Textiles for Circular Fashion

Part 1: Fibre Resources and Recycling Options

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Preface

People have three elementary needs in order to stay alive: food, shelter and clothing. Feeding the world is gaining a lot of attention all over the world, and studies show that the food demand, even with a growing population, can be met by diet changes and crop-yield improvements. The way we shelter ourselves is slowly changing, as we are more aware of the environmental burden of using unsustainable building materials and the benefits of an energy-efficient house. But the way we dress ourselves needs to change drastically, as the textile industry ranks among the highest emitting and polluting industries in the world and consumers love to wear new clothes.

So we decided to write a “textiles for dummies” publication, to contribute to this change. We both have a background in materials science and polymer chemistry, ample experience in the field of renewable materials in a circular and biobased economy, and we share a passion for making our own clothes. Textiles for circular fashion brings this all together. With this booklet we hope to shed more light on the options and feasibility of different routes towards better recycling of textiles. It is a combination of general information on materials and production methods, polymer science and knowledge of the circular and biobased economy.

This booklet is intended for a broad public, for everyone who is interested in the technology behind textiles. It is written through the eyes of two chemists, but we tried to simplify the chemistry as much as possible. It is the first part of a series, as we quickly realised that recycling is only one piece of the big puzzle called circular fashion. We hope you have as much fun in reading this publication as we had in writing it!

Paulien Harmsen and Harriëtte Bos

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1 Introduction

1.1 Why this study?

The production of textiles and apparel is a world-wide business. The yearly global fibre production for textiles and non-wovens amounts to over 100 million tonnes, or 14 kg per capita per year (Rex et al. 2019). However, the current textile industry uses large amounts of non-renewable resources and applies hazardous substances and polluting

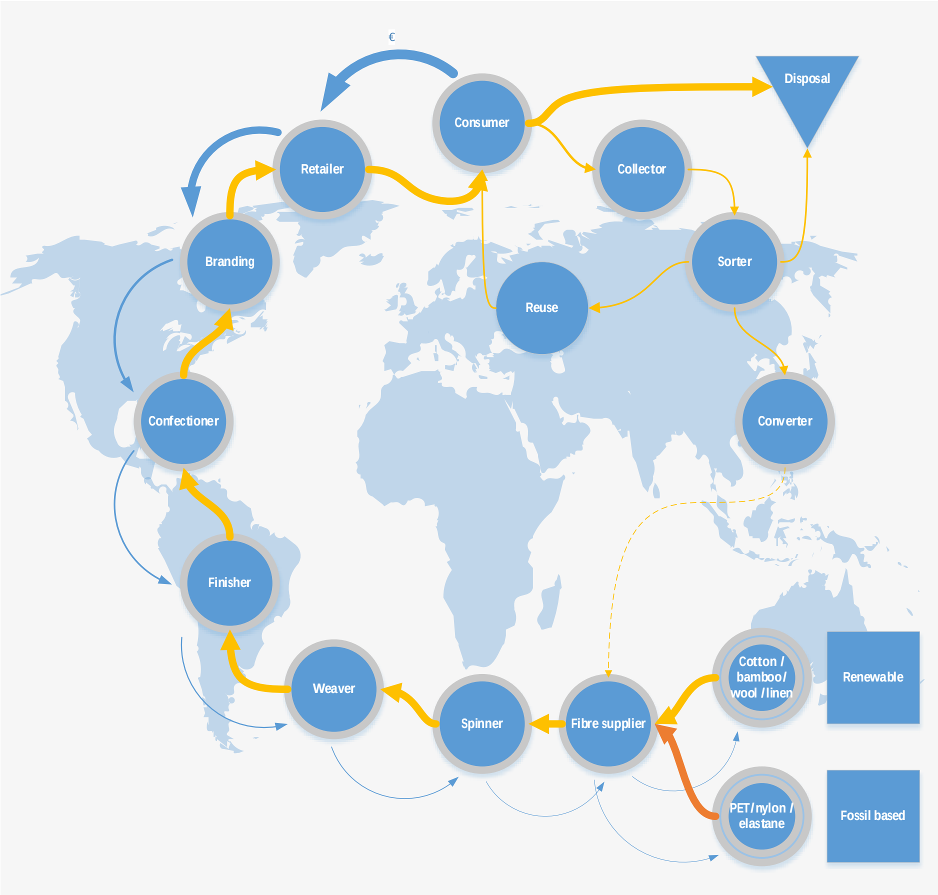


Figure 1.1: The textile value chain of stakeholders from fossil and renewable resources to the post-consumer disposal phase. The yellow arrows represent the flow of the materials, while the blue arrows indicate the flow of currency. Figure by Jan van Dam.

processes. The textiles and clothing industry is therefore increasingly put under pressure, since the awareness of the pollution it causes is increasing due to numerous reports, newspaper articles and documentaries. On top of this, the ever spreading trend of fast fashion has led to fast fashion retailers selling clothing that is expected to be disposed of after being worn only a few times (Carr 2012). It is estimated that between the years 2000 and 2015 the clothing production has approximately doubled, and in the same period the average number of times a garment is worn before it ceases to be used has decreased by 36%. These trends obviously put an ever-increasing pressure on resource availability. Next to this, textiles production ranks among the highest emitting and polluting industries in the world. As an example, approximately 20% of the global industrial water pollution is caused by the dyeing and treatment of textiles (Ellen MacArthur Foundation 2017).

The awareness for the polluting nature of the textile industry and especially the role of both brand owners and consumers in this respect is increasing. In the textile industry focus lies ever more on combatting global warming and thus reduction of greenhouse gas emissions. Furthermore, more sustainable production and higher resource use efficiency is gaining attention and is becoming an important topic for the sector.

Textile production is a global affair, and the chain of industries from resources to garments is complex and interwoven (Figure 1.1). Changing such an intricate system is not easy and it will take a combined effort to find a way to a more sustainable future. Multi-stakeholder dialogues are needed to find solutions and routes to reduce the impact of textile consumption on the planet. Next to this, new solutions to reduce the resource use of the textile industry need to be developed and implemented. One of the routes to go will be increasing circularity in the textiles and clothing industry (Ellen MacArthur Foundation 2017).

With this booklet on circular textiles we hope to contribute to this change towards more circularity, by shedding more light on the options and feasibility of different routes towards better recycling of textiles. In this booklet we especially focus on the market segment of apparel. But what is the definition of circularity related to the textile and clothing industry? We elaborate on this question in the next paragraph.

1.2 Circularity in textiles and fashion

Circularity is a concept that originates from the field of industrial ecology, combined with circular design concepts such as cradle to cradle. The underlying concerns are the ever-increasing depletion of non-renewable feedstock. Circular solutions thus aim at fulfilling societal demand while minimising the input of virgin resources. Circularity concepts therefore go much further than just recycling of materials into new products.

Figure 1.2 shows a hierarchy of circular solutions relevant for the textiles and clothing market segments. Ideally, waste is prevented by for instance changing consumer behaviour, to wear clothes for a longer period, or to implement other business models in the fashion industry, such as textile rental. When a garment is disposed of ideally it is reused by another customer through the 2nd hand market. When the garment is no longer wearable it can be downcycled into a product of lower value such as wiping rags. When the fabric is no longer usable as such, fibre recycling techniques come into play. And when fibre recycling is also no longer possible, energetic recovery (burning with energy recovery), or, worse, landfilling are the final options. In this booklet we focus mainly on the process of fibre recycling and we will try to unravel which are the logical and preferred recycling routes for different fibres (chapter 4), and how these choices are influenced by the difference in origin and properties of these fibres. In chapter 5 we focus on the recycling options for blended fabrics, which are these days generally made up of a mixture of different fibres.

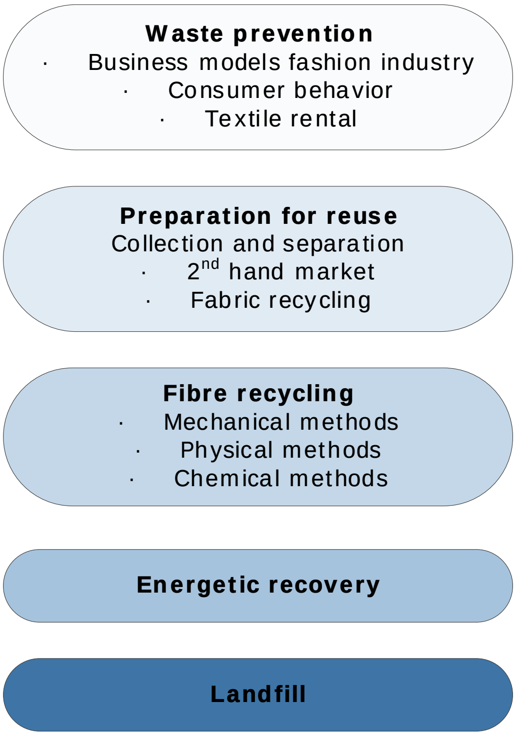


Figure 1.2: The different options for circularity of textiles. The higher in the order, the more preferable and sustainable the options generally are.

1.3 Classification of fibre groups

As touched upon briefly in the previous paragraph, the origin and make-up of the fibre are important parameters in defining the options available for recycling and a better circular use of textiles and garments. Classification of textile fibres can be done in many ways. A widely used method is to classify the fibres based on their origin and resources:

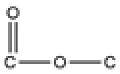
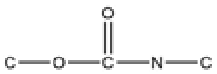
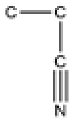
- *Animal fibres:* Protein-based fibres produced by animals (i.e. wool and silk).
- *Vegetable fibres:* Cellulose-based fibres from vegetable origin like seed fibres (i.e. cotton), bast fibres (i.e. linen) and leaf fibres (i.e. sisal).
- *Regenerated fibres:* Fibres from natural polymers that are not useable in their original form but can be regenerated (i.e. reformed) to create useful fibres. These can be based on cellulose (i.e. viscose) or protein.
- *Synthetic fibres:* Made by polymerisation of monomers to polymers in an industrial process (i.e. polyester and polyamide). These fibres are originally made from fossil resources (mostly fossil oil) but also biobased alternatives are available nowadays.

Figure 1.3: Production of fashion takes place at a large scale.

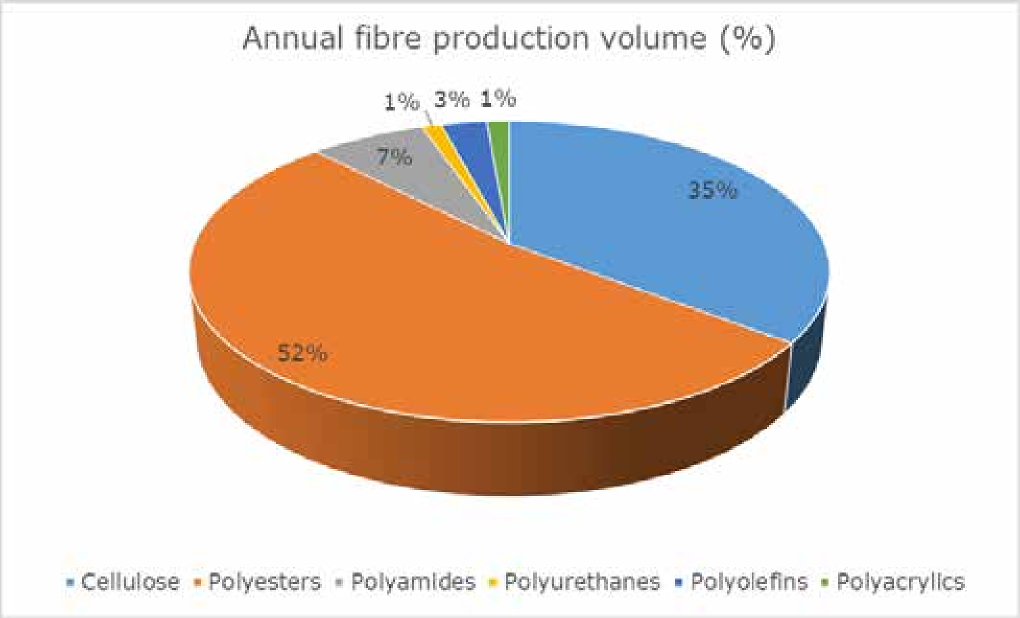
Another way of grouping textile fibres is making a division in natural and man-made fibres (including both regenerated fibres (i.e. viscose) and synthetic fibres (i.e. polyester and polyamide)). In this type of classification, the production process is leading.

A third method, used in this publication, is based on chemical groups/bonds that form the backbone of the macromolecules (polymers) the fibres are made of, and that impart characteristic properties of the fibres. It is useful to classify the various types of textile fibres on basis of their main chemical bonds, as fibres sharing the same kind of chemical bonds have similar chemical and often physical characteristics. Especially when recycling is considered, this way of classification is preferred as it helps in evaluating the options available. Table 1.1 shows the main polymer groups discussed in this publication, i.e. cellulose-based fibres, polyesters, polyamides, polyurethanes, polyolefins and polyacrylics.

Table 1.1: Classification of textile fibres based on polymer linkages.

Polymer	**Cellulose**	**Poly-esters**	**Poly-amides**	**Poly-urethanes**	**Poly-olefins**	**Poly-acrylics**
Linkage	β-glycosidic	ester	amide	urethane	alkane	acrylonitrile
		 $\overset{O}{\overset{\|}{C}}-O-C$	 $\overset{O}{\overset{\|}{C}}-N-C$	 $C-O-\overset{O}{\overset{\|}{C}}-N-C$	$C-C$	
Fibres	Cotton	PET	Wool	Elastane	PP	Acryl
	Flax	PTT	Silk		PE	Modacryl
	Viscose	PBT	Nylon			
	Lyocell	PLA	Protein			
	Acetate					

PET: polyethylene terephthalate, PTT: polytrimethylene terephthalate, PBT: polybutylene terephthalate, PLA: polylactic acid, PP: polypropylene, PE: polyethylene



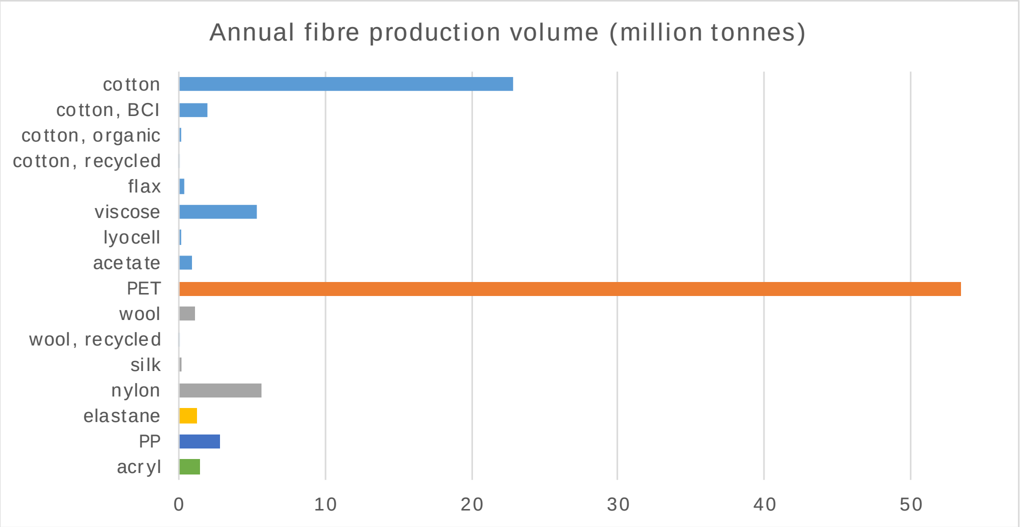


Figure 1.4: Global annual fibre production in production volume (in %) (upper figure) and breakdown of the polymer groups to specific fibres (in million tonnes) (lower figure). Total volume 102 million tonnes. Source: RISE (Rex et al. 2019) with data mainly from 2016. BCI=Better Cotton Initiative.

1.4 World production volumes and material flows

The global production volumes of fibres and non-wovens amount to 102 million tonnes per year. The volume % per polymer group is shown in the upper graph of Figure 1.4, and the volume in million tonnes of each fibre is shown in the lower graph.

The global industry saw an increase in production of 3.2% in 2016, mainly due to a strong increase in the production of cotton (Rex et al. 2019). But the growth of polyester PET was significantly faster than all other fibre types. In 1980 PET demand was only 5.2 million tons and by 2000 it had reached 20 million tons (Textile World 2019). Current production of PET fibres (2016) amounts to 53 million tonnes (Rex et al. 2019).

A comprehensive overview of the present situation in the textiles industry is given by the Ellen MacArthur Foundation (see Figure 1.5) (Ellen MacArthur Foundation 2017).

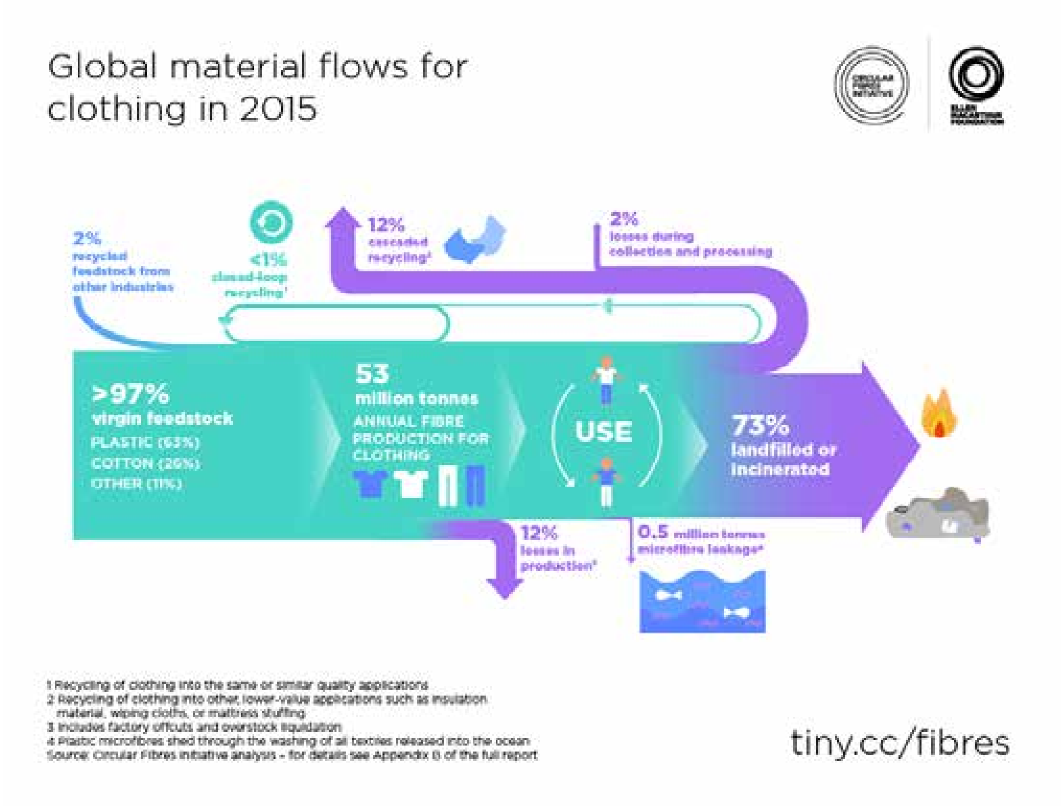


Figure 1.5: Global material flows in the clothing industry as presented by the Ellen MacArthur Foundation (Ellen MacArthur Foundation 2017).

