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Contents

Index of tables and figures

List of abbreviations

AOX	Absorbable Organic Compounds
BAT	Best available technology
BOD	Biological oxygen demand
Bt cotton	Bacillus thuringiensis cotton
COD	Chemical oxygen demand
GM	Genetically modified
GMO	Genetically modified organism
ILs	Ionic Liquids
IRT	Infrared thermometer
MJ	Megajoule
Mtoe	Million tons oil equivalent
PA	Polyamide
PES	Polyester
PET	Polyethylene terephthalate
PLA	Polylactide acid
$scCO_2$	Supercritical CO_2
SLM	Supported liquid membrane
UK	United Kingdom

1. Introduction

Scarcity of ecological resources is one of today's major challenges. The decreasing or limited supply of oil, water and land has to satisfy an increasing demand. The characteristics of this development appear on a global scale, in versatile areas, emphasizing even more global interdependencies.

The basic economical law, that increasing demand by declining supply leads to higher prices is in action, forcing the industries to find new ways to manage this challenge. This development is also true for the textile industry, which already faces price volatilities in raw material procurement as in case of for example, polyester due to its primary material crude oil. Assuming a recovery of the world economy, crude oil prices are projected to increase and therefore the synthetic man-made fibre raw material will increase in price.

Additional pressure applies the highly competitive and price-oriented demand side, putting the industry into a dilemma position. Also the global legal situation with different environmental laws on national and regional levels as well as the non-existence thereof on a global scale, puts less-regulated countries into allocation and cost advantages versus highly-regulated countries. However, resource scarcity is a global challenge with global effects; thus responsibilities have to be taken in every step of the process in every country involved.

Another extrinsic factor forcing increasing efficiency of resource allocation is the global movement of Corporate Social Responsibility, especially in ecological claims, led by the stakeholders of the companies which already resulted in voluntary company partnerships. The implications of these raising environmental challenges are therefore versatile and action is required to manage the scarcity of resources. Various technical improvements are already available and implemented, such as the usage of plasma technology for finishing processes or energy saving equipments such as heat exchangers, but further innovative technologies are required to achieve a breakthrough to a more efficient resource allocation.

The objective of this study is

i. To analyse the connection between textile production and the scarcity of ecological resources, and
ii. To present potential future approaches and technologies for tackling resource scarcity as well as reducing the dependency on common resources.

The first part of the study will focus on, the resources water, energy, land, and oil, as those are allocated in most textile production steps and, from a global perspective, are in challenging high demand for various applications, e.g. in agriculture. In the second part, selected technologies which are not commercially available yet and therefore might be a future BAT (Best Available Technology) are described and evaluated.

Focussing on the core processes of textile production, i.e. fibres, yarns, textiles, finishing, and manufacture, upstream processes, production of supporting products and machinery, resource consumption during retail, usage as well as questions of human resources will not be covered.

2. The textile pipeline

The textile pipeline depicts the general life cycle steps of a textile product from fibre to disposal:

Figure 1: The textile pipeline. Source: (Eberle et al. 2008)[1]

Fibres are the primary material for textile products, from which in the next step yarns will be produced. The yarns are further processed into textiles which are classified by the production technology used: woven, knits or non-wovens. The step of textile finishing encompasses various mechanical and chemical processes to improve and/or to beautify the produced material, e.g. dyeing. Clothing manufacture is either be done in industrial batch size or customised. At the end of the pipeline, there are various options for the product, depending on type, material and quality: reutilisation, i.e. as second hand clothes, recycling or disposal. Overall it has to be mentioned that the final product designs ex ante the individual steps of the textile pipeline.

In contrast to other producing sectors, the textile industry has always been a subject of highest political attention due to its size, which leads to the use of instruments as subsidies, and – in the past – to trade regulations. Additionally, clothing manufacturing is due to the labour intensive production depending on cheap labour, which leads to a global division of labour, as the example of a basic T-Shirt sold in the UK depicts: The cotton fibre is cultivated, harvested and spun in the USA. The further processing takes place in China, where knitting, dyeing and manufacturing are done. The finished product is then transported to the UK, where it is sold in retail, used by the customer and finally disposed (Allwood et al. 2006).

Also, production patterns are changing, moving from large batch manufacturing twice a year to much shorter production cycles due to the demand for new collections every few weeks. This leads not only to a speeding up of the production but also to the development and increasing quantity of full-service production companies (Allwood et al. 2006).

In the case of technical textiles, companies tend to move to their prospect markets to be as close as possible to the demand to guarantee just-in-time delivery to avoid stock.

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[1] Author's visualisation. The life cycle steps of technical textiles and home textiles can be assumed as being similar.

3. Classification of fibre types

Textile fibre types are classified as following.

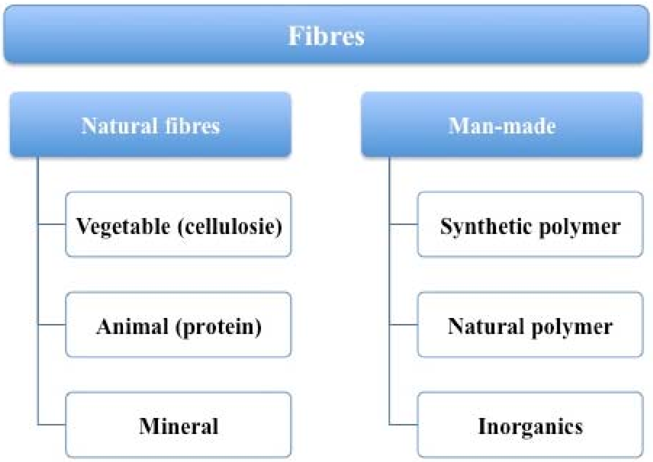

Figure 2: Classification of fibres. Source: (Eberle et al. 2008)

Due to the varying importance of the fibres types, the further focus will be on the natural and man-made fibres with the highest global demand: Cotton, wool, polyester, polyamide, and polyacryl.

Natural fibres

The bases for natural fibres are cellulose, proteins or minerals.[2] Cotton is the most important cellulosic fibre, part of the vegetable seed fibre family. The fibre consists of several layers of cellulose, each formed by fibrillar bundles consisting of cellulose macromolecules. As a plant, cotton is part of the mallow family, and sensitive to climate, needing a high amount of water for growing as well as heat for ripening. Its first usage can be traced back until 3000 B.C. as archaeological findings in both Pakistan and Mexico have proven.

Wool as an animal fibre is sourced by different kinds of sheep breeds, yet the fibre construction is identical. Consisting of keratin, a protein molecule which forms fibrils that re-form into fibrillar bundles as the mass of spindle cells, the structure of wool can be compared to the one of human hair. Already 7000 years ago wool felts were realised in China, Babylon as well as in Egypt (Eberle et al. 2008).

Synthetic polymer man-made fibres

Crude oil is the primary material for the production of the monomers, which can be processed in three different ways to generate polymers, i.e. to produce the spin masses:

i. Polyaddition, for e.g. elastane
ii. Polycondensation, for e.g. polyesters
iii. Polymerisation, for e.g. polyamide (IVC e.V. without year).

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[2] Asbestos, considered as a hazardous substance, is a natural, mineral fibre which is neglected in this context.

Polyester (PES) is a "Fibre composed of linear macromolecules having in the chain at least 85% by mass of an ester of a diol and terephthalic acid." (BISFA 2006).
In 1941, the first polyester polyethylene terephthalate (PET), which is nowadays the most important polyester, was made in the UK. PES fibres can be produced in two different ways: i. the melting and extrusion of polyester polymer chips, ii. by continuous process without creating chips. The share of PES using recycled PET bottles and other waste as primary material is increasing (CIRFS 2009).
Polyamide (PA) is "... composed of linear macromolecules having in the chain recurring amide linkages, at least 85% of which are joined to aliphatic cycloaliphatic units." (BISFA 2006). In 1938 the first fibres were produced in Germany as PA 6 based on polymerisation of caprolactam, and in the USA PA 6.6, via condensation polymerisation of adipic acid and hexamethylene diamine. Amongst all the various types of PA these two are produced in significant amounts (CIRFS 2009).
According to BISFA, **polyacrylonitrile** (PAN) is a "Fibre composed of linear macromolecules having in the chain at least 85% by mass of acrylonitrile repeating units." (BISFA 2006). In 1948, first commercial fibres were introduced in Germany and the USA. Acrylonitrile is produced out of propylene and ammonia, which react in the presence of a catalyst with oxygen. Through polymerisation polyacrylonitrile is formed (CIRFS 2009).
This classification and the examples show that the resources needed for the production of fibres are versatile, and different sources have to be considered when judging resource consumption of textile production.

4. Relationship of textile production and scarcity of resources

To examine resource consumption of textile production, the following chapter is divided into three sections:

i. A general overview of the global textile production amount to provide a picture of the fibre market,
ii. The consumption of the main resources oil, land, water, and energy to visualise the impact on textile production, and
iii. Conclusions of the state-of-the art of resource allocation.

