Biological degradation of textiles

And the relevance to textile recycling

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In cooperation with Carolijn Slottje and Michelle Baggerman (ArtEZ) and Ellen Sillekens (Sympany)

WAGENINGEN UNIVERSITY & RESEARCH

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Contents

1 Introduction

Biological degradation of textiles by microorganisms or insects is regarded as undesirable, as it diminishes the quality of textiles. It is encountered in materials of different chemical composition and degraded by different microorganisms under a variety of environmental conditions. However, it could be a means of removing textiles from the environment by a natural manner, a new type of textile recycling methodology, or a new way of raw material production from textile waste streams.
Research institutes ArtEZ and WUR work on production of Sustainable textiles, and one of the topics includes efficient use of resources by textile recycling. At ArtEZ, work is being done with clothes moths, as possible means of biological recycling of textiles, or as raw material producers. Sympany, a textile collection and recycling organization, deals with difficult, non-rewearable textile streams which cannot be re-used or recycled to new textiles, and are currently downcycled in applications of low value.
The objective of this report is to explore the possibilities of biological recycling as a new recycling technology, alongside existing technologies (mechanical, physical, and chemical recycling). It provides some background knowledge on biological degradation of textiles in general and describes relevant literature in Chapter 2. Chapter 3 describes a case study of Sympany, where recycling options for one of the non-rewearable textile streams (Mixed Sweaters fraction) are reviewed, including biological methods. This report is finalized with some conclusions in chapter 4.

2 Biological degradation of textiles

2.1 Introduction

To date, biological degradation of textiles is regarded as undesirable, and the sensitivity towards biological degradation is described by the biological properties of textiles. Biological properties of textiles comprise several aspects, among which the resistance to attack by microorganisms and insects. This attack may result in bad odour, fibre discoloration and material degradation. Microorganisms that can affect textiles include bacteria and fungi, and warmth and high humidity accelerate their action. In general, cellulosic fibres are most prone to attack by microorganisms. Protein fibres are less prone, and synthetic fibres are almost completely resistant, unless they contain impurities or additives that are susceptible. Amongst insects, clothes moths and several types of beetle can degrade wool fibres, while silverfish attack cellulosic fibres. Synthetic fibres are resistant to insects (Mather and Wardman 2015).
Table 1 summarizes the resistance of various textile polymers to biological degradation. Textile fibres containing cellulose include cotton, linen, hemp, jute, viscose and lyocell; textile fibres containing protein include wool and silk; synthetic textile fibres are often condensation polymers in the form of polyesters (PET) or polyamides (Nylon).

Table 1 ***Resistance of textile polymers to biological attack (Schindler and Hauser 2004, Szostak-Kotowa 2004, Mather and Wardman 2015).***

Polymer	Microorganisms		Insects		
	Bacteria	*Fungi*	*Clothes moths*	*Beetles*	*Silverfish*
Natural: Cellulose	Susceptible	Susceptible	Less prone	Less prone	Susceptible
Natural: Protein	Less prone	Less prone	Susceptible	Susceptible	Less prone
Synthetic	Almost resistant	Almost resistant	Resistant	Resistant	Resistant

Paragraph 2 describes the impact of microorganisms (bacteria and fungi) on textiles, and paragraph 3 the impact of insects.

2.2 Microorganisms: bacteria and fungi

2.2.1 Cellulose

Mode of action microorganisms
Degradation of cellulose results from the action of cellulolytic enzymes produced by a range of bacteria and fungi. This hydrolytic breakdown of cellulose, resulting in the formation of shorter molecules like cellobiose or glucose, is dependent on the accessibility of the cellulose molecule. For example, cotton is protected by a natural waxy layer (the cuticle). Only after removal or degradation of this layer the hydrolysis of cellulose can proceed.
Main effect of cellulose degradation by cellulolytic enzymes is decrease in molecular weight (degree of polymerization or DP), so that fibre structure is impaired and fibre strength is decreased (Szostak-Kotowa 2004). Crystallinity of the cellulose is also important, as amorphous cellulose is more easily attacked than crystalline cellulose.

Non-cellulosic substances
The presence of non-cellulosic substances influences microbial attack. The presence of natural substances like hemicelluloses or pectins (less relevant for cotton, more relevant for linen and hemp) promote degradation. Also, substances added to the fabric can provide additional nutrition for microorganism, e.g. finishes, adhesives, dyes and fillers, or limit accessibility of the fibres.