Over 97% of the resource input of the textiles industry is virgin feedstock, 2% is feedstock recycled from other industries and less than 1 % is formed by recycled textile. Moreover 73% of clothing is landfilled or incinerated after use, and only 12% is recycled into other applications than clothing. The graph also shows that 0.5 million tonnes of microfibres, which are released during wearing and washing, end up in the environment. Especially for the non-biodegradable fibres PET, nylon, acrylics and elastane this poses a serious environmental problem.

The expectation is that with the current trend the input of non-renewable feedstock will have tripled by 2050. It is therefore of urgent importance to change the way of working of the textile industry towards a more circular business model.

1.5 Reader’s guide

All the information in this publication is public. The next two chapters include general information on the production of garments from several resources (chapter 2) and the various fibres and their relevant properties (chapter 3). For these chapters we consulted mainly standard textile books which are abundantly available. Chapter 4 describes the mechanical, physical and chemical methods available for recycling of the different types of fibres and chapter 5 elaborates on the options we have for dealing with the huge amount of mixed waste generated by the apparel sector.

2 Basics: from resources to garments

2.1 Introduction

An extremely wide range of techniques are applied to turn raw materials into a garment. This chapter gives a brief general introduction of these techniques, with a schematic illustration of the overall process from resources to fibres, yarns, fabric and garments as guideline (see Figure 2.2 on the next page). Furthermore, the background of the most important properties of fibres related to their application in textiles is discussed, including an explanation of the most relevant fibre properties in the last paragraph.

2.2 From resources and fibres to yarns

Raw materials for textiles can be either from natural origin or from a fossil resources, and the origin is important for - especially the first - conversion steps. Next to this difference in origin, also the length of the fibres is an important aspect. Fibres can have a finite length, so called staple fibres, or they can have an infinite length and are then called a filament.

Figure 2.1: Linen is produced from the flax plant.

Fibres from natural origin need to be harvested from the plant or animal that produce the fibres (Figure 2.1). They need to be cleaned and can subsequently be spun (by yarn spinning) into a yarn by mechanically twisting the fibres around each other.

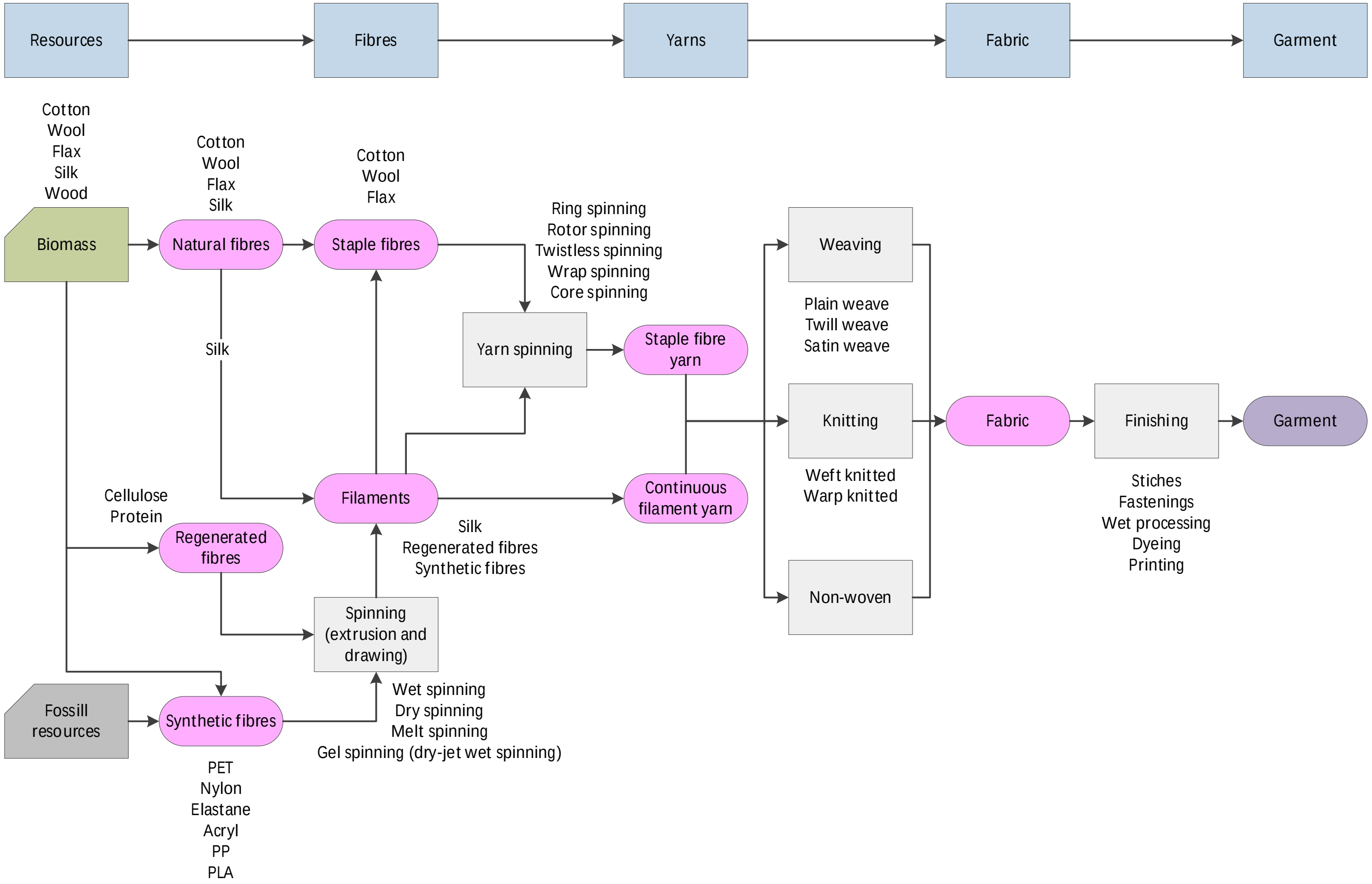


Figure 2.2: From resources to garments, a highly simplified scheme. Dyeing is in this scheme included only in the finishing part, but also yarns and fabric can be dyed.

For the production of synthetic fibres, first the polymer that will make up the fibre needs to be produced by a (chemical) polymerisation process where monomers are converted to a polymer. The origin of the raw material for synthetic fibres is often fossil oil. After the polymer is produced it is spun into a long (set of) filaments by first either melting or dissolving it, after which the filaments are formed (see paragraph 2.3). These filaments can be turned into a filament yarn by relatively simple processing or can be cut and used in the yarn spinning process.

Figure 2.3: Synthetic fibres are produced predominantly from fossil oil.

For the production of regenerated fibres, cellulose (or protein) is dissolved after which it is spun into a filament, which is subsequently turned into a yarn.

Spinning of synthetic and regenerated fibres is completely different from the mechanical yarn spinning process, and the fact that both processes are called spinning does not help to keep matters clear. Both these spinning processes are explained in more detail in the following two paragraphs (see paragraph 2.3 and 2.4 respectively).
Before the production of the yarn, fibres of different origin can be mixed in order to produce a yarn with optimal properties. Yarns are then turned into a fabric mostly by weaving and knitting (paragraph 2.5). Also during these processes, yarns from different origin can be mixed in order to finetune properties.

Somewhere between these processing steps the fibres are dyed. This can be done either with the fibres as such, or the yarn, the fabric or the whole garment. Dyeing is explained in more detail in paragraph 2.6.

2.3 Spinning (extrusion and drawing) of synthetic and regenerated fibres

Synthetic and regenerated fibres are spun by melt spinning or solution spinning (i.e. dry spinning, wet spinning or gel spinning) which all produce filaments of infinite length. When a polymer can be melted it is melt spun, when it needs to be dissolved first in a solution it is spun by solution spinning.

Melt spinning

Melt spinning is applied when the polymer can be processed from the melt without significant thermal degradation. Polyesters, nylons and polyolefins are generally spun from the melt and also elastane can be melt spun.

For melt spinning a granulate of the polymer is fed to an extruder, which heats the polymer to above its melting temperature and transports the molten polymer towards the metering pump. The polymer is then forced by the metering pump through a spinneret, a plate with very tiny holes, thereby forming the filaments. The spinneret holes are usually circular, forming filaments with a circular cross section. By changing the shape of the spinneret holes, fibres with other cross section, such as triangular or square, can be made, which gives slightly different fibre properties. The filaments then pass through a cooling chamber to solidify. Next the filaments are subjected to a drawing process, which orients the long molecular chains in the filaments and brings them closer together. This improves the mechanical properties. Drawing is carried out at a temperature below the melting temperature (Mather and Wardman 2015). Fibres with higher strength can be produced by applying a higher draw ratio, i.e. stretching the fibres further. The melt spinning process produces filament fibres of infinite length, but the filament can also be cut into staple fibres of a required length, for instance to ease blending with other staple fibres.

Solution spinning

Polymers that cannot be melted without thermal degradation can be spun by solution spinning. Regenerated cellulose (viscose and lyocell), acryl and elastane are spun in this way. The polymers are dissolved in a solvent and the polymer solution is forced through the spinneret by a metering pump. There are two main types of solution spinning: dry spinning and wet spinning. In dry spinning the solvent is evaporated by hot air after the solution leaves the spinneret, causing the filaments to be formed. In wet spinning the solution is spun into a precipitation bath, with a liquid that is compatible with the solvent, but in which the polymer does not dissolve. This causes the polymer to coalesce into filaments. Gel spinning is a similar method, used for the production of high-strength fibres.

Also after solution spinning the fibres are subjected to the drawing process, in order to align the macromolecules in the filaments and improve the mechanical properties. As with melt spinning, these spinning processes produce filament fibres of infinite length, but the filament can also be cut into staple fibres of a required length, for instance to ease blending with other staple fibres.

2.4 Yarn spinning

There is an enormous variety in the different types of yarn produced. A basic distinction is that continuous filament yarns are produced from infinite filaments and that staple fibre yarns are produced from staple fibres. Next to this, many different combined and textured yarns are produced. An important category are the covered yarns, often a combination of staple fibres and filaments, which are used widely in textile applications.

Staple fibre yarn

Natural fibres are generally staple fibres with a finite length. Also synthetic and regenerated fibres are often cut into staple fibres. In order to produce a yarn, staple

Figure 2.4: Cotton sliver production, a step in the yarn spinning process.

Figure 2.5: Yarn production in a textile factory.

fibres are spun by a mechanical spinning process. Different processes are available, with ring spinning as the most widely used method to produce staple fibre yarns.

First the staple fibres are blended, if desired, to the desired composition of different fibre types (polyester/cotton, viscose/polyester etc.). The blended fibres are then carded, which is a kind of combing process. The staple fibres are mixed well, parallelised in the process, and turned into a sliver (see Figure 2.4). The sliver is stretched by leading it through subsequent pairs or rollers rotating at different speed to form a roving of approximately pencil thickness. The roving is then spun during which the fibres are twisted around each other to produce an infinite staple fibre yarn (see Figure 2.5) (Elhawary 2015).

Continuous filament yarn

The infinite filaments produced during melt or solution spinning can be turned into a continuous filament yarn, where the infinite filaments are either twisted together or merely grouped together. Because of the infinite filament length, these yarns are very strong and used in a wide range of applications, like safety belts, ropes and upholstery, but they are also used for clothing. To improve the bulkiness and stretch properties at low tension, which are important properties for apparel applications, continuous filament

yarns are often textured. During the texturing process, waviness or even loops and entanglements between the filaments in the yarn are introduced.
The market for textured yarn in apparel applications is significantly larger than for untextured yarn. The most important polymers presently used for continuous filament yarns are polyester (PET), nylon (PA 6 and PA 6.6), polypropylene (PP) and polyurethane (elastane). Moreover, approximately 35 % of all the yarns used in textiles are continuous filament yarns, the remaining 65% are staple fibre yarns (Lawrence 2015).

Covered yarn

Covered yarns have a core that is completely covered by fibre or by another yarn. Elastane is often applied as a covered yarn. In this case the core of the yarn consists of infinite elastane filaments, and a filament yarn or a staple fibre yarn of another composition is wound helically around it, either in one or in two layers. In the case of two layers, the second covering is usually twisted in the other direction. In this way the elastic properties of the elastane fibres can be well exploited (Alagirusamy 2015).

2.5 Production of fabric

The two most important processes for producing fabric from yarns are weaving (see Figure 2.6) and knitting. With both processes an enormous variety of different fabrics can be produced. A third process produces nonwoven fabric. The definition of a

Figure 2.6: An industrial weaving facility.

nonwoven is that it is “a sheet of fibres, continuous filaments or chopped yarns of any nature or origin, that has been formed into a web by any means” (Mao and Russell 2015). Nonwovens are not further discussed in this chapter.

At this stage of the textile production there is no significant difference any more between the processing of fibres of natural origin and fibres of synthetic or regenerated origin.

Weaving

In weaving two sets of threads are interlaced to form the fabric. The warp threads run vertically through the length of the fabric and the weft threads run horizontally across the width of the cloth. For the warp threads strong yarns need to be chosen, as they need to withstand the tension of the loom during the weaving process. Normally a warp yarn will be equal to or finer than a weft yarn for a good quality cloth. Fancy yarns are usually placed in the weft (Stankard 2015).

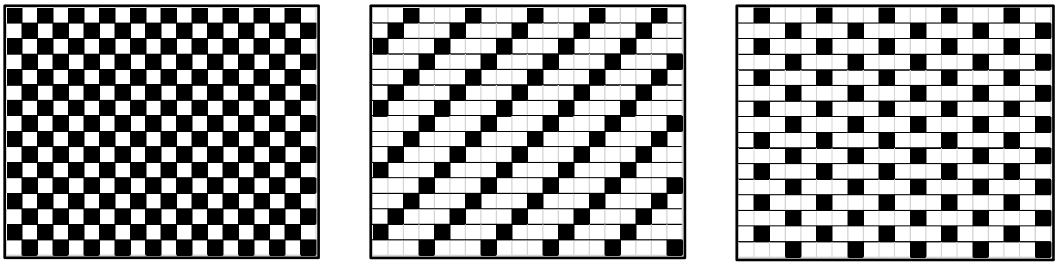


Figure 2.7: The three basic weave structures. From left to right: plain weave, twill weave and satin weave. The dark squares represent the warp threads, the white squares the weft threads.

All kinds of different weaving structures can be produced by varying the number of warp threads crossed by the weft. The three basic weave structures are plain weave, twill weave and satin weave (see Figure 2.7). The weave structure of a fabric influences its final properties, both the mechanical properties as well as its appearance and handle. Weaving normally produces fabrics with little stretch, unless fibre blends with elastane are applied. Woven fabrics are used for all kinds of garments, ranging from coats to intimate apparel.

Knitting

In knitting basically, a single yarn is turned into a fabric by forming a series of intermeshing loops (see Figure 2.8). Knitting produces textiles that have stretch, generally more in the horizontal than the vertical direction, and the properties of knitted fabrics differ vastly from those of woven fabrics. Whereas weaving is already mentioned in ancient stories and myths, dating long before Christ, knitting appears to be a much more recent invention, it became widespread in Europe from the 13th century on (Sheep And Stitch 2019). Knitting can be done by hand, but industrial production of knitted fabric is done mechanically at very high speeds. By varying the stitches, fabrics with different properties and appearance can be made. The most common structure is the single jersey structure that is used extensively for t-shirts and sweaters.

Figure 2.8: A typical knitted structure.

2.6 Dyeing

Dyeing is an extremely complex activity. There are literally thousands of dyes available, each with their specific applications and properties (Richards 2015), and dyeing can take place at different stages in the process from resources to garments. Basically, dyeing comprises the mixing of coloured molecules evenly throughout the fibre and making sure they stay there. The selection of the right dye relates directly to the chemical structure of the fibres, and this is mainly related to the hydrophilic or hydrophobic properties of the fibres.

Water-soluble dyes are dissolved in water, after which the fibres, yarns, fabric (see Figure 2.9) or whole garments are submerged in the solution. The dye molecules enter the fibres and in some dye systems an additional chemical reaction is performed to strongly bind the dye molecules to the fibre molecules. Hydrophilic fibres like cotton, flax and viscose, all made up of cellulose molecules, can be dyed with the same classes of dyestuff, although the details of the dyeing process may differ.
Fibres that do not take up enough water, like PET, are dyed with a different system. The dyes used are not soluble in water, so they are not dissolved in water but dispersed as very tiny droplets. The dye molecules enter the fibres directly from the dispersion as they have a higher affinity for the fibre molecules than for the water molecules.

Figure 2.9: Dyeing of a fabric.

In polymers that are melt spun or solution spun the dyes or pigments can also be added to the polymer melt or solution, to colour the polymer even before the filaments are formed. Especially for polypropylene (PP) fibres this is a valuable technique because they are not dyeable by conventional techniques, due to the lack of chemical groups to which the dye molecules may attach.

As the dyes are meant to be spread evenly through the fibres and preferably are firmly attached to the fibre molecules, it is very difficult to remove them during for example recycling. Moreover, because of the enormous choice of dye systems and colours, a batch of recycled textile will have more colours than the rainbow, all with a different brightness, which brings a large additional challenge to the application of recycled textiles.

2.7 Introduction to fibre properties

In this paragraph we briefly introduce some frequently used terminology to describe fibre properties and the background of these properties.

Fibre length

Fibres are by definition very long and very thin structures. In relation to fibre length two types of fibres are distinguished: staple fibres and (continuous) filaments. Most natural fibres are staple fibres, i.e. fibres of a certain length that can be twisted into a yarn. Typical fibre lengths of staple fibres range between 2 and 5 cm, although they may be shorter or longer. Man-made fibres (regenerated and synthetic fibres) are generally produced as an endless filament, a continuous fibre of long length. For the sake of, for instance, blending with other fibres, filaments are sometimes cut into staple fibres. Staple fibres give softer yarns than filaments. In general, longer staple fibres give higher strength yarns than shorter staple fibres.

Fineness

Fineness is the cross section of the fibres. Generally, fibres used for the production of yarns have cross sections ranging from 10 to 40 µm. The fineness of natural fibres can be dependent on the variety of the resources they are produced from. Synthetic fibres and regenerated fibres can be produced with varying degrees of fineness by adjusting the spinning process.

Tex

Tex is a measure for the fineness of the fibres. It is defined as the weight in grams of 1000 m of yarn. It is therefore a combination of the density of the fibres and their fineness, and thus a measure of the linear density.

Crimp

Crimp is the waviness of a fibre along its length. Wool is an example of a natural crimped fibre. Man-made fibres are sometimes crimped to improve blending with other fibres or to make them more bulky and comfortable. Crimped fibres have better insulating properties due to more entrapped air.

Tenacity

Tensile strength of fibres and yarns is the stress applied at the fibre at the breaking point. The tensile strength is dependent on the cross section of the fibres. Fibre strength is therefore often expressed as tenacity, which is the tensile strength relative to the linear density (fineness) or cross-sectional area of the fibre or yarn. Tenacity is influenced by a number of factors, such as molecular mass of the polymeric molecules that form the fibres, degree of crystallinity, degree of orientation of the molecules in the direction of the fibre axis, length of the staple fibre, density etc. For many fibres the tenacity in dry conditions differs considerably from the tenacity in wet conditions.

