that natural fibres other than cotton will replace significant volumes of synthetic fibre production in the textile sector, with short and medium term growth in demand for short staple fibres likely to be met by polyester (a significantly cheaper fibre). Natural fibres are likely to remain restricted to niche fashion sectors based on their higher cost, and as such additional land requirements are likely to remain low. However, for bast fibres such as hemp, flax and nettle, there appears, at least anecdotally, to be ample suitable land available, particularly in Eastern Europe and former Soviet Union should demand increase.

Natural fibres may have other benefits that are not well recognised in LCA approaches. For example, annual fibre crops such as flax or hemp, are valuable break crops in arable rotations and, with the exception of cotton, help to reduce the overall burden of agricultural production on the environment, as they have lower fertiliser and agrochemical requirements than most arable crops. Perennial crop, such as bamboo or coppices, lack this advantage.

5.4.5 Toxicity, eutrophication, and acidification

LCA data indicate that cotton performs worse than cellulosic and synthetic fibres in relation to risks of human toxicity, water toxicity, terrestrial toxicity and eutrophication of water, mainly due to the use of pesticides in production compared to the other cellulosic and synthetic fibres (Shen and Patel 2008b). In the same study, polyester is shown to have a high impact on depletion of abiotic resources due to its high use of non-renewable energy. One problem with such studies is lack of information on the emissions arising from textile processing to compare and contrast with impacts associated with pesticide use.

In LCA studies of synthetic and semi synthetic fibres, Elliott and Cisneros (2005) found little difference in air acidification potential between PTT, PET and nylon polymers (where effects were primarily due to sulphur oxide emissions, followed by NO_x emissions), though PTT was the least damaging of the polymers. In the same study, PET and PTT demonstrated a much lower water eutrophication potential than nylon production (around 2 g PO₃ eq per kg polymer compared to around 7-8 g PO₄ eq per kg for nylon). This was primarily due to lower outputs of nitrates, N₂O, and NO₂. Impacts on freshwater ecotoxicity potential identified PET as the most benign synthetic polymer and Nylon 66 as the worst performing, with Nylon 6 and PTT having intermediate effects.

A limited number of ecological footprint studies have been completed for textile fibres, and these warrant further development as sustainability indicators (e.g. Cherrett et al. 2005; Grant and Wackernagel 2006; Stott 2008).

5.5 Use and end of life

This review has assessed the environmental impacts of textile fibres during the fibre production and textile manufacturing stages. However, the overall environmental consequences of a fibre will be influenced by its impact during use, laundering, and end of life disposal or recycling. The approach taken throughout this report has been to evaluate the impact of each fibre individually. Although this is entirely appropriate for manufacturing processes, it is not practical for finished garments. Items of clothing may be made up of different fibres through the use of textile blends and through the use of multiple fabrics. This section comprises a qualitative analysis of the impacts associated with the use and end of life supply chain stages based on examples and case studies.

5.5.1 Use phase

A thorough analysis of the environmental impact of textile laundering in the UK has been conducted as part of the parallel Defra project “Reducing the Environmental Impact of Clothes Cleaning” (EV0419). Previous research has shown that laundering accounts for around 75–80% of the total life cycle energy use of an item of clothing (Franklin Associates 1993; Madsen et al. 2007). This is mainly due to the high energy requirement for heating water in washing machines and air in tumble driers. Consequently, the parallel Defra project made the following recommendations for ways of reducing the environmental impact of laundering (Bain et al. 2009).

1. Reduce ironing through the use of anti-crease fabrics.
2. Encourage line drying of clothes.
3. Increase the average spin speed of washing machines.
4. Increase washing machine energy efficiency.
5. Encourage lower temperature washes (the current realistic minimum temperature is 30°C).
6. Develop more compact detergents that are effective at lower doses and lower temperatures.

With the exception of anti-crease fabrics, these issues are primarily concerned with consumer behaviour, washing machine technology, and the chemical properties of detergents. However, fibre composition and garment manufacturing technology can also influence the environmental impact of laundering. Here, the example of cotton–polyester blends are used to show the importance of textile composition to the use phase impacts of a clothing product.

5.5.1.1 *Textile blends*

Many fibres are blended together to improve their overall technical characteristics, reduce shrinkage, improve laundering properties, or reduce the overall costs when using expensive fibres. Blending is normally carried out prior to the spinning phase, although an alternative method is to weave different fibre yarns to give a “union” fabric. These are typically made up of a cotton warp and a woollen weft or a linen warp and a cotton weft (Denton and Daniels 2002). Most natural fibres are found in blends with cotton, with the exception of regenerated soybean fibre, which is usually blended with cashmere. Around 50% of acrylic is found in blends with wool (EC 2003). However, by far the most common blend combination is the cotton–polyester blend, which accounts for between 55 and 60% of all polyester fibres.

Cotton–polyester blends are used for all types of clothing and bed linen. The preferred mixing ratios are 33:67 (for garments worn close to the skin), 50:50, and 80:20 cotton:polyester (EC 2003). Disperse dyes are used for the polyester component while reactive, vat, and direct dyes are used for the cotton part. Disperse dyes can cause slight staining of cellulose fibres and these stains are removed by washing (EC 2003).

5.5.1.2 *Laundering of blends*

Despite the increased demands on energy, water, and labour, blending fibres can actually reduce the overall environmental impact of the final garment or textile product by improving longevity and laundering properties. Kalliala and Nousiainen (1999) conducted a detailed analysis of the environmental profile of cotton and 50:50 cotton–polyester blended materials of similar weights used as sheets in the hotel sector. The analysis examined both fibre production and lifetime energy and water use.

Production of cotton fibres in the Kalliala and Nousiainen study used 40% less energy than production of polyester fibres (compared to a range between 36% and 49% less in this study). In contrast, 22,200 kg water were required to produce 1 kg cotton fibre, compared to just 12.2 kg water for polyester (this is a much greater difference than that found in this study where overall water use in cotton was much lower). Material losses during spinning were also high for cotton (20% compared to 2–3%). However, the environmental profiles of the two products were dominated by their performance during the laundering phase. Pure cotton sheets required 20% more energy during laundering due to their longer drying requirements. Furthermore, the abrasion resistance of cotton–polyester sheets was twice that of pure cotton sheets and so the useful lifetime of blended sheets was estimated to be twice that of pure cotton sheets. The environmental impacts of the two products over a 100 wash lifetime are shown in Table 30.

Over a lifetime of 100 washes, use of pure cotton sheets would result in 73% higher energy use and a threefold increase in water use. Use of pure cotton also increases the risk of pollution of watercourses during the fibre production phase and increases

Table 30. Whole life cycle environmental impacts of pure cotton and cotton–polyester blend sheets over a 100 wash lifetime (Kalliala and Nousiainen 1999).

Impact	Cotton–polyester blend	Pure cotton
Acidification (kg SO ₂ eq kg ⁻¹)	22.3	54.9
Energy (MJ kg ⁻¹)	116	199
Eutrophication (g O ₂ eq kg ⁻¹)	5.7	10.2
GHG emissions (kg CO ₂ eq kg ⁻¹)	5.6	14.6
Air pollution (g kg ⁻¹)*	8,499	19,599
Water (kg kg ⁻¹)	12,400	52,200

*Air pollution refers to total emissions of phosphate, phenols, oil, and oxygen-depleting materials

emissions to air. Therefore, although the technical properties of polyester prevent it from completely replacing cotton, the use of cotton–polyester blends can significantly reduce the environmental impact of textiles during both the production and use phases.

5.5.1.3 Wash frequency

The above example has shown how fibre choice and blending can influence overall environmental impact by increasing the longevity and durability of textiles. A further means of reducing the impact of washing is to reduce the frequency of laundering. Blackburn and Payne (2004) suggest that the application of antimicrobial coatings to textiles could reduce odour and so decrease the need for frequent washing of apparel. However, the production and application of any such material must not use more energy than would be saved through reduced laundering frequency.

5.5.2 End of life

Approximately 2 million tonnes of unwanted textile waste is generated in the UK per annum with only an estimated 24% being recovered and the remainder going to landfill (Morley et al. 2009). This has significant waste and resource depletion impacts and hence the importance of understanding how fibre type can influence the reduction of these. The parallel Defra project “Maximising Reuse and Recycling of UK Clothing and Textiles” (EV0421) has provided an analysis and discussion of the key environmental impacts of various options for clothing disposal. The project found that, in terms of energy use and carbon dioxide emissions, the impact of reuse is lower than that of recycling, which is lower than that of incineration for energy recovery or disposal in landfill (Morley et al. 2009). Therefore, reuse is the lowest impact option for unwanted clothing, followed by recycling.

Recycling of clothing requires effective identification of material composition and separation of different textile fibres for processing. As typical garments may be made up of numerous different fabrics held together by yet more types of thread, identification and separation represent significant barriers to recycling. Morley et al. (2009) gives some examples of commercial efforts to simplify these processes. The Eco Circle system, developed by the Japanese company Teijin Fibers Ltd, aims to provide a closed loop recycling scheme for polyester fibres. Garments produced under the scheme carry the Eco Circle Product Mark and the name of the participating

distributor company. The product can then be returned to the company from which it was purchased, which sends the items back to Teijin for chemical recycling. Although zips and buttons are separated during chemical recycling, the fabric itself must be made up of at least 80% polyester for the process to be effective.

The Eco Circle system has been shown to reduce energy consumption and carbon dioxide emissions by 84 and 77% respectively (Morley et al. 2009). Data collated by the US clothing company Patagonia shows that even when apparel is distributed and collected in the USA for recycling in Japan, the Eco Circle system provides significant reductions in GHG emissions compared to polyester produced from virgin materials (Patagonia 2009). Furthermore, energy use during fibre production and preparation of Eco Circle polyester is substantially lower than during the production of any of the fibres examined in this report with the exception of flax (Figure 46). This is the result of a reduced need for polyester fibre precursor resource acquisition and consumption.

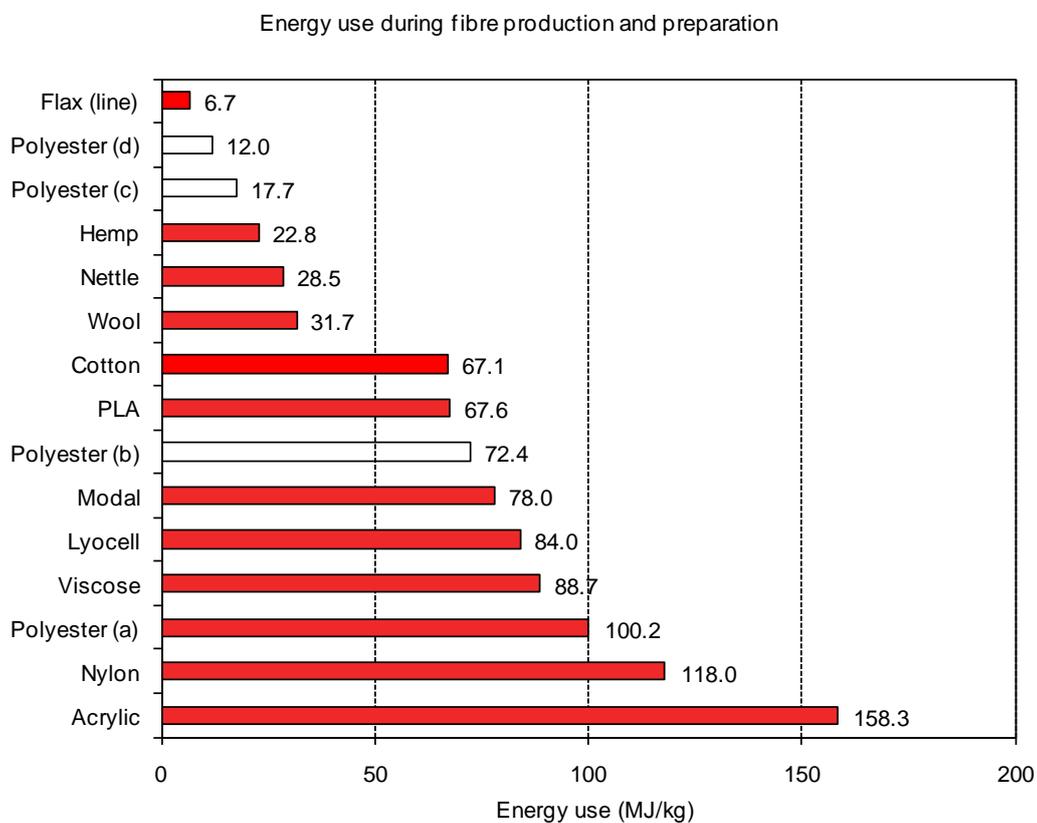


Figure 46. Typical energy use during fibre production and preparation

The values shown for polyester are (a) mean values derived for ranges of polyester energy use data in this report, (b) virgin polyester produced from mineral oil by Teijin (Teijin, 2009), (c) Eco Circle recycled polyester collected in the USA and recycled in Japan, and (d) Eco Circle recycled polyester collected and recycled in Japan (Patagonia 2009). Red bars represent mean energy use data derived from data ranges used in this report; open bars represent Teijin polyester data.