Microorganisms
The most active microorganisms involved in cellulose degradation are listed in Table 2. Fungi play a more important role in biological degradation of textiles than bacteria, as they can grow at much lower relative humidity compared to bacteria, generally requiring conditions in which the fabric is saturated with moisture.

Table 2 ***Bacterial and fungal strains involved in cellulose degradation (Szostak-Kotowa 2004).***

Bacteria		Fungi	
Cytophaga	*Bacillus*	*Chaetomium*	*Alternaria*
Cellulomonas	*Clostridium*	*Myrothecium*	*Trichoderma*
Cellvibrio	*Sporocytophaga*	*Memnoniella*	*Penicillium*
		Stachybotrys	*Aspergillus*
		Verticillium	

2.2.2 Protein: Wool

Keratin in wool fibre
The main polymer in wool is a protein called keratin. Keratin is build-up of the amino acid cysteine, and two cysteine molecules are bound together by a disulphide bond to cystine (Figure 1). These disulphide bonds are of particular significance in wool chemistry and are the source of natural resistance of keratin against polymer degradation.

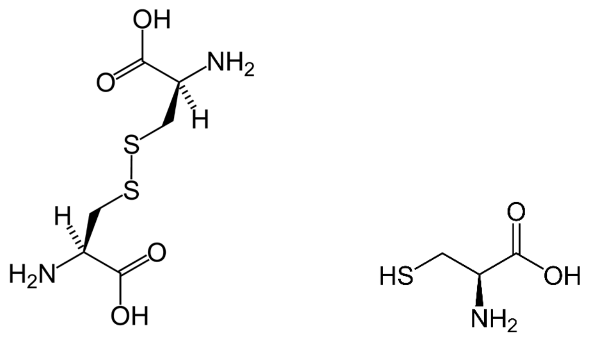

Figure 1 ***Cystine in its neutral form (left), which is two cysteines (right) bound together by a disulphide bond***

Mode of action microorganism
Degradation of wool by fungi starts by denaturation of keratin by fission of the disulphide bridges, followed by hydrolytic degradation of the protein by extracellular proteinases. This process is called keratinolysis. The rate of degradation depends on the chemical composition, molecular structure and degree of polymerization (Szostak-Kotowa 2004, Lange, Huang et al. 2016).
Microorganisms can utilize substances added to the fabric during the production cycle. Availability of nutrients, high humidity, favourable temperature and acidity promote microbial growth.

Raw wool contains many impurities that are susceptible to microbial attack. During processing, wool is also degraded by microorganisms. Degradation of wool by fungi is hard to detect and is not noticed until degradation is well advanced (Szostak-Kotowa 2004). The first symptoms are odour and staining in different colours.

Type of microorganisms
Biodeterioration of wool is caused by both bacteria and fungi. Keratin is degraded to a higher degree by fungi than by bacteria.

Table 3 **Bacterial and fungal strains involved in keratin degradation (Szostak-Kotowa 2004).**

Bacteria	Fungi	
Bacillus	*Microsporum*	*Aspergillus*
Pseudomonas	*Trichophyton*	*Penicillium*
actinomycetes	*Fusarium*	*Chaetomium*
	Rhizopus	

2.2.3 Protein: Silk

Silk is the natural fibre most resistant to biodeterioration. Raw silk consists of protein fibres (fibroin) joint by another protein (sericin). Nowadays silk fabric is produced from degummed silk, i.e. silk devoid of sericin. Fibroin and sericin display different degradation behaviour. For example, investigations of silk biodegradation in soil showed that bacteria more readily use sericin than fibroin as a source of carbon (Szostak-Kotowa 2004).