Elongation at break

Elongation at break is the strain at which the fibre breaks. Fibres with a high elongation at break can be stretched further before they are damaged.

Elastic recovery

Elastic recovery is the degree to which fibres return to their original length after they are stretched. For small elongations most fibres will recover by almost 100%, but for longer elongations many fibres do not recover completely. This leads to clothes becoming baggy. Some fibres, especially elastane, show an almost 100 % elastic recovery even at high elongation, which makes them very suitable for applications such as sportswear and skinny jeans in combination with other fibre types.

Moisture regain

The ability of a fibre to take up water is assessed by determining its moisture regain, which is defined as the mass of the absorbed water at ambient conditions divided by the mass of dry fibre multiplied by 100%. Some fibres can take up more moisture than others, due to their molecular composition and build-up. Fibres that take up little moisture may feel hot and clammy in warmer conditions and become smelly more easily. Also, fibres that take up little moisture tend to accumulate static electricity. Fibres with a high moisture uptake are in general more comfortable to bare skin. On the other hand, fibres that do not take up moisture but are able to quickly lead moisture away from the skin are well suited for use in sports garments.

Thermal properties

Thermal properties describe the behaviour of fibres at elevated temperature, for instance during ironing. Most synthetic fibres are thermoplastics, which means that they melt at high temperatures. Natural fibres and regenerated fibres will not melt, but they may degrade and turn yellow at high temperatures.

Dyeability

There are many different dyes and dyeing techniques available for dyeing fibre or fabrics. Generally, these dyes are specific for the molecular structure the fibre is made of, as explained in more depth in paragraph 2.6.

Washability

The temperature at which fibres can be washed differs. Some fibres can be boil washed, other will shrink at higher temperatures. Some fibres can be washed only at delicate cycles, or not at all. Also tumble drying is not suitable for some fibres. In addition, the optimal pH of water with detergent (neutral or alkaline) during washing is different for fabrics.

Shrinkage

Most fabric production processes involve the application of high tension to the fibres. This leaves residual strains in the fabric. If these strains are not removed by the manufacturer before the fabric is converted into a garment, the garment may shrink considerably during washing or ironing due to the humidity and high temperatures (Nayak 2015). Different fibres show different sensitivity towards shrinkage.

Biological stability

Fibres, especially natural fibres, can be susceptible to mildew which degrades the fibres and gives black spots on the fabric. Also, a number of fibres are susceptible to attack of insects, for instance clothing moths that lay their eggs in natural fabrics or silverfish that eat starch finishing. On the other hand, biodegradability of fibres can be an advantage for their end-of-life stage.

Electrical properties

Electrical properties, and especially the susceptibility towards build-up of static electricity, which can be very annoying for the wearer, is mainly connected to the moisture uptake of the fibres.

Wrinkling

Wrinkling arises from laundering or folding. Especially cotton and linen are very susceptible to wrinkling. Wrinkling behaviour of a fabric depends on the type of fibre and yarn, the construction of the fabric and the finish applied to the fabric. Thinner fabrics are also more prone to wrinkling (Nayak 2015).

3 Fibre properties of the most relevant textile fibres

3.1 Introduction

This chapter focuses on the properties of the most applied textile fibres. For each of these fibres we describe the raw materials they are produced of, the way of production, and the most relevant properties of both the fibres and the fabrics made from them. The chapter is structured along the lines of the polymeric material that make up the fibres, because this basic structure is important for properties, recycling- and end-of life options of the materials. We have thus subsequently grouped cellulose-based fibres (cotton, flax, viscose, lyocell and acetate), polyesters, polyamide-based fibres (wool, silk, nylons), polyurethanes (elastane), polyolefins and polyacrylic fibres.

3.2 Cellulose

3.2.1 Introduction

Cellulose-based fibres are based on cellulose, a natural polymer made up of glucose units. Here we distinguish natural cellulosic fibres, (man-made) regenerated cellulosic fibres and (man-made) cellulose derivatives (Figure 3.1). Natural cellulosic fibres can be obtained from the seed (e.g. cotton), the stem (e.g. flax and hemp) or the leaves (e.g. sisal, abaca) of the plant. Regenerated cellulose fibres and cellulose derivatives can be made from all types of biomass containing cellulose, but up till now mostly wood or

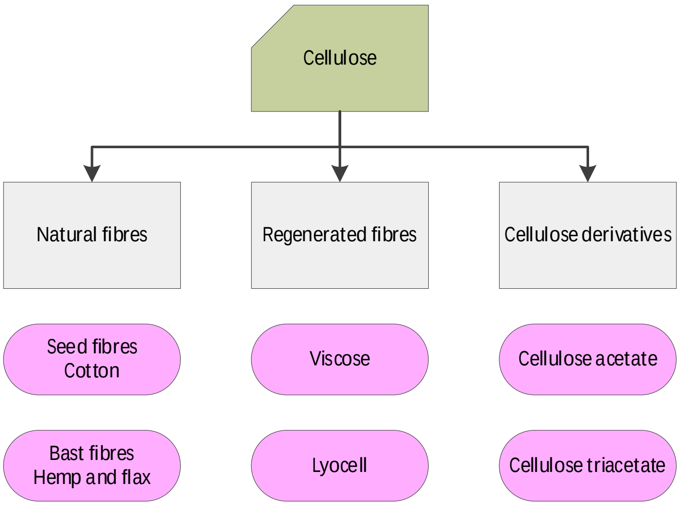


Figure 3.1: Cellulose-based fibres.

cotton is used. Depending on the initial cellulose content in the biomass, minor or major processing is required to obtain a cellulosic fibre that can be used as a textile fibre. In these paragraphs first the natural fibres are discussed, followed by regenerated cellulose fibres and finally cellulose derivatives.

3.2.2 Cotton

3.2.2.1 Introduction

Cotton is the most popular natural fibre, and by far the most used natural fibre for textiles. It is the combination of fibre length, strength and 3D-structure that enables cotton fibres to be spun into yarn or threads by yarn spinning. Cotton is soft, absorbs water very well, is breathable, strong and machine-washable.

3.2.2.2 Raw materials and origin

Cotton is a seed hair coming from the perennial cotton plant (Seagull and Alspaugh 2001), but for commercial purposes cotton is grown as an annual crop. The shrub grows in many parts of the world, but main producers of cotton are China and India (Yu 2015). The mature cotton bolls are removed from the plant by hand or by mechanical harvesters, which can be cotton strippers or cotton pickers. Cotton strippers remove the complete boll from the plant, resulting in a higher trash content of harvested seed cotton (Seagull and Alspaugh 2001).

3.2.2.3 Fibre production

After harvesting, the seed cotton is transported to the ginning factory, where the long cotton fibres are separated from the seed, other plant matter (twigs, leaves etc.), and shorter cotton fibres. Only the long lint fibres are packed into bales and transported to spinning mills (Yu 2015). The shorter fibres, called ‘cotton linters’, are unsuitable for spinning but are an excellent source of pure cellulose for the production of value paper or regenerated cellulose fibres (see paragraph 3.2.4).

Besides mechanical cleaning also other purification processes are required. After harvesting, the raw cotton fibres contain around 90% or more cellulose and the surface is coated with waxes to protect them from the elements (Table 3.1), making the fibres hydrophobic (water repellent). It is necessary to remove this waxy layer, otherwise the cotton cannot be dyed. After purification processes, where amongst others waxes and oils are removed by detergents, the fibre contains 99% cellulose and has become hydrophilic (water loving).

Table 3.1: Chemical composition of total and surface of cotton fibres (Mather and Wardman 2015).

Substance	**Percentage of substance**	
	Total fibre	**Fibre surface**
Cellulose	88-96	52
Pectins	0.7-1.2	12
Wax	0.4-1.0	7
Proteins	1.1-1.9	12
Other organics	0.5-1.0	14
Ash	0.7-1.6	3

3.2.2.4 Chemical structure polymer

The main component in cotton is cellulose. Cellulose is a highly crystalline polysaccharide. The repeating unit of cellulose is cellobiose, which is formed by two glucose units linked together alternately (see Figure 3.2). The 6 OH-groups present in cellobiose play an important part in in the formation of crystalline regions through hydrogen bonding (Mather and Wardman 2015).

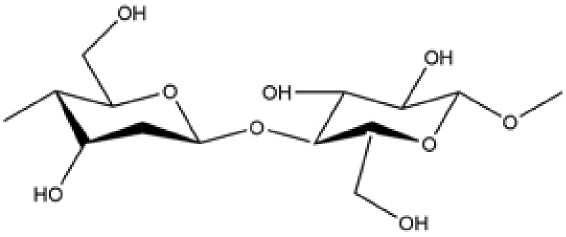


Figure 3.2: Structure of cellobiose (two linked glucose molecules), the repeating unit of the cellulose polymer.

3.2.2.5 Physical and mechanical structure and properties

There are four main parts to the cotton fibre structure: the cuticle, the primary wall, the secondary wall and the lumen. The cuticle is the waxy outer layer that is removed after harvesting. The primary wall consists of fibrils of cellulose, but the bulk of the cellulose fibrils are in the secondary wall. The cellulose fibrils are about 20 nm thick and spiral

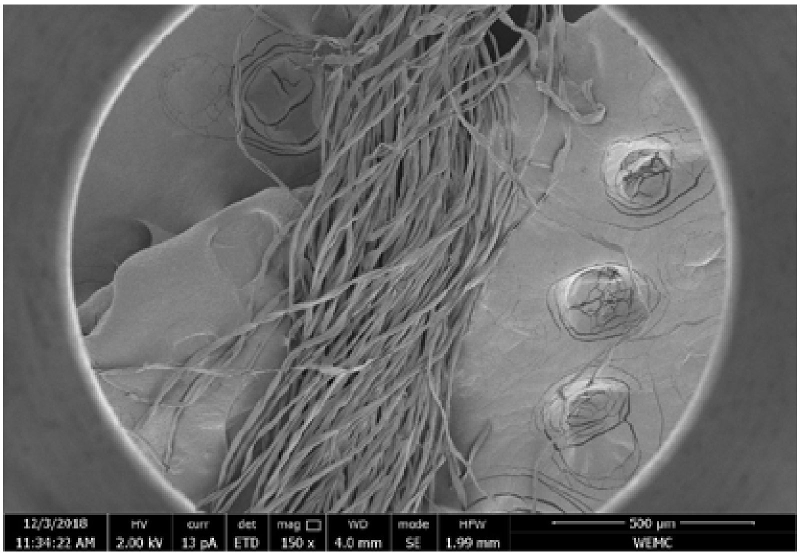


Figure 3.3: Scanning electron micrograph of a bundle of cotton fibres, clearly visible is the twisted structure with convolutions.

along the fibre axis. The lumen is the hollow opening in the middle of the fibre that runs along the length of the fibre (Yu 2015).

When the boll opens and the fibre dries in the sun, the lumen collapses, resulting in a bean-shaped cross-section. This collapse causes the fibre to twist and form so called

Table 3.2: Physical and mechanical properties of cotton fibres (Yu 2015).

Property	**Cotton**
Fibre length	Long-staple 30-40 mm, medium-staple 25-33 mm, short-staple 10-25 mm
Fineness	10-20 µm
Specific gravity	1.54
Tenacity dry	2.6-4.4 cN/dtex
Tenacity wet	3.2-5.3 cN/dtex
Elongation at break	3-7%
Elastic recovery	70% at 2% elongation
Thermal properties	No melting point and heat resistant

convolutions. These convolutions differentiate cotton fibres from all other forms of seed hair fibres and are partially responsible for many of cotton's unique characteristics, for example the possibility to spin cotton fibres into yarn or threads (Seagull and Alspaugh 2001).

The properties of cotton fibres are shown in Table 3.2. In general, cotton fibres are fairly strong, but what makes them unique is that they become 10-20% stronger when wet.

3.2.2.6 <u>Fibre properties related to textiles for fashion</u>

Cotton is comfortable, breathable and soft, making it very pleasant to wear on bare skin. Other textile properties are listed in Table 3.3.

Table 3.3: Textile properties of cotton fibres (Yu 2015).

Property	**Cotton**
Washability	Can be boil washed, dry cleaned and tumble dried
Shrinkage	Fabrics may shrink during laundering
Moisture regain	8.5%
Dyeability	Good affinity for dyes.
Biological stability	Highly susceptible to mildew
Electrical properties	Creates no static electricity
Wrinkle	Crease easily, does not recover well from wrinkling
Abrasion resistance	Fair to good

3.2.2.7 <u>Fibre applications</u>

Cotton is a popular fibre and is extensively used for underwear, shirts, dresses, knitwear, sportswear and of course jeans. Application of cotton fibres is mainly based on the staple length and availability (Yu 2015):

- Long-staple (30-40 mm), highest quality, limited availability. Applications are mainly fine fabrics, yarns and hosiery.
- Medium-staple (25-33 mm), plentiful and standard, 90% of current world production. Applications include apparel, home furnishing, and industrial products (medical supplies, industrial threads).
- Short-staple (10-25 mm), coarse cotton. Fibres are too short for textile processing, so commonly these are not used in textiles.

3.2.3 Bast fibres: flax, hemp and others

3.2.3.1 Introduction

Bast fibres are obtained from the stems of plants like flax, hemp, jute and bamboo. For the apparel sector flax is the most important one of these fibres, therefore this chapter will focus mainly on flax.

Flax is probably the oldest textile fibre known to mankind (Harvard Gazette 2020). Flax is the raw material for the production of linen, and it has been used since ancient times. Linen was found in graves in Egypt dating from before 5000 BC (Bos 2004), but it seems plausible to assume it has been cultivated for textile purposes even thousands of years before that. Flax was the all-important fibre used for war outfit, until circa 1950, after which synthetic fibres took over (Dewilde 1983). The flax industry has been declining ever since 1955, with the introduction of synthetic fibres. These days flax is occasionally blended with synthetic fibres to combine the advantages of both materials.

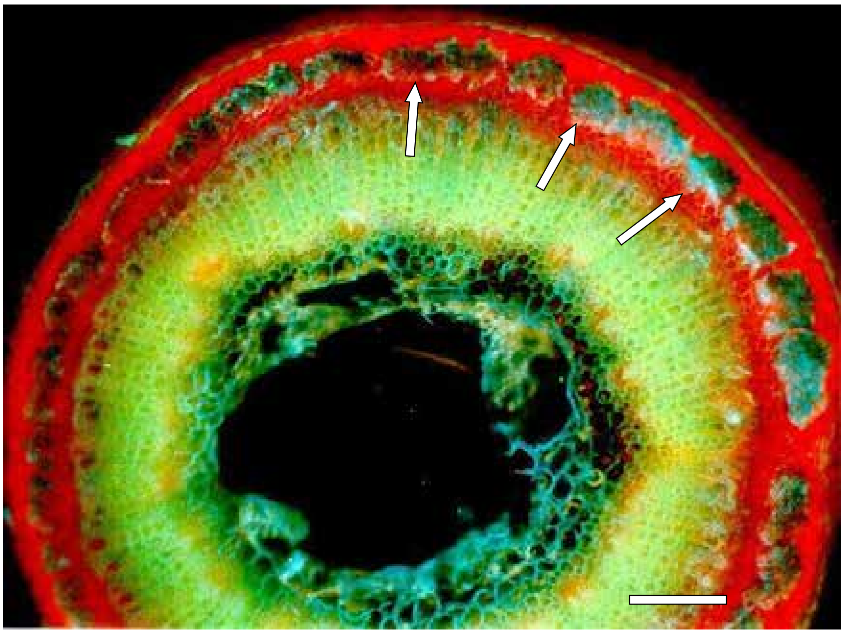


Figure 3.4: Cross section of the flax plant. The white arrows show the technical fibres located near the surface of the plant. The scale bar in the lower right corner represents 0.1 mm (Bos 2004).

Production methods for making yarn and fabric from bast fibres, as described in the following paragraphs, are similar for the various bast fibre types. Also a small portion of bamboo-based yarn is produced with these techniques, although most bamboo yarns are produced in a process resembling the viscose production process (see paragraph 3.2.4).

3.2.3.2 Raw materials and origin

In bast fibre plants, the long and strong fibres suitable for the production of yarn are located near the surface of the woody stems and generally are as long as the plants are high, for flax circa 1 meter. These long fibres are called technical fibres and comprise a large number of shorter fibres (the plant cells), also called the elementary fibres. In flax these elementary fibres have lengths between 2 and 5 cm and diameters between 5 and 35 µm, and they are glued together by an interphase mainly consisting of pectins and hemicelluloses (Bos 2004).

Flax requires a temperate climate and can be grown in many parts of Europe. The best fibres are obtained from the coastal regions of Northern France, Belgium and the Netherlands (Mather and Wardman 2015). Hemp can also be produced in temperate climates, whereas jute and bamboo are found in more tropical areas.

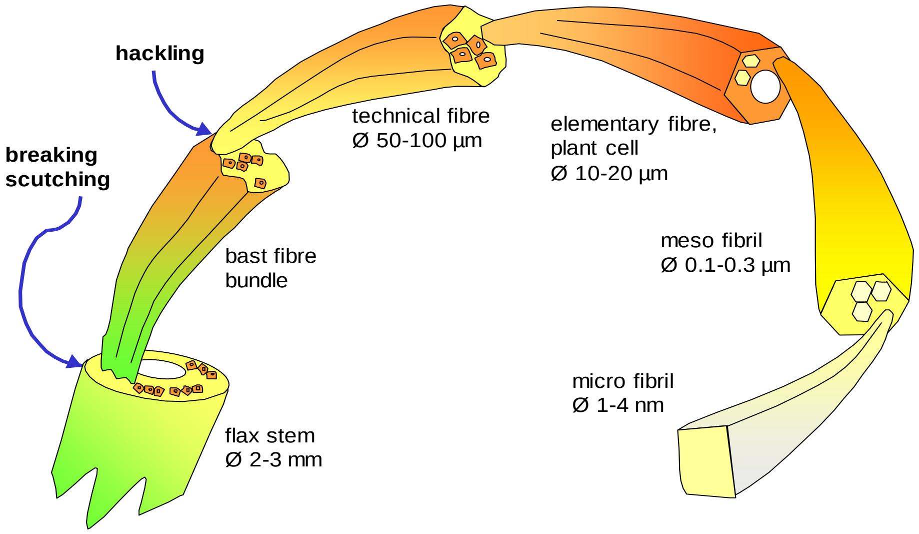


Figure 3.5: Schematic representation of the flax plant and flax fibres from stem to microfibrils (Bos 2004).

3.2.3.3 Fibre production

After harvest of the flax plants the fibres need to be loosened from the woody stem. This is done in a process called retting, where micro-organisms break down the cellular tissue surrounding the fibres, waxes and pectins, which bind them to the stem. Often this is done by dew retting, which means just spreading the harvested plants on the soil for a number of weeks, until the fibres come loose. The morning dew and the heat of the sun help the retting process. After retting the flax stems are led through the fluted rollers of a brake in order to break the woody core in small pieces, the shives. The shives are removed through a process called scutching, and the resulting fibre bundles are refined to thinner technical fibres by hackling, which is a combing process and formed into a tow. The tow can then be spun into a yarn.

3.2.3.4 Chemical structure

The main constituent of flax and the other bast fibres is cellulose (see Figure 3.2). Around 70% of the fibre is cellulose, other constituents are hemicellulose, pectin and lignin. The cellulose lies in the cell wall of the elementary fibres and forms strongly oriented fibrils. In flax the fibrils are oriented spirally at approximately +10° compared to the fibre axis, which makes the fibres relatively stiff.