In a similar initiative, the German outdoor clothing company Vaude has launched the Ecolog brand (Morley et al. 2009). These products are made from 100% polyester, including all zips, labels, cords, fasteners, and fabrics. Consequently, entire Ecolog

garments can be shredded and melted to produce new polyester fibres and the expensive, time-consuming, and energy-intensive process of material separation is completely avoided. These examples highlight the importance of designing for the end of a product's useful life. By taking responsibility for garment end of life, the fibre manufacturer is provided with a clear incentive to reduce the complexity and cost of recycling.

The success of such recycling systems will depend on the ability to control and maintain a separated waste recycling chain for such fibres, and to ensure that there is little mixing with other fibres in garments. These issues are difficult to address in practice and are likely to limit the potential of such innovative developments.

While not directly related to clothing disposal, polyester recycling can also be used to produce clothing fibres from plastic bottles and other solid polyester waste (Al-Salem et al. 2009). Teijin estimate that their ECO PET recycled polyester textile fibre, produced from recycled bottles, reduces carbon dioxide emissions by 47% and energy consumption by 33% compared to conventional fossil-derived polyester where products are incinerated at end of life (Teijin 2009).

The examples given above show the dominance of polyester in current textile fibre recycling systems. PLA also has the potential for recycling and re-use. The relatively straightforward process of granulating and melting pure or near-pure polyester products makes this and other similar synthetic polymers particularly suited to chemical recycling. However, this is reliant on development of dedicated supply chains to produce and protect the integrity of more sustainable branded forms of polyester and other fibres suited to recycling.

There are some examples of cotton fibre recycling, although irreparable damage to cellulosic fibres makes this process more difficult than polyester. In the USA cotton from denim is collected by the Allan Company and used to produce cotton fibre insulation material (Bonded Logic 2009; Cotton Inc. 2009; JBM Fibers 2009). Another approach to cotton recycling is to make use of discarded off-cuts produced during the clothing manufacturing process (Ecotec 2007; Howies 2009; Lion Brand Yarn 2009). However, as this fibre has not previously been used in any product, production of these yarns and textiles should be seen as a means of reducing waste rather than of recycling textiles.

5.5.3 Summary

Use and disposal must be taken into account when evaluating the overall sustainability of a textile fibre. Garment longevity, durability, and washing and drying requirements are key determinants of the environmental impact of clothes cleaning. Increased use of blends can help minimise energy use during the important laundering phase of use. However, efficient recycling to deliver improved sustainability depends on uniformity of fibre composition and minimal use of coatings and other applications. The dominant role of laundering in determining whole life cycle energy demand combined with greater scope for reuse may make more durable and easily cleaned blends a more sustainable option than single-fibre fabrics.

5.6 Organic and GM cotton

Globally the paramount agricultural textile fibre is cotton. The geographical spread of cotton production across the globe and its presence as a crop in both developed and developing countries means that now a very wide range of cotton production husbandry methods, from low input/labour intensive production through to high input/high fibre yield systems, can be found. In general, this husbandry (crop rotation, planting, crop nutrition and protection, harvesting and storage, etc) is not much considered beyond the necessity or target of application, as the worth of any cotton fibre is ultimately determined by the technical properties of the fibre rather than how it is produced. However, two specific areas of interest in cotton crop husbandry have developed in recent years in the cotton supply chain:

- Organic cotton production: the production of cotton crops without inorganic fertilisers or chemical pesticides or use of genetically modified (GM) organisms. Approved third-party certification organizations verify that organic producers use only methods and materials allowed in organic production.
- Genetically modified cotton: the production of cotton fibre from cotton varieties that have been developed using transgenic methods, rather than conventional plant breeding.

Use of certified organic and GM approaches are currently mutually exclusive, as certified organic production does not allow the use of GM crop plants.

No assessments of the overall environmental impacts of GM and certified organic textile production were found in the literature, but some broad general conclusions can be drawn about the overall contribution of such developments to sustainable textile production.

A Global Organic Textile Standard (GOTS) has been developed. The aim of the standard is to define requirements to ensure the organic status of textiles, from harvesting of the raw materials, through environmentally and socially responsible manufacturing up to labelling, in order to provide a credible assurance to the end consumer. The GOTS standard for organic textiles covers the production, processing, manufacturing, packaging, labelling, exportation, importation and distribution of all natural fibres and treatment of wastes, including waste waters and requirements on maximum permissible residues in finished materials. This works to encourage change in the fibre processing chain as well as in the field, through prohibition of use of GM technologies, certain chemicals, (including those posing high human and environmental risk) and some processes.

Both certified organic production and GM technologies have the potential to reduce inputs into fibre crop production thereby reducing energy inputs, air emissions and water pollution from pesticides. Reducing pesticide usage has potential additional benefits for developing nations, where pesticides are less well regulated and frequently applied using hand-held equipment. However, there are arguments about

the knock-on impacts that GM technologies have on pesticides use (use of other inputs may rise as yields rise).

Certified organic farming practices may help to reduce eutrophication of water by dramatically reducing the range of chemical materials and synthetic fertilisers that can be applied to crops. There are implications for yield potential in certified organic production systems, particularly where alternative permissible organic sources of nutrients are limited. Therefore there may be impacts on the crop area resource required per unit of fibre produced when using organic practices. However, in low-yielding areas of production, where crop inputs are already lower than average, the impacts will be much reduced. The balance of such impacts needs careful examination.

5.6.1 GM production

GM cotton fibre is derived from cotton plants that have been genetically engineered. The most common traits incorporated into cotton include pest-resistance to cotton boll weevil (which otherwise requires significant insecticide input) and herbicide-tolerance, to improve weed control by engendering cotton insensitive to herbicides with a broad spectrum of activity. In the major cotton producing countries, such as USA, China, India, and Pakistan, most of the cotton produced is GM, but in other countries (e.g. Brazil and in the EU) cultivation of GM cotton is not permitted, although in the case of Brazil it is being considered (Meyer 2009).

In total GM cotton currently accounts for almost 50% of the global cotton area, although there is considerable regional variation (Table 31) (USDA, 2009; James, 2008). Although GM cotton seed is more expensive than conventional seed, which is anticipated to restrict access to such technology in developing countries, the technology has seen an extremely fast uptake where available. For example, in India GM cotton varieties were sown on 6.5 million hectares in 2007, a 63% increase between 2006 and 2007 alone. In 2002 just 0.5% of the Indian cotton area was sown to GM varieties. Uptake of GM cotton in India has been extremely fast, even in comparison to China where the % area of cotton sown to GM varieties rose from 0.7% in 1997 to 68% in 2007/08.

The uptake of GM cotton varieties is expected to be similarly fast in Brazil now the crop can be grown in the country. The appeal is significant yield increases, ranging from 10% in China, 80% in India and up to 250% in South Africa. The overall environmental impacts of GM technologies depend on the modified trait involved. The most common form of GM cotton is *BT cotton*, which is resistant to attacks from Boll weevils. The use of this technology has had the effect of reducing pesticide use on cotton crops, with corresponding cost savings.

Fivefold decreases in pesticide applications are reported for use of cotton containing the naturally occurring *Bacillus thuringiensis* toxin (Baffes, 2005). Indeed in certain instances cotton can now be grown on land where previously the crop had to be abandoned due to excessive pest problems.

Where herbicide tolerant cultivars are utilised, herbicide applications may also be reduced, or more environmentally benign (lower ecotoxicological risk) herbicides

may be used, but the resulting fields may also be left as monocultures, reducing their value to other species. Where GM technology has been most vigorously increased, the attraction has been higher fibre yields increasing farm incomes in countries with large numbers of very small farmers (<2 ha cotton per farm), such as India (Bennet *et al* 2006).

At current growth rates, almost all cotton production in the major producing nations could be GM within five years (Baffes, 2005). Such growth is being driven by the development of new varieties of GM cotton, particularly in India and China. In these countries the public sector is developing new varieties, while elsewhere the GM technology is provided by the private sector.

Table 31. Major producers of GM cotton.

Country	Percentage GM cotton (%) (Baffes, 2005; James, 2008)
Australia	95
Argentina	95
South Africa	90
USA	86
India	76
China	68
Mexico	57
Columbia	31
Burkina Faso	1.5

One of the downsides of the technology is lack of accessibility to developing countries and those with small-scale cotton production. Increasing production in developed economies leads to reduced world cotton prices for growers in developing nations who cannot access the technology for their own benefit. However, it has been suggested that the increased use of GM varieties in small, developing cotton producing countries could be significantly benefit farmer's incomes by increasing fibre yields even if fibre prices do not rise significantly (Anderson, et al, 2006).

Unfortunately, there is very little reliable information at present to help weigh up the balance of such impacts. For example, use of BT cotton can significantly reduce insecticide use, most of which pose a risk to water-borne environments and pollinators. However, reducing chemical inputs has very little impact on the overall energy demand in agriculture. GM technologies could help to reduce the ecotoxicological impacts associated with natural fibre raw material production, but not to the extent possible where pesticides are eliminated, such as in certified organic cotton production, and where additional impacts are effected in downstream processing to further reduce risks to the environment.

5.6.2 Organic production

Certified organic cotton fibre is produced from cotton plants grown in agricultural systems approved to "organic" standards, with overarching standards being set through initiatives such as the GOTS, backed up by certification inspections and approval by International Federation of Organic Agriculture Movements (IFOAM) accredited regional certification bodies (such as the Soil Association in the UK, which incorporates the GOTS standard into its own organic textile standards).

Organic cotton is currently being grown successfully in many countries; the largest producers are Turkey, India, the USA, and China. Production is also growing in smaller nations in Africa (EJF, 2009a). In 2007, around 60,000 tonnes of organic cotton were produced and worldwide production has been growing at a rate of more than 50% per year. However, this still represents less than 0.2% of the global cotton crop (Organic Exchange 2007), and supply has outstripped demand in Europe in recent years (EJF, 2009a).

However, to resort to natural methods of fertility building and pest control leads to a number of issues (Cherrett *et al.*, 2005)

- Yields are 20-50% lower
- A greater land area would be required to replace an equivalent amount of conventional cotton production
- Costs are higher for cultivation (cultivations used rather than agrochemical inputs) cleaning (due to contaminants) and labour (for hand weeding etc). Costs for US organic cotton lint are 37-65% higher. Impacts in less developed countries, historically less reliant on conventional agricultural inputs, may be lower.

A premium is required by growers to overcome the above problems.

Clearly eradicating pesticide use would have a significant impact on the ecotoxicological impacts of cotton production, which relies heavily on insecticides for pest control in the absence of GM technologies. It is difficult to quantify effects on energy use since pesticide inputs to cotton vary between countries, in terms of types of materials used and frequency of application. Although organic cotton fibre production in general consumes less energy than other systems of cotton production this is in part a reflection of the manual techniques employed by small holder organic cotton producers. In more industrialised organic cotton production systems increased field cultivations (mechanical weeding and ploughing operations) are likely to be required, resulting in higher diesel use. In cultivation of temperate arable crops, pesticides have a relatively modest impact on energy use in crop production compared to use of fertilisers and fuel (Turley *et al.* 2008). Intensive applications to cotton may increase such impacts, but this needs further study.

Risks of eutrophication would also be lower in certified organic production due to the absence of artificial fertilisers. However, water use is likely to be similar per kg of fibre. As a result organic cropping of cotton is unlikely to have a significant impact on water use. A further un-quantified benefit is the value to wider biodiversity associated with organic cropping systems.

The GOTS has been introduced to ensure the organic status of textiles, from harvesting, through environmentally and socially responsible manufacturing, to labelling, and is designed to assure end consumers. This not only covers issues associated with controlling the use of inputs and water use in organic textile production, but also the types of materials that are used in textile processing and dyeing, and may pose specific risks to human health or the environment. Suppliers are also expected to have written environmental policies to encourage positive and continued improvement in reducing impacts on the environment. Such initiatives should help to significantly reduce environmental impacts of textile production though further detailed work is required to specifically verify the benefits.

In addition to the GOTS, the Organic Exchange (OE) 100 and OE Blended Standards have been introduced to ensure blends of organic cotton fibre comply with the stated organic content and to encourage organic cotton farming. Such developments show that it is possible to track and guarantee the integrity of fibre produced to specific environmental and social standards agreed in each scheme.