4.1 Global production of textile fibres

In 2008, there has been a total fibre production of 67,300,000 t (IVC e.V. 2009). The historical development, comparing 2008 figures with the base year of 1975, shows clearly different production quantity developments of the main fibre types:

	1975 (in kt)	2008 (in kt)	Growth (%)
Polyester	3,370	30,320	799,7
Polyamide	2,490	3,560	42,9
Acrylic	1,390	1,890	72,66
Cellulosic man-made	3,200	3,530	10,3
Wool	1,580	1,200	-24,0
Cotton	11,720	24,300	107,3
Total production	**23,940**	**67,300**	**181,1**

Table 1: Development of global fibre production. Source: (IVC e.V. 2009)

Table 1 shows that the significant growth of the volume of textile fibre production is predominantly driven by polyester and cotton.

Two main reasons for this significant growth of textile fibre demands can be identified:

i. The economic growth, particularly in developing and emerging markets, and
ii. Increasing world population.

China, Southeast Asia as well as India are economically fast growing regions with large populations, having an annual textile fibre consumption between 3 and 9 kg per capita vs. 35 kg in the USA and 20 kg in Western Europe. This consumption gap in combination with increasing fashion consciousness and growing wealth in both developing and emerging markets will provide the textile industry with new potentials for growth. The high-tech sector can be seen as main driver for textile demand in industrial countries, where technical textiles more and more substitute common used materials, e.g. plastic or metal in automobile construction or building materials industry (The Indian Textile Journal 2007).

The growing fibre demand has a significant impact on the resources used for fibre production. The following chapter will illustrate the consumption of the resources oil, water, land, and energy.

4.2 Resource consumption

The resource consumption in textiles production varies depending on the product. For providing an overall view of resource allocation, this chapter will cover the main ecological resources oil, water, and land as well as energy consumption. The following scheme depicts resource input and possible problematic output:

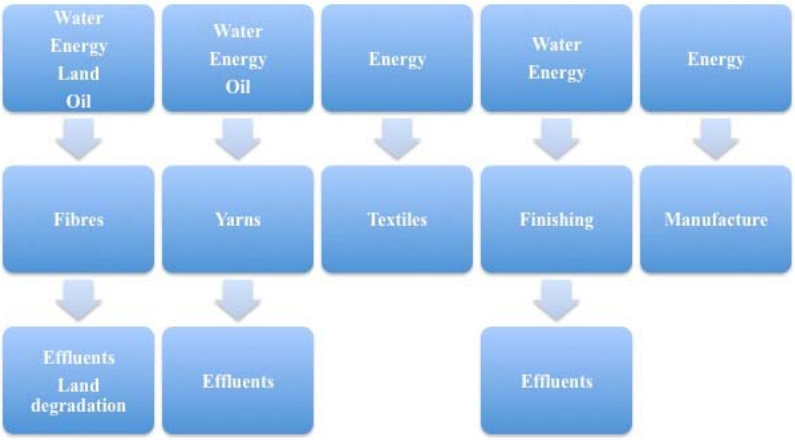

Figure 3: Resource input and output in textile production. Source: Author's visualisation.

To emphasise the varying importance of each resource, the data for both cotton and polyester are given to illustrate differences between the most important natural and synthetic fibre.

4.2.1 Land

Natural fibres, both animal and vegetable, as well as cellulosic man-made fibres require different amounts of land for cultivation. Cotton as a plant is cultivated on fields. Based on the data of the American National Cotton Council, the top five cotton producing countries in 2008 were USA, China, India, Pakistan and Brazil (NCC 2009).

The following table shows the area required for producing 1 t of fibre and for covering the total production in 2006:

	area/t (in ha)	total area (in km^2)
Wool	67	867,000
Cotton	1.3	344,000
Cellulosic man-made	0.8	44,000
Synthetic man-made	0	400

Table 2: Area consumption per fibre. Source: (IVC e.V. 2008), author's visualisation

With 867,000 km^2 wool requires the biggest land area for cultivation, despite the comparably low market share, followed by cotton with 344,000 km^2. The need for land in case of cellulosic man-made fibres is due to wood area for cultivating the cellulosic raw materials; when coming to synthetic man-made fibres, land is necessary for production facilities.

The limitation of land is a challenge, especially for cotton, as it is projected that the world cotton area will further decline by 3% to 30.1 million hectares in 2009/2010 the third year consecutively. There are three main reasons leading the farmers to switch crops:

1. Decreasing revenues
2. Competing crops like corn, soybeans, and wheat gaining more attractive prices, as well as
3. Anticipated difficulties in financing the inputs required for cotton cultivation (ICAC 2009).

Also the cotton cultivation itself influences biodiversity, due to e.g. the usage of pesticides and genetically modified crops as well as extraction of fossil fuels. The intensive cultivation of cotton and the resulting salinisation lead to the abandonment of approx. 5 Mha of arable land globally, which equals 4% of the global area (Madsen et al. 2007).

A third threat to the resource of land is the impact of global warming on crop yields, as a research carried out by the Columbia University, New York depicts for the USA. Yields of corn as well as soybeans increase until a temperature of 29°C, respectively 33°C for cotton. However, if this temperature level is overstepped, temperature is a threat, leading to a significant decline in yields. In case of a slow global warming scenario, yields are estimated to decline until the end of the century by 44% in the case of corn, by 33-34% when regarding soybeans, and 26-31% for cotton. Assuming a fast warming scenario, with continuous use of fossil fuels, decreases in yield are even more drastic: minus 79-80% of corn, 71-72% of soybeans, and minus 60-78% for cotton (Schlenker et al. 2006).

Efficient allocation of the resource land, facing the impact of various threats, will be one of major future challenges. Conventional cotton cultivation has a significant impact on the soil, which may lead to a further decline in the land available. Furthermore, with growing demand for food due to the increasing world population and projected demand for bio energy crops, a target conflict could evolve, and potentially lead to new allocations and different usages according to which crop my be economically most interesting.

4.2.2 Oil

Naphtha is the primary material for all synthetic man-made fibres, derived by crude oil. In 2007, 13% of Naphtha, i.e. 0.8% of crude oil became synthetic man-made fibres (IVC e.V. 2009). Relating this figure to the global fibre production of 70,600,000 t in the same year, one can conclude that 0.8% of crude oil covered 57.5% of world fibre production (IVC e.V. 2008).

This leads to the assumption that the textile fibre production is in less need for crude oil than other industries; however, it is highly depending on oil as a resource for fibre production and therefore very responsive to variations in oil supply as well as the resulting prices due to missing substitute primary raw materials.

IEA's World Energy Outlook 2008 scenario states, that oil is today's and tomorrow's source of energy, with primary demand rising annually by 1%, from 85 million barrels/day in 2007 to a projected 106 million barrels/day in 2030 despite its decreasing share in total global energy use, where it moves from 34% to 30% in the projected time frame. Real import prices of crude oil are expected to rise from $100/barrel in the time frame 2008-2015 to a price of over $120/barrel in 2030 and short-term volatility of prices is expected to become the norm, especially within the next one or two years (OECD/IEA 2008).

The time of the point of decline – known as Peak Oil – cannot be detected exactly yet. However when facing increasing insecurity in supply and volatility of prices, affordable and available substitute primary materials have to be found to produce synthetical textiles to cover growing demand in the long-term.

Transporting textile goods also consumes oil resources; however this topic will not be covered and energy consumption of textile production will be analysed in subsection 4.2.4 “Energy consumption”.

4.2.3 Water

According to the WWF, an estimated 378 billion litres of water are used annually by the textile industry. This demand, especially due to the water consumption of cotton, already led to environmental catastrophes like the reduction of the surface area of the Aral Sea by 85%, resulting from cotton cultivation in Uzbekistan and Turkmenistan (WWF 2007).

Not every production step consumes water, however, when needed, water is used in high amounts:

	Cotton	Polyester
Fibre (l/kg)	7,000 - 29,000	4,000
Yarn	0	N/A
Textiles (knitting & weaving)	-	
Pre-treatments & dyeing (l/kg)	− Desizing: 12.5-35 − Scouring/washing 2.5-43 − Bleaching 2.5-125 − Mercerization 23-95 − Dyeing 38-143	− Desizing: 12.5-35 − Scouring/washing 25-42 − Dyeing 38-143
Making-up	N/A	

Table 3: Water consumption in textile production steps. Sources: (Laursen 1997, IVC e.V. 2008)

Table 3 shows that fibre production and the finishing processes are water intensive production steps. Water consumption of cotton can be traced back to the intensive water demand of the plant itself of 50 cm – supplied by rainfall or irrigation – to grow and is depending on the cultivation area (Laursen 1997). Irrigation is necessary, as cotton needs certain amounts of water at different vegetation stages, which cannot solely supplied by rainfall. Therefore, best yields are achieved in dry desert climates, e.g. Pakistan and Egypt, where cotton can be irrigated exactly when needed. The irrigation of cotton is estimated with an annual 200 to 1,500 l/m^2 (Paulitsch 2004).