3.2.3.5 Physical and mechanical structure and properties

The physical properties of flax are illustrated in Table 3.4. Flax fibres are stronger, more rigid and have a lower elasticity than cotton, partially because of the low angle of orientation of the cellulose fibrils relative to the fibre axis (Bos 2004).

Table 3.4: Physical and mechanical properties of flax fibres (Yu 2015, Mather and Wardman 2015, Bos 2004).

Property	**Flax**
Fibre length	1 m (technical fibre), 2 – 5 cm (elementary fibres)
Fineness	5 – 35 µm
Specific gravity	1.54
Tenacity, dry	Ca. 5.5 cN/dtex
Tenacity wet	Ca. 6.6 cN/dtex
Elongation at break	Ca 2%
Elastic recovery	Almost complete, but very low strain at break
Thermal properties	No melting point and very heat resistant

3.2.3.6 Fibre properties related to textiles for fashion

The properties of flax in relation to textile applications are shown in Table 3.5. Linen is very comfortable in warm weather as it has a high moisture regain and releases heat easily. Linen is resistant to chemicals and bleaches and is easily maintained.

Table 3.5: Textile properties of flax fibres (Yu 2015).

Property	**Flax**
Washability	Can be boil washed, dry cleaned and tumble dried
Shrinkage	Very little, but show relaxation during laundering
Moisture regain	12%, linen dries slowly
Dyeability	Not very good
Biological stability	Susceptible to mildew
Electrical properties	Creates no static electricity
Wrinkle	Wrinkles badly
Abrasion resistance	Fair to good

3.2.3.7 Fibre applications

Flax is mostly used for clothing and household textiles, such as table linen. Linen cloth releases heat easily so linen garments feel cool in the heat. Therefore, linen is mainly used for summer clothing. The other bast fibres are used mainly for other textile applications besides clothing. Linen can be mixed with other fibres such as viscose or cotton to make it feel softer and less prone to wrinkling.

3.2.4 Regenerated cellulose fibres; viscose and lyocell

3.2.4.1 Introduction

In the previous paragraphs we described the use of cellulose-based natural fibres as textile fibres. Another option is to isolate the cellulose from the biomass and make new cellulose-based fibres. These fibres are then called regenerated cellulose fibres.

As discussed before, cellulose does not melt upon heating and is not easy to dissolve. Already in the 19th century chemists and inventors tried to find ways to dissolve cellulose. The process to produce viscose was patented in 1893 in England. The viscose process is a long and relatively messy process, involving the use of a number of chemicals including carbon disulphide, which is toxic, explosive and smells terrible (Wikipedia 2019). Much effort has therefore been devoted to trying to find other solvents for cellulose and developing other processes for cellulose-based fibres. A successful result of this is the development of lyocell fibres during the 1970s. Both viscose and lyocell fibres are used today in textiles for fashion.

3.2.4.2 Raw materials and origin

The raw material for regenerated cellulose is wood, for instance beech wood, but also other cellulose-containing feedstock is or can be used, like cotton linters and bamboo (Textile Learner 2019). To produce regenerated fibres, first the cellulose-containing biomass is treated by a number of processes (resembling production of paper pulp) where nearly all non-cellulosic substances like lignin and hemicelluloses are removed to produce a highly pure cellulose fraction (>90%) called dissolving pulp.

3.2.4.3 Fibre production

For the viscose process, the dissolving cellulose pulp is treated with carbon disulphide in order to form cellulose xanthate, which is subsequently dissolved in sodium hydroxide. The fibres are then produced by wet spinning: the solution of cellulose xanthate is extruded and forced through a spinneret, a plate with thousands of small holes of circa 50 µm in diameter, into a bath containing sulfuric acid, sodium sulphate and zinc sulphate. In the bath the cellulose xanthate reacts back (is regenerated) to cellulose, forming the viscose fibre. During the regeneration process the core of the fibre shrinks, which causes the outer layer to wrinkle. This gives viscose fibres their typical jagged cross-sectional shape and striations along their length (Mather and Wardman 2015). After extrusion, thousands of filaments lie parallel to each other and form a tow. The tow is drawn in order to increase its strength and is then usually cut into staple fibres of approximately 40 mm length. The staple fibres are formed into a yarn, optionally after blending with other types of fibres.
Modal is a viscose fibre which is spun in a slightly different way, into a bath with a different chemical composition, to obtain a stronger fibre which is very soft to the touch.

Lyocell is also produced from dissolving pulp, but the process is chemically less complicated because the cellulose is dissolved directly in a solvent called N-methyl-morpholine-N-oxide (NMMO). NMMO is an amine oxide, a highly polar and water-soluble compound, in which cellulose can be dissolved at 100 °C. The fibres are spun by a so called dry-jet wet spinning process. After leaving the spinneret and before entering the water bath, the fibres pass through an air gap, which causes the filaments to stretch and giving a strong orientation of the polymeric molecules. Lyocell fibres are therefore more crystalline and more oriented than viscose fibres, and as a result they possess a higher strength than viscose fibres, both under wet and dry conditions.

The difference between the viscose and lyocell process is clearly visible in Figure 3.6.

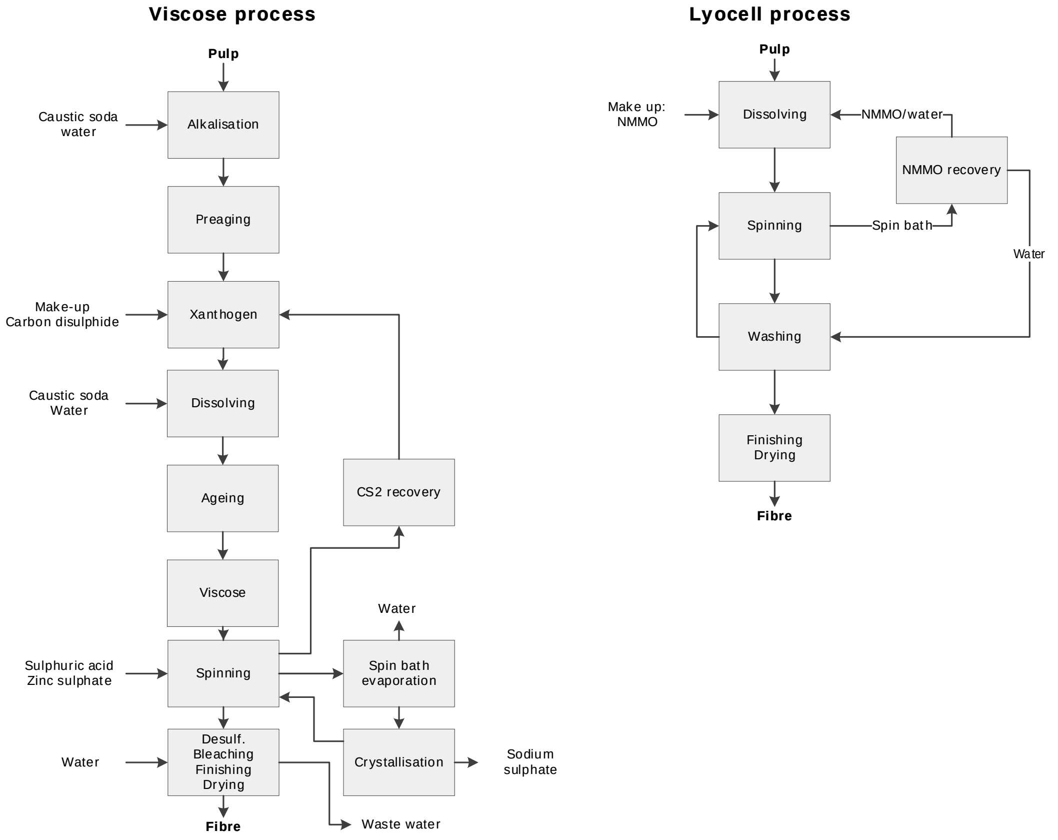


Figure 3.6: Key stages in the manufacture of viscose and lyocell fibres. After Mather (Mather and Wardman 2015).

3.2.4.4 Chemical structure

Regenerated cellulose fibres consist of almost completely pure cellulose, and the chemical structure is like that of cotton.

3.2.4.5 Physical and mechanical structure and properties

The cellulose molecules in viscose have a much lower molecular mass compared to for instance cotton, which results in a much lower strength. The number of glucose units (DP, degree of polymerisation) in wood cellulose is around 1000 (for cotton this is around 10.000), and after processing the DP of cellulose in viscose is around 270. For lyocell this is about 600, over twice the value of viscose (Mather and Wardman 2015). Unlike cotton, viscose and lyocell fibres have a lower strength when they are wet than when they are dry, but the difference is larger for the viscose fibres. The properties of viscose and lyocell are illustrated in Table 3.6.

Table 3.6: Physical and mechanical properties of viscose and lyocell (Chen 2015, Mather and Wardman 2015).

Property	**Viscose**	**Lyocell**
Fibre length	Filament, often cut to staple fibre of circa 40 mm	
Fineness	~20 µm	unknown
Specific gravity	1.52	unknown
Tenacity, dry	2.6 – 3.1 cN/dtex	4.8 - 5.0 cN/dtex
Tenacity wet	1.2 – 1.8 cN/dtex	4.2 - 4.6 cN/dtex
Elongation at break, dry	20-25 %	25-30 %
Elongation at break, wet	14-16	16-18
Elastic recovery	Not very good	unknown
Thermal properties	No melting point, will yellow under a hot iron	

3.2.4.6 Fibre properties related to textiles for fashion

The fibre properties for viscose are illustrated in Table 3.7. The lyocell fibre is similar to viscose in many physical aspects, but exhibits enhanced properties in terms of softness, drapability, dimensional stability, dye uptake and colourfastness. Moisture regain of lyocell is around 11 %, somewhat lower than viscose, mainly because the lyocell spinning process is different and produces a fibre with higher cellulose crystallinity (Chen 2015).

3.2.4.7 Fibre applications

Viscose is used frequently in undergarments, in linings and in shirts, blouses, skirts and dresses. Because modal and lyocell fibres are stronger, they are also used in denim-like applications.

Table 3.7: Textile properties of viscose fibres (Chen 2015).

Property	**Viscose**
Washability	Can be laundered at 40 °C
Shrinkage	Can shrink at high temperatures
Moisture regain	12 – 13 %
Dyeability	Good, excellent colour retention
Biological stability	Susceptible to mildew
Electrical properties	Does not build up static electricity
Wrinkle	Wrinkles easily
Abrasion resistance	Reasonable

3.2.5 Cellulose acetate and triacetate

3.2.5.1 Introduction

Cellulose acetate and triacetate are cellulose derivatives and therefore not considered a regenerated cellulose fibre. Triacetate is cellulose of which all the hydroxyl groups (three on each glucose ring) are converted to an acetate ester, resulting in a degree of substitution of 3. Cellulose diacetate is cellulose with a substitution degree of 2.4 and is commonly known as cellulose acetate.

Cellulose triacetate was for the first time prepared in 1869 by the reaction of cellulose with acetic anhydride. This product was soluble in dichloromethane, and later it was discovered that by partial hydrolysis of triacetate a product was formed, diacetate, that was soluble in acetone. During World War I a solution of cellulose acetate in acetone was used by the Dreyfus brothers in England to cover the cloth in the wings of fighter aircrafts to provide a light airproof skin and protect the structure from the elements. After the war the demand collapsed, and a new process was developed to prepare cellulose acetate fibres under the trade name ‘Celanese’ (Mather and Wardman 2015). Production reached its peak in the early 1970s, after that synthetic fibres took over their applications, partly due to toxicological problems of the organic solvents used in the production of cellulose acetate fibres.

The introduction of cellulose acetate fibres in the 1920s lead to the development of a new type of dye, disperse dyes (see also paragraph 2.6), that became an important dyeing technique for nylon and polyester fibres developed during the 1940s and 1950s.

3.2.5.2 Raw materials and origin

For the production of acetate, dissolving cellulose pulp from wood (see paragraph 3.2.4.2) or the very short staple fibres from cotton (cotton linters) can be used.

3.2.5.3 Fibre production

Cellulose is first converted to cellulose triacetate by a reaction of acetic anhydride and sulphuric acid. After this acetylation reaction, the solution is run into water for partial hydrolysis of the acetyl groups (in the case of acetate). Triacetate is converted to diacetate when roughly 1 out of 6 acetate groups is replaced by 1 hydroxyl group. Once the reduction of acetyl groups has taken place the solution is put into water where the cellulose acetate is precipitated as flakes (DP 350-400). For spinning purposes, the acetate is dissolved in acetone-water and fibres are prepared by a dry spinning process. For the production of cellulose triacetate fibres, the polymer is dissolved in dichloromethane and methanol (Mather and Wardman 2015).

3.2.5.4 Chemical structure

The chemical structure of cellulose acetate and cellulose triacetate (Figure 3.7) is comparable to that of cellobiose (Figure 3.7), where most of the OH-groups are converted to acetate groups.

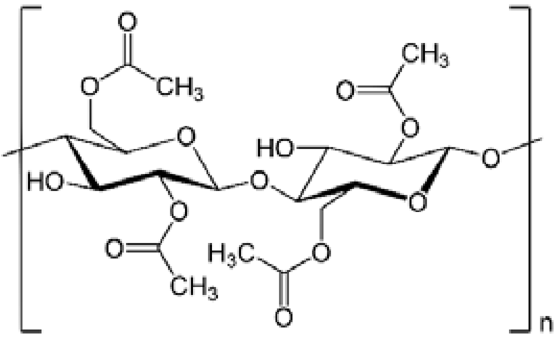


Figure 3.7: Structure of cellulose (tri)acetate.

3.2.5.5 Physical and mechanical structure and properties

Cellulose acetate fibres mainly differ from other cellulose-based fibres in terms of thermal behaviour and strength. They are thermoplastic and soften and melt upon heating, and they are not so strong.

Table 3.8: Physical and mechanical properties of cellulose acetate fibres (Mather and Wardman 2015).

Property	Cellulose acetate	Cellulose triacetate
Fibre length	Filament, often cut to staple fibre	
Fineness	Can be adjusted by the spinning process	
Specific gravity	1.32	
Tenacity, dry	1.5 cN/dtex	1.3 cN/dtex
Tenacity wet	1.0 cN/dtex	0.9 cN/dtex
Elongation at break	25%	20-28%
Elastic recovery	Highly elastic up to 5% extension	Does not recover well from stretching
Thermal properties	Melts at 230 °C, softens easily	Melts at 290 °C

3.2.5.6 Fibre properties related to textiles for fashion

Cellulose triacetate contains no free hydroxyl groups and is therefore less hydrophilic than cellulose acetate. This explains the differences in moisture regain (see Table 3.9).

Table 3.9: Textile properties of cellulose acetate fibres (Chen 2015).

Property	Cellulose acetate	Cellulose triacetate
Washability	Good, easy care	
Shrinkage	Resistance to shrink	
Moisture regain	6.5%	4.5%
Dyeability	Good with dispersed dyes	
Biological stability	Resistant to biological attack	
Electrical properties	Does not build up static electricity	
Wrinkle	Good resistance to wrinkle, better for triacetate	
Abrasion resistance	Poor	Better than acetate

3.2.5.7 Fibre applications

When cellulose acetate fibres were introduced they served as a low-cost alternative to silk. Their brightness, lustre and handle were the main advantages. Nowadays they are widely used for linings in jackets and skirts. Another significant market, outside the apparel sector, is in the manufacture of cigarette filters (Mather and Wardman 2015).

3.3 Polyesters

3.3.1 Introduction

This paragraph describes the class of polymers called polyesters. The term ‘polyester’ is a generic name for all polymers containing ester-linkages (-O-CO-) in their polymeric chain, but in the apparel sector polyester stands for one of these types of materials: polyethylene terephthalate or PET. Polyesters are synthetic fibres, they are build up by polycondensation of two monomers, e.g. a diacid and a dialcohol. Here we describe PET but also other, less familiar, polyesters will be discussed.

3.3.2 Polyethylene terephthalate (PET)

3.3.2.1 *Introduction*

PET is nowadays by far the most applied fibre in textiles. It was first synthesised in 1941 and further developed and marketed in the following years both in the UK, as Terylene, as well as in the USA, as Dacron. Both these brands became very successful and by the mid-1970s production of PET fibres overtook that of polyamide (nylon) fibres (Mather and Wardman 2015). These days there is a global overcapacity of PET production, leading to low prices. The combination of low price and desirable properties are the reason behind the success of PET fibres for textiles.

3.3.2.2 *Raw materials and origin*

PET is produced from two molecular building blocks, terephthalic acid (TPA) and 1,2 ethanediol or ethylene glycol (EG) (Figure 3.8). The material for PET fibres is chemically the same as the materials used in PET bottles. The building blocks are generally produced from fossil resources, but there are several parties trying to develop processes to produce the building blocks from renewable feedstock. These days most PET is produced in China (Mather and Wardman 2015).

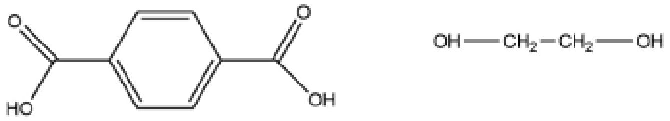


Figure 3.8: Monomers terephthalic acid (left) and ethylene glycol (right).

3.3.2.3 Fibre production

The two building blocks for PET are produced from naphtha, a side-fraction from the production of diesel and gasoline. After polymerising the building blocks into a polymer at the polymerisation plant, the polymer is formed into a granulate. PET fibres are produced by melt spinning of these granules (see paragraph 2.3). The melted polymer is spun at a temperature of 280-290 °C. The spinneret holes are generally 0.2-0.4 mm in diameter. Drawing is usually carried out at a temperature of 60-90 °C (Mather and Wardman 2015). Fibres with higher strength can be produced by applying a higher draw ratio, i.e. stretching the fibres further. The spinning process produces filament fibres of infinite length, but the filament can also be cut into staple fibres of a required length, for instance to ease blending with other, often cellulose-based, fibres.

3.3.2.4 Chemical structure

PET is a molecule that consists of alternating units of terephthalic acid and 1,2 ethanediol, linked together by ester bonds (Figure 3.9).

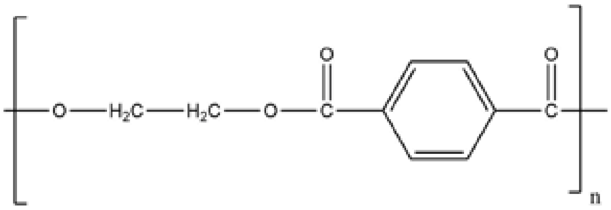


Figure 3.9: Chemical structure of polyethylene terephthalate (PET).

3.3.2.5 Physical and mechanical structure and properties

The properties of PET fibres are shown in Table 3.10. PET fibres are thermoplastic, which means they can be re-melted by heating them above their melting temperature. PET is not easy to dissolve and requires strong solvents.

Table 3.10: Physical and mechanical properties of PET fibres (Mather and Wardman 2015).