5.6.3 Better Cotton Initiative (BCI)

In addition to certified organic production, other initiatives are in developments that specifically seek to improve the environmental impact of cotton production. The BCI is a new global initiative of the United Nations Environment Programme (UNEP) and the World Wide Fund for Nature (WWF), working in partnership with major companies including; Adidas, IKEA, Gap and H&M. The BCI aims to influence cotton production on wide scale. Part of its remit is to reduce the environmental impacts of cotton production, particularly water and pesticide use. It has the aim of creating common standards for global cotton production. The BCI is currently “in its design and testing phase” and has yet to have a major impact on the cotton market (BCI, 2009b).

5.7 Social impacts

In any consideration of sustainability, social aspects also need to be taken into account. While this was not a major focus of this project, some important issues and key areas of concern are highlighted. There is a lack of reliable, peer-reviewed data on the social impacts of textile fibre production. However, recent interest in developing a standard method for assessing these social factors, akin to the more environmentally focused LCA approach, may lead to greater availability of information in the near future.

Most of the issues highlighted below relate to the production of natural fibres due to commonly highlighted concerns with pesticide and water use in cotton. In addition the concerns raised about use of forced child labour in Uzbekistan (EJF, 2009b), a major cotton exporting country has forced a number of UK suppliers to consider the ethical stance of their sourcing of fibre materials. Issues affecting more industrialised sectors associated with synthetic fibre production are less well reported.

More than two thirds of the world’s supply of cotton is produced by developing economies (Baffes, 2005), and cotton production plays a significant role in the contribution to GDP in a number of developing countries. Clearly any interventions into markets for natural fibres, to support production or change working practices will have significant impacts on some of the most impoverished workers in the textile industry.

5.7.1 Impacts of subsidies

Cotton production is heavily subsidised in various regions, including the USA, the EU, and China. Baffes (2005), reported that in 2002, support to the cotton sector amounted to \$6 billion, equivalent to a quarter of the value of global production. It has been estimated that if US cotton subsidies were removed, global average cotton prices would increase by 6–14% and cotton producer incomes in West Africa would increase by 8–20% (Bassett, 2009). The WTO has ruled that US policy distorted world cotton prices to the detriment of developing nations but has failed to enact effective reform (Bassett, 2009). Reduction or abolition of subsidies paid by major cotton producers may lead to an initial drop in global cotton production but would

stimulate cotton production and raise incomes for cotton growers in developing countries (Bassett, 2009).

5.7.2 Health and welfare

Environmental protection law affecting industrial and agricultural practices varies across the globe, posing higher levels of risks to workers in the agricultural and textile industries in developing countries. Low levels of safety awareness, lack of access to protective apparatus, illiteracy, poor labelling of pesticides and inadequate safeguards all exacerbate the damage caused by cotton pesticides to low-income communities (EJF 2007).

Barriers to change in developing nations include, price, availability, and lack of regulation restricting the use of modern spraying equipment and protective clothing. In addition, lack of common agreement on the safety and approval for use of pesticides results in sales of pesticides in developing countries that have been banned on ecological grounds in developed countries, but which may end up treating cotton imported into the developed economies.

The Environmental Justice Foundation (EJF) published statistics on the use of pesticides in cotton plantations in developing countries (EJF, 2007). It estimated that in India cotton accounts for 5% of the agricultural area but 54% of pesticide use and between 1 and 3% of agricultural workers are reported to suffer from some form of pesticide poisoning. Such impacts are preventable and steps need to be taken to encourage the supply chain to address these issues.

Encouraging practices such as organic farming in developing countries can significantly reduce workers' exposure to pesticides and provide access to a premium market. Surveys have shown the willingness of Western consumers to pay a premium for organic cotton products, although retailers have sometimes had to pay a proportion of the added costs (Casadesus-Masanell et al. 2009).

Another potential means of reducing pesticide inputs would be cultivation of genetically modified (GM) cotton, if the technology could be made affordable to rural populations. Development and wide adoption of the BCI could also help to reduce such problems, but this is as yet an unproven scheme.

5.7.3 Trade initiatives

Given the distorting effect of subsidies, it is important to ensure that appropriate recompense is paid to textile growers and workers in developing nations. Growing concern over the social inequality resulting from the global trade in agricultural products have led to a number of initiatives that aim to protect and promote the rights and welfare of farmers and workers in developing nations. A particularly high profile example is Fair-trade. This strategy requires participating companies pay sustainable prices to agricultural producers in developing nations. The produce can then be sold with the Fairtrade Mark. In recent years, consumer recognition of the Fairtrade Mark has increased, with 64% of people in the UK associating it with "a better deal for producers in the developing world" (Fairtrade Foundation 2009). Initiatives such as

Fair-trade also encourage the use of best practices to protect workers, although at present these programmes reach only a very small number of farms (Bassett 2009). Although more established in the food sector, the strategy has also been applied to cotton production. Sales of Fairtrade cotton in the UK totalled £77.9 million in 2008, though this represents a small component of the overall cotton market (Fairtrade Foundation, 2009).

Fairtrade encourages organic agricultural practices, and improves issues such as gender equality among producers (Bassett 2009). However, the Fairtrade programme is currently very limited in scope, covering less than 1% of cotton producers in Western Africa (Bassett 2009).

The Better Cotton Initiative (BCI), like Fairtrade, aims to reduce the social and environmental impact of cotton production. The BCI has established structures and advisory boards to set indicators for different regions (West Africa, Asia, Brazil) with the aim of creating common standards for global cotton production. What differentiates it from Fairtrade is its aim to set standards at a level which could bring in as many as 50% of cotton producers, rather than the much smaller proportion likely to attain the Fairtrade and certified organic cotton mark (estimated at around 5%). The BCI is only focused on cotton currently and it is planned that resulting products would not carry a standard mark or logo (BCI, 2009a). As reported previously, the BCI is still “in its design phase” (BCI, 2009b).

A number of civil society initiatives based in the UK campaign for and support companies to improve working conditions for garment workers. These include the Ethical Trading Initiative (ETI), an alliance of companies, trade unions, charities and campaigning organisations that work together to improve working conditions in global supply chains. Their ultimate goal is to ensure that the conditions of workers producing for the UK market meet or exceed international labour standards. Campaign groups specifically targeting textiles and clothing also include “Labour Behind the Label” and the “Clean Clothes Campaign”.

Being able to trace and assure a supply chain is critical to assuring sustainable practices are being followed. However, it has been argued for cotton and other fibres that it is difficult to trace such internationally traded commodities with relatively long processing chains. But the development of these initiatives demonstrate that it is possible to ensure that fibres are produced to the highest ethical standards by engaging with suppliers in the industry.

Other initiatives like ‘Made by’ have been established by industry interests to help identify the most sustainable fibre choices. ‘Made by’, is a member-led initiative to develop an environmental benchmark for fibre to yarn production. Fibres are assessed in relation to a number of impact parameters including; greenhouse gas emissions, human toxicity, eco-toxicity energy input, water input and land use. This is used to allocate fibres into a single indicative impact category (A (good) to D (poor)). Recycled materials, lyocell and organic cotton came out scoring relatively well, hemp, flax, PLA, acrylic, polyester, and Modal were moderate and conventional cotton, nylon, wool and viscose scored relatively poorly. In more detailed reporting, effects noted were the same as, or similar to, those found in this study in terms of relative impacts.

Energy input – ‘good’ fibres were recycled and those sourced from natural sources. ‘bad’ fibres were all man-made fibres.

Greenhouse gas emissions – ‘good’ fibres were recycled, ‘bad’ fibres were man-made, though it was noted that regenerated cellulosic materials were better than man made in this respect.

Water input – all fibres scored ‘good’ except cotton and viscose.

Land use impacts – matched those observed in this study.

The consultants involved in developing Made-by (Brown and Williams) also highlight the ‘missing data’ problems that hampers impact determinations for fibres such as silk and bamboo. Clearly such developments, along with this current study and discussions of its results with stakeholders will help to increase the understanding and help develop commonalities in the approach to addressing the sustainability impacts of textile fibres.

5.8 Summary conclusions

The key environmental concerns cradle to gate for fibres are; water use in crop and fibre production, the amount of water discharged and its chemical loading, energy use, greenhouse gas emissions, and other chemical pollutants. Emissions to water and air from textile operations are not well characterised in the literature. Waste waters are known to contain a mixture of chemicals reflecting both the various processes involved and origin of textile fibre.

5.8.1 Energy use

The synthetic fibres nylon and acrylic are the most energy intensive, reflecting high energy demands in raw polymer and fibre production. Regenerated cellulosic fibres also show moderate energy demands, due to energy intensive pulping operations. Polyester, although classed as having a moderate energy demand in this study, typically has a slightly higher overall energy demand than regenerated cellulosic fibres. PLA has an energy demand just below that of regenerated cellulosic fibres, reflecting the high energy inputs to fermentation operations. Cotton also has a moderate energy demand, reflecting high inputs in raw material cultivation (pesticides, fuel, irrigation and fertiliser). In contrast the remaining natural fibres and wool have a relatively low energy demand.

Energy use in dyeing and finishing is reported to be similar for most fibres, most of which require hot water dye treatments, but this requires further detailed examination. Protein fibres are treated at lower temperatures during dyeing and finishing and hence energy demand is expected to be lower here.

5.8.2 Water use

Cotton is the most water demanding fibre, far outstripping the water demands of all other fibres. Nylon also has a high water use compared to other synthetic fibres.

Regenerated cellulose fibres also have a relatively high water demand, though lyocell demand for water was found to be the lowest of the regenerated cellulosic fibres. Silk has a high water demand in the spinning phase that results overall in a relatively high demand for water.

Polyester has a relatively moderate water demand, while acrylic has a low water demand. However, in both cases more detailed information is required to confirm this. With the exception of cotton, natural plant-based fibres all have relatively low water demands. Wool has high water demands in both fabric production and finishing due to high cleaning and washing requirements, but compared to most synthetic and regenerated cellulosic fibres water use from cradle to gate is relatively low.

5.8.3 Impacts on global warming potential

Regenerated cellulosic fibres have the lowest impact on global warming potential, due to use of forestry feedstocks with low input demands and high carbon sequestration potential. In contrast synthetic fibres have the highest impact, through a high use of fossil fuels. Cotton and PLA have intermediate effects, including the impact of energy consumption in the production of inputs such as fuel, fertilisers and pesticides.

5.8.4 Impacts on chemical use and waste output

Waste waters are contaminated with dye and finishing chemicals. When processing wool pesticides can also be found. Wool processing produces very high waste water volumes, while synthetics like polyester produce the lowest volumes. Cotton has an intermediate impact. Regenerated cellulosic fibres are anticipated to be similar in effect to cotton.

Cotton and blends with wool tend to use more basic chemicals in finishing operations than are used with synthetic fibres, though use of dyestuff and auxiliaries in the dyeing process are relatively similar. EU 'Best Available Technology' Guidance Notes developed for Integrated Pollution Prevention and Control licensed facilities (for textiles these include large textile manufacturing plants in the EU only) define best practice for reducing the environmental impacts of textile production (see EC 2003).

5.8.5 Land use

In terms of fibre production per unit area, cotton is a land-demanding crop compared to other natural plant fibres and regenerated cellulosic fibres. PLA has a relatively low land requirement – around a third of that typically required for natural plant-derived fibres. However, increased demand for PLA, PTT and soybean protein have the potential to compete with food production, unless growth substitutes for other natural fibres. Additional land requirements for other natural fibres are likely to remain low. However, for plant bast fibres such as hemp, flax and nettle, and for production of forestry for regenerated cellulosic fibres, there appears, at least anecdotally, to be suitable land available in Eastern Europe and former Soviet Union should demand increase. Care needs to be exercised in sourcing regenerated cellulosic materials to ensure safeguards are in place to avoid direct destruction of high biodiversity value forest.

5.8.6 Alternative cotton production methods

Both organic production and GM technologies have the potential to reduce inputs into fibre crop production. Organic practices may also help to reduce eutrophication of water by avoiding the use of synthetic fertilisers. However, yields are often significantly lower which has implications for land demand. The balance of such impacts need to be carefully examined. GM technologies can help to reduce the ecotoxicological impacts associated with crop inputs for natural fibre raw material production, but not to the extent possible with organic production. Use of GM varieties in pest-affected situations can also lead to significant yield increases relative to conventional crops, allowing increased production on a smaller area of land.

Development and implementation of the Better Cotton Initiative could also help to reduce the environmental impacts of cotton production. The development of certified organic cotton schemes such as GOTS can also help to reduce the environmental impact of cotton production through its influence on downstream processing operations, but uptake of organic cotton production needs to be significantly increased to have any significant impact.

5.8.7 Use and end of life

Use of blends can increase clothing longevity and reduce drying impacts, leading to lower energy demands during the use phase, subject to consumer behaviour enabling this. Blending also results in the need for additional processing and dyeing operations. However, laundering can account for up to 70-80% of the lifetime energy use of an item of clothing and so the environmental benefits of blends may outweigh the additional costs if such benefits are effectively exploited.