In the production steps of yarn production, knitting and weaving, as well as making-up water is not directly required for the process. However, the steps of pre-treatment and dyeing are very water intensive.

To provide a holistic picture, not only the amount of water consumed but also the quality of the waste water has to be considered.

Cotton needs in addition to a high amount of water also strong protection from insects, weeds, diseases, and nematodes, making the use of pesticides necessary, which will be emitted into the waste water during textile processing (Laursen 1997). After corn, winter wheat and soybeans, cotton ranks as number four of the world’s most fertilised crops. Additionally, it is consuming 25% of global insecticides as well as 10% of global herbicide demand (defra 2007).

When producing polyester filament fibres, versatile water-borne emissions can be detected in the waste water, e.g. Ammonia, Chromium, and oil (Laursen 1997).

As table 3 shows, pre-treatment and dyeing consume water in different applications, leading to various forms of water pollution:

- Desizing: Before weaving, warp-ends have to be sized, i.e. coated with a film, to overcome the production stress. The size can be based on insoluble starch or on soluble compounds such as poly vinyl alcohol, acrylic resins, or carboxymethylcellulose (CMC) (Fiscus et al. 1995). Desizing is a highly polluting step, contributing the major part of up to 60% of the chemical oxygen demand (COD) in pre-treatment. It is possible to recover and reuse synthetic sizes, which cuts water-borne pollution. Sizes based on (modified) starch cannot be recovered because of their degradation to achieve desizing (Laursen 1997).
- Scouring/washing: The waste water from this process can contain versatile residuals, like waxes, hemi-cellulose, spinning and needle oils, as well as residues of pesticides, i.e. residuals of substances and auxiliaries which have been used during processing. These substances and the solvents used lead to a waste water contaminated with various chemicals (Laursen 1997).
- Bleaching: Chlorine-based bleaches release absorbable organic compounds (AOX) into waste water, which are toxic to terrestrial and aquatic organisms. Therefore hydrogen peroxide is a preferred bleaching agent that decomposes into water and oxygen, not generating AOX (Laursen 1997).
- Mercerization: A treatment of cotton to improve luster and mechanical dyeing properties. The process is carried out under tension in strong alkaline medium (NaOH). The waste water contains values in both biological oxygen demand (BOD) and solid substances (Laursen 1997).
- Dyeing/Printing: Printing can be defined as localised colouration and used to create coloured patterns on a fabric as well as garments. The colour can be pigment, mixed with binder to attach to the fabric or dye, which has to be steamed after printing for fixation and washed for removal of unfixed dyestuff (Perkins 1996). In the colouration process of dyeing whole fabrics are treated in a dye bath, containing dyestuff, and further auxiliaries necessary for dyeing.

There are overall seven main types of dyes, which are applied according to the chemical structure of the fibre material to be dyed, as the following table shows:

Dye Class	Fibres used for	Pollution
Direct	Cotton, linen, viscose, silk	Salt, unfixed dyes, copper salts, cationic fixing agents
Reactive	Cotton, linen, viscose, wool, silk	Salt, unfixed dyes, Alkali
Vat	Cotton, linen, viscose	Alkali, oxidizing agent, reducing agent
Sulphur	Cotton, linen, viscose	Alkali, oxidizing agent, reducing agent, unfixed dye
Acid	Cotton, linen, viscose	Unfixed dyes, organic dyes
Metal complex	Wool, silk, nylon	Metals, organic acids
Disperse	Acetate, polyester, nylon	Carriers, reducing agent, organic acids

Table 4: Dyestuff and pollution. Sources: (Eberle et al. 2008, Dyes & Pigments 2009), author’s visualisation

The versatile substances used result in many problems when it comes to waste water treatments. Colourants used will have an environmental impact through the waste water, which comes from dyebaths, washing processes when using dyestuffs for colouration, disposal and spillage of not used dyebaths as well as pigment print pastes. Discharges to local sewage plants may influence the ability of aerobic treatment micro-organisms to biodegrade regular sewage, due to certain dyestuffs and pigments. Carriers used in disperse dyeing can be highly toxic to the environment. Additionally, heavy metals used are partly emitted to the waste water and disposed in the sludge. Furthermore, chromium is produced in several reduction processes and formaldehyde is released in some processes (Laursen 1997).

Even in Germany, where textile waste water discharge into water bodies has to fulfil high requirements, remains of several residual substances are allowed:

Parameters	Amount/Level
COD	160 mg/l
BOD_5	25 mg/l
Phosphor	2 mg/l
NH_4-N	10 mg/l
Total Nitrogen	20 mg/l
Sulphite	1 mg/l
Toxicity for fish eggs (G_{Ei})	2
Spectral absorption coefficient at	in m^{-1}
− 436 nm (yellow area)	7
− 525 nm (red area)	5
− 620 nm (blue area)	3

Table 5: Requirements for waste water of textile production and finishing. Source: (AbwV 2009), author's visualisation

Especially the residual dyestuffs are of concern, as these may lead to shadow effects in aquatic environments causing a reduction of the photosynthesis reaction (Laursen 1997).

Waste water is already today a tremendous challenge in some areas. The southern Chinese province of Guangdong provides 23% of China's total export of textiles and apparel, which results on the other hand in heavy water pollution also from both the residing textile and chemical industry. Around the area of the province's capital Guangzhou, a population of 2,5 million people are increasingly confronted with contaminated drinking water and corresponding health risks (BRS 2008b).

Approximately 3.3 billion people worldwide already experience water scarcity or face economic shortage. It is projected that in 2025, 1.8 billion people will face an absolute scarcity, and additionally, two-thirds of world population could be confronted with water stress (FAO/UN 2007).

Even though China owns the global 6th biggest water volume, the enormous population of 1.3 billion people reduces significantly the water amount available per capita, resulting in a water resource volume per capita to 28% of the global average. Despite this fact, the rate of industrial waste water reused is 55%, in comparison to 80% in industrialised countries due to pollution policies. Additionally, water prices are 70-80% lower than in countries where water supply is sufficient (BSR 2008a).

To manage the water use and the discharge of waste water within the global textile supply chain, the "Sustainable Water Group" was founded in 1995. Current members are amongst others Nike Inc. and

Levi Strauss & Co (BSR 2009). However, it appears that this initiative is only covering water use as well as waste water discharge and does not include preliminary water intensive processes as e.g. cotton cultivation.

One can conclude that not only the high consumption of water due to missing price pressure is a challenge for the textile industry, even more the processes used to modify textiles and the resulting waste water and its treatment require action to optimise the allocation of this source.

4.2.4 Energy

Energy is needed for every production step, and with increasing prices, it is important to assign its allocation to the single production steps.

	Energy consumption (in MJ/kg)	
	Cotton	Polyester
Fibre	48.65	109.41
Yarn (cotton spinning system)	6.33-18.36	N/A
	all fibre types	
Textiles	knitting: 5-20/weaving: 10-30	
Pre-treatments & dyeing[3]		
− Singeing	0.4-1.2	
− Desizing/scouring/washing	1.8-8.8	
− Bleaching/washing/drying	4.80-28.7	
− Mercerization/drying	5.6-11.0	
− Dyeing/washing/drying	3.4-13.2	
− Printing/drying/fixation (with pigments)	1.69	
− Finishing	4.05-8.00	
Making-up	1.75-8.5	

Table 6: Energy consumption in textile production steps. Source: (Laursen 1997, Wiegmann 2002), author's visualisation

Table 6 illustrates that all textile production steps require a significant amount of energy. The energy consumption in the production process is highly depending on the fibre type produced and processed, the properties required and the final product. Making-up for example includes the production steps of cutting, sewing and ironing, where T-shirt production is presumed to use 1.75 MJ/kg in contrast to more complex products as e.g. coats, which are calculated to consume 4.9-8.5 MJ/kg.

In 2006, the global textile industry consumed for the production of 60 billion kg of textiles 1.074 billion kWh of energy (Rupp 2008).

The World Energy Outlook 2008 depicts the following historical and prospected future development of world primary energy demand: Demand for energy will grow by 45% from 2006 until 2030, which equals a raise from 11,730 Mtoe (Million tons oil equivalent) to 17,010 Mtoe. Despite a projected scar-

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[3] The treatment applied is depending on the fibre type. For generating an overall picture, all processes with data available have been listed. In this case, finishing is defined as a treatment adding properties, e.g. crease resist finish or coating.

city of exhaustible resources, the demand for those will continue, whereas nuclear power will decline to a level of 5%, and renewables are slowly increasing in share. Additionally, the energy-related CO_2 emissions have to be considered: According to present trends, the emitted greenhouse gases will lead to a rise of 6°C of the average global temperature in long term (OECD/IEA 2008).
Energy consumption and its efficient allocation will become even more important in the future to manage scarcity and reduce environmental pollution.