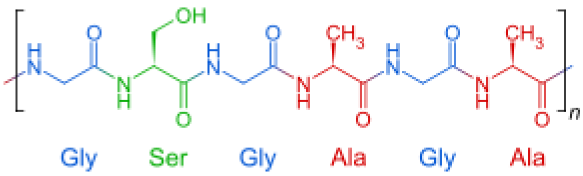

Figure 2 **Chemical structure of fibroin**

2.2.4 Synthetic polymers

Synthetic polymers are seldom suffering from biodegradation by microorganisms. Nevertheless, synthetic fibres contain groups like ester, amide, ether, or other functional groups that can be oxidised or hydrolysed (chemical or enzymatical). Also, it is often the addition of finishes, adhesives, dyes, or fillers that promote microbial attack. Growth of fungi on synthetic fibres involve a decrease in aesthetic properties and as a result product quality (Szostak-Kotowa 2004).
Of all synthetic textile fibres, the polyester polyethylene terephthalate (PET) is the largest in volume. It is an aromatic polyester of terephthalic acid (aromatic compound) and ethylene glycol. Due to this aromatic terephthalic acid group, PET is resistant to biodegradation. It is known that aliphatic polyesters (without an aromatic group) like PLA (polylactic acid) are more readily degraded, but their use in textiles is limited due to less favourable (thermal) properties.
Differences in chemical structure of the aromatic polyester PET and the aliphatic polyester PLA are illustrated in Figure 3.

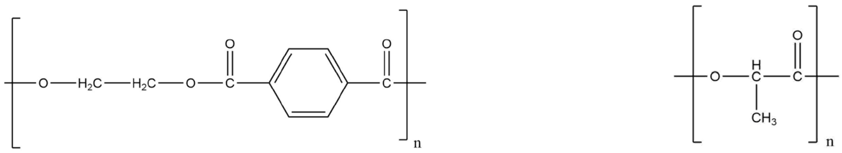

Figure 3 **Chemical structure of PET (left) and PLA (right)**

2.3 Insects: Clothes moths

2.3.1 General description of clothes moths

2.3.1.1 Tineola bisselliella[1]

Tineola bisselliella, known as the common clothes moth or webbing clothes moth, is a species of fungus moth (family Tineidae, subfamily Tineinae). It is a small moth of 6–7 mm wingspan.

[1] https://en.wikipedia.org/wiki/Tineola_bisselliella

Females lay eggs in clusters of between 30 and 200 which adhere to surfaces with a gelatine-like glue. These hatch between four and ten days later into white caterpillars which immediately begin to feed. Development to the next stage takes place over the course of between one month and two years until the pupal stage is reached. At this point, the caterpillars spin cocoons and spend another approximately 10–50 days developing into adults. Unlike the caterpillars, the adult moths do not feed: All feeding damage to textile is done by the caterpillar form.
The range of recorded foodstuffs includes cellulose (cotton, linen) and protein (silk and wool) as well as furs. They will eat synthetic fibres if they are blended with wool. Most favourable conditions are 24 °C and 70-75% relative humidity; unfavourable conditions can slow development but will not always stop it.


Figure 4 ***Left picture: Tineola bisselliella, by Olaf Leillinger - Own work, CC BY-SA 2.5***
https://commons.wikimedia.org/w/index.php?curid=929181
Right picture: Larval form, by Guido Gerding - own photograph
URL: Ex :: Natura - Freies Portal für Umweltbildung (Environmental Education), CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=532340

2.3.1.2 *Tinea pellionella*[2]

Tinea pellionella, the case-bearing clothes moth, is a species of tineoid moth in the family Tineidae, the fungus moths. This species has a cosmopolitan distribution, occurring nearly worldwide. The adult is typically encountered during summer and early autumn, but populations that live in human dwellings may be seen at other times of the year. *Tinea pellionella* is silvery grey to shiny light brown in colour, with dark grayish hairs on the top of its head. The adult of this species has a wingspan of 9 to 16 mm. The larva eats mainly fibrous keratin, such as hairs and feathers. It can become a pest when it feeds on carpets, furs, upholstery, and woolen fabrics. It stays inside a snug case it constructs from debris such as fibres and hairs.

Figure 5 ***Tinea pellionella, by © entomart***
https://commons.wikimedia.org/w/index.php?curid=1256118

[2] https://en.wikipedia.org/wiki/Tinea_pellionella

2.3.2 Keratin digestion

The caterpillars of the clothing moth *T. bisselliella* can feed on clothes and carpets made of wool. *T. bisselliella* has adapted to feed predominantly on materials rich in keratin, such as feathers, and woollen clothes and carpets. Insects are the only animals that can digest keratins (Yoshimura, Tabata et al. 1988). Wool contains keratin, and keratin is particularly resistant to proteolytic degradation (degradation of proteins by enzymes) because of its abundant disulphide bonds, which distinguishes it from other structural proteins such as collagen and elastin (Vilcinskas, Schwabe et al. 2020).. In the paragraphs below, research on keratin digestion is described in chronological order.