Recycling of textiles is an effective means of significantly reducing the energy demand in raw fibre production, even when collection and transport it taken into consideration. However, efficient recycling of textile fibres relies on consistent use of materials, easy separation of different fibres, and access to suitable processing facilities, all of which pose problems in currently exploiting such use. Polyester is demonstrably well suited to recycling and PLA also has the ability to be recycled.

5.8.8 Social impacts

Incomes are low for the majority of farm workers producing textile fibres in the developing world, partly a result of protectionism by major fibre producers. Adoption of alternative farming techniques such as organic production could provide increased income as long as demand continues to grow. Wider use of GM and organic farming can also help to alleviate the problems of pesticide poisoning among workers in the developing world. Initiatives such as Fair-trade help to improve working and pay conditions for farmers and textile workers but are at present, like organic production, restricted to a small minority of workers.

Wider-scale programmes designed to improve the environmental and social impacts of cotton production, such as the Better Cotton Initiative, have yet to take effect, and such initiatives need to be expanded to cover other textile fibres. While the social

impacts of cotton and cotton textile production in developing countries is well reported, there is little or no information on the impacts associated with other natural fibres or in production of textiles based on man-made fibres. Fairtrade and organic initiatives in the textile sector show that it is possible to provide end users with textile products of a guaranteed specification in terms of specific environmental or social demands, despite the complexity of fibre production and supply chains and the globalisation of the textile industry.

6 Knowledge gaps

6.1 Current and future markets

- Data on the fibre production, and market potential of, ramie, Spanish broom, and bamboo were unavailable or very limited.
- Clothing composition data only include the primary fibre component. A more complete and representative picture of UK fibre use in clothing would improve our understanding of how new fibres are being taken up in the market place, given that they are often included in blends to reduce costs during early stages of development.

6.2 Environmental impacts

- There is a lack of LCAs in the textile sector that take account of a wide and contrasting range of fibre types. Few take account of any natural fibre other than cotton.
- Where there are LCAs, they commonly only consider water and energy issues, and only during a limited part of the textile chain. There is a specific need for LCAs that account for a wider range of environmental impacts than water and energy use, particularly the impacts of chemical use in fibre production and processing.
- On a wider perspective, studies should take account of the durability and lifetime of apparel products (including end of life use or re-use) to enable impacts associated with production phases alone to be examined in a wider context.
- Linked to the above, although again not a main consideration of this particular study, few LCAs consider the impact of blended materials, which in some cases can deliver reduced environmental impact in the use phase.
- LCA studies should take appropriate account of detail in the analysis. For example, ensuring allocation of appropriate environmental burden sharing to co-products of natural fibre production to reduce overall impact on fibre production alone and enable more appropriate comparisons between fibres.
- It is important that the LCA literature concentrates less on the specifics of production in a specific location and by a specific approach, but contributes more widely to generic assessments of the environmental impacts of different textile fibres, while highlighting the sources of variability that help identify where reduced environmental impacts can be achieved.
- While it is relatively easy to obtain data on the actual rates of use of chemicals in industrial process and generation of wastes, it is less easy to identify the actual potential environmental risks arising from their use. In many cases specific practices are put in place to ensure there is minimal environmental impact, and wastes are disposed of by licensed means. It is not sufficient to

detail just what chemicals are used, but to determine what is released into the environment at ‘end of pipe’ or chimney and what the consequences of this are.

- There is a further need to agree approaches to balance or weight different environmental impacts in a meaningful way for the textile industry so more simplified eco-ratings can be developed for textiles and textile fibres.
- There is little information on pesticide use on crops in developing countries. This undermines attempts to assess the ecotoxicological impacts of natural fibre production and compare and contrast materials produced in different localities.
- A more thorough understanding of bamboo fibre and soybean protein fibre production is required to allow a more complete and reliable environmental assessment.
- There is a general lack of environmental data for emerging fibres, including bamboo, jute, nettle, ramie, and soybean. Environmental data were also lacking for the more established fibres silk and viscose. There is a need for more information on these crops and fibre developments to be placed in the public domain to enable appropriate comparative analysis.

6.3 Social impacts

- With the exception of cotton, there are few published data on the social impacts of all types of fibre production. Communities in industrial areas can equally be affected by mal and poor practice as rural communities engaged in natural fibre production and processing which has received more attention.
- There is also a lack of a standard method for assessing the social impacts of products and processes. Social life cycle assessment (SLCA) is a novel approach and has yet to be used to analyse the social implications of textile fibre production. In the absence of standard, objective measures of social issues, work such as this relies on isolated and subjective reports.

6.4 Next steps

This study is a collation of the existing published information pertaining to the cradle to gate environmental impacts of clothing fibres and influencing factors relevant to fibres associated with the use and end of life supply chain stages. This study has identified where relevant information is available in the public domain as well as the significant gaps that exist in current understanding. The environmental impact tables for energy and water use in fibre production presented in this report provide a simple, high level indicator for identifying the key environmental impacts of a fibre, but is not intended as an accurate comparison, as the underlying data has significant gaps and comparability limitations. Further research to develop data/methods and tools to support the textile sector in line with best LCA practice and wider sustainable products initiatives are key next steps. Credible LCA data development initiatives taking into account the need for global consistency in approaches across the textile

sector should be utilised. For example the European Platform on LCA's and its International Reference Life Cycle Data-System (ILCD) should be targeted to support the textile sector in improving data availability. The ILCD in particular is developing globally consistent independent peer-reviewed sources of LCA information using anonymised data collated from manufacturers. Similarly tools (e.g. Environmental Product Declarations (EPD 2009)) already available for several sectors should be developed for the textile sector as a means of developing a standard approach to conducting textile LCAs to help compare the environmental impacts of different products. To date, only one PCR on performance apparel exists. Several of the large fibre manufacturers and clothing Original Equipment Manufacturers (OEM's) have their own proprietary LCAs and sustainability material assessment tools that can contribute significantly to this. Many are participating in the Sustainable Clothing Roadmap which provides an industry framework to move forward with these next steps. In addition, industry support organisations and commercial consultancies have developed early tools to help identify the environmental impacts of fibres. These can be built upon.

Given the technical, cost and production barriers affecting the market development of emerging fibres such as hemp, soybean protein, PLA and cellulosic materials, that on-balance (and within the limited information currently available) may provide more sustainable alternatives to either dominant natural or synthetic fibres, priorities for further work in the short term should focus on textiles that are more widely represented in the market place i.e. on cotton and polyester. Impacts on procurement decisions with regard to polyester and cotton are likely to have the greatest short-term impact to reduce fibre-related sustainability impacts across the textile industry.

If the gathering of more complete environmental data show benefits to switching to other textile fibres and technological developments ensure that emerging and niche fibres provide equivalent or better product performance, then measures may be necessary to promote the use of novel fibres or fabrics on a sustainability basis to overcome any cost barriers. The information contained in this review provides a first step collation of fibres impacts. This report highlights the complexity of issues affecting sustainability assessments and also where information is limited.

7 Interpretation and policy implications

7.1 Rationale and approach

Textile fibre production has more than doubled over the past 30 years, leading to increased demands for both biological and fossil resources as well as larger volumes of clothing waste. The impacts of this demand must be controlled. However, it is important that any novel means of production or consumption adopted are economically sustainable and do not compromise human health and welfare. This project has aimed to evaluate the market potential, environmental impact, and social implications of established, niche, and emerging textile fibres used in clothing. It has also sought to identify key knowledge gaps and opportunities for further research.

7.2 Major production trends

7.2.1 Natural fibres

Natural fibre production over the last 30 years has been characterised by the continued and growing dominance of cotton, which now accounts for 78% of the global natural fibre market. The growth in the production of cotton is almost entirely due to yield increases; the global cotton area has remained relatively static since 1977. Other natural fibres, such as flax, have generally shown modest increases in absolute production, but declines in market share. However, wool production is undergoing a long-term decline and hemp output has decreased markedly over the last 30 years. Ramie, flax, and hemp remain relatively expensive to produce and so are restricted to small-scale, high-value, luxury products.

7.2.2 Man-made fibres

Despite the increase in cotton production, still greater increases in man-made fibre production have meant that the market share of natural fibres has declined from 60% to 44% over the last 30 years. During this period, total man-made fibre output increased from 12.3 million tonnes to 44.1 million tonnes. This rise is almost exclusively the result of increased polyester production. There has been an eightfold increase in polyester output since 1977 and this trend is expected to continue for the foreseeable future. Polyester now accounts for 70% of all man-made fibres and its production has become increasingly concentrated in China, which manufactures more than half of the world's polyester fibre.

7.2.3 Potential markets

This report has used a “business as usual” scenario to predict future trends in global textile markets. This is not intended to represent an ideal situation or an inevitable set of circumstances; rather it is provided to show the likely consequences of current industrial and commercial activity. The examination of the market and sustainability

implications of these trends is used to inform our overall assessment, policy recommendations, and suggested directions for future research. In summary, our market predictions provide a baseline scenario, which can be used to make more informed policy and market decisions.

The immediate future of the clothing textiles market is expected to be dominated by cotton and polyester. Together, these two fibres currently account for 75% of all garments and this proportion is predicted to continue to increase. At present rates of growth, emerging fibres are unlikely to make significant market gains. Although production of ramie and PLA is expected to increase, their role in the global fibre market is expected to remain small. High production costs, inferior technical qualities, and incompatibility with existing equipment present a barrier to growth of natural fibres such as hemp, jute, nettle, and Spanish broom.

7.3 Sustainability assessment

7.3.1 Major impacts

The sustainability assessment has examined the energy, water, greenhouse gas, chemical, and land use implications of textile fibre production. This analysis and the underlying data have gaps, comparability limitations, and only enable high-level, indicative comparisons. The results of this cradle to gate analysis are summarised in Table 32 and Table 33.

Although evidence was lacking, the potential impacts of organic cultivation and GM varieties of natural fibre crops has been discussed. In general, natural fibres are characterised by low energy use, low water demands, and a high direct requirement for land area. Cotton has a particularly high water demand and is frequently irrigated. Wool production needs very large amounts of grazing land, but sheep farming also produces meat and can take place on land unsuitable for crop cultivation. Part of the land demand impact for wool fibre production can be offset by allocation to meat produced as a by-product, but this is anticipated to only have a limited impact, given that energy and water use in raw wool production is already low, and only up to a third of the impacts are typically allocated to non-fibre applications.

Considering impacts from cradle to gate, in contrast to natural fibres, synthetic fibres tend to have a higher energy demand in feedstock and fibre production. While fossil fuels remain the primary source of energy, greenhouse gas emissions will be strongly coupled to energy demands. With the exception of nylon and cotton, both with high water use, water use in natural fibre (non protein) and synthetic fibre production is typically relatively low. The only exception to this is hemp where water based-retting operations are used. By comparison, regenerated cellulosic fibres have an intermediate water demand.

The direct land requirement of fossil-derived synthetic fibres is negligible. However, regenerated cellulosic fibres and starch-based polymers do require land for cultivation of raw materials. Viscose and modal require less land than most natural fibres but have high water requirements and moderate energy demands during production. The direct land requirements of PLA are low compared to both natural and regenerated

fibres. Energy use during PLA production is also comparatively low, but more information is required on use of this polymer as a textile fibre and its impacts on water and energy use, as well as impacts in use and at end of life.

7.3.2 Alternative cultivation techniques

GM cotton now accounts for approximately 50% of the global cotton area. Despite this, there has been very little detailed research into the environmental impacts of these novel varieties and so it is difficult to make conclusive statements about their sustainability. GM cotton is typically modified for pest-resistance or herbicide-tolerance and there is some evidence of increased yields and lower pesticide usage than conventional cultivars, suggesting a potential for lower environmental impacts. In contrast, organic cotton accounts for 0.2% of the current global cotton area. While there is the potential for higher revenues for growers, average yields are lower than those for conventional cotton and there may be increased processing costs and larger direct land requirements. However, the organic “brand” may be a way of increasing the value of existing low-input cotton crops in developing nations where pesticide use and inorganic fertiliser applications are already low. It also has the potential to reduce the environmental footprint of downstream processing operations through its prohibition of certain chemicals and processes, required to gain organic certification.

7.3.3 Social impacts

Recent developments in social life cycle analysis (SLCA) may provide a means for analysing the social implications of products and processes in future. Evidence on the social impacts of fibres was very limited and is not qualitative but quantitative. At present, cotton markets are distorted by subsidies paid to producers in industrialised nations, leading to lower incomes for farmers in developing countries. Low levels of safety awareness, poor enforcement of regulations, and lack of access to protective equipment also make pesticide use a major health concern in the developing world. Initiatives such as Fairtrade encourage sustainable economic development for farmers in poorer areas, but currently only reach a minority of cotton producers. Organic farming may increase product value and better access to GM varieties could increase yields and profits, but at present the two techniques are seen as mutually exclusive by certification organisations and by buyers in industrialised countries.