4.3 Resource allocations and conclusions

Crude oil is the primary material for currently approx. 60% of world fibre production, i.e. the synthetic man-made fibres. With manifold application fields particularly in the sector of technical textiles, e.g. filters, as part of composites in light-weight constructions, or insulation materials, **new substitute materials or processes** on the same quality level have to be found to cover these tasks when crude oil is becoming scarce and therefore becoming less economical to use.
In the case of **land**, scarcity is already affecting fibre cultivation. The limited area available results in switching crops according to economical performance. In the case of cotton, substitutes are corn, wheat, and soybeans, which proves a clear interdependency between the prices of the harvested goods and the land allocated. However, it cannot be clearly predicted what will happen to land use if prices for cotton become competitive again. A further challenge is the decreasing amount of land available due to degradation as a result of cotton cultivation as well as the projected global warming. Different measures have already been taken to stabilise cotton supply, and to increase and maintain the long-term productivity of the soil, but further optimisation is necessary.
The scarcity of **water** is one of today's most acute problems. Facing looming water stress and scarcity, it has to be questioned how **water intensive processing steps** of textile production like cotton irrigation and dyeing can and have to be modified to not further weaken the future water supply. On a larger scale, international and global waste water regulations as well as laws are needed to push this development. Using improved water management systems as well as developments of non-aqueous dyeing systems promise a more efficient allocation of water.
The majority of textile production processes are rather **energy intensive**, and therefore energy has to be allocated in the most efficient way possible to prevent waste and costs. However, not only considerations in terms of energy reduction based on energy costs and the corresponding potential for cost saving should be done, also customers claims of CSR (Corporate Social Responsibility) have to be satisfied. Customers are expecting products with justifiable carbon foot prints, which means a reduction of CO_2 emissions and thus reducing the energy consumption in production steps. An already implemented energy saving device is the thermal insulation for dyeing machines. Dryers as well as heat recovery systems for washing machines show significant cost savings through reduced energy consumption. In the context of the current energy discussion, it can be expected that further improvements will be developed.
Considering the current state-of-the art technology on the one hand and knowledge about the areas to improve on the other, it can be assumed that the textile industry is aware of scarcity of resources, even if the efforts are predominately driven by cost reasons.

Within the next chapter selected approaches to manage scarcity or to substitute existing methods are described and evaluated regarding their future potential.

5. Approaches in the textile sector to manage resource scarcity

There have always been approaches to a more efficient allocation of resources, like the Lyocell® process in which solvents and water are recycled. Motivations for improvement processes are versatile and range from cost savings over environmental and social aspects to performance improvement approaches.

The following table shows selected promising approaches to reduce resource consumption, which will be discussed and evaluated regarding their future potential.

<table>
<tr><th>Land</th><th>Oil</th><th>Water</th><th>Energy/Processes</th></tr>
<tr><td colspan="4">Recycling & Reutilisation</td></tr>
<tr><td>Organic cotton
GM/Bt cotton</td><td></td><td></td><td></td></tr>
<tr><td></td><td>PLA fibres
Bionics: spider silk</td><td></td><td></td></tr>
<tr><td></td><td></td><td>Efficient Irrigation</td><td></td></tr>
<tr><td></td><td></td><td colspan="2">Plant oil waste water treatment</td></tr>
<tr><td></td><td></td><td colspan="2">Supercritical CO_2 dyeing</td></tr>
<tr><td colspan="4">Ionic liquids</td></tr>
<tr><td></td><td></td><td colspan="2">Enzymatic pre-treatment of cotton</td></tr>
<tr><td></td><td></td><td colspan="2">Ultrasound</td></tr>
<tr><td></td><td></td><td colspan="2">Nanotechnology applications</td></tr>
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Table 7 Approaches to optimise resource allocation

5.1 Recycling and reutilisation of disposed textile products

Saving primary resources is one approach to manage scarcity as there are also approaches developed, which act on the level of recycling to create raw materials of second grade.

Recycling of textiles is divided into different fields depending on the processing after disposal as the following table shows:

Reutilisation	Recycling
− Direct utilization: i.e. second hand or charity − Different application area: e.g. using disposed textiles for cleaning purposes	− Mechanical − Chemical − Thermal

Table 8: Reutilisation and recycling possibilities of textile materials. Source: (Laursen 1997), author's visualisation

Disposed textiles, depending on the quality of the product, can be reutilised, as e.g. second hand clothing, or can become a secondary raw material.

Mechanical recycling means that fabrics are decomposed by hackling, shredding or brushing or a combination of these processes to regenerate fibres. The quality of the secondary raw material is highly depending on the manual pre-sorting of the disposed materials, which is why this is often out-sourced to low-cost countries. The raw material is then reprocessed into e.g. fibres, yarns, non-wovens, insulation products. In 2007, a total of 834,000 t of textiles in Germany have been further processed (bvse 2009). A very successful initiative is Cotton Inc.'s "Cotton. From blue to Green®", in which denim products are collected for transformation into insulation material installed in houses by Habitat for Humanity. A total of 89,799 pieces of denim have been collected since the start of the project in 2006, which have been converted into 185,000 sq. feet of insulation material (Cotton Inc. 2009a).

Depolymerisation, cleaning and polymerisation are the steps in chemical recycling. Annually, 40% of PET bottles in Europe are reprocessed into secondary raw material for synthetic man-made fibres, which saves a raw material equivalent of 200,000 t (IVC e.V. 2009). In the case of thermal recycling, pulverised thermoplastic materials are extruded followed by granulation or spinning of new fibres (Laursen 1997).

Another way of chemical recycling is the use of textile waste like cotton seed husks as biomass. The investments in new bio refineries may also lead to the generation of new raw materials which could be used for textile production. As there are no results from extensive researches available yet, final conclusions cannot be made.

Nevertheless, reutilisation and recycling of textiles saves resources that would have been allocated to produce a new product. In the case of energy, the substitution of one kg of virgin cotton by second hand clothing saves 65 kWh, and for polyester 90 kWh respectively. Or from a different point of view, reusing 1 tonne of polyester or cotton garment requires only 1.8% or 2.6% respectively of the energy needed to produce the product from primary raw material (Woolridge 2006).

Recycling structures as well as procedures prove working. However, it should be noted that chemical and thermal recycling lead to a loss of quality of the secondary raw material, because not all of the educts can be separated again, leading to a decreasing quality with each recycling cycle. Therefore, this recycling can be seen as one approach to save resources but with limitations when it comes to the quality of the secondary raw materials.

5.2 Land: Optimisation of use and reduction of pollution

This resource is limited due to the finite area available as well as it is projected to decrease e.g. due to soil degradation as a result of monoculture cultivation and global warming. Following, two approaches to maintain the long-term quality of the soil are described: Organic cotton and genetically modified (GM) or Bacillus thuringiensis (Bt) cotton.

5.2.1 Organic cotton

According to the US-based Organic Trade Association, "Organic cotton is grown using methods and materials that have a low impact on the environment. Organic production systems replenish and maintain soil fertility, reduce the use of toxic and persistent pesticides and fertilisers, and build biologically diverse agriculture." (OTA 2009). Conventional cultivation of cotton, however, leads to decreasing outputs latest in the third year of cultivation and requires a crop change or field rest of one or more years (Paulitsch 2004).

Thus, the cultivation of organic cotton can be seen as the contrary to conventional grown cotton, as the usage of toxic, persistent agro-chemicals and cultivation of genetically modified organisms is prohibited. The difference starts with the type of seed, as no GM material is allowed. Achieving soil fertility without the use of synthetic fertilisers, crop rotation, cover cropping, more environmentally approaches in weeding, cultivation, insect management systems as well as mechanical harvesting methods are the major differences in comparison to conventional cotton cultivation.

The global market of organic cotton is structured as follows: In the crop year 2007-2008, a global total of 145,872,000 t in 22 countries on 161,000 ha were produced. The growing demand for organic cotton was driven by retailers worldwide. Major organic cotton producer was India, supplying over 50% of the world production, reaching 73,702,000 t, followed by Turkey and others like Syria and China (OTA 2009). The market share of organic cotton is 0,55 % of the global cotton production (Ecotextile News 2008).

The ecological advantages of growing organic cotton are obvious but to provide an overall base for judgement, also economical parameters have to be considered. A research carried out in the San Joaquin Valley in California found out that the production of organic cotton led to a production cost increase of 50% in comparison to conventionally produced cotton. The main driver for this increase is the labour intensity which is needed for e.g. manual weeding operations, as well as the costs for the certification fee, which is paid to the organisation to overlook the operations on the fields. Additionally, if a transition from conventional to organic cotton is planned, fields need a conversion time of three years to get an organic certification. On the quality side however, no difference in fibre length, micronaire, i.e. the fibre diameter, or strength have been detected (ATTRA 2003).

Despite these parameters, in 2008 the global organic cotton sales value reached US $ 3.2 billion, which equals a growth rate of 63% vs. 2007. The demand is also growing, as many brands with different price positioning are planning to offer more organic cotton products. Retails sales figures support this development, as organic cotton is projected to have a global sales value in 2009 of US $ 4 billion as well as US $ 5.3 billion in 2010 (Ecotextile News 2009).