Property	**PET**
Fibre length	Filament, so infinite length. Can be cut into staple fibre
Fineness	Can be produced in a wide range of fineness
Specific gravity	1.38
Tenacity, dry	3.8-5.3 cN/dtex (dry and wet)
Elongation at break	15-40%
Elastic recovery	80% from 8% stretch
Thermal properties	PET will melt above 260 °C

3.3.2.6 Fibre properties related to textiles for fashion

PET fibres are hydrophobic, as a result they have a low moisture regain and are water repellent (Table 3.11).

Table 3.11: Textile properties of PET fibres.

Property	**PET**
Washability	Very good, mostly recommended 40°C, can be tumble dried
Shrinkage	Do not shrink
Moisture regain	0.4 %
Dyeability	Very good
Biological stability	Very resistant to biological attack
Electrical properties	Can build up static electricity
Wrinkle	Shows little wrinkling
Abrasion resistance	High

3.3.2.7 Fibre applications

PET fibres are strong, and they do not shrink or wrinkle. They can be easily laundered and because they take up very little water they dry quickly. A fabric made only of PET however may feel clammy and take up odour quickly. PET is therefore often blended with other fibres to combine the good properties of both. PET/cotton blends, also known as polycotton, are used for shirts, skirts, dresses, etcetera. PET can also be blended with wool for suits and trousers, or with viscose into a fabric that can resemble wool, suitable for people who are allergic to wool (Clan 2019).

3.3.3 Other polyesters

PET is by far the most used polyester for textile applications but there are a number of other polyesters available as well, such as polybutylene terephthalate (PBT) and polytrimethylene terephthalate (PTT). Both of these polyesters are also based on terephthalic acid, but with a different comonomer: 1,4 butanediol for PBT and 1,3 propanediol for PTT. PBT finds only limited applications in textiles for fashion.

PTT is becoming more widespread since the development of an economically viable process for 1,3 propanediol. This building block is made from corn starch on a commercial scale and PTT is therefore partly bio-based. Its properties are fairly similar to PET, but the fibres are softer and recover better from applied strain. It is used for a variety of applications, notably swimwear and underwear and many other apparel applications (DuPont 2019).

PLA or polylactic acid is another polyester fibre that has been developed in recent years. PLA is made from renewable resources and is 100% biobased. The building block of PLA is lactic acid. In many of its properties PLA resembles standard PET fibres, and on top of this it is biodegradable under composting conditions. It has a good elongation and recovery from stretch, low moisture absorption, excellent wicking properties and low odour retention (NatureWorks LLC 2019). PLA, however, has a low melting point, this may cause problems during the production of garments. Furthermore, ironing PLA should thus be done at a very low temperature. Next to this, PLA degrades under alkaline conditions, which implies that considerable care must be taken when laundering PLA garments (Mather and Wardman 2015).

3.4 Polyamides

3.4.1 Introduction

Polyamides are a class of polymers that are characterised by the presence of an amide bond (R_1-CO-N-R_2), which can be of natural origin or man-made. Natural protein fibres fall under the class of polyamides, because the main linkages in their polymeric chains are amide bonds. Natural protein fibres include keratin fibres like (animal) hair or fur or protein fibres secreted by insects like silk. Synthetic (man-made) polyamides are known by the generic name nylons. In this paragraph the two major classes of natural polyamides are described, i.e. wool and silk. Of the group of synthetic polymers nylon 6 and nylon 6,6 are covered.

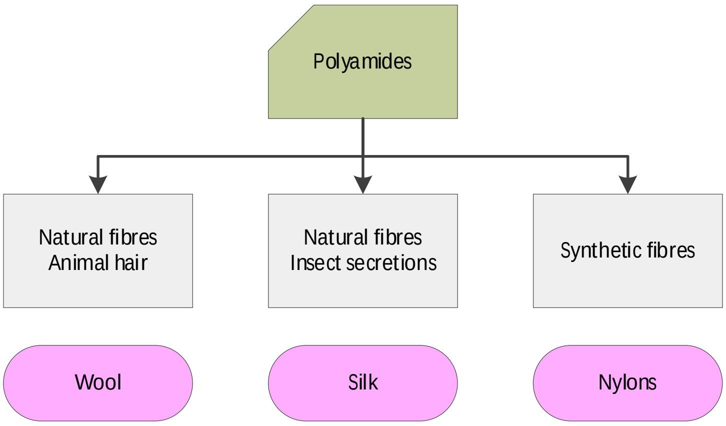


Figure 3.10: Polyamide-based fibres.

3.4.2 Wool

3.4.2.1 Introduction

Wool, the hair of sheep, is one of the most complex textile fibres in terms of mechanical, physical and chemical properties. Wool is after flax possibly the next-oldest fibre known to humans, it was one of the first fibres to be spun into a yarn and woven into a fabric.

3.4.2.2 Raw materials and origin

The term wool is generally used for the hair of sheep (Figure 3.11), a highly crimped protein fibre mainly composed of keratin. Other animal hair is usually specified after which animal it is gained from, like angora from rabbits, mohair and kashmir from goats, camelhair from camels and alpaca wool from alpaca’s (Babu 2015). Often wool is considered as the by-product of meat production and not all the wool produced is processed and used for textile manufacturing.

3.4.2.3 Fibre production

The wool is removed from the sheep by sheering. Fleece is a ball of wool, weighing around 5-9 kg, taken from a single animal. The sheared wool is called raw wool and is cleaned before further processing. It contains considerable amounts of vegetable matter and dirt, but also valuable wool grease or lanolin, which is extensively used in the health and personal care sector. The cleaned wool is carded, i.e. brushed, to orient the fibres,

Figure 3.11: A herd of sheep on the campus of Wageningen.

which eventually leads to stronger yarns. The carded fibres are gently scraped into strands called roving, and the roving is then spun into a yarn (WoolFiber 2019).

3.4.2.4 Chemical structure

Clean wool fibres consist mainly of protein, with less than 1% non-protein matter. Proteins are abundantly present large natural molecules made up of amino acid building blocks, which are linked into a polymer chain via amide bonds. About 80% of the proteins in wool are keratins, highly crosslinked proteins made up of over 19 different amino acids. Cysteine is the most important amino acid in keratin, containing sulphur and

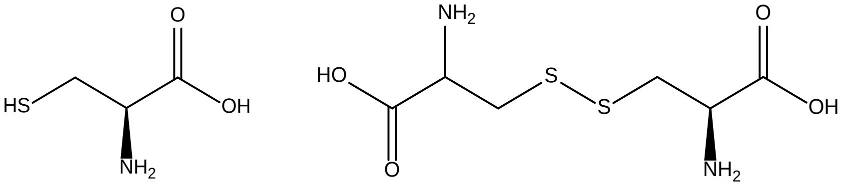


Figure 3.12: Amino acid cysteine (left structure) and the oxidized dimer form with the disulphide bonds called cystine (right structure).

forming crosslinks between adjacent chains through disulphide bonds (Figure 3.12). Keratin differs from most other proteins because of its large sulphur content of about 3-4%. Due to its cross-linked structure wool does not melt and it can also not be dissolved. The wool fibres are therefore always applied as such and not (re)processed into another form or shape.

3.4.2.5 *Physical and mechanical structure and properties*

The morphology of wool fibres is complex. There are essentially two main categories of cells: cortical cells or cortex, accounting for around 90% of the wool fibre, and cuticular cells or cuticle, on the surface of the fibre. The cuticle is separated from the cortex by a cell membrane complex, forming the only continuous phase in a wool fibre, providing adhesion between the cells (Mather and Wardman 2015).

Wool fibres are characterised by an enormous variation in their structure. By far the most important parameters are the fibre length and diameter or fineness. This can range from coarse fibres for carpets to fine fibres for delicate garments. Wool fibres have moderate strength and elasticity.

Table 3.12: Physical and mechanical properties of wool fibres (Mather and Wardman 2015).

Property	**Wool**
Fibre length	50-125 mm
Fineness	Range of diameters: coarse (25-70 µm) to fine (10-25 µm)
Specific density	1.32
Tenacity dry	0.9-1.5 cN/dtex
Tenacity wet	0.7-1.4 cN/dtex
Elongation at break	25-35%
Elastic recovery	High, 50% recovery from 10% stretch
Thermal properties	No melting point, flame retardant

3.4.2.6 *Fibre properties related to textiles for fashion*

Wool fibres display a higher moisture regain compared to other fibres. Due to the hydrophobic surface wool fibre repels water, but the inner core absorbs moisture. This is why woollen fabrics tend to feel dry and comfortable, even in damp weather.

In addition, the absorbency of wool results in a natural resistance to wrinkles, holds down static electricity, and acts as flame retardant (Wool Fiber 2019). Wool fibres are not so strong, but the extent of stretching before break is considerable, particularly for wet fibres.

Table 3.13: Textile properties of wool fibres.

Property	**Wool**
Washability	Needs to be handled with care. Severe mechanical agitation and tumble drying can induce felting. Neutral detergents, stable to acids, susceptible to alkali.
Shrinkage	Susceptible to shrinkage
Moisture regain	14-18%
Dyeability	Good
Biological stability	Susceptible to moths
Electrical properties	No accumulation of static electricity
Wrinkle	Resistance to wrinkles
Abrasion resistance	Low for apparel wool

3.4.2.7 Fibre applications

Wool is not applied in large volumes in the fashion sector, it accounts for only a few percent of all apparel fibres, but it is appreciated for its beauty and durability. Wool marketing has switched from quantity to quality. In contrast to synthetics, wool is a fibre that reacts to changes in body temperature: it helps to stay warm when it is cold, and cool when the weather is hot. Main applications are high-quality business suits, warm sweaters, jackets, coats and skirts, made from woven fabrics of varying weights and knitted fabrics (Wool Fiber 2019).

The popularity of wool in apparel has declined over decades, partly due to competition with synthetic fibres and improved isolation and heating of homes and offices. Innovative blends with other fibres like PET is increasingly being used.

3.4.3 Silk

3.4.3.1 Introduction

Silk is an animal fibre produced by some insects to build their cocoons or webs. Most silk that is used for textile application is produced by the caterpillar of the mulberry silk moth Bombyx Mori (see Figure 3.13). This silk moth has been domesticated in China over 5000 years ago (Wikipedia 2020). The practice of breeding silkworms for the production of raw silk is called sericulture.

Silk is widely valued for its strength and lustre, and because it can be dyed to bright colours. However, it accounts for only 0.2% of the world textile fibre production (Mather and Wardman 2015).

3.4.3.2 *<u>Raw materials and origin</u>*

The mulberry silkworm (the caterpillar) is fed on leaves of the white mulberry. Approximately 35 days after hatching the caterpillars have increased 100 times in weight, and are ready to start spinning the cocoon (Babu 2015). The caterpillar forms the silk filament by extruding two different proteins each from two internal glands: fibroin and sericin. The latter is a water-soluble gum that envelops the fibroin fibre and binds the two fibroin filaments together. The cocoon is spun from one continuous filament which can be 1 to 2 kilometre in length (Mather and Wardman 2015). Approximately 5000 to 6500 cocoons are needed to produce a kilo of silk (Wikipedia 2020).

3.4.3.3 *<u>Fibre production</u>*

After harvesting the cocoons, they are immersed in heated water, which enables the filaments to be unwound as yarns. Typically the single threads from 4 to 20 cocoons are combined while being unwound onto a reel, the threads are slightly twisted together to

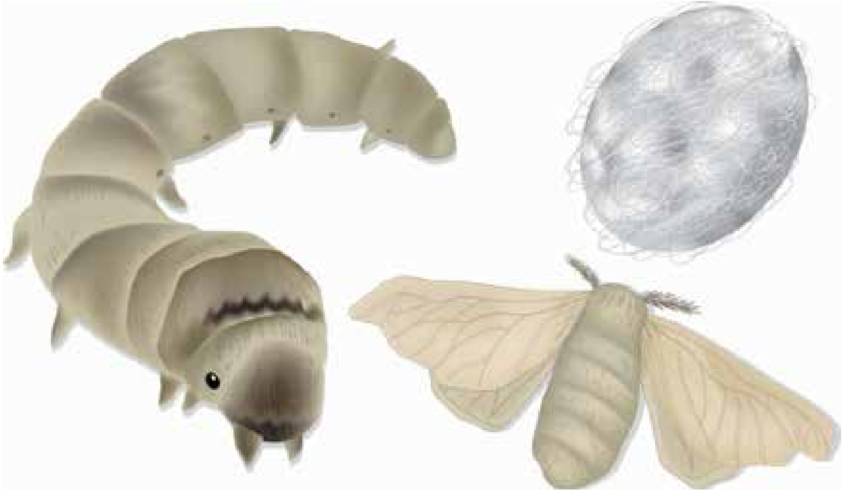


Figure 3.13: Production of silk: the caterpillar, moth and cocoon.

form a single raw silk yarn (Babu 2015). Hereafter the silk can be degummed, a process under alkaline conditions, to dissolve the water soluble sericin, and only leave the fibroin fibres. Sometimes degumming is done even later in the process, after the fabric is woven, since the non-degummed fibres can better withstand abrasion and wear of the processing equipment.

3.4.3.4 Chemical structure

Silk fibres are made up of protein, built from amino acids, and are therefore member of the polyamide family. The silk proteins contain a large number of different amino acids, but the bulk (more than 80%) is made of only three amino acids: glycine, alanine and serine. These three main components are the amino acids with the smallest side-chain groups. Silk therefore has a high degree of crystallinity, circa 70%.

3.4.3.5 Physical and mechanical structure and properties

Silk fibres are relatively strong, and they have a high elongation at break (see Table 3.14). Therefore, silk was originally also used for parachute fabrics, but nylon has now replaced it in this application.

Table 3.14: Physical and mechanical properties of silk fibres (Mather and Wardman 2015).

Property	**Silk**
Fibre length	Endless filament
Fineness	A single thread has a cross section of 15 – 25 µm
Specific density	1.33
Tenacity dry	3.8 cN/dtex
Tenacity wet	3.0 cN/dtex
Elongation at break	23-38%
Elastic recovery	Medium, 50% recovery from 10% stretch
Thermal properties	No melting point

3.4.3.6 Fibre properties related to textiles for fashion

Silk has a relatively high moisture regain and is very comfortable to wear (see Table 3.15). It is cool at higher temperatures, yet warm in colder conditions, and therefore also well suited for evening gowns.

Table 3.15: Textile properties of silk fibres (Mather and Wardman 2015, Babu 2015).

Property	**Silk**
Washability	Needs to be gently washed with only mild agitation
Shrinkage	Susceptible to shrinkage
Moisture regain	10-11%
Dyeability	Good
Biological stability	Susceptible to moths
Electrical properties	No accumulation of static electricity
Wrinkle	Prone to wrinkling
Abrasion resistance	Moderate

3.4.3.7 Fibre applications

Due to its lustre, strength and the fact it can be dyed to bright colours, silk is still considered a premier textile material and is used in luxury clothing and haute couture. It is furthermore used in scarves, ties and furnishing fabrics.

3.4.4 Polyamides; nylon 6 and nylon 6,6

3.4.4.1 Introduction

Synthetic polyamides, better known under the generic name nylons, are a major class of synthetic polymers. Nylons were the earliest synthetic fibres to become major commercial products. Scientists at the chemical company du Pont de Nemours in the USA produced in the 1930s the first nylons, including nylon 6. In 1939 nylon 6,6 was commercially produced, for nylon stockings but also for parachute fabrics. In the early 1950s, polyamide almost completely dominated the synthetic fibres market. Now this is overtaken by PET, but nylons are still an important polymer in today’s fashion.

3.4.4.2 Raw materials and origin

Nylons are produced via polycondensation of a diacid and a diamine, or ring-opening polymerization of a lactam (cyclic compound with an amide group). Nylon 6 (from caprolactam) and Nylon 6,6 (from adipic acid and hexane diamine) are the two most manufactured polyamides which are commonly used in a wide range of applications from apparels, ropes, carpets, tyre cords and innumerable textile applications.

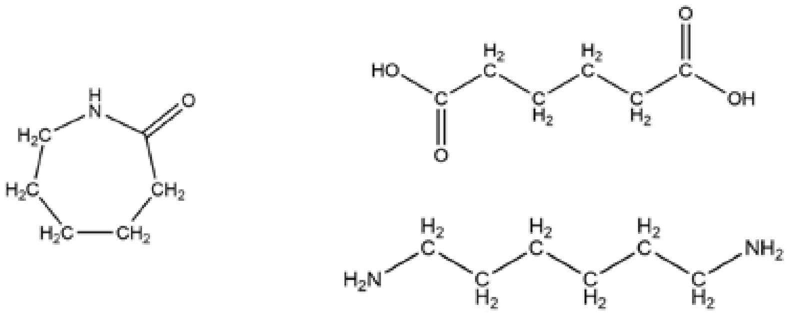


Figure 3.14: Building blocks for nylons: caprolactam for nylon 6 (left structure) and adipic acid (right structure, top) and hexane diamine (right structure, bottom) for nylon 6,6.

3.4.4.3 Fibre production

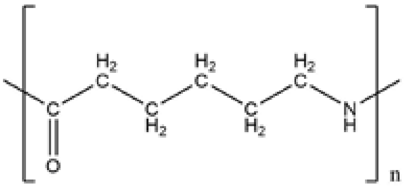
Nylon 6 is produced from caprolactam. A catalyst is required to convert a small amount of caprolactam to ε-aminocaproic acid, which in turn aides the polymerization process. Water is usually used as a catalyst to control the polymerisation reaction that takes place at temperatures between 250 and 270 °C and at atmospheric pressure (Mather and Wardman 2015).

For nylon 6,6, hexane diamine and adipic acid are reacted in methanol at high temperature to form hexamethylene diadipate, so called nylon salt. This salt is precipitated from the methanol solution and dissolved in water to a concentration of 60% and further concentrated to >80% by evaporation. The material is then heated to around 250 °C for polycondensation after which nylon 6,6 is formed (Mather and Wardman 2015).

The nylon is then fed into an extruder where it is melted and subsequently spun into filaments. The filaments are subjected to a drawing process to improve the fibre properties such as tensile strength and stiffness.

3.4.4.4 Chemical structure

Nylon 6 and nylon 6,6 are condensation polymers, linked together with amide bonds. Figure 3.15 illustrates the structural differences between the two nylon types.



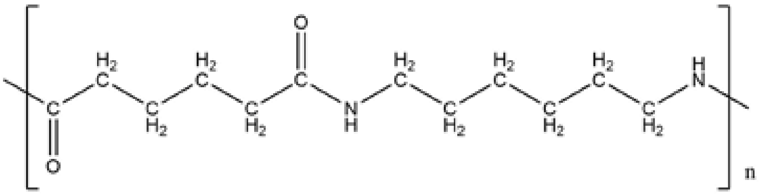


Figure 3.15: Chemical structures of nylon 6 (upper structure) and nylon 6,6 (lower structure).

3.4.4.5 Physical and mechanical structure and properties

Nylon is relatively strong and has a good elastic recovery, the properties of Nylon 6 and Nylon 6,6 differ slightly (see Table 3.16)

Table 3.16: Physical and mechanical properties of nylon fibres (Deopura and Padaki 2015, Mather and Wardman 2015).