7.3.4 Importance of whole life cycle impacts

Parallel Defra projects have shown the importance of taking into account the use and end of life phases when assessing the overall sustainability impacts of clothing and textiles and providing recommendations for ways to reduce these impacts. The fibre manufacturing processes examined in this report can affect these laundering impacts in two broad ways. Use of blends can increase the longevity of clothing and improve its drying characteristics. Laundering accounts for between 75 and 80% of the lifetime energy use of a garment and so the difficulty in recycling blended and coated items of clothing may be outweighed by the improved washing performance.

7.4 Summary and conclusions

This report has focused on the social and environmental sustainability of a range of existing and emerging fibres used for clothing textiles. The assessment has informed the business case for these fibres, considering their market potential against their relative sustainability impacts. The results of this analysis have shown that current dominant fibres have relatively high environmental impacts. Compared to most natural fibres, polyester has relatively high energy requirements and consequently, greenhouse gas emissions. Cotton production uses large areas of land, requires frequent pesticide inputs, and consumes enormous quantities of water. Some of the niche and emerging fibres examined as part of this project have much smaller environmental profiles, but their production and use is restricted by other factors. Flax has low energy and water use requirements, but requires cottonisation for general use and is relatively expensive to produce. Hemp has low energy, moderate water, and low pesticide demands but is incompatible with existing cotton-producing machinery. The starch-based polymer PLA has smaller land and water requirements than cotton and moderate energy requirements (similar to polyester). However, this fibre is still in the early stages of development and growth in production will remain low for the foreseeable future. Further technical development is required if these fibres are to go from being niche fibres to being major textile materials.

The literature review has also revealed significant gaps in our present understanding of textile fibre sustainability impacts. Life cycle assessments are lacking for many niche fibres and information beyond energy and water demands is scarce for all materials. Further research will be required to quantify and compare the environmental impacts of different fibres. Information on the social implications of textile fibre production is even more incomplete and further work is necessary.

Environmental impacts are not fixed and the data presented in this report represent a snapshot of current technology and prevailing practices. Development and adoption of novel techniques and materials will affect environmental performance. Furthermore, changes outside the textile industry could also affect sustainability. For example, a large-scale move from fossil to renewable energy sources would reduce the indirect greenhouse gas emissions associated with fibre production without any change being made to the production process. Consequently, sustainability assessment should be seen as a continuous process that takes into account the ongoing technological changes that affect the textile fibre industry.

7.5 Future directions

7.5.1 Information gathering

This report has provided an overview of the available data on the life cycle environmental and social impacts of textile fibres. However, there remain significant gaps in the literature. Further research is required to provide basic LCA information on the energy and water demands of niche and emerging fibre production. There is also a need for more detailed data on the wider environmental impacts of all fibres, including chemical pollution, greenhouse gas emissions, land use, waste water production, and biodiversity impacts Platform on LCA's and its International

Reference Life Cycle Data-System (ILCD) should be targeted to support the textile sector in improving data availability. The ILCD in particular is developing globally consistent independent peer-reviewed sources of LCA information using anonymised data collated from manufacturers. Similarly tools (e.g. Environmental Product Declarations (EPD 2009)) already available for several sectors should be developed for the textile sector as a means of developing a standard approach to conducting textile LCAs to help compare the environmental impacts of different products. To date, only one PCR on performance apparel exists. Several of the large fibre manufacturers and clothing Original Equipment Manufacturers (OEM's) have their own proprietary LCAs and sustainability material assessment tools that can contribute significantly to this.

. Detailed comparisons of different cultivation techniques (including conventional, organic, and GM cotton) are also lacking. In addition, the social impacts of fibre production are difficult to quantify at present. Development of credible metrics and collection of data are necessary for a complete sustainability assessment of textile fibre production, processing, use, and end of life.

7.5.2 Technology development

The available data indicate the possible environmental advantages of using niche fibres such as hemp, flax, and PLA in clothing textiles. However, wider use of these fibres in clothing will require development of processing technologies and improvements in product performance. Better environmental data may identify other promising fibres with low environmental profiles.

7.5.3 Market drivers

Cotton and polyester are expected to maintain and consolidate their dominant positions in the global fibre market. If more complete environmental data show benefits to switching to other textile fibres and technological developments provide equivalent or better product performance, then measures may be necessary to promote the use of novel fibres or fabrics. The environmental impact tables for energy and water presented in this report allow a high-level comparison of the environmental impacts of the different fibres. Further development of the underlying methods and data will be required to enable a reliable, credible basis for accurate comparison. Further development of the methods and data for life cycle fibre impacts in line with best LCA practice are key next steps.

Table 32. Summary of market potential and environmental impacts of textile fibre production.

Fibre	Current Volume (raw fibre)	Growth prospects in textiles	Fibre Cost \$/kg (typical and recent highs in brackets)	Relative impacts between fibres (+ = relatively low impacts, ++++ = relatively high impact)					
				Energy use	Water use	Greenhouse gas emissions	Waste water production	Chemical use in finishing	Land requirement
Acrylic	2.5m t	declining	2.7	+++	++	(+++)	+++	(++ - +++)	N/A
Bamboo	9000t	limited	ID	(++)	(+++)	(+)	(++)	(++ - +++)	(++)
Cotton	27.5m t	increasing	1.2-1.5 (c. 3.3 organic)	++	++++	++	++	+++	+++
Flax	0.45m t	limited	2.0-3.0 (up to 3.5)	+	+	(++)	(++)	(+++)	+++
Hemp	0.08m t	declining	0.5-1.5 (up to 2.0)	+	++	(++)	(++)	(+++)	++ - +++
Jute	3.3m t	limited	<0.5	ID	ID	(++)	(++)	(+++)	++
Lyocell	0.25m t	increasing	ID	++	++	+	(++)	(++ - +++)	+
Modal	Part of viscose share	increasing	ID	++	+++	(+)	(++)	(++ - +++)	++
Nettle	negligible	v.limited	(estimate - high)	(+)	+	(++)	(++)	(+++)	+++
Nylon	4.1m t of which 1.5 m t textiles	increase	2.84	+++	+++	++++	+	(+ - ++)	N/A
PLA	c. 0.01m t	increasing	1.5-2.4	++	(+)	++	ID	(+ - ++)	+
Polyester	30.7m t (17.1m t textile yarn)	increasing	1.1-1.65	++	+	+++	+	+ - ++	N/A
PTT	ID	ID	ID	++	+	+++	(+)	(+ - ++)	(+)
Ramie	0.29m t	limited	3.0-3.5	ID	ID	(++)	(++)	(+++)	++++
Silk	0.1m t	limited	15-26	ID	+++	ID	(++)	ID	ID
Soybean	3000t	limited	ID	ID	ID	ID	(+++)	(++ - +++)	ID
Spanish b.	negligible	v.limited	ID	ID	+	(++)	(++)	(+++)	ID
Viscose	2.92m t	increasing	2.95	++	+++	+	(++)	(++ - +++)	++
Wool	1.2m t	declining	2.8-6.6	+	+	ID	++++	++ - +++	++++

ID = insufficient data, NA = not applicable, Figures in brackets based on use of information from similar fibre types

Table 33. Ranking of fibres by environmental impacts.

	Energy use	Water use	Greenhouse gases	Waste water	Direct land use
 Decreasing environmental impact	Acrylic	Cotton	Nylon	Wool	Wool
	Nylon	Silk	<i>Synthetic</i>	<i>Regen. cellulosic</i>	Ramie
	Polyester/PTT	Nylon	Polyester	<i>Natural bast fibres</i>	Cotton
	<i>Regen. Cellulosic</i> (viscose Modal)	<i>Regen. cellulosic</i>	Lyocell	Nylon	Flax
	PLA/cotton/lyocell	Acrylic	PLA	Polyester	Hemp
	Wool	Hemp	Viscose		Viscose and modal
	<i>Natural bast fibres</i> (nettle, hemp flax)	Wool	Modal		Jute
		<i>Natural bast fibres</i>	Cotton		PLA
		Polyester	<i>Natural bast fibres</i>		Lyocell
			Wool		<i>(Synthetic)</i>

Where insufficient data were available, fibres have been omitted from this table.

Appendix A Steering group and stakeholder consultees

A.1 Project steering group

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A.2 Project stakeholder group

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Jane Ashdown, Burton.

Alison Atkins, Howies.

Rebecca Atwood, Environmental Justice Foundation.

Jonathan Bain, Bio Intelligence Service.

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Sue Blacker, Blacker Sheep Ltd.

Josie Cartridge, Sainsbury's.

Gareth Coates, SMART, Loughborough University.

John Danes, Fat Face Ltd.

Pamela Daniels, Ethical Fashion Forum.

Alberto De Conti, Levi Strauss.

Lucy Drage, Sainsbury's.

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Eraina Duffy, Nike Inc.

John Easton, DyStar UK Ltd.
Andrew Filarowski, Society of Dyers and Colourists.
Kate Fletcher, Kate Fletcher Designs.
Robert Franck, The Textile Institute and Rafex European Ltd.
Linda Gallagher, Intertek Labtest (UK) Leicester.
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Nora Harper, NHS.
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Anita Nagarajan, MOSAIC Fashions.
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Kate Wells, University of Ulster.

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Karen Whittingham, Avery Dennison.

Dilys Williams, London College of Fashion.

Tara Young, Tesco Clothing.

Appendix B Fibres of interest

B.1 Existing fibres

B.1.1 Natural

B.1.1.1 Cotton

Cotton fibres are cellulosic fibres and are the seed hairs of the cotton plant (*Gossypium* spp.). As the plant grows, the fibres develop as hairs inside a boll (seedpod) around the seed. When mature, the boll bursts open and the cotton fibre appears as soft, fluffy wads. Three types of cotton fibre are used by the textile industry for the production of clothing: *Gossypium hirsutum* (e.g. American upland cotton); *Gossypium herbaceum* and *Gossypium arboreum* (e.g. Indian short staple cotton); and *Gossypium babudense* (e.g. pima cotton and extra long staple cotton). World cotton production was approximately 26.24 million tonnes in 2007/2008, but consumption in the same period was approximately 26.86 million tonnes, resulting in a decline in end stocks. In 2008/2009 world cotton production is predicted to fall to approximately 24.57 million tonnes, but consumption is estimated at 25.98 million tonnes, resulting in a further decline of end stocks (Meyer 2009). The world's largest producers are China and India. The USA is the world's largest cotton fibre exporter.

In Europe, cotton production (growing and ginning) occurs mainly in Greece and Spain, with Greece the major EU producer with approximately 80,000 cotton producers on 400,000 hectares. Minor levels of cotton production have recently been present in Portugal and Bulgaria (LMC International 2007). Although cotton production in the EU is small in global terms, textile products produced entirely in the EU from Greek cotton may be given a "label of origin" under EU rules on geographical indications and designations of origins of agricultural products.

Cotton is used widely in clothing and is the most popular natural fibre for casual garments such as jeans, t-shirts and sports apparel. Surface treatments applied to cotton fabrics impart easy-care, non-iron, and crease resistant properties. Blending cotton with polyester achieves similar effects. Polyester-cotton blend fabrics are produced in a range of blends and fabric weights for clothing, with fabric weights typically ranging from 145 to 300 grams per square metre. Increasingly, cotton fibre is being used in spring and summer knitwear collections. In addition to its use in clothing, both virgin cotton fibres and by-product fibres from cotton processing are widely used in domestic and household textiles.

B.1.1.2 Flax (line)

Flax is a cellulosic bast fibre (fibre from the stem of the plant) and has been grown for centuries for the production of long "line flax" fibres, or linen. End uses are mainly for domestic textiles and apparel. Approximately 75,000 tonnes of linen fibres are produced each year, two thirds of this in China, although 53% of raw world flax fibre

production occurs in the EU from approximately 105,000 ha of flax (20% of the world flax crop area) (Anon. 2008a). Use of linen as a fibre for clothing is highly fashion-dependent and sales of linen garments fluctuate from year to year. It has a staple use as a lightweight suiting fabric for men and women, and for ladies summer garments.

B.1.1.3 Silk

The annual global production of the filament protein fibre silk is around 135,000 tonnes. Production has approximately doubled over the past 30 years despite the increased production of manmade fibres. This is due in part to fabric finishes rendering silk easy-care and washable, and also to a sharp decline in world silk prices. China and Japan are the main silk producers, with China responsible for around 70% of global production in 2004. The process of obtaining silk from the cocoon of the silkworm is a very labour-intensive process.

B.1.1.4 Wool

Wool is the proteinaceous fibre, widely used for apparel, especially the finer types. Annual global production of wool is around 1.2 million tonnes, produced mainly in Australia, New Zealand, Uruguay and South Africa (Oerlikon 2008; Meyer 2009). The traditional use of wool fibre has always been as suiting due to its resilience and durability; however, its use is in decline as the demand for heavy overcoats and suits has reduced. Lighter weight wool fabrics are available such as challis and voile that are similar in weight to cotton. Generally wool is in oversupply at a global level despite recent decreased raw wool production in Australia and New Zealand, the world's two largest producers of wool.