The cultivation of organic cotton does not only reduce the usage and contamination of water but also handles the resource of land in a more ecoloigcal friendly way than conventional cotton cultivation. The power of success or failure lies also with the consumers, which are able to force companies to use more organic cotton, and with increasing demand, the importance of this sector might increase, resulting in more cultivation area needed.

5.2.2 Genetically modified (GM) / Bacillus thuringiensis (Bt) cotton

A second development is the cultivation of GM or Bt cotton, with the major cultivation countries USA, China, and India. As the following table shows, this type of cotton is successfully substituting non-GM crops:

	Cultivation Area in Million ha			
	Total Cotton	GM Cotton	GMO Ratio	GMO Growth
USA 1997	5.21	1.3	25%	146 %
USA 2008	3.7	3.2	86%	
China 1998	4.72	0.034	0.7%	11,076 %
China 2008	5.6	3.8	68%	
India 2002	7.85	0.04	0.5%	17,275 %
India 2008	9.1	6.95	76%	

Table 9: Cultivation area of conventional and GM cotton in USA, China, India. Source: (GMO 2009), author's visualisation and calculation.

This data prove the impressive success of GM crops in the countries cultivated, overall starting from a very low level, having increased significantly.

GM crops can have both environmental as well as economical advantages for the farmers, as the example of China shows. A reduction of insecticide demand of 80% combined with fewer application lead to a significant decrease of costs resulting from labour and inputs. Due to the reduced application of chemicals, also the rate of poisonings of workers dropped to 5% vs. 22%. Additionally, the output per ha increased from 3.18 t with non-Bt cotton to 3.37 t with Bt cotton. In total, the production costs for Bt cotton were 28% lower than the costs for conventional cotton. However, besides the clearly visible advantages there are also disadvantages of GM crops in general, which have to be considered.

- Crops are developed for farming on a large scale, but not for small farmers in developing countries.
- There is a potential for a quasi-monopoly structure on the supply side of the market, which could result in prices higher than the real price equilibrium.
- Patenting challenges, i.e. protection of learnings generated by public sectors and generations of farmers.
- Food safety, i.e. impact of GM crops on other plants.
- Consequences for biodiversity or contamination of organic crops (FAO 2002).

The cultivation of GM or Bt cotton may be a viable future approach to save resources, but there are strong concerns about the impact of these crops on the environment, especially as long-term studies and impact assessments are not available yet and future developments cannot be projected yet.

5.3 Oil: Substitute raw materials and new fibre developments

To decrease dependency on raw oil as resource for synthetic man-made fibres, new man-made fibres using substituting raw materials are being developed. The following chapter will illustrate some examples.

5.3.1 Polylactide (PLA) fibres

PLA, polylactide or polylactic acid, is not a new polymer, however it gained interest due to the current discussion on environmental protection. It "… is a biodegradable, thermoplastic, aliphatic polyester from lactic acid." Lactide acid is produced from cane sugar or corn starch by fermentation of bacteria (Bioplastics Magazine 2009). PLA is used for manifold applications, e.g. for packaging material, disposable plates or agricultural foil.

One of the leading producers of PLA with the brand name INGEO™ is Natureworks LLC, a joint venture of the Cargill and Teijin Limited, using US-grown No. 2 yellow dent field corn as raw material. To produce 1 kg of INGEO™, 2.5 kg corn with a moisture content of 15% is needed (Natureworks LLC 2009a, 2009b).

The following table compares tenacity and melting point of PES, Nylon, cotton, and INGEO™ staple fibres:

	Tenacity (cN/tex)	Melting point (°C)
PES	25-65	255
Nylon	40-60	215
Cotton	25-50	-
INGEO™	30-35	170

Table 10: Comparison of tenacity and melting points of PES, Nylon, Cotton and INGEO™. Sources: (Eberle et al. 2008, Natureworks LLC 2009c), author's visualisation.

Tenacity is a very important property as it expresses which force can be applied to a fibre without breakage, and is an indicator for the strength of a textile material. The unit for tenacity is cN/tex, expressing the force applied to the mass defined in g/1,000 m. The melting point is the threshold value where synthetical polymers denaturise, therefore cotton as natural polymer has none as it starts to burn. The relatively low melting point in comparison to other synthetic fibres is a main obstacle due to the high temperatures in production processes. The application for technical textiles is limited because of the lower tenacity value. Further research is necessary to improve the fibre properties. A major advantage can be seen in the industrial biodegradability of these fibres, which provides a valuable alternative to landfill disposal or incineration. A main barrier for mass market application, besides the material properties, might be the sourcing of primary materials, as PLA is in direct competition to nutrition. This is a result of the fact that resources of land are allocated to crops with higher revenues, a decision led by potential prices to be achieved on the trade markets. A potential independence from oil as resource could therefore turn into an even stronger dependence on the limited resource of land.

5.3.2 Bionics: spider silk

As in many other fields, in textile research nature functions as the archetype and inspiration for developing new materials or new properties of existing materials. Especially spider silk has always been of interest due to its unique properties, which would offer a wide range of applications like in medical or personal protective textiles. Spider silk performs a lot of tasks in nature, e.g. building the web. Up to seven types of silk fibre with varying properties can be produced.

Particularly the fibres' properties in terms of strength, elongation and breaking energy compared to other fibres and materials are of interest:

	density in g/cm^3	elongation in %	tensile strength in cN/tex	energy absorption up to breaking point in kJ/kg
Steel	7.90	1-2	22-29	2
Glass	2.5	2-5	70-120	-
Kevlar® (para-aramid fibre)	1.45	2-5	170-270	30
Nomex® (meta-aramid fibre)	1.38	15-30	44-53	-
Polyamide PA 6, technical	1.14	15-25	60-90	-
Polyamide PA 6, textile	1.14	20-60	40-60	80
Natural silk (Bombyx mori)	1.25	10-30	25-50	70
Dragline spider silk	1.36	10-32	22-132	≤100
Capture thread spider silk	1.36	≤200	≤36	≤160

Table 11: Comparison of mechanical properties of different materials and fibres. Source: (Bauer 2008), author's visualisation

As commercial spider silk production with spiders is not possible particularly due to most spider types tend to cannibalism, researches were carried out to develop an industrial production process. Canada-based Nexia Biotechnologies generated silk from the milk of transgenic goats. However, the state of the development of an industrial process is unknown.

The Technical University of Munich (TUM) announced in 2008 the breakthrough to a synthetical production of spider silk, as it was succeeded in both simulating the processes that happen in the spider's spinning channel and the production of enough protein building block raw material through the genetically programming of bacteria (TUM 2008). In December 2008 AMSilk GmbH was founded to develop, amongst others, a spin silk production process of industrial scale.

The Leibniz-Institut für Pflanzengenetik und Kulturpflanzenforschung (IPK) derived in 2001 spider silk proteins from genetically modified potatoes and tobacco plants, and research was still done in 2007 (IPK 2001, 2008).

Fibres derived from spider silk would be highly competitive not only due to their properties but also to their potential versatile application fields. Furthermore, these fibres are assumed to be biodegradable, and therefore would reduce waste. However, due to the current state of development, data regarding resource input for the production process are not available, and therefore final conclusions cannot be made yet.

5.4 Water: Reduction of consumption and improving waste water quality

As mentioned in subsection 4.2.3 “Water”, the textile dyeing process is not only water consuming but also produces critical waste water carrying versatile residues, which have to be treated before reintegration into the hydrosphere. The following chapter will illustrate some approaches to reduce water consumption and to limit discharged waste water.

5.4.1 Efficient cotton irrigation

Irrigation, the artificial supply of plants with water, is common practise in agriculture, and it is estimated to consume approximately 70% of all water available (SIWI 2009).

In most countries where irrigation is applied, water is already a scarce source, and conventional irrigation effectively uses only 50% of the allocated water, with the residual 50% being evaporated or wasted. There are some starting points to allocate water more efficiently when irrigation is needed, e.g. demand management, crop technology, or by improving and fixing of existing irrigation systems and municipal structures (World Economic Forum 2009).

In the case of cotton this development is also of high importance, as cotton needs in most cultivation areas irrigation to grow. The following examples show the viability of an improved irrigation water management: A trial in Pakistan, using the combination of bed and furrow irrigation practises with water scouting, led to a saving of two to four irrigation cycles per farm and season. Drip as well as sprinkler irrigation methods are able so save up to 70% of water, as this allows precise watering. Further approaches are water storing of e.g. rain water, recollecting water flowing off already irrigated fields, or participatory groundwater management at local level (WWF 2007).

Additionally, some developments in the water management processes promise high potentials to a more efficient allocation of water. Computer models have been developed, that are able to predict water allocation based on information about the plant’s growth stage as well as weather data. Soil moisture sensors are able to monitor the soil moisture and provide information via a transmitter, if there is enough water available in the soil for the crop. On the plant leaves itself, thermal infrared thermometers (IRTs) measure the temperature and depending on that information, deriving data regarding the water need, as the temperature of the leaves increases with decreasing water level (Cotton Inc. 2009b).