Property	**Nylon 6**	**Nylon 6,6**
Fibre length	Filaments	
Fineness	Fineness can be tuned by the spinning step	
Specific gravity	1.14	
Tenacity, dry	4-6 cN/dtex	
Tenacity wet	4-6 cN/dtex	
Elongation at break	20-30%	Up to 40%
Elastic recovery	Very good, 100% from 4% stretch	
Thermal properties	Melts around 215 °C	Melts around 260 °C

3.4.4.6 *Fibre properties related to textiles for fashion*

Nylon is very abrasion resistant, but need to be washed with care, otherwise the fabric distorts and wrinkles due to breakage of intermolecular hydrogen bonds on absorption of water (Mather and Wardman 2015). Nylon is hygroscopic, but the moisture regain is limited by the high crystallinity (Deopura and Padaki 2015).

Table 3.17: Textile properties of nylon fibres (Mather and Wardman 2015, Deopura and Padaki 2015).

Property	**Nylon 6 and Nylon 6,6**
Washability	No washing in hot water and only subjected to gentle agitation
Shrinkage	Does not shrink
Moisture regain	4.0-4.5%
Dyeability	
Biological stability	Stable, also against many chemicals
Electrical properties	Does build up static electricity
Wrinkle	Does not wrinkle
Abrasion resistance	High

3.4.4.7 *Fibre applications*

Nylons are widely used in both apparel and industrial sectors. For apparel, lightweight and sheer garments are produced from nylon 6 and nylon 6,6, where extensibility, high strength and good abrasion resistance are important. Nylon fabrics made from 15 denier monofilaments are used for hosiery products, where polyamides are often combined with elastane (Lycra). Nylon fabrics also have excellent shape retention due to good elastic recovery behaviour. Wool is blended with nylon to improve its durability (outerwear, floor coverings) (Babu 2015).

3.5 Polyurethanes

3.5.1 *Introduction*

Polyurethanes are a family of polymers with a wide range of characteristics and applications. They are formed by the polymerisation of polyols (compound with two or more hydroxyl groups) with (di)isocyanates (compound with two or more isocyanate groups). The final properties of polyurethanes are determined by the characteristics of the polyols and isocyanates. Current applications vary from soft and hard foams to coatings, adhesives, sealants and textiles. In textiles specific polyurethane structures with an extremely high elasticity are applied, known as elastane. In this paragraph the elastane fibre is discussed.

3.5.2 Elastane

3.5.2.1 Introduction

Elastane fibres are synthetic fibres which exhibit a very high degree of stretch under stress and will return to their original shape when the stress is relieved. They are an alternative to natural and synthetic rubbers. Elastane fibres are also known by their trade names Spandex (used in America) and Lycra (used in Europe).

3.5.2.2 Raw materials and origin

Elastane fibres are made up of two main building blocks, a polyester or polyether polyol and an aromatic di-isocyanate. Furthermore, a bifunctional chain extender, such as ethylene diamine, is used to form the final polymer. Generally, all these building blocks are produced from fossil oil, but especially the polyols can also be produced from a bio-based (sugar) source. Lycra markets a fibre that is for approximately 70% bio-based, based on corn starch (Lycra 2019).

3.5.2.3 Fibre production

Elastane fibres can be produced by melt spinning, wet spinning and dry spinning. The dry spinning method is applied most (Mather and Wardman 2015).

3.5.2.4 Chemical structure

Elastane fibres are made of so-called block copolymers. This is a molecular structure with alternating ‘soft’ and ‘hard’ blocks (-S-H-S-H-S-H-). The soft blocks are coiled in their unstressed balance state. When force is applied, the soft blocks uncoil and become stretched and will be aligned approximately along the fibres axis. When the stress is released the soft blocks relax back into their balance state. The hard blocks on the other hand can form very strong inter-chain bonds with other hard blocks from a neighbouring chain. These strong bonds work as cross-links in a netted structure that prevent slipping of the molecular structure in the stretched state, and make sure that the fibre relaxes back into its original shape. The bonds between the hard segments of neighbouring chains are formed mainly by hydrogen bonding. This implies that, contrary to rubbers, elastane fibres can be dissolved and/or melted (Mather and Wardman 2015).

3.5.2.5 Physical and mechanical structure and properties

A summary of physical and mechanical properties of elastane is given in Table 3.18.

Table 3.18: Physical and mechanical properties of elastane fibres.

Property	**Elastane**
Fibre length	Continuous filament
Fineness	2-600 tex
Specific gravity	1.21
Tenacity, dry	0.5-1.4 cN/dtex
Tenacity wet	0.5-1.4 cN/dtex
Elongation at break	400 – 650 %
Elastic recovery	Almost complete recovery
Thermal properties	They melt at 250 °C and become sticky at 150 °C

3.5.2.6 Fibre properties related to textiles for fashion

Generally, only a small amount of elastane (2 - 5%) is enough to give fabric its desirable stretch properties. Because of this small percentage the other properties of the fabric are mostly determined by the rest of the fibre types in the fabric.

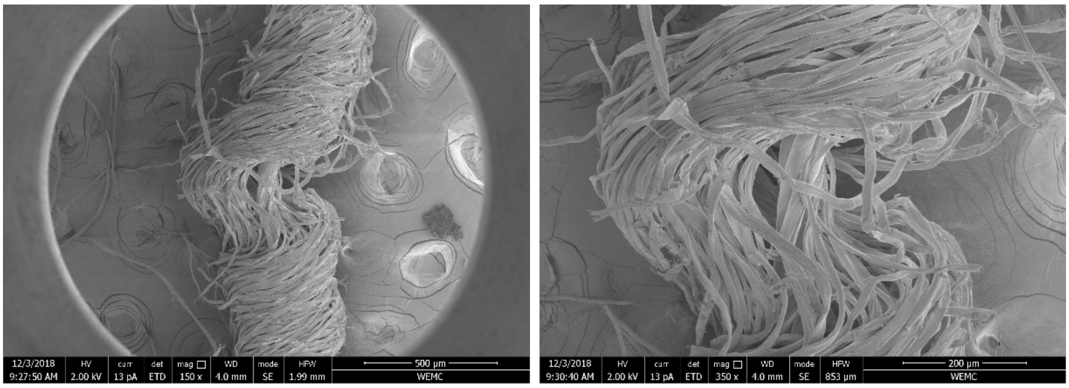


Figure 3.16. Core spun elastane-cotton. The elastane fibres are the thicker fibres in the centre.

3.5.2.7 Fibre applications

Elastane fibres are always used in combination with other fibres to make a fabric. They can be used bare, but often elastane fibres are covered with other types of fibre, which can be spun helically around an elastane core (Figure 3.16). Covered elastane fibres are used extensively in cotton, cotton/polyester and woollen garments.

3.6 Polyolefins

3.6.1 Introduction

Polyolefins form the largest group of synthetic polymers in production volume, with polyethylene or PE as the most common example of polyolefins. They are produced by polymerising an alkene monomer (-C=C-) into a chain. In this paragraph the olefins relevant for textiles are described, i.e. polypropylene (PP) and a few other examples.

3.6.2 Polypropylene (PP)

3.6.2.1 Introduction

Polypropylene (PP) is the second largest polymer in the world in terms of production volume. It finds application in a wide variety of products, including packaging applications and all sorts of containers. PP can also be spun into a fibre with a relatively high strength which makes it suitable for application in ropes, carpets, medical and hygiene products. PP is also used in textiles for fashion but mainly in sportswear such as walking socks, swim wear and lightweight wear for climbers.

3.6.2.2 Raw materials and origin

PP is produced from propylene (or propene) which is a by-product from the production of transport fuels from fossil oil. The propylene is polymerised into polypropylene and turned into granules that can subsequently be used in the spinning process (see Figure 3.17).

Figure 3.17: Propylene (left structure) and polypropylene (right structure).

3.6.2.3 Fibre production

PP fibres are produced by melt spinning. The melting temperature of PP is relatively low, around 160–170 °C, so the spinning process is done at lower temperatures than for example PET spinning.

3.6.2.4 Chemical structure

PP consists solely of carbon and hydrogen atoms and is therefore very hydrophobic, it will not take up water. This makes PP difficult to dye. PP is sometimes modified to improve its dyeing properties.

3.6.2.5 Physical and mechanical structure and properties

PP fibres are strong and have a high elasticity (see Table 3.19). They have a specific gravity lower than 1, therefore PP can in principle be separated by flotation separation.

Table 3.19: Physical and mechanical properties of PP fibres (Mather and Wardman 2015, Sinclair 2015).

Property	**PP**
Fibre length	Infinite, but can be cut into staple fibre
Fineness	Can be produced in a wide range of fineness
Specific gravity	0.90
Tenacity, dry	3-8 cN/dtex
Tenacity wet	3-8 cN/dtex
Elongation at break	15 – 35 %
Elastic recovery	High, >90% recovery from 8% stretch
Thermal properties	Melt temperature around 160 °C

3.6.2.6 Fibre properties related to textiles for fashion

PP as textile fibre is mostly applied in outdoor applications, it is less suitable for normal garments since it takes up no moisture. On the other hand it is very resistant to biological attack (see Table 3.20).

3.6.2.7 Fibre applications

PP fibres are applied in sportswear and activewear. They do not take up moisture and they transport water very easily. They are therefore used for undergarments that keep

Table 3.20: Textile properties of PP fibres (Mather and Wardman 2015, Sinclair 2015).

Property	**PP**
Washability	Very good
Shrinkage	Unknown
Moisture regain	0%
Dyeability	Dyeing is very difficult
Biological stability	Very resistant to biological attack
Electrical properties	Will build up static electricity
Wrinkle	Shows little wrinkling
Abrasion resistance	High abrasion resistance

the wearer dry and warm during activity, by transporting sweat away from the skin to an absorbent outer layer. PP fibres do however take up body odour, which is very difficult to remove (Ellis 2019).

Figure 3.18: Protective fencing suit (plastron) made from PE.

3.6.3 Polyethylene (PE)

Of the other members of the polyolefin family, only PE is widely applied as fibre. PE can be spun in a special process called gel spinning which produces fibres of exceptional strength with a tenacity of 25–37 (cN/dtex). Gel spun PE is known under the trade names Dyneema and Spectra. The fibres possess good cut and puncture resistance, and they are therefore applied in items such as protective clothing, cut-resistance gloves and fencing suits (see Figure 3.18).

3.7 Polyacrylics

Polyacryl polymers have as their main monomeric building block acrylonitrile (see Figure 3.19). Pure polyacrylonitrile fibres are mainly used as precursors for the production of carbon fibres. For textile fibres, next to acrylonitrile, other co-monomers are incorporated in the acrylic polymer chains. Polyacrylonitrile was first synthesised in 1894, but it was not soluble in solvents available at that time, and it could not be molten. The polymerisation was again explored in 1930 (Wikipedia 2019). The development of acrylic textile fibres was done in the mid-1940s. Du Pont marketed the first acrylic fibre under the name Orlon in 1944 (Mather and Wardman 2015). It became important in the market for textiles during the 1950s (Wikipedia 2019).

3.7.1 Acrylic fibres

3.7.1.1 Introduction

Acrylic fibres are fibres that need to contain at least 85% of the acrylonitrile monomer. Acrylic fibres are bulky and warm and have been used a lot for replacing (expensive) wool for instance in sweaters and scarves, and as linings in boots and gloves.

3.7.1.2 Raw materials and origin

The raw material for acrylonitrile as well as the comonomers is fossil oil. Polyacrylic is produced by polymerising acrylonitrile mostly together with other comonomers. The

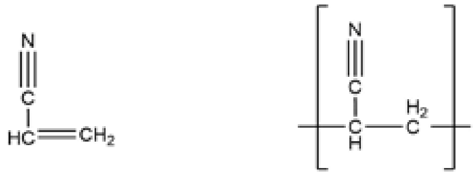


Figure 3.19: Chemical structure of acrylonitril (left structure), main monomer of the polymer polyacryl (right structure).

polymer is formed by reacting the main monomer and comonomers in the same step. One of the functions of the other comonomers is to create a more open fibre structure, in order to enable easier processing. Typical comonomers are vinyl acetate and methacrylate which are also produced from fossil oil.

3.7.1.3 Fibre production

Acrylic fibres will decompose below their melting temperature. They cannot be melt spun but are produced by solution spinning. The solvent used is partly dependent on the types of comonomers that are present in the polymer. After spinning, the filaments are generally cut into staple fibres for further yarn spinning.

3.7.1.4 Chemical structure

Polyacrylics are addition polymers made from various monomers. Chemical structure of polyacrylic is shown in Figure 3.19.

3.7.1.5 Physical structure and properties

The properties of acrylic fibres depend on the comonomers incorporated during polymerisation and thus many properties span a range of values.

Table 3.21: Properties of acryic fibres (Mather and Wardman 2015, Sinclair 2015).

Property	**Value**
Fibre length	Infinite, but can be cut into staple fibre
Fineness	Can be produced in a wide range of fineness
Specific gravity	1.14-1.19
Tenacity, dry (cN/dtex)	1.0-3.5
Tenacity wet (cN/dtex)	0.8-2.8
Elongation at break	25 – 60
Elastic recovery	Not very high
Thermal properties	Melting point of pure polyacrylic is 300 °C. Can withstand 150 °C but might discolour slightly

3.7.1.6 Fibre properties related to textiles for fashion

Acrylic fibres are often applied in knitwear as a replacement for wool (see Figure 3.20) or combined with wool. They are fairly stiff compared to nylon and polyester.

Table 3.22: Textile properties of acrylic fibres (Mather and Wardman 2015, Sinclair 2015).

Property	**Value**
Washability	May need some additional care, known to show pilling, sometimes handwashing is recommended
Shrinkage	Do not shrink
Moisture regain	1 – 4.5%
Dyeability	Good, can be improved by adding certain co-monomers
Biological stability	Very good
Electrical properties	Less build-up of static electricity than polyester or nylon
Abrasion resistance	Moderate abrasion resistance

3.7.1.7 *Fibre applications*

Acrylic fibres have lost most of their applications in textiles, where they were previously used in knitwear, socks, fleeces, etcetera. They still find application in products where

Figure 3.20: Acrylics are still used in knitwear such as scarves (photographs: Allard Bosch and Wanne Aarnoutse).

their mould resistance and long term light and weather fastness is essential such as awnings, boat covers and garden furniture (Sinclair 2015).

3.7.2 Modacrylic fibres

Modacrylic fibres are defined as acrylic fibres which consist of 50-85% of acrylonitrile monomers and which are copolymerised with mostly halogen (bromide or chloride) containing comonomers such as vinyl bromide and vinyl chloride (which is the monomer for PVC). The halogen makes the fibres flame-resistant and they are therefore applied in for instance protective clothing and children’s nightwear.

3.8 Blending of fibres

In the previous paragraphs the most common fibre types used in textiles were described. Nowadays, most of the garments are not made from single fibres but are composed of many different types of fibres, intimately blended. The reason for this is illustrated by Figure 3.21, where some of the fibre properties are shown for the various types of fibres.

This figure illustrates the large differences in characteristic properties between the fibres. For example, cotton is a relatively strong fibre and becomes even stronger in a wet state. It is comfortable to wear due to high moisture regain. Viscose is not so strong but also very comfortable due to high moisture regain. PET is a strong fibre but is not so comfortable on bare skin as it does not absorb moisture. So a single-component textile such as 100% polyester or 100% cotton often does not fulfil the requirements of today’s fashion. Fibre blending, by combining two or more fibres to a new yarn, can combine the best qualities of each fibre.

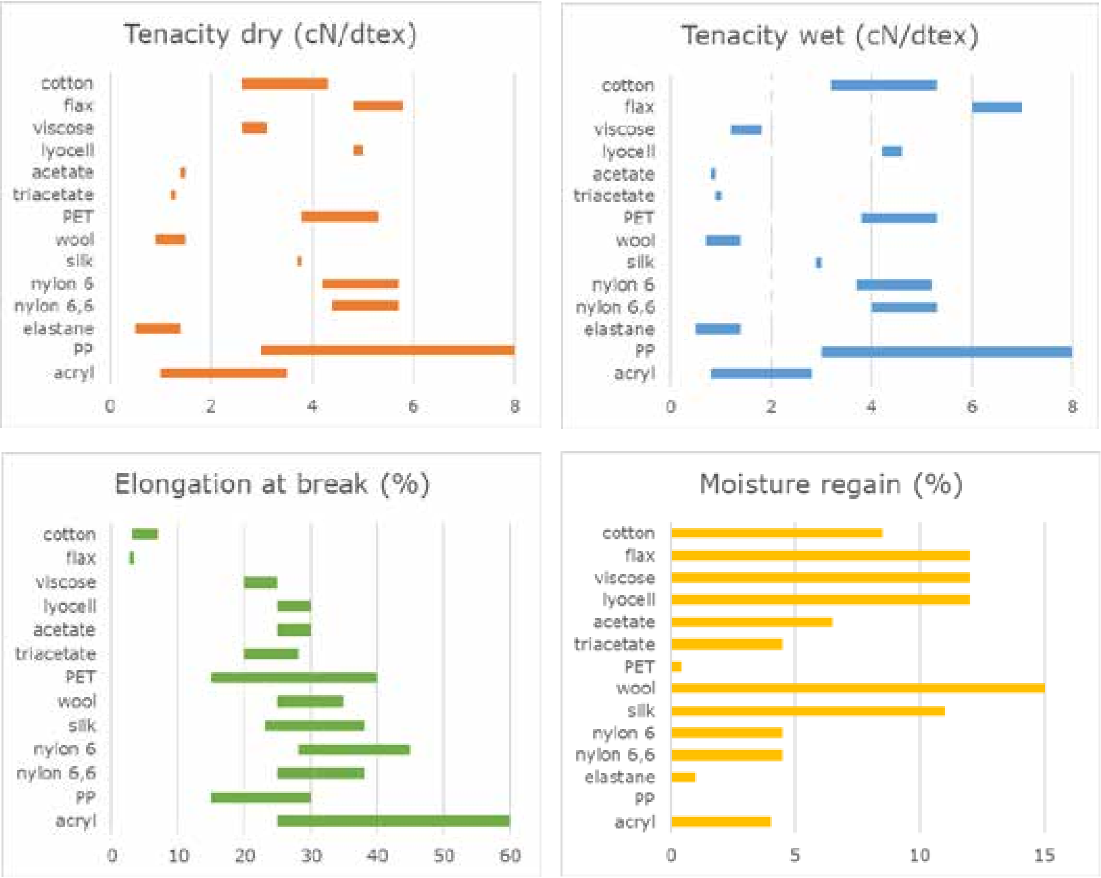


Figure 3.21: Comparison of number of characteristic properties of various fibres. Elongation at break for elastane is 400-650% and is not shown in the graph.

4 Recycling options for monomaterial textiles

4.1 Introduction

In this chapter we explore the end-of-life options for the different types of fibres discussed in the previous chapter. We look at recycling options for the fabric, fibre or for the polymer that make up the fibre. We describe the options per (unmixed) type of textile fibre. The complexity of end-of-life options for mixed textiles will be discussed in the next chapter.

According to Directive 2008/98EC (European Parliament 2008), recycling means 'any recovery operation by which waste materials are reprocessed into products, materials or substances, whether for the original or other purposes' (Piribauer and Bartl 2019). In this booklet the main focus lies on the options of recycling textile fibres back into textiles, but other end-uses of the recycled fibres are also mentioned. In that respect it is important to introduce the term downcycling. Short fibres that cannot be re-spun into a yarn often end-up in non-woven products or as fibre flock, used in construction materials or as viscosity modifier. Other downcycling processes are the production of fabrics to wiping rags, insulation materials or for upholstery.