B.1.2 Regenerated

B.1.2.1 Viscose

Viscose rayon is a regenerated cellulose fibre, produced by extruding dissolved cellulose into an acid bath. Cellulose from wood or cotton is treated with sodium hydroxide and carbon disulfide to form cellulose xanthate before being dissolved in sodium hydroxide. It is then extruded into an acid bath through a spinneret to form viscose rayon fibre. First developed in the late 1800s, the viscose process demands relatively high water and energy use, and results in production of polluting by-products, which have led to developments of the viscose process which include modal and lyocell (sold as "Tencel" by Lenzing Inc.). These fibres are considered an improvement on the original viscose rayon fibre due to the closed loop solvent system for dissolving cellulose. Viscose has very attractive technical properties, including softness, elasticity, lustre, absorbency and a drape similar to that of silk. The fibre can be used alone or (more typically) blended with natural fibres. Viscose rayon is widely used in apparel, particularly women's tops and underwear.

B.1.3 Synthetic

B.1.3.1 Acrylic

Acrylic is a synthetic fibre made from the polymer polyacrylonitrile, first developed in 1941 by DuPont. Most acrylic fibres incorporate copolymers of other monomers to improve subsequent wet processing, when the copolymer content exceeds 15%, the fibre is called modacrylic. The production process includes dissolving the polymer in a solvent such as sodium thiocyanate, extruding as filaments through a spinneret, then wet or dry spinning, followed by washing, stretching and crimping. Lightweight, soft and warm, acrylic is often used as a cheaper substitute for wool or cashmere. Acrylic production is in long-term decline (Oerlikon 2008). Acrylic is very durable but has a tendency to feel harsh and for this reason it is often blended with other fibres. Uses include knitwear.

B.1.3.2 Nylon

Nylon is the generic name given to the group of synthetic polymers comprising of repeating units bridged by amide linkages and is frequently referred to as a polyamide fibre. Invented in 1935, it was the first synthetic fibre produced. The most common forms of nylon for apparel are nylon 6 and nylon 6,6. As a clothing fabric, nylon is lightweight and possesses exceptional strength characteristics; it is very durable and has good laundering properties. It is used widely in apparel such as swimwear, active wear, and foundation garments among others. Although typically used to produce fabrics comprising 100% nylon, the fibre can be blended with a range of other fibres.

B.1.3.3 Polyester

Polyesters are long chain polymers chemically formed by reaction of a diol with a carboxylic acid. The main polyester used for apparel is polyethylene terephthalate (PET), made from the condensation polymerisation of ethylene glycol and terephthalic acid. PET fibres and fabrics are extremely strong and durable and possess excellent laundering properties. For this reason, it is widely used in clothing as either filament yarn or staple fibre, and is undoubtedly the most widely utilised synthetic fibre. PET can be woven into lightweight fabrics, for example suiting materials. Laundering and wear properties of polyesters are improved by blending with natural fibres such as cotton or wool, which also improves its handle as 100% polyester fabrics can feel “cold” to the touch.

B.2 Emerging fibres

B.2.1 Natural

B.2.1.1 *Flax (short fibre) and tow*

During the mechanical extraction of the long fibres (scutching and hackling) various grades of short-fibre flax are produced, known as “tow” fibre. Some of the tow fibre produced during this processing is suitable for carding and spinning on cotton spinning frames to produce flax/cotton blend yarns. Flax suitable for spinning on cotton frames is known as cottonised or affined flax. The cultivation of flax crops producing a whole yield of fibre suitable for cottonisation has also been investigated and demonstrated as potentially viable (FAIR 2001; TEXFLAX 2001). At present, there is a growing demand for short fibres for cottonisation.

B.2.1.2 *Hemp*

Hemp (*Cannabis sativa*), like flax, is a bast fibre plant with fibres contained in bundles in an outer stem layer. Traditionally, hemp fibre was produced for a number of industrial end-uses such as rope or canvas fabric making. In non-woven applications, hemp fibre is used in a number of industrial end-uses. Textile yarns and fabrics, suitable for apparel are available from China and Eastern Europe, though not in high volumes. Hemp fibre produced by traditional methods is relatively coarse and limited to use in heavy industrial fabrics. However apparel fabrics can be produced by using selected hemp fibre and spinning from bleached rove, but this is expensive compared to cotton and coarse compared to linen (Sponner 2005). Significant attempts to develop hemp fibre processing methods are underway in Europe, Canada and China to extract fibres more suitable for use in high quality textiles, primarily as a replacement for cotton. Certainly there is a niche market for clothing made from hemp within the “environmentally aware” marketplace, but overall fibre hemp production is stagnant, after declining sharply over the last two decades.

B.2.1.3 *Jute*

Jute is a bast fibre produced from two particular *Corchorus* plants: white jute (*Corchorus capsularis*) and tossa jute (*Corchorus olitorius*). The major producers of jute are India and Bangladesh, but some is also produced in China, Nepal and Thailand. In addition, there are a number of plants that can produce a similar fibre to jute (woody-stemmed herbaceous dicotyledons bast fibre plants) and can be produced in the same sub-tropic and tropic regions. The commercially important types of jute substitute are kenaf (*Hibiscus cannabinus*) and rosella (*Hibiscus sibdoriffa*). Jute and its substitutes are mainly used in the manufacture of cheap low grade fabrics, such as hessian (burlap) sacks and upholstery fabrics.

Jute fabrics tend to be heavyweight and finer fibres are needed for spinning into the lightweight fabrics suitable for apparel. This requires significant chemical modification of the fibres for spinning into textile yarns. High strength characteristics,

high abrasion and heat resistance, combined with durability and washability mean that jute fabric can be used for the manufacture of protective aprons and gloves. Jute can be blended with viscose, cotton, acrylic and polyester fibre, jute–viscose blends enable the production of finer yarns.

B.2.1.4 *Nettle*

Nettle (*Urtica dioica*) fibre has been widely used historically for ropes and cloth. Recent investigations have shown that there is a demand for the fibre for end uses as diverse as fashion apparel, furnishing fabrics, and geo-textiles (STING 2004; Johannes 1998). The demand within Europe alone is estimated to be similar to that of other high-value, specialist fibres. The production of nettle fibre for textiles has been proposed and investigated as an industrial crop for the European area (Johannes 1998; van Dam and Elbersen 2004), current research work being carried out in Germany aims to develop nettle plants with fibre yields approaching those of flax and hemp (Schneider et al. 2008).

B.2.1.5 *Ramie*

Ramie fibre is a bast fibre extracted from the stems of the shrubby plant *Boehmeria nivea*. The main countries of production are China, Brazil, Philippines, and South Korea. Ramie fibre production has expanded significantly in the previous 10 years and global production is approximately 220,000 tonnes per year (Jianchun 2008). A significant amount of this fibre is used for the production of clothing, being blended with cotton and used in knitted and woven fabrics. Ramie fibres are long, naturally white and lustrous with a silk-like appearance. The fibres are used in knitwear and linen-look textiles. However ramie fabric has a tendency to wrinkle but the application of surface finishes or blending with synthetic fibres overcomes this problem in woven fabrics. Commonly, ramie is blended with cotton, a typical mix is 55% ramie and 45% cotton. Potentially, ramie could be more widely used in clothing production, as it is a low cost fibre and the processing technology for fibre extraction is suitably well developed (Dempsey 1975).

B.2.1.6 *Spanish broom*

Fibres extracted from Spanish broom (*Ginestra* spp.) have been used for textiles since ancient times. There was a revival of interest in the fibre during the Second World War and the plant has recently been the subject of a seven-year investigation into the extraction and processing of fibre for textile end uses. Although current production levels are small, the fibre does have proven use in apparel as a high-value niche market fibre. Production of *Ginestra* fibre for textiles has been proposed as an industrial crop for the Europe area (van Dam and Elbersen 2004).

B.2.2 Regenerated

B.2.2.1 Bamboo

The supply of natural bamboo fibre is limited. Bamboo fibre currently on the market is regenerated bamboo, produced using the viscose process. As such, it will have been through several chemical processes before it emerges as a textile fibre. It is argued that the control of these processes is far more stringent than when the viscose process was introduced and therefore the process has less of an environmental impact. The bamboo fibres produced have properties that are the same as viscose fibre. Currently regenerated bamboo fibre is finding applications in clothing where the combination of its distinctive characteristics of moisture absorption and antibacterial properties makes it a suitable fibre for underwear, sportswear, t-shirts and socks. Regenerated bamboo fibre is found in a range of blends with other fibres in the same way as viscose.

B.2.2.2 Lyocell

Lyocell is a regenerated cellulosic fibre sold under the brand name Tencel by Lenzing Inc. Lyocell is the generic name of fibres produced using a solvent system based on N-methylmorpholine-N-oxide (NMMO). Produced using a closed loop system, lyocell fibres are perceived to be environmentally advantageous in comparison to other regenerated fibres (White 2001). Solvent recovery is high and very close to 100% and the use of water in the process is relatively low compared to viscose. The raw material for the process is wood pulp, primarily from eucalyptus trees (*Eucalyptus* spp.). However, there is potential to utilise other forms of cellulose. Lyocell is claimed to be a sustainable fibre. The wood used as a source of the pulp raw material is renewable, but the major difference is that the harvesting of the trees occurs every 8–10 years, rather than annually as with natural fibres. Lyocell fibres have a water-absorbing nanostructure and lyocell has become popular in clothing due to the comfort-in-wear properties, especially in conditions of high humidity (Schuster et al. 2006). Fabrics are produced comprising 100% lyocell and woven fabrics manufactured from blended yarns with cotton or polyester may typically contain 50–65% lyocell.

B.2.2.3 Modal

Modal is a regenerated cellulose fibre derived from beech trees (*Fagus sylvatica*) and can be considered as a form of rayon, which is made from the wood pulp of a number of different trees. Modal fabric has a texture similar to cotton or silk, however it has the advantage over cotton in that it resists shrinkage and absorbs approximately 50% more water than cotton. It is widely used in apparel as a replacement for cotton and in cotton blends. Modal has very similar properties to cotton and these fibres are therefore optimal blending partners, especially in dyeing behaviour and mercerisation. Blending cotton with Modal improves yarn regularity and produces an improved fabric surface (Lenzing 2009).

B.2.2.4 Soybean

Soybean fibre is a regenerated protein fibre derived from the residual material of the soybean after the oil has been extracted for food use. Regenerated protein fibres were the focus of considerable attention during the 1930s and 1940s and there is now renewed interest due to sustainability issues. Because the fibre is produced from a waste material from the food industry, the quantity of raw material available is large. In addition, minimal waste products are generated. Fabrics made from this fibre are similar to natural fibres such as cotton, wool, hemp, and silk (Yi-You, 2004) with a lustrous appearance and good drapeability characteristics. Soybean fibre can be blended with cashmere, wool, silk, and cotton.

B.2.3 Synthetic

B.2.3.1 Polylactic acid (PLA)

Poly(lactic acid) (PLA) is a polyester made from the polymerisation of lactic acid; renewable resources such as corn starch and sugarcane are fermented by bacteria to produce the lactic acid. The PLA polymer is processed into fibre using conventional melt spinning processes. The fibres have the advantage of being compostable under the right conditions, and this combined with the potential sustainability issues, have made them of interest in recent years. Commercially it is sold as Ingeo when used in apparel fibres. Compared to polypropylene, nylon, and polyester, PLA fibres exhibit improved water absorbance and moisture transmittance properties, allowing for improved breathability of garments such as shirts, dresses and underwear.

B.2.3.2 Polytrimethylene terephthalate (PTT)

Polytrimethylene terephthalate (PTT) was first synthesised in the 1940s, but has recently received much attention as an emerging fibre under the brand name “Sorona” by DuPont, as one of the two base chemicals was derived from sugar. PTT is synthesised from the condensation polymerisation of petrochemical-derived terephthalic acid and 1,3-propanediol, which in the case of Sorona is derived from sugar. Sorona fibres are claimed to possess good stain resistant properties, have a soft handle, with high strength and stiffness characteristics.

B.3 Fibres excluded from this study

B.3.1 Natural

Kapok fibre (also known as silk cotton) is a fine white fibre obtained from the seed capsules of *Ceiba pentandra* trees native in Central America, Java, Borneo, and Sumatra. The fibre has the general appearance of cotton, with the lustre of silk. The fibre is short (less than 25 mm staple length), low in strength, and sufficiently smooth in texture to prevent it from being spun into a yarn. It is typically used in mattresses, cushions, and upholstery.

Sisal fibres are extracted from the leaves of cactus like plants of the *Agave* spp., primarily *Agave sisalana* grown in South East Asia, South China, and East Africa. The fibre is coarse and hard in comparison to other plant fibres and is primarily used for industrial purposes such as ropes and twines, decorative household textiles, or a constituent of carpets.