Waterhouse (Waterhouse 1952) described the digestive juices of larvae of the clothes moth *Tineola bisselliella*. The alkaline (pH 10) midgut digestive juices reduce the disulphide bonds of cystine of wool, forming sulphydryl groups and hydrogen sulphide (H_2S). Larvae fed on silk (which contains no sulphur) did not produce sulphides unless a sulphur-containing material was added to the diet. This suggests that wool and silk, both protein polymers but of different composition, are degraded via different mechanisms.

Powning (Powning 1953) demonstrated that *Tineola* larvae have a highly active enzyme called cysteine desulfhydrase. In *Tineola*, the sulphur of wool is not secreted to any large extent as inorganic sulphate or as sulphur dioxide but mainly as cystine. They found that cystine, rather than sulphate, was the important sulphur-containing excretory product in *Tineola* and *Attagenus* (the black carpet beetle feeding on wool), and probably also in the closely related genera *Tinea.* From previous research (Waterhouse 1952) it was known that the midgut pH of larvae of *Tineola* is high (pH 10), but Powning stated that neither *Attagenus* (with a midgut pH of 7) nor Tineola depend solely upon gut alkalinity for the digestion of wool.

Yoshimura (Yoshimura, Tabata et al. 1988) partially purified the enzyme responsible for digestion of keratin and examined its role. They reported that H_2S formation from cysteine in *Tineola* larvae is mainly due to cysteine lyase which catalyses β-replacement of cysteine.

An important step in the digestion of wool by certain insect pests is the reductive cleavage of protein disulphide bonds to open the fibre for protease action. In a study by Robinson, cystine reductase was shown not to be present in *T. bisselliella* larvae (Robinson, Ciccotosto et al. 1993). "An earlier study, showing that cysteine lyase/desulphydrase is present in these larvae, is confirmed and extended to demonstrate that the activity is localised to the gut of larvae. This activity is also present in the larval gut of another clothes moth, *Tinea pellionella*, but is absent from the gut of the carpet beetle, *Anthrenus flavipes*, suggesting that larvae of moths and beetles use different mechanisms to reduce the disulphide bonds of wool." (Robinson, Ciccotosto et al. 1993)

Vilcinskas (Vilcinskas, Schwabe et al. 2020) proposes that keratin digestion is a multistep process: Cleavage of disulphide bonds by a thiol-disulphide oxidoreductase, thereby enhancing the accessibility of the reduced keratin for a cocktail of peptidases and proteases (enzymes).
The enzymes digest keratin into shorter peptides and free amino acids, which are sequestered by transport proteins and assimilated.
There is also a possibility that *T. bisselliella* produces its own enzymes that contribute to keratin digestion. Keratin-degrading bacteria were isolated. Such keratinase-producing bacteria are of interest for biotechnological applications, particularly in the conversion of keratin-rich waste such as feathers, hair and woollen textiles for recycling purposes.

2.3.3 Excreta of clothes moths

The moth *B. mori* is known for its silk production. The caterpillar of the moth builds silk-feeding tubes or cocoons for their protection, and the silk is produced by the silk glands (SG) (Prudhome 1985). *B. mori* belongs to the group of lepidopteran species, i.e. the order of insects that includes butterflies and moths, among others *B. mori* (known for its silk production) but also the clothes moth *T. bisselliella*.

Molecular studies made it possible to analyse protein composition of various silks in more detail. Some of these proteins represent novel silk structural components, while others are cellular proteins (enzymes, other proteins) released into the SG lumen by an apocrine-like secretory mechanisms, or deposited into the silk from the digestive system (Gesase and Satoh 2003).

A study by Rouhova (Rouhova, Kludkiewicz et al. 2021) analysed the silk from *T. bisselliella*. A detailed examination of the cocoons by scanning electron microscopy (SEM) revealed that they consisted of sparce mesh of thin (diameter 0.5-1 µm) fibres (see Figure 6). The mesh-like structure of the cocoon suggested that the amount of adhesive in the *T. bisselliella* silk is relatively low compared to that of the silkworm.