In the textile industry classification of textile recycling is defined on the level of fabric, fibre, polymer or monomer. *Fabric recycling* implies that the fabric is recovered and used

Figure 4.1: Post-consumer textiles ready for recycling (left picture) and post-industrial waste from a sewing factory (right picture).

in a new product. Preserving fibres, after disintegration of the fabric, is referred to as *fibre recycling*. If the fibres are dissembled but the polymers remain intact, the process is called *polymer recycling*. *Monomer recycling* implies that only the chemical building blocks are reused. Whether a garment is suitable for fabric, fibre, polymer or monomer recycling is strongly determined by the fibre composition and the chemical structure of the polymers that make up the fibres of the garment.

Each type of recycling requires (several) recycling methods to come to a desired product. As recycling methods we distinguish sorting, mechanical-, physical- and chemical methods. In Table 4.1 the classification of textile recycling is coupled to the corresponding recycling methods. From this table it is clear that for all recycling initiatives, extensive sorting is needed as mixtures of different materials and colours results in resources of poor quality. Also mechanical methods are often required; for fibre recycling this is the last step, but for polymer and monomer recycling it is a treatment prior to physical or chemical recycling methods. The table also illustrates the complexity of the various classes of textile recycling.

Table 4.1: Classification of textile recycling and corresponding recylcing methods.

Classification of textile recycling	**Recycling methods**		
Fabric recycling or material reuse	Sorting		
Fibre recycling	Sorting	Mechanical methods	
Polymer recycling	Sorting	Mechanical methods	Physical methods
Monomer recycling	Sorting	Mechanical methods	Chemical methods

Furthermore, there is a distinct difference in the use of post-industrial waste (waste stream from the textile production itself) and post-consumer waste (waste stream of garments and fabric after wearing) (see Figure 4.1). Post-consumer waste is usually more contaminated, and also the fibre length and fibre strength has decreased substantially due to wearing and washing. As a result, it is much more difficult to recycle post-consumer waste than to recycle post-industrial waste.

Throughout the textile industry, terms like “mechanical recycling” or “chemical recycling” are not always interpreted in the same way by various stakeholders. For the sake of clarity in this booklet we use the following definitions that help us to orderly and recognisably present the different recycling methods for textile fabrics:

Mechanical methods imply the use of mechanical processes (cutting, tearing, shredding, carding) to separate the fibres or to reduce size. This means that the structure of the fibres remains intact. Mechanical methods generally break down the yarn and may result in fibre length reduction, which causes quality loss. Cotton and wool are examples of fibres that can be mechanically recycled.

Physical methods use physical processes to make the fibres or polymers suitable for reprocessing, which means either melting or dissolving them. With physical recycling the structure of the fibres is changed, but the polymeric molecules that make up the fibres remain intact. After melting or dissolving, either melt spinning or solution spinning can be used to form a new filament. An example is the recycling of cotton or cellulose-based fibres to create a regenerated cellulose fibre by dissolving the cellulose in a solvent, followed by solution spinning. Another example is PET that can be melted and spun to a new filament.

Chemical methods exploit chemical processes to break down the fibres, which means that the polymers that make up the fibres are either modified or broken down (chemical bonds are broken), sometimes as far down as to their original building blocks. This can be done by chemical or biological methods (e.g. with enzymes). After chemical recycling, the building blocks can be used to build-up a new polymer or find use in other applications. An example of chemical recycling is degradation of PET or nylon to its building blocks and polymerisation of these molecules into a new molecule.

In the previous chapter we discussed the most relevant textile fibres and categorized them in the main polymer groups cellulose, polyester, polyamide, polyurethane, polyolefin and polyacrylic. In this section the most relevant recycling options for these monomaterials is further explained.

4.2 Cellulose

4.2.1 Introduction

The cellulose molecules show a high degree of crystallinity and intermolecular hydrogen bonding. This is the reason why cellulose will not melt at high temperatures and will not dissolve in common solvents. Consequently, for cellulose-based fibres there are two routes available when fibres are envisioned as end-product: through mechanical recycling and through physical recycling by dissolving and (re)spinning of the cellulose to a regenerated cellulose fibre. A third option, often leading to other end-products than fibres, is the breakdown of cellulose to glucose molecules by chemical methods.

4.2.2 Mechanical recycling methods

As cotton is by far the most applied cellulose fibre, recycling processes of cellulose fibres are mostly developed for cotton. Mechanical cotton recycling consists of the following steps: after collection and sorting the fabric is cut in small pieces, next the fabric pieces are broken down further in a process called tearing, which pulls the yarns apart. When the recycled cotton is to be reused as a textile the resulting fibres are formed into a sliver, which is subsequently re-spun by a yarn spinning process (see Figure 4.2).

One of the problems with mechanical recycling is the length reduction of the fibres; often the resulting fibres are too short to be spun in a yarn with appropriate strength. Recycled cotton therefore often ends up in applications such as non-wovens (see Figure 4.3) or paper-like products. The fibres are thus lost for apparel applications.

Figure 4.2: An example of a T-shirt from mechanical recycled cotton fibres.

Mechanical recycling of bast fibres, for apparel applications mostly linen, could in principle be done in the same way. However, the market share of linen is so small that according to our knowledge there is no dedicated linen recycling party.

Regenerated cellulose (viscose and lyocell) and also cellulose acetate can in principle also be mechanically recycled. However, since their fibre strength is much lower than the strength of cotton, even further fibre length reduction due to the mechanical

Figure 4.3: Non-woven from mechanically recycled textiles.

processing is to be expected. Reuse in apparel applications is therefore probably not a viable option and no commercial activities are known.

4.2.3 Physical recycling methods

Cotton fibres are almost fully made up of cellulose and therefore are in principle good candidates as feedstock for the lyocell process and the viscose process, and this is already applied at a small scale by a number of parties (see paragraph 4.2.5).
Bast fibres (flax/linen) contain far more non-cellulosic components, which would need to be removed before they can be applied as feedstock for the lyocell or viscose process.
Viscose and lyocell would in principle be suitable for reprocessing in their own process (viscose or lyocell). Bottlenecks for applying these processes for recycling fibres are contamination of the fabric, the presence of finishing agents and the presence of dyes. The recycled fibres need to be cleaned from these components before they can be used as feedstock.

4.2.4 Chemical recycling methods

Degradation of cellulose to glucose or oligosaccharide can be achieved with acids or with enzymes. Mineral acids like hydrochloric acid (HCl) or sulphuric acid (H_2SO_4) have been used for the hydrolysis of cellulose, often at elevated temperature (>100 °C) and pressure. Cellulases are enzymes that can break down cellulose polymers to glucose under much milder conditions, e.g. 50 °C and atmospheric pressure.

The resulting glucose molecules are obviously not intended for the construction of a new cellulose molecule (as this is not possible) but can be used for the production of all kinds of new chemical building blocks (Harmsen et al. 2014) and in the end to new polymers.

4.2.5 Initiatives of cellulose-based material recycling

Fabric recycling: downcycling of textiles to cleaning and wiping rags is a widely used option for recycling of post-consumer textiles. Only textiles with high water absorption capacity are feasible for this process, limiting the application mostly to cellulose fibres like cotton and viscose. Production of wiping rags is limited by the market price of the wiping rags and the labour cost in the country where they are produced (Piribauer and Bartl 2019).

Table 4.2: Initiatives of fibre recycling of cellulose-based materials (Textile Exchange 2018).

Company	Input stream	Product	Application	Status
Frankenhuis	Post-consumer textile waste	Textile fibres for nonwovens	Non-wovens	Commercial, the Netherlands
Wolkat	Post-consumer textile waste	Yarns	Textiles and non-wovens	Commercial, the Netherlands and Morocco
Belda Llorens	Cotton waste	Eco Life® yarns	Textiles, blended with virgin	Commercial, Spain
Geetanjali Woollens	Cotton waste	Recycled cotton fibre and yarn	Textiles, blended with virgin	Commercial, India
Hilaturas Ferre	Cotton waste	RECOVER, range of yarns and threads	Textiles*, blended with virgin	Commercial, Spain
Martex Fiber	Post-industrial cotton fibres and clippings	Eco2cotton®, cotton-like fluff	Textiles**, blended with virgin	Commercial, US
Velener Textil GmbH	Post-industrial yarns	WECYCLED® cotton fibres	Textiles, blended with virgin	Commercial, Germany

** High % mechanical recycled cotton, blended with recycled PET from bottles*

*** For yarns made with Eco2cotton other acrylic, PET or eco fibres are added to enhance performance and colour*

Fibre recycling of cellulose-based materials (mostly cotton) yields fibres typically for the nonwoven industry and as flock (very small fibres used to create texture on surfaces). Recycled cotton staple fibres are shorter than virgin cotton fibres and thus more difficult to spin. For woven applications, mechanical recycled fibres are often mixed with other virgin fibres like PET or cotton. About 95% of the recovered fibres by mechanical recycling cotton textiles are directly processed into nonwovens for the automotive industry, appliances, drainage systems and geotextiles (Gulich 2006). An overview of some initiatives on fibre recycling is shown in Table 4.2.

Table 4.3: Initiatives of polymer recycling of cellulose-based materials (Textile Exchange 2018).

Company and technology	**Input stream**	**Product***	**Status**
Lenzing AG with the Refibra™ process (lyocell)	20% post-industrial cotton scraps combined with 80% virgin cellulose pulp from wood	Tencel™ lyocell fibres (regenerated cellulose fibres)	Commercial, Austria
Asahi Kasei	100% cotton linter, post-industrial residue of cotton processing	Bemberg™ cupro fibre	Commercial, Japan, 17.000 mt/y
Re:newcell	High-content cellulose waste (cotton, regenerated cellulose)	Dissolving pulp	Demonstration, Sweden, 7000 mt/y
Evrnu with the Nucycle process	High-content cellulose waste (cotton, regenerated cellulose)	Regenerated cellulose fibres	In development, USA
Infinited Fibre	High-content cellulose waste (cotton, regenerated cellulose)	Regenerated cellulose fibres	In development, Finland
Aalto University with the Ioncell™ process	High-content cellulose waste (cotton, regenerated cellulose)	Ioncell™ fibres (regenerated cellulose fibres)	In development, Finland
SaXcell with the SaXcell® process (lyocell)	High-content cellulose waste (cotton, regenerated cellulose)	SaXcell® fibres (regenerated cellulose fibres)	In development, the Netherlands

** All products are intended for textile applications*

Polymer recycling of cellulose-based materials to yield regenerated cellulose fibres is a good option to recover and reuse cellulose polymers from waste streams. Initiatives in this field are listed in Table 4.3.

Monomer recycling of cellulose-based textile materials is mostly applicable for textile blends and will be discussed in the next chapter.

4.3 Polyesters

4.3.1 Introduction

The recycling of PET fibres, the main polyester in textile, has become increasingly important with the increasing use of PET in textiles. Recycling of PET is originating from polymer recycling by physical methods of transparent, 100% PET packaging materials like PET bottles, and initiatives in this field are numerous. As PET-based textiles are less suitable for polymer recycling by physical methods, due to contamination by dyes and other additives, monomer recycling routes are being developed.

4.3.2 Mechanical recycling methods

Mechanical recycling of PET textiles can be done in similar way as cotton or wool. However, since physical recycling (re-melting) and chemical recycling give fibres with

Figure 4.4: Transparant PET-bottles for the production of recycled PET fibres.

good properties (near virgin quality), very little activity on mechanical recycling of PET can be found.

4.3.3 Physical recycling methods

PET is a thermoplastic, it melts at elevated temperature (>260 °C) and can be re-spun into fibres again. This process can be feasible for clean monomaterials but has limitations for processing of multi-materials. As with cellulose, contaminations such as dyes and finishes may pose a problem in these kinds of processes. It is therefore that, instead of using waste textile fibres, recycled PET fibres for textiles are often produced from transparent PET bottles (Figure 4.4). The loss in molecular weight that occurs during the use of PET fabric or bottles can be undone by a process called solid state post condensation (Awaja and Pavel 2005), which rebuilds the chemical bonds between the polymer molecules that were broken. Discussions are ongoing whether PET from bottles should be used for the production of new bottles (circular use) or for the production of textile fibres, as textile PET is much harder to recycle than packaging PET (downcycling).

4.3.4 Chemical recycling methods

Chemical recycling methods are well suited for polyester fibres. During chemical recycling the polyester molecules are broken down to smaller fragments. This gives the great advantage that removal of contaminants and dyes is much easier because the smaller fragments can be cleaned in solution. In addition, the building blocks (monomers) can be purified using common techniques like recrystallisation and distillation. After removal of the impurities, the polyester monomers can be repolymerised towards their original state and properties (virgin quality).

Chemical recycling entails the depolymerization of PET into shorter building blocks (monomers, dimers or trimers), followed by polymerisation of these building blocks to a new polymer. In this process (part of) the ester linkages are broken down by chemical means or by enzymes. The larger the remaining building blocks, the lower the subsequent processing costs are.

Production of building blocks by chemical PET recycling can result in the original monomers: ethylene glycol (EG, also called monoethylene glycol) and terephthalic acid (TPA). Other processes result in somewhat larger molecules, dimers or trimers of the original building blocks, such as bis(2-hydroxyethyl) terephthalate (BHET) or dimethyl terephthalate (DMT).

The technology of PET degradation or depolymerization is done by so called solvolysis, a reaction in a solvent of which one of the reactants is a solvent molecule. It can be divided into the following solvolysis techniques, common for depolymerization of polycondensation polymers like polyesters, polyurethanes and polyamides (Datta and Kopczyńska 2016):

- *Chemically catalysed hydrolysis*
  Chemical hydrolysis involves the reaction of PET in water at high temperature (>200 °C) and pressure. Hydrolysis occurs through two processes: water diffusion into the matrix, followed by the hydrolysis reaction. Hydrolysis of PET can be carried out under acid, alkaline or neutral conditions. Reaction products are EG and TPA.
- *Enzymatically catalysed hydrolysis*
  Enzymatic hydrolysis is the hydrolysis of PET under much milder conditions and catalyzed by enzymes (e.g. cutinases, lipases), yielding EG and TPA. Enzymatic hydrolysis reactions suffer from long reaction times, as enzymes are big protein molecules that cannot penetrate the PET fabric easily to reach all bonds that need to be broken (Piribauer and Bartl 2019).
- *Glycolysis*
  Glycolysis is a typical depolymerization reaction for condensation polymers like PET. Compounds acting as glycolysis agents have at least two hydroxyl groups, for example ethylene glycol (EG). Glycolysis of PET is done between 180 and 240 °C and results in the formation of BHET.
- *Methanolysis*
  In methanolysis, methanol is the decomposing agent. Methanolysis of PET is usually done at temperatures higher than 200 °C yielding the monomers DMT and EG.

4.3.5 Initiatives of PET recycling

An extensive overview on the production of recycled PET is presented by Textile Exchange in their annual report (Textile Exchange 2019). From this report it is obvious that physical recycling of PET bottles into PET fibres is implemented world-wide. Post-consumer transparent PET bottles are relatively clean and result in a high quality rPET (recycled PET) suitable for yarn production. More challenging is the use of less pure post-consumer PET items like coloured bottles, PET trays and films, or PET recovered from the ocean and also textiles. If these sources cannot be sufficiently cleaned it might be necessary to use chemical recycling methods.

Initiatives on polymer and monomer recycling of PET are listed in Table 4.4 and Table 4.5. Various companies are upscaling and validating their technologies.

Table 4.4: Initiatives of polymer recycling of PET (Textile Exchange 2018).

Company and technology	Input stream	Product	Status
Velener Textil GmbH	PET bottles	WETURNED® PET-woven fabric	Commercial, Germany
Teijin	PET bottles	EcoPET staple fibre and spun yarn	Commercial, Japan
Cumapol with CuRe Technology	Coloured PET from various sources	Transparent PET granulate	In development, the Netherlands

Table 4.5: Initiatives of monomer recycling of PET (Textile Exchange 2018).

Company and technology	Input stream	Product	Status
Ioniqa with glycolysis	(Coloured) PET from various packaging materials	BHET rPET	Commercial, the Netherlands, 10 ktons/y
Jeplan with glycolysis	(Coloured) PET from various packaging materials	BHET	Commercial, Japan
Teijin	Bottles and other PET materials	DMT to EcoCircle™ filament yarns	Commercial, Japan
Ambercycle with enzymatic hydrolysis	Unknown	Unknown	In development, USA
Carbios with enzymatic hydrolysis	PET	Monomers EG and TPA	In development, France
Eastman with chemical recycling	Polyester	Unknown	In development, USA
Gr3n with microwave radiation	PET	Monomers	In development, Switzerland
Loop Industries/Indorama joint venture, with methanolysis	Unknown	Monomers DMT and EG	In development

4.4 Polyamides

4.4.1 Introduction

The two main polyamide fibre groups, wool and nylon, have very different recycling options. Wool can only be recycled mechanically, whereas for nylon, being a meltable polycondensation polymer, similar recycling options as for polyesters are viable (physical and chemical). Both wool and nylon recycling options are described in this section.

4.4.2 Mechanical recycling methods

Recycled wool has a long tradition and is the single example of successful mechanical recycling of post-consumer textiles to new yarns. Mechanical recycling of wool is done in similar steps as mechanical recycling of cotton. Sorted fabrics are cleaned and turned into fibres by cutting and tearing. Post-industrial waste is used, but also the mechanical recycling of post-consumer waste is feasible. The mechanical recycling of wool knitwear yields fibres of sufficient length to be carded and re-spun into yarns of pure wool or of blends. These yarns are then converted back into knitwear, providing a cost-effective wool-fibre supply (International Wool Textile Organization 2020).

Mechanical recycling of nylons can be done in similar way as cotton or wool. However, physical recycling (remelting) gives fibres with good properties (near virgin quality), and very little activity on mechanical recycling of nylons can be found.

Figure 4.5: Fishing nets are a feedstock for recycled nylon.

4.4.3 Physical recycling methods

Physical recycling methods for polyamides are only relevant for the nylons and not for wool. Just as with polyesters, nylon can be remelted, and thus reshaped into new fibres of appropriate length and strength. Nylon recycling is preferably done with relatively pure waste-streams, recycling of nylon mixed with other fibres is challenging (see also chapter 5). Pure nylon waste is available as carpets and fishing nets, and these forms of nylon waste are an important feedstock for physical nylon recycling (see Figure 4.5).

4.4.4 Chemical recycling methods

4.4.4.1 Wool

Chemical recycling is in general regarded as ‘the depolymerization of polymers into monomers that can be polymerized and subsequently converted into virgin quality polymers again’. However, in textile recycling the selective degradation of a fibre or polymer from a textile blend can also be a powerful tool. In that sense, the fibre or polymer is degraded but not converted to a new fibre again.

Wool fibres contain amide bonds that can be degraded by hydrolysis. This is a very slow process and in living organisms this process is catalysed by enzymes known as peptidases (to break down peptides) or proteases (to break down proteins). So in theory, polyamides like wool (and nylons) can be enzymatically degraded, but in practise this will not work as the bonds are most likely not accessible to the enzymes and processes are too slow.

4.4.4.2 Nylons

Chemical recycling methods are well suited for nylons. During chemical recycling the molecules are broken down to smaller fragments, giving the advantage that removal of contaminants and dyes is much easier because the smaller fragments can be cleaned in solution. After removal of the impurities, the nylon monomers can be repolymerised towards their original state and properties.