Coir fibres are extracted from the fibrous outer covering of the seeds of the coconut palm (*Cocos nucifera*), particularly produced in the Kerala state of India. As with sisal, coir fibres are coarse and lack the flexibility to be used in textiles, but they are stronger fibres than flax, hemp or cotton. Major end-uses for coir fibre include carpets, industrial matting, and various low-grade non-wovens.

Pina fibre is extracted from the leaves of pineapple (*Ananas comosus*). The fibre has an established tradition of production in the Philippines, but has received further interest recently in China for the production of fibres for a range of end uses, from apparel to upholstery fabrics. In general, the fibres can be used in the production of clothing, but softer cotton and flax fibres are preferred.

Abaca (*Musa textilis*) is a plant of the banana family found in tropical areas, particularly the Philippines and Ecuador. Fibre, of a very wide range in quality, can be extracted from the leaves of the plant at various stages in growth. Similar to the other natural “hard-fibres” (leaf rather than stem), such as sisal, the fibre less suited to the production of fine yarns and is used in the production of twines and ropes and woven into industrial fabrics such as sacking and disposable fabrics.

An extremely wide range of animal fibres can be used in textiles, but overall they constitute less than 5% of the total mass of fibres produced globally. Of the animal fibres, wool is overwhelmingly the most produced and significant. There are numerous other animal fibres that have a special position in the textile trade but they are only produced in very limited quantities due to their high cost. In many cases, these minor animal fibres have not experienced an expansion of production for many years and are uncompetitive with wool and man-made fibres. The most significant minor animal fibres include: mohair (Angora goat); cashmere (cashmere goat); and llama wool.

B.3.2 Regenerated

A range of protein fibres generated from vegetable sources have been developed, particularly during the Second World War. These included the peanut protein fibres “Ardil” (UK) and “Sarelon” (USA) and the maize protein fibres zein and “Vicara” (Brooks 2006). Regenerated protein fibres were produced commercially from milk in the 1930s, known initially as “casein silk” with brand names including “Aralac”, “Lanital”, “Fibrolane”, and “Merinova” (Brooks 2006). To date these brands have not remained commercially viable, but milk protein fibre is increasingly available commercially from China (Brooks 2006).

Chitin and chitosan fibres exist as “Crabyon” and “Chitopoly” brands of fibres regenerated from chitin (and deacetylated chitosan) extracted from shellfish waste (such as crab shells). The resulting fibre which has anti-microbial properties has been successfully used commercially in medical textiles, and as a component in athletic

socks, sportswear, towels, and underwear (Whang et al. 2006). It remains a functional additive to textiles, rather than being a fibre for garments in its own right.

Regenerated keratin fibres extracted from chicken feathers have been produced in a number of trials and at a limited scale commercially for use in clothing applications. The raw material is a by-product of the chicken meat industry with an estimated 5 million tonnes produced annually, most of which ends up in landfill (Poole et al. 2008). Textiles were developed in the 1940s in the US for use in military applications, however the odour associated with the resulting products was said to make them unusable. Research is ongoing in the US for applications of odourless keratin fibres in non-wovens (University of Southampton 2009). In addition, regenerated fibres have been produced from gelatine, extracted from animal hooves and bones, as well as horse and chicken meat including German fibre “Carnofil” (University of Southampton 2009).

B.3.3 Synthetic

Polypropylene (PP) is an addition polymer with the advantage that it requires less energy in production compared to other synthetic fibres; produces less waste and is recyclable. It is excluded from this study as it is not used significantly in apparel, primarily because it is not easily dyeable; it does find some use in thermal clothing as an insulator material. There is limited evidence of research to developing dyeable PP, but this is very much at the concept stage.

Nylon 11 is a plant derived fibre produced by melt spinning with ricinoleic acid extracted from the oil of the castor bean plant. Its dyeability performance is the same as that of Nylon 6 and 6.6, however it exhibits a greater resistance to abrasion. Although nylon 11 is ultimately derived from a plant source, it is not biodegradable. It is used in high-performance applications but not in apparel.

Elastane is a generic name for fibres comprised of synthetic linear macromolecules containing at least 85% of polyurethane groups by mass. The fibre can revert substantially to its unstretched length after extension to three times its length. Elastane fibres typically contain highly inextensible segments alternating with highly extensible segments in the molecular chain (Denton and Daniels 2002). Elastane is also known as spandex, the most famous brand name associated with these fibres is Lycra. Elastane is used in apparel requiring stretch properties such as sportswear, lingerie, and foundation wear. It is excluded from this study as it is essentially a low content (typically less than 3% by weight) functional fibre and it not a textile fibre for garments in its own right.

Appendix C Life cycle assessment data

The following tables collate the data found in the literature for energy and water use associated with various stages of textile processing, and from which the results in sections 5.2.1 to 5.2.3 are drawn. The source references can be found in the full reference list. Studies varied in the range of processes covered, and the degree of clarity by which results were allocated to specific processes or range of processes. For each fibre and each source of information, data is entered against an individual process, or range of processes based on the study teams interpretation of what the data actually refers to in each reference source, and by reference to results from other studies where available.

C.1 Existing fibres

C.1.1 Natural

C.1.1.1 Cotton (conventional)

Reference	Energy use (MJ/kg)											Notes	
	Growing, incl. fert, fuel, etc)	Pesticide use	Ginning and baling	Fibre preparation	Spinning	Fabric production	Desizing	Washing	Bleaching	Mercerization	Dyeing		Finishing
Cherrett et al. (2005)	25.6												Conventional US cotton, methods unclear
Kalliala and Nousiainen (1999)	59.8				39.5							Review of published data	
Laursen et al. (1997)	48.7		6.3-18.4				1.8-8.8	2.5-10.4	4.8-28.7	5.6-11.0	3.4-13.2	4.1-8.0	Review of published data

continued overleaf

Cotton (energy use continued)

	Growing	Pesticide use	Ginning and baling	Fibre preparation	Spinning	Fabric production	Desizing	Washing	Bleaching	Mercerization	Dyeing	Finishing	Notes
Shen and Patel (2008a)	49			0	15-45	5-30					3.5-13	4-8	Review of published data (data from Laursen et al. 1997)
Reference	Water use (L/kg)											Notes	
Blackburn and Burkinshaw (2002)											145		Lab experiment; remazol RR
											105		Lab experiment; procion H-EXL
											125		Lab experiment; cibacron F
Chapagain et al. (2005)	1818												Global average
	4377												Max of top five producers
	576												Min of top five producers
Cherrett et al. (2005)	9788-9958												Review of published data
Kalliala and Nousiainen (1999)	22200				3900							Review of published data	
Laursen et al. (1997)	7000-29000							2.5-43	2.5-125	23-95	38-143	24-135	Review of published data – typical data for cotton-type finishing operations
Yilmaz et al.(2004)	2154												Review of published data

Values marked with an asterisk (*) are calculated from data given in the literature (e.g. to convert between units).

C.1.1.2 Cotton (organic)

Reference	Energy use (MJ/kg)						Notes
	Growing	Pesticide use	Ginning and baling	Fibre preparation	Fabric production	Dyeing and finishing	
Cherrett et al. (2005)	11.7						Organic Punjab cotton, methods unclear
Kalliala and Nousiainen (1999)	53.6						Review of published data
Reference	Water use (L/kg)						Notes
	Growing	Pesticide use	Ginning and baling	Fibre preparation	Fabric production	Dyeing and finishing	
Kalliala and Nousiainen (1999)	24,000						Review of published data

C.1.1.3 Flax (line)

Reference	Energy use (MJ/kg)												Notes
	Growing	Fertilizer	Pesticide use	Ginning and baling	Fibre production	Spinning	Desizing	Washing	Bleaching	Dyeing and finishing	Sewing	Transport	
Dissanayake et al. (2008)	0.96-2.25	3.8	0.8		5.89-6.3	22.9							Life cycle assessment for cement reinforcement
Huxtable and Turley (2008)	11.66												Life cycle assessment
Shen and Patel (2008a)	3.95*	3.95*			2.7	2.9						Review of published data	
van der Werf and Turunen (2008)	261												Review of published data

(continued overleaf)

Flax (line) continued

Reference	Water use (L/kg)											Notes	
	Growing	Fertilizer	Pesticide use	Ginning and baling	Fibre production	Spinning	Desizing	Washing	Bleaching	Dyeing and finishing	Sewing		Transport
van der Werf and Turunen (2008)				72.3									Review of published data

Values marked with an asterisk (*) are calculated from data given in the literature (e.g. to convert between units).

The above data apply to line flax. The raw material production data should also apply to short fibre flax.

C.1.1.4 Silk

Reference	Water use (L/kg)					Notes
	Raw material production	Fibre preparation	Spinning	Fabric production	Dyeing and finishing	
Lee (1999)		800-1000				UN FAO manual

C.1.1.5 Wool

Reference	Energy use (MJ/kg)											Notes	
	Fertilizer production	Farming	Shearing	Scouring	Carding	Combing	Spinning	Transport	Weaving	Dyeing	Finishing		
Barber and Pellow (2006)	20			21.7				1.5				Life cycle assessment; extensive farming; includes primary energy; New Zealand	
	23.4			21.7				1.5				Life cycle assessment; medium intensive farming; includes primary energy; New Zealand	
	24.2			21.7				1.5				Life cycle assessment; intensive farming; includes primary energy; New Zealand	
EC (2003)				4.28-19.98					39.6-75.6			Review of data from mills	
Harwood (2009)	13.9*			7.47*					4.26*	9.1*		Personal communication	
Laursen et al. (1997)		8†										Accounts for meat by-products in raw material phase, New Zealand	
Reference	Water use (L/kg)											Notes	
EC (2003)				5-10								70-314	Review of data from mills; fine wool
				10.3-13.2									Review of data from mills; coarse wool
				7.1-14									Review of data from mills; extra fine wool
Harwood (2009)				10						3.75		Personal communication	
Laursen et al. (1997)		125†								40-150	24-135	Accounts for meat by-products in raw material phase New Zealand	

Values marked with an asterisk (*) are calculated from data given in the literature (e.g. to convert between units).

Values marked with a dagger (†) explicitly account for allocation of energy and water use to both meat and wool production in raw material production phase (figures allocated for wool production only in table).

C.1.2 Regenerated

C.1.2.1 Viscose

Reference	Energy use (MJ/kg)												Notes
	Wood production	Energy production	Transport	Pulp production	Transport	Fibre preparation	Waste treatment	Spinning	Fabric production	Washing	Dyeing	Finishing	
Laursen et al. (1997)	26.3					33.3 (not including waste treatment)							Review of published data
Shen and Patel (2008b)	107												Life cycle assessment; Asia
	70												Life cycle assessment; Austria
Reference	Water use (L/kg)												Notes
Laursen et al. (1997)				55		420-750				17-33.5	38-143	24-135	Review of published data
Shen and Patel (2008b)	319												Life cycle assessment; Asia
	445												Life cycle assessment; Austria

C.1.3 Synthetic

C.1.3.1 Acrylic

Reference	Energy use (MJ/kg)									Notes
	Feedstock	Raw material production	Transport	Spinning	Fibre preparation	Washing	Fabric production	Dyeing	Finishing	
Laursen et al. (1997)		42.5			46.3					Review of published data
			157							
Shen and Patel (2008a)	60	52			46.3					Review of published data (draws on Laursen et al. (1997))
Reference	Water use (L/kg)									Notes
Laursen et al. (1997)	210 (data limited - estimated based on waste water emissions)					50.0-66.8		38-143	24-135	Review of published data

C.1.3.2 Nylon

Reference	Energy use (MJ/kg)						Notes
	Feedstock	Raw material production	Spinning	Fibre preparation	Fabric production	Dyeing and finishing	
Boustead (2005)	116.1 (excl energy production & delivery)						Review of published data
BTTG (1999)	55			110			Unknown methods
Ramachandran (2005)	38.9	80.6					Shell data
Reference	Water use (L/kg)						Notes
Boustead (2005)		663					Review of published data
BTTG (1999)				110			Unknown methods

C.1.3.3 Polyester

Reference	Energy use (MJ/kg)											Notes	
	Feedstock	Melting	Filament production	Polymerization	Spinning	Fibre preparation	Fabric production	Washing	Bleaching	Dyeing	Finishing		
Cherrett et al. (2005)	104.5											Review of published data; Europe	
	126.7											Review of published data; USA	
Franklin Associates Ltd (1993)	97	14.5									4	86.8	Life cycle assessment; USA
Kalliala and Nousiainen (1999)	97.4											Review of published data	
Shen and Patel (2008a)	46	50	13.6									Review of published data	
Ramachandran (2005)	38.7	38.6										Shell data	
Reference	Water use (L/kg)											Notes	
Kalliala and Nousiainen (1999)	17.2											Review of published data	
Laursen et al. (1997)								25-42	0	38-143	24-135	Review of published data	

C.2 Emerging fibres

C.2.1 Natural

C.2.1.1 *Flax (short fibre) and tow*

See flax (line)

C.2.1.2 *Hemp*

Reference	Energy use (MJ/kg)								Notes
	Growing	Pesticide use	Ginning	Baling	Transport	Fibre preparation	Fabric production	Dyeing and finishing	
Cherrett et al. (2005)	15								Review of published data; organic
	32.6								Review of published data; conventional
Huxtable and Turley (2008)	12.98								Life cycle assessment
Shen and Patel (2008a)	1.8				0.2	1.8	2.9		Review of published data
van der Werf and Turunen (2008)	255								Water retting – includes direct energy ? method unclear
	358								Bio retting (as above)
Reference	Water use (L/kg)								Notes
van der Werf and Turunen (2008)	199								Water retting
	221								Bio retting

C.2.1.3 *Jute*

No LCA data were obtained for Jute

C.2.1.4 *Nettle*

Reference	Energy use (MJ/kg)							Notes
	Growing	Pesticide use	Ginning	Baling	Fibre preparation	Fabric production	Dyeing and finishing	
Huxtable and Turley (2008)	25.83	Not used						Life cycle assessment

C.2.1.5 *Ramie*

No LCA data were obtained for ramie.