However, increasing the efficiency of irrigation leads to more costs due to more labour allocation, equipment as well as fuel. These additional costs have to be compensated by increasing yield output. This proves to be an obstacle especially in countries such as Australia, where the costs for water used for farming are comparatively low and therefore low interest in water saving activities is given (WWF 2007).

Nevertheless, it can be assumed that water prices will increase globally in the long-term, therefore the efficient irrigation of cotton is an important step in significantly improving the allocation of water and for generating a cost advantage.

5.4.2 Dye removal from wastewater with the support of plant oils

The major dye types for cotton colouration are reactive dyes. Due to their structure, these can react with the fibre and form a covalent bond as fixed dyestuff, but also react with water, i.e. are hydrolyzed which is an undesired side-effect from both economical and environmental point of view.

Reactive dyes are structured as follows: CHROMOPHORE─NH─REACTIVE GROUP.

The chromophore, e.g. monoazo, is responsible for the colour, and connected to a reactive group through the bridge of a -NH- group to avoid a reaction of both. The reactive group, having no or little influence on the colour itself, will react with the fibre in the dyeing process (Spencer 1996).

In general, azo dyes with the -N=N- characteristic can be found in nearly all dye classes, and as they can be modified in their chemical constitution, nearly every dye type can be covered, resulting in more than 50% of the dyes available belonging to this general group. Especially the azo part is of concern and suspected to be carcinogenic. As there are no data available regarding the toxicity to humans, no assumption can be made. However, long-term tests on animals showed, that " … the metabolism of benzidine dyes in animal and human organisms results in the formation of the carcinogenic benzidine through reductive cleavage of the azo group. […] With the ingestion of large quantities of such dyes, an increased risk of bladder cancer can no longer be ruled out." (Rouette 2001).

Precipitation of azo dyes from the waste water therefore is a vital process. Additionally, the removal of reactive dyes from waste water is a challenge due to their synthetic origin, the rather complex aromatic construction as well as the high solubility. In general a wide range of chemical, biological and physical waste water treatment is available, varying significantly regarding costs, treatment products and performance.

A research team of the Department of Process Engineering and Applied Science of Dalhousie University in Halifax discovered that conventional plant oils are able to remove dye from textile waste waters using the Supported Liquid Membrane (SLM) technique. The objective of the research was defined as "…to investigate the potential of using […] non-toxic, natural plant oils as a liquid membrane for the removal of the dye remazol brilliant blue from the textile wastewater. The specific objectives were: (a) to evaluate the effectiveness of five oils (cottonseed oil, olive oil, canola oil, sunflower oil and used cooking oil) for removal of the textile dye remazol brilliant blue and (b) to investigate the effects of pH and temperature on the dye removal efficiency." (Mahmoud et al. 2007).

The four commercially available oils – cottonseed, olive, canola, and sunflower, all bought at a supermarket –, as well as the used cooking oil – from a local restaurant – were investigated under five different pH values as well as five different temperatures in three repetition, resulting in a total of 375 treatments. The following table shows the findings:

Oil	pH	Temperature in °C	Reduction in %
Cotton seed	13	55	58.06
Olive	13	55	87.00
Canola	7	55	53.06
Sunflower	13	55	58.08
Used cooking oil	13	55	95.45

Table 12: Performance of different plant oils in dye removal. Source: (Mahmoud et al. 2007), author's visualisation

With increasing temperature, the dye removal of all oils increased under all pH conditions tested, with pH 13 being the most efficient value for all oils except canola. Additionally the efficiency of removal is correlated to the viscosity of the oil used, with viscosity increasing with the time fried (Mahmoud et al. 2007).

The removal of reactive dyes from waste water with the support of plant oil is efficiently done by used cooking oil as best performer. Itself a waste-product the price might be relatively low and no further new and unused resources need to be consumed. Further research should be carried out to increase the removal of the dyestuffs as well as how the contaminated oils are able to be recycled or disposed without having an impact on the environment. One obstacle to be considered might be the alkali waste water resulting of this process.

Considering the high amount of oils used for food preparation globally, this process has the potential for up scaling presuming further research in process engineering to increase efficiency. Obstacles may be the potential competition to nutrition as well as the organisation needed to collect and transport the used plant oil from the restaurants to the dye houses. A further potential target conflict could be seen in connection with biofuels using plant oils as primary raw materials, which can be presumed to be a by far bigger market and therefore interesting for suppliers due to competitive pricing. Nevertheless, this process is an environmental friendly approach to improve the quality of waste waters after dyeing, and significantly reducing the impact of azo dyes.

5.5 Processes: New systems reducing resource allocation

There have not only been researches and developments to reduce input of one resource, several researchers and institutes develop integrated approaches combining process steps in order to save various resources.

5.5.1 Supercritical CO_2 ($scCO_2$) dyeing process

The movement of “green chemistry” has the objective to be “… a chemical philosophy encouraging the design of products and processes that reduce or eliminate the use and generation of hazardous substances.” (Chemie.de 2009a). One development is the use of supercritical CO_2 as solvent. CO_2 is a non-toxic, inert and nearly inexhaustible resource. These properties offer a wide area of applications, also in the polyester dyeing process, substituting the dyeing liquor. The latest version of this non-aqueous dyeing process covers the treatment procedures of cleaning, dyeing, and removal of excess dyestuff.

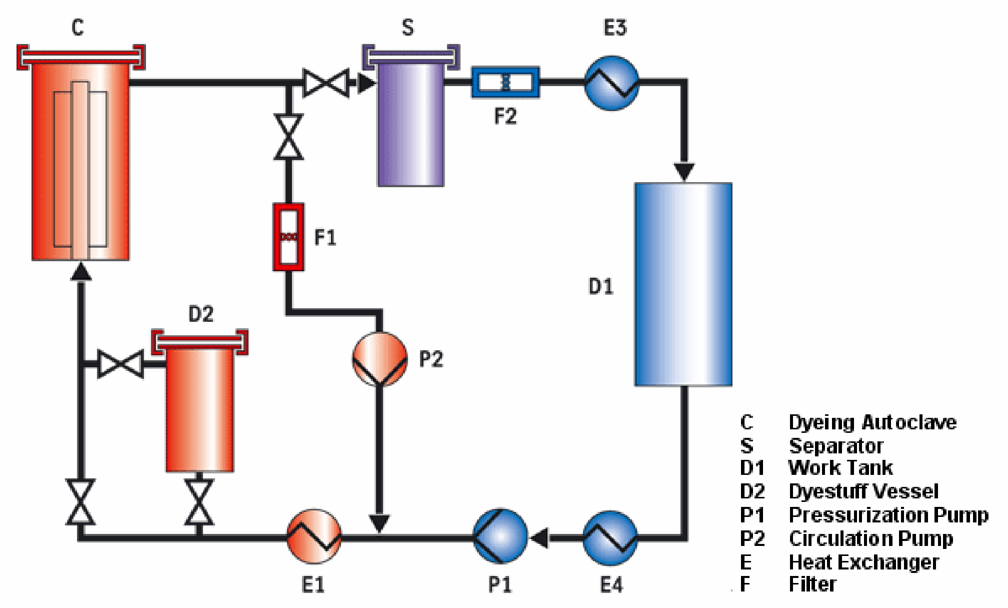

Figure 4: Technical construction of dyeing procedure with $scCO_2$ by Uhde HPT GmbH. Source: (Uhde HPT 2009)

First, the textile material is pre-treated with $scCO_2$ to remove all production process residues and other hydrophobic substances. After passing the textile and solving residues, the $scCO_2$’s pressure is decreased and the removed pollutants are separated. The clean $scCO_2$ is re-entering the circle. In the dyeing process, the dyestuff is solved by the $scCO_2$ and passes the textile material in the autoclave, where the dyestuff is absorbed. To remove excess dyestuff, the dyestuff receiver is released of the circle and $scCO_2$ is expanded which leads the remaining dyestuff to precipitate and being collected in the separator unit. This circuit is repeated until plant and textile material are cleaned. Compared to conventional dyeing methods, this process offers significant environmental advantages:

i. As it is a non-aqueous system, there is no water pre-treatment or contaminated waste water which has to be treated,
ii. Fibres are not damaged,
iii. Due to the absence of water, there is no need for a drying process, which saves up to 80% of energy (Uhde HPT 2009).

The application of this process, however, depends on the fibre type. This showed a research carried out by the Delft University of Technology. The fibre materials of polyester, cotton, aminated cotton, silk, and wool were treated with reactive dichlorotriazine dye in $scCO_2$. Polyester achieved a good colouration result, which increases with growing application of pressure but is independent of temperature. Also, silk and wool can be dyed with this process using the above-mentioned dye. But changes in temperature or pressure did not show to have any effects, and for generating a covalent bond between dye and silk, water will be needed. Cotton dyeing will be a challenge, as the colouration result can be judged as poor, and aminated cotton only offering a slightly better result, due to lower polarity and the amino groups present in comparison to untreated cotton (Kraan et al. without year).