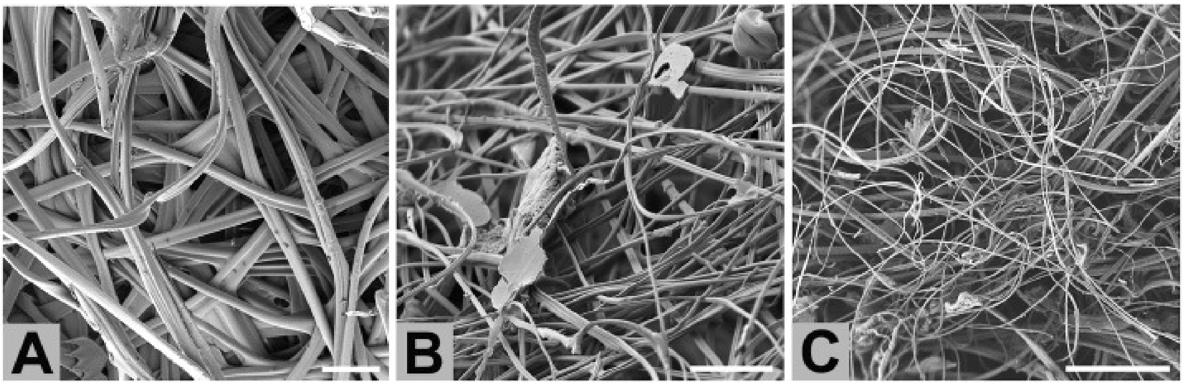

Figure 6 **_Comparison of cocoons (outer sides) visualized by scanning electron microscopy. (A) B. mori (B) T. bisselliella (C) E. variegata. Scale-bars: A and C, 100 µm; B: 10 µm. (Rouhova, Kludkiewicz et al. 2021)_**

Identification of the silk proteins revealed that the most abundant silk candidates included homologs of known structural silk proteins (fibroins and sericins). They found that the basic configuration of the SG was similar to other Lepidoptera. However, it was estimated that the larvae of *T. bisselliella* produce a cocoon (about 0.1 mg) which is about 1.7 % of their average body weight, in contrast to *Bombyx* cocoon shells (0.26 g) which is about 9% of larval body weight. (Rouhova, Kludkiewicz et al. 2021).

2.4 Summary

This chapter provides some background information on biological degradation of textiles. The most important aspects are listed here:

- Biological degradation of textiles may result in bad odour, fibre discoloration and degradation of the fibres and polymers, ultimately leading to holes in the fabric.
- Biological degradation of textiles can be caused by microorganisms (fungi and bacteria) or by insects (clothes moths, beetles, silverfish). Often, fungi and bacteria are both present on the fabric in a symbiotic relationship. Degradation is catalysed by enzymes produced by the microorganisms or insects, which are specific for the organism.
- Type of fibre (natural or synthetic) and the chemical bonds in the polymers are the most relevant parameters. Natural fibres or semi-synthetic fibres composed of natural polymers (cellulose or protein) are susceptible to biological degradation, while synthetic fibres are almost resistant. Also, substances added to the fibres (size, thickener, lubricants etc) and dirt provide a food source for bacteria, fungi, and insects.
- Secondly, the structure of the polymer (e.g. crystalline or amorphous, aromatic, or aliphatic) and the functional groups or binding sites are relevant. For example, amorphous cellulose is more easily attacked than crystalline cellulose, and the same goes for aliphatic polyester (PLA) versus aromatic polyester (PET).