C.2.1.6 *Spanish broom*

No LCA data were obtained for Spanish broom.

C.2.2 **Regenerated**

C.2.2.1 *Bamboo*

No LCA data were available for bamboo.

C.2.2.2 *Lyocell*

Reference	Energy use (MJ/kg)									Notes
	Wood production	Energy production	Transport	Pulp production	Transport	Fibre preparation	Waste treatment	Fabric production	Dyeing and finishing	
Shen and Patel (2008b)	102									Life cycle assessment; current practice
	66									Theoretical with energy recovery during waste incineration
Reference	Water use (L/kg)									Notes
Shen and Patel (2008b)	263									Life cycle assessment; current practice

C.2.2.3 *Modal*

Reference	Energy use (MJ/kg)									Notes
	Wood production	Energy production	Transport	Pulp production	Transport	Fibre preparation	Waste treatment	Fabric production	Dyeing and finishing	
Shen and Patel (2008b)	78									Life cycle assessment
Reference	Water use (L/kg)									Notes
Shen and Patel (2008b)	472									Life cycle assessment

C.2.2.4 Soybean

No LCA data were obtained for soybean.

C.2.3 Synthetic

C.2.3.1 Polylactic acid (PLA)

Reference	Energy use (MJ/kg)									Notes	
	Feedstock energy	Growing corn	Transport	Dextrose production	Lactic acid production	PLA pellet production	Fibre preparation	Fabric production	Dyeing and finishing		
Vink et al. (2003)	28.4	4.9	0.4	9.4	26.3	13.2				Review of published data; current practice	
		48.8									As previous, but using improved lactic acid production technology
Vink et al. (2003)		29.2									As previous, but also using biorefinery sugar and steam; grid electricity (theoretical future prospect)
		7.4									As previous, but also using biorefinery sugar and steam; wind turbine electricity (theoretical future prospect)
Reference	Water use (L/kg)									Notes	
Vink et al. (2007)		69*									Life cycle assessment

Values marked with an asterisk (*) are calculated from data given in the literature (e.g. to convert between units).

C.2.3.2 Polytrimethylene terephthalate (PTT)

Reference	Energy use (MJ/kg)				Notes
	Raw material production	Fibre preparation	Fabric production	Dyeing and finishing	
Szanto and Winch (2008)	83.8				Du Pont data
Ramachandran (2005)	94.6				Shell data, includes feedstock energy

C.2.3.3 Generic fibre/textile data sources

Reference	Energy use (MJ/kg)								Notes
	Raw material production	Fibre preparation	Spinning	Yarn dyeing	Weaving	Knitting	Dyeing	Finishing	
Shen and Patel (2008a)			15-45		10-30	5-20	3.5-13	4-8	Estimated; based on cotton and polyester
World Bank Group (2007)				13.3-19.6*			13.6-81.6*		Yarn dyeing; knitted fabric
				13.3-19.6*			31.8-75.4*		Yarn dyeing; woven fabric
							31.8-75.4*		No dyeing; woven fabric
Reference	Water use (L/kg)								Notes
World Bank Group (2007)				45-80			70-120		Yarn dyeing; knitted fabric
				45-80			50-100		Yarn dyeing; woven fabric
				0			< 200		Fabric dyeing; woven fabric
				0			50-100		No dyeing; woven fabric

Values marked with an asterisk (*) are calculated from data given in the literature (e.g. to convert between units).

Glossary

Definitions of terms conform to those given by Denton and Daniels (2002).

Basic dye	A cationic dye characterised by its substantivity for standard acrylic, modacrylic, basic-dyeable polyester fibres, and basic-dyeable polyamide fibres.
Bast fibres	Fibre obtained from the outer (bast) layers of the stems of certain plants. These include hemp, flax, nettle, ramie, and jute.
BCI	Better Cotton Initiative.
Beam dyeing	Dyeing of textile materials wound on to a hollow perforated roller (beam) through the perforations of which dye-liquor is circulated.
Bleaching	A process for improving the whiteness of textile material, with or without the removal of natural colouring matter and/or extraneous substances.
Bleaching agent	A chemical reagent capable of destroying partly or completely the colouring matter present in textile materials, leaving them white or considerably lighter in colour.
Carding	A process used in preparation for spinning that may include blending, and involves parallelising fibres to form a continuous web and sliver (or slubbing).
CAP	Common Agricultural Policy. European Union agricultural policy and subsidy system.
Continuous process	A process in which material passes in sequence through a series of stages to give a continuous output of processed material.
Decortication	Mechanical or chemical process for separating certain vegetable fibres, particularly bast fibres from other vegetable matter present in the plant.
Defra	Department for Environment, Food and Rural Affairs.
Degumming	The removal of unwanted gums from fibres, yarns or fabrics without causing damage to the underlying fibres, used particularly in silk and bast fibre production. This usually consists of a hot alkaline treatment, although more recent developments include enzymatic degumming.
Desizing	The removal of size from woven fabrics.
Disperse dye	A substantially water-insoluble dye having substantivity for one

or more hydrophobic fibres, such as polyester, and usually applied from fine aqueous dispersion.

Dissolving pulp	A specially purified form of cellulose made from wood tissue.
Drafting or drawing	A process used to achieve the required weight per metre of sliver prior to spinning, making use of drafting or drawing frames.
Dye	A colourant, usually organic, soluble or dispersed in its medium of application and which is designed to be absorbed or adsorbed by, made to react with, or deposited within a substrate in order to impart colour to that substrate with some degree of permanence.
Dyeing	The application and fixing of a dye to a substrate, normally with the intention of obtaining an even distribution throughout the substrate.
EA	Environment Agency.
Filament yarn	A yarn composed of one or more filaments that run essentially the whole length of the yarn.
Finishing	Descriptive of processes, physical or chemical, applied to a substrate to produce a desired effect, for example, smoothness, drape, lustre, gloss, or crease resistance.
Flax line	Long flax fibres produced by hackling.
Flax tow	Short fibres produced by the scutching or hackling processes.
Ginning	The removal of lint (seed hairs) from the harvested cotton seed. Mechanical cotton gins may be of either a saw gin or roller gin type.
Hackling	The operation of combing line flax (or hemp) in order to remove short fibres, parallelise the remaining long (line) fibres and also remove and extraneous matter which might be mixed up with the line flax presented to the hackling frame.
Handlooms	A hand operated machine for producing cloth by weaving. In some instances, the shedding is performed by foot operation.
HB	Hemp bio-retting.
HW	Hemp water retting.
Jet dyeing machine	A machine for dyeing fabric in rope form in which the fabric is carried through a narrow throat by dye-liquor circulated at high velocity or a machine for dyeing garments in which the garments are circulated by jets of liquid rather than by

mechanical means.

Jigger	A machine in which fabric in open width is transferred repeated back and forth from one roller to another and passes each time through a relatively small volume of a dyebath or other liquid. Jigs are frequently used for dyeing, scouring, bleaching and finishing.
Knitting	The process of forming a fabric by the intermeshing of loops of yarn (warp or weft knitting).
Mercerization	The treatment of cellulosic textiles in yarn or fabric form with a concentrated solution of caustic alkali whereby the fibres are swollen; the moisture regain, strength, and dye affinity of the materials are increased; and their handle is modified.
Open-end spinning	A spinning system in which sliver feedstock is highly drafted, ideally to individual fibre state, and thus creating an open end or break in the fibre flow. The fibres are subsequently assembled on the end of a rotating yarn and twisted in. Various techniques are available for collecting and twisting the fibres into a yarn, most notably rotor and friction spinning.
Package dyeing	A method of dyeing in which the liquor is circulated radially through a wound package (this may be slubbing in top form or cones of yarn).
Pad-batch	A sequence of operations involving padding and batching without intermediate drying.
Perennial	A term applied to plants which can be harvested multiple times without the need for replanting each year
Powerlooms	A loom driven by a source of power such as an electric motor.
Reactive dye	A dye that, under suitable conditions, is capable of reacting chemically with a substrate to form a covalent dye-substrate linkage.
Reduction clearing	Removal of unfixed dyestuff (usually disperse) by an aqueous alkali/reducing system, usually sodium hydroxide/sodium dithionite.
Reeling	The process of unwinding continuous filaments or strands of raw silk from silk cocoons, prior to throwing to form a spinnable yarn.
Retting	The decomposition of pectins that bind fibres to the other parts of the stems of leaves, usually by the action of enzymes produced by bacteria or fungi.

Ring spinning	A continuous system of spinning in which twist is inserted into a yarn by using a circulating traveller. The yarn is wound on to the package since the rotational speed of the package is greater than that of the traveller.
Rotor spinning	A method of open-end spinning which uses a rotor (a high speed centrifuge) to collect and twist individual fibres into a yarn.
Roving	A name given, individually or collectively to the relatively fine fibrous strands used in the later or final processes of preparation for spinning.
Scouring	The treatment of textile materials in aqueous or other media in order to remove natural fats, waxes, proteins and other constituents, as well as dirt, oil and other impurities. Treatment varies with the type of fibre.
Scutching	The process of removing line flax fibre from tow and extraneous matter such as shiv, earth pebbles and weeds. When referring to this process in connection with other fibres the term “decorticating” is usually used.
Shiv	A name given to the woody core of bast fibre plants such as hemp and nettle, also known as hurd.
Short-staple spinning	The use of cotton spinning machinery to produce staple yarns from cotton or any other type of fibre possessing similar length and fineness characteristics.
Shuttle loom	A term loosely used to describe a hand loom, treadle loom, or weaving machine that uses a shuttle to insert the weft.
Shuttleless looms	Power operated weaving machines without shuttles. These may be projectiles, rapier looms and jet looms (machines in which the weft thread is taken through the shed by a jet of air or liquid).
Silk, raw	Continuous filaments or strands containing no twist, drawn off or reeled from silk cocoons.
Silk, wild	Fibres extracted by insect larvae other than <i>Bombyx mori</i> .
Silk-spun	A term applied to staple yarn produced by dressing or combing and spinning on machinery originally designed for processing waste silk into yarn.
Sizing	A gelatinous film-forming substance, in solution or dispersion, applied normally to warps but sometimes to wefts, generally before weaving, to protect the yarns from abrasion; to strengthen them; and, by the addition of oils and fats, to

lubricate them. The main types are carbohydrates and their derivatives, gelatin, and animal blues. Other substances such as linseed oil, polyacrylic acid, and polyvinyl alcohol are also used.

Sliver	An assemblage of fibres in continuous form without twist.
Spinning	The process or processes used in the production of yarns or filaments.
Step cleaning/opening	The action of separating closely packed fibres at an early stage in the processing of raw material. This may involve the removal of non-fibrous material (cleaning).
Throwing	A term meaning to twist or turn, used especially in the silk and manufactured fibre industries to describe the twisting or folding of continuous-filament yarns.
Thrown silk	A yarn twisted from continuous-filament silk.
Top	Sliver that forms the starting material for the worsted and certain other drawing systems, usually obtained by the process of combing, prior to spinning.
UNEP	United Nations Environment Programme.
Union fabric	A fabric made with warp of one kind of fibre and weft of another (originally the term related to fabrics made from cotton warp and wool weft or from linen warp and cotton weft).
Vat dye	A water-insoluble dye, usually containing keto groups, which is normally applied to the fibre from an alkaline aqueous solution of the reduced enol (leuco) form, which is subsequently oxidized in the fibre to the insoluble form.
Warp and weft	The warp is the set of lengthwise parallel threads (spun yarns) attached to a weaving frame, through which the weft is woven.
Weaving	The action of producing fabric by the interlacing of warp and weft threads.

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