A potential barrier from the economical point of view for this technology is the investment in new equipment for dyeing systems. As the process needs a special temperature as well as a special pressure to keep the CO_2 in supercritical phase, special autoclaves are needed, which are not available commercially yet (Anderson 2008a).

However, also the lower costs for water and the abolishment of waste water treatment have to be considered. Based on the data given of water consumption for polyester pre-treatment and dyeing, 75.5 - 220 l/kg could be saved.

The $scCO_2$ dyeing process can be assessed as a process with high future potential, despite the necessary costly equipment modification. Facing the future growth of polyester as main fibre and an enormous scarcity of water in the future, this process would prevent unnecessary further contamination especially in countries like China, where water is already scarce.

5.5.2 Ionic liquids

Within the field of textiles, the research focus for Ionic Liquids (ILs), i.e. potential future application fields are cellulose regeneration, chemical recycling, and dyeing. ILs, e.g. 1-Butyl-3-methylimidazolium hexafluorophosphate, are salts with the special property of having a melting point lower than 100°C. Additionally, all ILs are of high polarity, remain in the liquid phase until 300°C, do not evaporate in high vacuum, and are inflammable (Chemie.de 2009b). ILs are applicable for textile processing, as well as for industrial processing in general, as the individual properties, e.g. hydrophobicity or hygroscopicity, can be designed to the solvent's application through the combination of anions and cations.

ILs as solvents also provide economical and technical viable access to the usage of renewable resources, as the case of cellulose regeneration shows. Due to the missing appropriate solvents in the past, only 2 billion tons of the annually produced 40 billion tons of cellulose are further processed. Producing cellulosic man-made fibres via the complex viscose process needs, besides other auxiliaries and water, carbon disulfide (CS_2) as solvent, which has to be disposed after the spinning process. As ionic liquids can be recycled the effluents in the production process are reduced (Anderson 2008b).

To analyse the application potential of ILs in cellulosic man-made fibre regeneration, a research cooperation between BASF, ITCF Denkendorf, and TITK Rudolstadt was founded, uniting all competences for textile production. Cellulosic man-made fibres regenerated with ILs technology showed similar properties as conventionally produced cellulosic man-made fibres (Hermanutz et al. 2006).
In 2007, scientists from the Yamaguchi University, Ube, succeeded in recycling polyamides with the help of ILs into caprolactam.

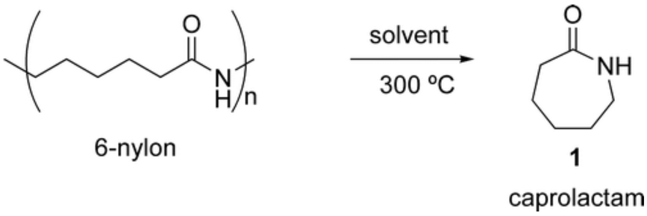

Figure 5: Reaction Nylon 6 with solvent. Source: (Kamimura et al. 2007)

As chemical recycling is the best method to generate high quality raw material of second grade, the findings of this research are significant. The tests were carried out with common laboratory glassware and without high-pressure equipment. Different solvents were used to monomerise Nylon 6, and best performance was obtained with the IL PP13 with the recycling rate of 86% with the use of a catalyst. Also, there was no significant performance loss (from 86% to 78%) of the ILs itself, as it has been recycled at least five times in the reaction present (Kamimura et al. 2007).
First trials in the field of dyeing with ILs have been successful. Different fibre materials were treated with conventional available dyes: Cotton with direct and bi-functional reactive dye, polyester with disperse dye, polyacrylonitrile with cationic dye, Polyamide 6.6 with a metal-complex dye, and a polyester/cotton blend with disperse dye. The textiles were treated with the dyes solved in ILs in a non-pressure system, without addition of supporting auxiliaries, heated up by a circulating air oven. After the dyeing process, the samples have been rinsed and washed several times, the samples treated with disperse dyes were additionally treated with acetone. All processes achieved good dyeing results, and good washing fastnesses (Knittel et al. 2007).
As there is no water needed and therefore no waste water produced, this process might have a high potential in industrial use. However, the acetone used for rinsing has to be filtered out. Also due to the low energy demand in the lab tests of 80-140°C in a non-pressure system for a period of 30-60 minutes are noticeable aspects for this approach. However, the acetone used for rinsing is volatile, and has to be filtered out after application. Further research has to be carried out to develop processes for an economical use of this green chemistry.
ILs application is particularly interesting in the field of synthetic man-made fibre recycling, if the process applied to Nylon could be transferred to a recycling process for polyester, saving the raw material of crude oil. Also, first trials in the process step of dyeing are also promising, as with ILs the major fibre and dye types are able to be processed without water as well as without supporting auxiliaries required in conventional dyeing processes.

Nevertheless, ILs are still a relatively new solvent technologies in comparison to existing systems, therefore research is still needed to increase output from a laboratory to industrial level. This also results in a lower demand, resulting in comparatively higher prices for the ILs material.

As there has not been intensive research yet regarding the environmental impact of ILs, conclusions cannot be drawn yet if and what kind of effect the potential industrial use will have. One obstacle might be the only poorly biodegradability, or the toxicity of some ILs to micro-organisms, therefore this property has to be built in during the design stage (Anderson 2008b).

5.5.3 Enzymatic pre-treatment of cotton

As the subsection 4.2.3 "Water" and 4.2.4 "Energy" explained, treatment processes for cotton are water as well as energy intensive. However, these processes are necessary to prepare further process steps, e.g. dyeing applicable, as well as to produce a qualitative product.

An approach to reduce energy and water usage can be found within the field of industrial biotechnology using enzymes for processes (white biotechnology). In the textile industry, enzymes are conventional tools used for treatment processes:

Enzyme	Effect
Cellulases	− Splitting of cellulose (into saccharides) in cotton softening − Biological degradation of cotton − Carbonation − Non-stone jeans treatment − Fashionable effects − Carboxymethylcellulose (CMC) desizing
Ligninases	− Pectinases for soaping, galacturonases: splitting of lignin during carbonisation and scouring
Lipases	− Removal of fats and waxes
Pectinases	− Vegetable fibre stripping
Peroxidases	− Oxidation of natural pigments
Proteases	− Splitting of albuminous proteins (into amino acids) during degumming − Felt-free finishing − Animal fibre stripping − Changes of wool properties
α-Amylases	− Splitting of starches (into saccharides) in desizing

Table 13: Enzymes used in textile production processes. Source: (Rouette 2008), author's visualisation

In comparison to non-enzymatic processes, the use of enzymes offers several significant advantages, e.g. their selective working method using the key-lock-principle, usage in catalytically concentrations under neutral pH-values as well as low temperature requirements. Furthermore, enzymes are biodegradable and can be handled without special care.

To take more advantage of the performance of enzymes, a process for cotton pre-treatment has been developed to replace the alkaline scouring, a water and chemical intensive treatment. A liquor containing commercial α-Amylases, pectinases as well as hemicellulases was used to treat the textile material, followed by the step of hot bleaching to remove residual coloured cotton compounds, both procedures applied on conventional industrial equipment.

This process gained competitive results in comparison with a conventional desized, scoured and bleached material as the selected parameters show:

Parameter	Conventional Procedure	Combination of desizing and bio scouring
Degree of desizing	8-9	8
Drop penetration time (in s)	3	1
Rel. weight loss of material /in %)	-11.2	-8.0
Degree of whiteness	90.2	90.5
Tensile strength (in daN)	61.6	63.0
Elongation at F_{max} (in %)	24.4	24.7

Table 14: Comparison of results of cotton pre-treatment with conventional and enzymatic processes. Source: (Opwis et al. without year), author's visualisation

The degree of desizing ranges on rank 8 out of 9, which is directly comparable to the conventional procedure. The lower weight loss of the fabric in the combined system is a result of lower damaging due to partial hydrolysis, a major challenge in alkaline scouring. This results in a higher tensile strength as well as elongation. Also, the degree of whiteness is comparable.

The application of the combination of desizing and bio scouring also provides significant savings in terms of resource consumption and therefore costs:

Water demand	6,000l
Energy	2.21 GJ or 615 kWh
CO_2	115-250 kg
NaOH	75 kg
Costs (calculated based on average German middle-class textile finishing company)	226.00 €

Table 15: Potential savings of cotton pre-treatment with enzymes. Source: (Opwis et al. without year), author's visualisation

Table 15 shows the energy, water and costs savings for the treatment of one metric ton cotton.

It was also analysed whether the subsequent process of bleaching can also be carried out using enzymatic treatment. By the application of a combination of glucose, GOD and CPO a whiteness degree of 66% can be reached (Opwis et al. without year). This shows the potential of enzymes also in bleaching and further research is needed to investigate the future potential.

Enzymatic pre-treatment of cotton is an environmentally friendly, effective process and might have the potential to substitute conventional, water and energy consuming processes when available in industrial scale. The approach on a meta level to combine and integrate process steps to save resources can be judged as an effective starting point to manage scarcity.