In the chemical recycling process all of the amide bonds are broken down by chemical means or by enzymes. This in contrast to PET, which is preferably only partly depolymerised. Nylon 6 is depolymerised to retrieve its original building block caprolactam. According to DSM this process is not more expensive than the production of virgin caprolactam, and it is much more environmentally benign (Buijs 2020). Nylon 6,6 is in theory converted to adipic acid and hexane diamine. In general, nylon 6 and nylon 6,6 are more difficult to recycle chemically than PET. Chemical hydrolysis and glycolysis are solvolysis processes used to depolymerize nylons, with a reaction temperatures well above 200 °C (Datta and Kopczyńska 2016).

4.4.5 Initiatives of wool and nylon recycling

4.4.5.1 Wool

Wool can be successfully recycled by mechanical means to new yarns for textiles. *Post-industrial* wool processing waste (fibre, yarn and fabric waste generated during production) is routinely recycled back into the manufacturing process flow for reasons of economic efficiency (Russell et al. 2016). Applicability of *post-consumer* waste is partly dependent upon effective ways to minimise fibre breakage and maximise residual fibre length after the mechanical pulling process.

High quality materials are processed to yarns and converted into clothing using conventional processes. Wool extracted from post-consumer garments, particularly knitwear, is a useful raw material because of its compatibility with woollen yarn manufacture. A bale of mixed coloured woollen sweaters in Europe is usually more valuable than one comprising mixed synthetics (Russell et al. 2016).

Low quality materials are used for the production of nonwoven fabrics by means of garneting, carding or airlying to produce webs, followed by mechanical, thermal or chemical bonding.

World-wide initiatives of fibre recycling of wool are listed in Table 4.6.

Table 4.6: Initiatives of fibre recycling of wool.

Company and technology	**Input stream**	**Product**	**Status**
Cardato with carding	Post-industrial Post-consumer	Yarns, "Cardato Recycled" Brand	Commercial, 22.000 mt/y, Italy (Prato)
Wool Again	Post-consumer	Yarns, 10%-80% wool, the rest being acrylic and polyester	USA
BENU Wool	Unknown	Unknown	Switzerland
Boer Group	Post-consumer	Yarns	Commercial, Netherlands
Geetanjali Woollens	Unknown	Unknown	Commercial, India
Novetex	Unknown	Unknown	Commercial, Hong Kong

4.4.5.2 Nylons

Polyamides are more difficult to recycle than polyesters, and initiatives in this field are limited (see Table 4.7). Recycled polyamide can be produced from post-industrial waste like scraps, and post-consumer waste like discarded fishing nets or carpets. Post-consumer garments are usually not recycled.

Table 4.7: Initiatives of monomer recycling of nylon.

Company and technology	**Input stream**	**Product**	**Status**
Aquafil with Econyl® technology (depolymerization to caprolactam)	Nylon 6 fishing nets, carpets, post-industrial textiles	Econyl® yarn, nylon 6	Unknown
Fulgar with the MSC process (physical recycling)	Post-industrial waste	Q-Nova®, 50/50 regenerated/virgin nylon 6,6 fibre	Unknown

4.5 Polyurethanes

Recycling of elastane, a polyurethane and a polycondensation polymer, is a challenge. At present, no methods are available on pilot or demo scale. Furthermore, elastane is usually present in textiles in only a very small fraction, a few percentages (see Figure 4.6). Elastane is usually not recycled but removed from the fabric to facilitate recycling of other fibres. This can be done with solvolysis methods suitable for polycondensation polymers (see paragraph 4.3.4).

Figure 4.6: Elasthane (Lycra) generally comprises only a small fraction of a fabric.

4.6 Polyolefins

Polyolefins such as PE or PP are thermoplastics and can in theory be physically recycled by melting and re-spinning to new fibres and yarns. Polyolefins cannot be recycled by chemical means, e.g. depolymerized to their monomers by solvolysis methods. These polymers can be degraded through a free radical mechanism at high temperatures, but this does not result in the formation of monomers that can be used again. Instead, heterogeneous mixtures of gasses, liquids and tar are produced (Ignatyev et al. 2014).

4.7 Polyacrylics

Polyacrylics can be mechanically recycled similar to wool. The process involves colour sorting, cleaning, unravelling and spinning again (Boer Group 2020). Polyacrylics cannot be melted, and although they can be dissolved, presumably no physical recycling methods are under development. Just as the polyolefins, polyacrylics are formed by an addition polymerisation and can therefore not be depolymerized by solvolysis methods.

4.8 Summary

In this chapter the recycling options of each type of fibre has been discussed. It is a complex topic, as each fibre has its own recycling option. Main findings are listed below and shown in Table 4.8:

- Recycling of *fabrics* is limited to conversion of cellulose-based materials to wiping rags.
- Recycling of *fibres* by mechanical means is only suitable for natural fibres like cotton and wool, and probably also for polyacrylics. In the case of wool, the fibres can be re-spun into yarns for the production of knitwear, whereas for cotton the fibres often end-up in applications other than apparel.
- For the recycling of *polymers* we distinguish the following groups:
    - Cellulose-based polymers (cotton, viscose, linen) can be recycled by the viscose process or lyocell process, where the cellulose is dissolved and re-spun to a new fibre again, suitable for textile applications. Input for these processes is a dissolving cellulose pulp, containing >90% cellulose.
    - Polycondensation polymers (polyesters, polyamides) can be recycled by melting the material at high temperature and re-spinning to fibres. Input for these processes needs to be highly purified material.
- For the recycling of *monomers* only the polycondensation polymers are suitable. Input for these processes can be less pure material, although for (re)polymerisation the monomers need to be 100% pure.

In general, polymers produced by an addition polymerisation reaction, like polyolefins and polyacrylics have very limited possibilities for polymer and monomer recycling.

Table 4.8: Most relevant (green), less relevant (orange), and impossible (red) recycling options for main polymer groups.

Classification	Cellulose		Poly-esters	Poly-amides		Poly-olefins	Poly-acrylics
	Cotton	Viscose	PET	Wool	Nylon	PP	Acrylics
Fabric	🟩	🟩	🟨	🟨	🟨	🟨	🟨
Fibre	🟩	🟨	🟨	🟩	🟨	🟨	🟩
Polymer	🟩 a	🟩	🟩	🟧	🟩	🟧	🟧
Monomer	🟨	🟨	🟩 b	🟧	🟩 b	🟧	🟧

a *To another type of polymer*
b *To the same type of polymer*

5 Recycling options for blended textiles

5.1 Introduction

Current textiles are more and more composed of a variety of fibres, as single-fibre textiles often do not fulfil the requirements of today's fashion. Fibre blending, by combining two or more fibre types to a new yarn or fabric, can combine the best qualities of each fibre. In this way, the functionality of the fabric is improved. A well-known example is the presence of a few percent of elastane in jeans to improve wear comfort. Another example is a blend of PET and cotton to combine strength and comfort, but also to reduce the price, as polyester fibres are cheaper than cotton fibres. Another reason can be to improve ease of processing, as synthetic fibres can be produced in a broad range of fibre lengths compared to the relatively short length of natural fibres, making spinning easier.

A wide range of fibre combinations are used. Elastane is not only combined with cotton in jeans but also with PET, nylon, wool or other fibre combinations to create clothing that stretches with the body. And PET is not only combined with cotton but also with e.g. viscose and nylon. In the end, complex textiles are obtained based on 2 or 3 fibres, but also combinations of 4 or 5 fibres are not unusual. But for sustainability and end-of-life options blending might not be such a good idea. In this chapter we explore recycling options for blended fabrics and garments.

Figure 5.1: Discarded post-consumer textiles pose a serious problem.

5.2 Post-consumer waste streams

The biggest issues with blended textiles relate to *post-consumer* waste streams in the form of garments. *Post-industrial* waste streams are often well-defined and more homogeneous, as they can be collected as fibres, yarns or fabrics, thus well before the garment is produced. Post-industrial sources therefore have a much greater chance of achieving cost-effective, high quality recycling than post-consumer streams (Greenblue 2017/2018) and some of these recycling methods are already implemented. However, according to the Ellen MacArthur Foundation, less than 1% of material used to produce clothing is recycled into new clothing. This includes recycling after use, as well as recycling of factory offcuts (Ellen MacArthur Foundation 2017).

In the ideal situation all post-consumer textiles are collected and sorted, but in reality this amount is never reached (see Figure 5.1). For the Dutch situation around 30% is collected: 75 kton is collected separately, whereas 160 kton ends up as residual waste. The amount of discarded textile per capita increased from 4.2 to 4.7 kg/y over the past 10 years (van der Wal and Verrips 2019). Approximately half of the collected textiles are suitable for the 2nd hand market (mostly abroad), and the remainder is only suitable for recycling. Due to the rise of fast fashion (see Figure 5.2) and shrinking of the 2nd-hand market, the amount of textile only suitable for recycling (non-wearable fraction) increases every year.

Figure 5.2: Large scale fashion outlet.

The composition of this non-wearable fraction is not well-defined. Sorting companies like Leger des Heils (Salvation Army) and Sympany sort by hand toward main categories such as denim, white cotton, coloured cotton, sweaters. Advanced sorting technologies like the Fibresort can sort textiles based on composition (e.g. wool, cotton, nylon, PET) and even on colour, but this works only for monomaterials. Although we cannot support this with data, we assume that monomaterial garments are outnumbered these days by blended textiles, creating a big problem for textile recycling. Converting post-consumer monomaterial textile fibres into new textiles is on a limited scale possible (see previous chapter), for blended textiles the options are even more scarce.

5.3 Common textile blends

Although the composition of post-consumer textiles is not well-defined, there are combinations that are frequently used. In this paragraph, the main fibre blends are discussed for each group of polymers, including possible recycling strategies.

5.3.1 Cellulose

5.3.1.1 Combination of cellulose fibres

Blends of cellulose-based fibres are created for example for linen fabrics. Linen can be combined with viscose and/or cotton to improve properties, as linen wrinkles badly. These types of fabrics are very well suited for conversion to regenerated cellulose fibres by the viscose, lyocell or other cellulose-dissolving processes.

5.3.1.2 Cellulose with elastane

Cellulose-based fibres are endlessly combined with other fibres. A well-known blend is cotton with a few percent of elastane. For this blend, mechanical recycling of cotton to recycled cotton fibres would be the most viable option, but elastane causes problems during mechanical processing. In addition, the cotton fibre can be of an inferior quality after usage. In that case, a better option is the conversion of cotton to a regenerated cellulose fibre. Depending on the solvent or process applied, elastane may end up in the solid residue while cellulose is dissolved and spun into a new fibre. The same holds for blends of elastane with other cellulose fibres like linen, viscose or lyocell.

5.3.1.3 Cellulose with PET

A well-known combination is a blend of 50/50 cotton and PET, also known as polycotton. Cotton is breathable, while PET is strong and durable. This combination is often used for workwear and production volumes are high. According to Palme from Chalmers

University of Technology, four approaches can be followed to deal with polycotton waste streams (Palme 2016):

1. Dissolve cellulose, maintain PET
2. Degrade cellulose, maintain PET
3. Maintain cellulose, dissolve PET
4. Maintain cellulose, degrade PET

In general, approaches 1, 3 and 4 (where the cellulose remains intact as much as possible) are preferred, as only PET monomers can be polymerised into a new polymer. Challenge here is to use mild conditions to preserve the cellulose, as most of the solvolysis methods of PET (see paragraph 4.3.4) will certainly degrade cellulose to smaller polymer fractions. Palme selected alkaline hydrolysis of PET at moderate temperatures (70-95 °C) as a good option to recover both the PET monomers and the cellulose fraction.

5.3.2 Polyesters

The main polyester in textiles is PET, and it is blended with almost all other textile fibres mentioned in this publication. Although PET recycling from bottles is well underway (also due to proper collection systems), recycling of textile fibres is less developed. Polymer recycling by melting and spinning to new textile fibres is not possible due to contaminations, leaving monomer recycling as the only option. Results from a study by GreenBlue indicate that, for the chemical recycling technologies being evaluated, a minimal purity level of 70–80 % of PET is required for an economically feasible process (Greenblue 2017/2018).

A typical blend for fashion textiles is PET with a few percent of elastane. For this blend, monomer recycling of PET to the building blocks TPA and EG or BHET, followed by polymerization to PET is the most viable option. Research question here is the fate of elastane, as it is possible that elastane is also degraded under solvolysis conditions.

5.3.3 Polyamides

Polyamides can be of natural origin or man-made. The two main classes of natural polyamides include wool and silk. These natural fibres are often used as monomaterial and blends are limited, especially for silk. Wool can be combined with acryl and still look like a woollen garment. Depending on the composition, it might be possible that also blends of wool and acryl can be mechanically recycled, like purely woollen garments.

The man-made polyamides, nylons, are frequently combined with other fibres like cotton (e.g. in lace) or viscose (e.g. in knitted fabric). Similar approaches as for the polycotton could be taken here (see 5.3.1.3). Another combination is nylon and a high percentage of elastane (15-18%) in sportswear and legwear (tights/pantyhoses). Most viable recycling option is monomer recycling of the polyamide by solvolysis, followed by polymerization to preferably a new nylon polymer. Again, the fate of the elastane is unknown.

Figure 5.3. Many clothes are these days designed to be worn only a few times.

5.3.4 Polyurethanes

Elastane, a polyurethane, is usually present in textiles in only a very small fraction when combined with cellulose or PET. In the combination with nylons we see larger percentages of elastane. Elastane is typically not recycled but removed from the fabric to facilitate recycling of other textile fibres. Removal of elastane is a major challenge, and no methods are available yet on pilot or demo scale.

Elastane can be dissolved, so physical recycling is therefore in principle possible, but methods to remove elastane from a blended textile, while keeping the other fibre(s) intact, will first need to be developed. Chemical degradation methods are under development, and mainly fall in the category of solvolysis methods (like for PET and nylon) (Datta and Kopczyńska 2016).

5.3.5 Polyolefins and polyacrylics

Polyolefins are to our knowledge seldom combined with other fibres in textiles for fashion. Polyacrylic fibres are often combined with wool or nylons. Recycling options for polyacrylic fibres are limited to mechanical methods combined with wool fibres.

5.4 Initiatives of blended textiles recycling

As discussed, current clothing is often made from blended textiles, making recycling a challenging operation. Table 5.1 shows initiatives of companies and start-ups that work on these challenges. The majority of these initiatives deal with an input stream of cotton and PET, and produce a stream of PET monomers and regenerated cellulose fibres.

Table 5.1: Initiatives of recycling of blended textiles (Textile Exchange 2019).

Company and technology	**Input stream**	**Product**	**Status**
HKRITA/H&M Foundation with hydrothermal method	Cotton/PET	New textile fibres	Pre-industrial size facility in Hong-Kong
Worn Again with dissolution of PET and cellulose	Cotton/PET	Cellulose pulp for regenerated cellulose fibre and PET	Industrial demonstration plant to be launched in 2021
Blend Re:Wind (Rise and Chalmers University)	Cotton/PET	Viscose filaments and PET monomers	Sweden, status unknown
Sodra with Once More	Cotton/PET	Cellulose pulp for textile	Sweden, status unknown
Tyton Biosciences	Cotton, PET, polycotton	Cellulose and PET monomers	USA, status unknown
Block Texx	Cotton/PET	Cellulose pulp and PET	Australia, status unknown
Resyntex with monomer recycling	Cotton, nylon, PET, wool	Monomers (glucose, TPA, EG) protein hydrolysates, polyamide oligomers	EU-project
Trash2Cash with polymer recycling	Blended textile and paper waste	Regenerated cellulose	EU-project

5.5 Concluding remarks and actions to be taken

In general there are good recycling options for pure material waste streams. Physical or chemical recycling of PET leads to virgin quality PET, and cotton can be processed to regenerated cellulose fibres like viscose or lyocell. But what happens when fibre blends are used instead of only cotton or polyester? And when in each garment a few percent of elastane is present? Then the recycling technologies for monomaterials do not fit anymore as each textile fibre has its own optimal recycling process and elastane, amongst others, acts as a contaminant. In this case, recycling becomes technically complicated, energy-consuming and expensive and will most likely not become a profitable business.

Textile recycling (of specially post-consumer waste) is still in its infancy and will be a major challenge for the coming years. For some materials recycling options will become available, while for others the only option is energy recovery or even worse, landfill. Technologies that can deal with impurities and result in (near) virgin quality products might be successful, like dissolving cellulose for regenerated cellulose fibres, or degradation of PET or nylons to monomers for the formation of new polymers. In that sense, cellulose-based fibres and polycondensation polymers like polyesters and polyamides are most promising, polyaddition polymers like polyolefins and polyacrylics are less interesting.

Besides trying to reduce the amount of textile waste, it is still far better to prevent the formation of it by waste prevention strategies. Focus should therefore not only lie on recycling but on all measures that will help to change the whole system. Here are some suggestions:

- Design for disassembly or recyclability. Outdoor apparel brands like Patagonia and The North Face have been experimenting with different design and material selection strategies that enhance the recyclability of their products. Examples are the use of fabrics based on one type of fibre, use of fibres with better recyclability profiles, and creating a market demand for recycled materials (Greenblue 2017/2018).
- Prevent intimate blending of different types of fibres that require different recycling methods.
- Stimulate the use of natural fibres (cellulose-based and wool), as they are based on renewable resources and have good recycling options.
- Develop regenerated cellulose fibres that are strong enough, so that blending with PET or nylon is not required anymore.

- Develop a bio-based alternative for elastane which causes no problems during recycling.

Another important topic in textiles for circular fashion is the replacement of fossil feedstock by renewable inputs for the new textiles economy. What will be the route to fossil-free production of textile fibres? Natural fibres are often hydrophilic and will not cover the whole spectrum of required properties, so we still will need fibres with a properties profile like PET has. When specific (hydrophobic) properties of synthetic fibres are required that cannot be fulfilled by natural fibres, which biobased alternatives are available or can be developed, that can at the same time be properly recycled? And besides that, how can we combat the contribution of (fossil-based) textiles to the plastic soup and the microplastics problem? What kind of bio-based fibres are available or can be developed to replace the fibres that pose the biggest problems here? Enough food for thought for a new publication in the series of Textiles for Circular Fashion.

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List of abbreviations

BHET	Bis(2-hydroxyethyl) terephthalate
DP	Degree of polymerization
DMT	Dimethyl terephthalate
EG	Ethylene glycol or 1,2 ethanediol
PA	Polyamide
PBT	Polybutylene terephthalate
PE	Polyethylene
PET	Polyethylene terephthalate
PLA	Polylactic acid
PP	Polypropylene
PTT	Polytrimethylene terephthalate
PVC	Polyvinyl chloride
TPA	Terephthalic acid

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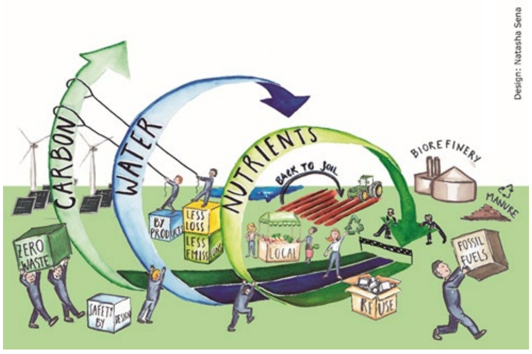

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