5.5.4 Ultrasound

Ultrasound is defined as sound waves that are inaudible for humans, ranging from 16 kHz to 1 GHz. The application fields are manifold, e.g. the cleaning of medical equipment or the extraction of substances, and in the field of textile it is a tool for thermal cutting.

A further potential use of this technology is in enzymatic cotton pre-treatment processes, where it is able to support desizing with amylase as well as bio scouring with pectinase. The application of ultrasound increases the performance of enzymes, as the double-sided mass transfer from fabric to liquor and vice versa is increased as well as it activates enzymes with big molecules. This additional treatment results in a significantly higher desizing degree and increases fabric wettability compared to an enzymatic treatment without ultrasound. Regarding fabric weight loss and breaking strength, the application of ultrasound led to an increase in both values, but to a justifiable extend, and not largely varying from the sole enzymatic application. However, when using two baths, one for desizing and one for scouring, the results are better than compared to both processes being applied in one bath. On the other hand, the process in one bath is of more interest due to economical and environmental aspects as it needs less time, water, energy and generates less waste (Karaboğa et al. 2007).

The performance of the environmental friendly and economical approach of using enzymes in textile treatment can be further increased by using ultrasound as a catalyst. Toxic effluents could be further reduced, and by reaching common levels in desizing and scouring, even conventional processes might be substituted.

5.5.5 Nanotechnology applications

In April 2008 PEN – The Project on Emerging Nanotechnologies, a partnership between the Woodrow Wilson International Center for Scholars and the Pew Charitable Trusts – listed in its database 609 nanotech goods. It is estimated, that by 2014 products worth $ 2.6 trillion will feature nanotechnology. Silver as nanomaterial is used in 20% of the products in the inventory (PEN 2009).

There is a general discussion on how to handle nanotechnology. On the one hand, it is a highly promising technology, offering new areas of application as well as improving existing methods and products. On the other hand, not all compounds are stable, as the following examples of the toxic socks will illustrate. Silver nanoparticles are used to give socks the properties of odour elimination. As they are known to be toxic to aquatic organisms, e.g. fish, it was tested, in which amount silver nanoparticles were released by successive washing new, modified socks. The result was that half of the particles stayed on the fabric material, while the other half dissolved and converted into a silver ion without properties of nanomaterials. The treatment of the contaminated waste water led to the learning that silver nanomaterials interact with the biomaterial of the waste water, later to be used as biosolid fertilisers for non-food crops. However, the environmental impact cannot be projected yet but caution and responsible handling should be mandatory (Crytzer Fry 2008).

Researchers of the Victoria University of Wellington succeeded in dyeing merino wool with silver nanoparticles, which are stable in washing and rub fastness. As this process is expensive, the application field is currently targeted and limited for high-end premium products (Kelly, Fern M. et al. 2008).

Nanotechnology might be able to convert textile fibres presently not in the centre of interest due to insufficient properties into high tech fibres that could substitute conventional fibres. Flax, as renewable primary source with high fibre strength and low elasticity, could be coated with additional nanolayers and used for technical textile applications like bulk good containers and substitute crude oil polymer derived synthetic fibres.

Nanotechnology also offers manifold applications for modifications in the fields of textile. Besides benefits for consumers, there is further research required regarding environmental behaviour of especially silver as nanoparticle as well as to define potential applications for resource savings, as processes using nanotechnology designed to save resources in textile production could not be detected.

5.6 Overview and evaluation of potential future approaches (1/2)

	Status quo	Assessment of potential	Research Institutes/Organisations
Supercritical CO_2 dyeing	− Industrial test trials successful − Ready for industrial upscaling	+ In comparison to conventional PES dyeing processes significantly lower water and energy consumption + Integration of cleaning and dyeing process + Elimination of drying process + No effluent production, recycling of dyestuff and CO_2 + Increasing production efficiency	− DTNW, Krefeld
Ionic liquids	− Laboratory trials successful	+ Promising green chemistry technology + Substitution of chemicals + Recyclable − Obstacles: Impact on environment not defined yet − Further research required	− Dyeing: DTNW, Krefeld − Nylon 6 Recycling: Yamaguchi University, Ube − Cellulose regeneration: BASF, University of Alabama, ITCF Denkendorf, and TITK Rudolstadt
Bionics: spider silk	− Laboratory trials successful − Industrial production process in development	+ Excellent properties for application in technical textiles + Reduction of CO_2 emission compared to other fibre raw materials + Increasing independence from synthetic man-made fibres	− Technical University of Munich (TUM)/AMSilk, Munich

Table 16: Overview and evaluation of approaches

5.6 Overview and evaluation of potential future approaches (2/2)

	Status quo	Assessment of potential	Research Institutes/Organisations
Plant oil waste water treatment	− Laboratory trials successful	+ Promising end-of-pipe solution − Obstacles: Raw oil quality, sourcing prices, potential competition to biofuels and nutrition − Only indirect improvement of resource consumption − Alkaline waste water quality	− Department of Process Engineering and Applied Science, Dalhousie University, Halifax
Enzymatic pre-treatment of cotton	− Industrial scale trials successful	+ Environmental friendly process + Reduced consumption of water and energy + Increasing production efficiency	− DTNW, Krefeld
Ultrasound in enzymatic cotton pre-treatment	− Laboratory trials successful	+ Environmental friendly process + Increasing production efficiency	− Ege University, Department of Textile Engineering, Izmir
Nanotechnology application: merino dyeing	− Laboratory trials successful − Industrial upscaling in progress	− Environmental impact of effluents not determined yet − Expensive process, technology for niche markets	− Victoria University of Wellington

Table 16: Overview and evaluation of approaches

6. Status quo and outlook

Scarcity of resources is a complex challenge for the textile industry. The status quo of this development can be illustrated as following:

The impacts appear on versatile levels and in different areas, demanding measures for a more efficient resource allocation. This means that every production process step is affected, independent of the amount or type of resource consumed. As the examples show, the resources needed for textile production are each scarce in different dimensions: **Oil** is an exhaustible resource itself. **Water** is not at risk of scarcity but due to non-efficient allocation scarce in some regions. **Land** is available in a finite amount, therefore allocation is driven by best economical input and output. **Energy** can be both from exhaustible and renewable origin but has to be allocated in the best possible way to reduce costs and CO_2 emissions.

Given working market mechanisms, the first short-term impact of scarcity would be a higher price for the resources due to increasing demand meeting a stable or decreasing supply. However, this mechanism is not in action as a result of market interventions like subsidies, for e.g. cotton cultivation, water or energy, distort markets, leading to artificially created prices, and destroying real competition on the global market.

Despite economical challenges, technological approaches to manage scarcity are already implemented or currently developed:

Substitution fibre technologies, e.g. PLA fibres, are already conventionally available however will need further modification to achieve quality level of the conventional fibres aimed to substitute, like PES.

Recycling concepts prove to be working, however the quality loss of the secondary raw material is a challenge to be addressed as well as the further development of efficient processes for the most demanded fibres.

New process developments, with the potential to improve or substitute conventional processes, are promising. Nevertheless, further investments and researches are necessary for industrial upscaling as well as to generate in-depth knowledge about possible, today unknown, side effects and possible environmental impacts.

Keeping the current state of development in mind, the requirements to manage resource scarcity in the textile production pipeline can be derived as following:

As resource scarcity is a global challenge, **global environmental protection guide lines** are needed to manage this problem. When looking at most low-cost production countries, environmental protection laws do either not exist or cannot be implemented due to the non- or not sufficient existence of administrative infrastructure. This leads to a low motivation to allocate efficiently, comparable higher pollution and waste rate in areas where resources like water are already scarce, therefore extrinsic pressure is needed as in certain areas in China.

Development of fibre raw material substitutes, which are on a comparable quality level to conventional fibres and whose raw material procurement is not in competition with nutrition. With growing demand of land for other agricultural purposes than cultivation area for PLA fibre raw material, supply may be threatened to decline due to economic interests. The current decline in the cotton cultivation area due to financial motivation is proving that land as resource is allocated on the basis of economical aspects.

The majority of promising, environmental friendly production processes require significant **investments from textile industry** side for further research or upscaling. Textile companies, if producing or trading, should be aware that investments in long-term technologies are amortised over a longer time period but a first move towards more environmental friendly production could lead to a significant competitive advantage, which is able to repay on a higher level.

Additionally, the power which lies in the hands of end-consumers should also be taken into account, i.e. the necessity of a valid, reliable and lived **corporate social responsibility policy (CSR).** Consumers as stake holders make purchase decisions, which are also based not only on hard facts like price or characteristics, but also on soft facts like corporate behaviour and environmental policy. An environmental approach for production is highly appreciated by consumers which can even overcome potential price barriers when quality is at the same level, i.e. lead to an acceptance of a higher price, as the example of increase for more expensive but organic cotton shows.

There is not “the only way” to go to manage resource scarcity in textile production, but there are in fact promising technologies literally waiting for further investments to be scaled up to industrial dimensions, as well as interesting approaches in development. Nevertheless, extrinsic motivation, in a monetary and legislative way, is needed to push the pace of implementation.

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