- Textile containing cellulose (e.g. cotton, linen, hemp, jute, viscose, lyocell) is susceptible to microorganisms and less to insects. Degradation of cellulose results from the action of enzymes (e.g. cellulases) produced by a range of bacteria and fungi. This breakdown of cellulose is dependent on the accessibility of the cellulose molecule. Main effect is decline of the molecular weight of the cellulose chain, ultimately leading to reduced fibre and fabric strength.
- Textile containing protein (e.g. wool and silk) can be attacked by microorganisms as well as insects. Raw wool contains many impurities that are susceptible to biological degradation, while the main polymer in wool, keratin, is a recalcitrant polymer due to the disulphide bonds.
  In literature it is stated that only insects can digest keratin. In silk, the main protein polymers include fibroin and sericin, of which sericin is more susceptible than fibroin.
- Insects, and especially clothes moths, can eat a range of foodstuffs. But unlike other organisms, they can digest the recalcitrant keratin. Only the caterpillars or larvae of the moths feed on and damage the textile, not the adults. In general, digestion of textile by insects is a slow process (weeks, months), and unfavourable conditions (in terms of temperature and humidity) can slow development of the insects.
- Digestion of keratin is limited to insects. Keratin is resistant to enzymatic degradation due to the disulphide bonds, which distinguishes it from other proteins like collagen, elastin, fibroin and sericin. The mode of action of keratin digestion by clothes moths is complex, and recent literature on this topic is scarce. A paper by Vilcinskas (Vilcinskas, Schwabe et al. 2020) proposes that keratin digestion is a multistep process: first enzymatic cleavage of disulphide bonds (thereby enhancing the accessibility of the reduced keratin for a cocktail of other enzymes), followed by a further digestion of keratin into shorter peptides and amino acids.
- In general, the result of biological degradation of textiles is the conversion of polymers (cellulose, keratin) into shorter components like cellobiose and glucose (in the case of cellulose), and peptides or amino acids (in the case of keratin). Only the caterpillars of specific moth species, for example *T. bisselliella* (clothes moth) and *B. mori* (silk producing moth), feed on keratin and build silk feeding tubes of cocoons for their protection. This silk (produced by the silk glands) might be a new source for textiles, as is the case for the silk producing moth.
- A recent study by Rouhova ((Rouhova, Kludkiewicz et al. 2021) analysed the silk from the clothes moth and compared that to the silk moth. They found that the basic configuration of the silk gland was similar, but the size of the cocoon of the clothes moth was much smaller than of the silk moth.

3 Case study: Sympany

3.1 Introduction

Sympany is a non-profit textile collection and recycling organization, which aims to maximize textile re-use and recycling. Each year, Sympany collects about 25 million kg of used textiles, which are separated into re-usable and recyclable qualities and then sold. The used and recycled textile market is a highly volatile and low-margin market, which leads to much uncertainty on the revenues which are earned. This is an undesirable situation from a financial perspective. Diversification of outlet channels for the collected textiles could significantly mitigate these financial risks. At the same time, both internal and external stakeholders expect Sympany to become a circular company and to increase its re-use/recycling rates and at the same time apply the textiles in more high-value and sustainable applications. Because of these developments, an analysis into alternative recycling and valorisation options could present new opportunities to Sympany. Sympany has therefore asked Wageningen University and Research to come up with a proposal to identify new re-use, recycling, and other valorisation options to serve as input for a new circular strategy for the company.

3.2 Research questions

Currently, Sympany separates 10% of the collected textiles in its facility in Assen. The remainder is sent to the Baltic States to be separated in a large facility managed by Humana. From these separation facilities, 5 non-rewearable textile streams remain which cannot be re-used and are currently downcycled in applications of low value. To increase the circularity of the collected textiles, the research should provide guidance into which recycling options are available for these 5 categories of non-rewearable textiles:

1. Bulk Blue (Jeans)
2. White Cotton (White cotton, potentially with stains or fading colours)
3. Coloured cotton (socks, underpants, t-shirts)
4. Mixed Sweater (sweaters of different materials)
5. Mixed Winter (winter clothes, like jeans, jackets, scarfs, caps)

In determining the best recycling options, the 4R hierarchy (reduce, re-use, recycle, recover) should be considered. A key aspect of recycling textiles is the separation and recycling of different textile fibres. More homogenous textiles (e.g. textiles composed of only cotton) are easier to recycle than blends of different fibres (e.g. polyesters, elastane, polyamides and cotton). Apart from the composition of the garment, applicable technologies for end-of-life and circular use of textile fibres are strongly determined by the chemical structure of the polymers that make up the fibre. We distinguish three different approaches of fibre recycling:

- Mechanical recycling implies the use of mechanical processes (cutting, shredding, carding) to separate the fibres, while aiming to keep the structure of the fibres intact, even though the fibre may be broken down and quality loss occurs. Natural fibres like cotton and wool are examples of fibres that can be mechanically recycled.
- Physical recycling uses physical processes to make the fibres/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. Cotton or cellulose can be recycled to create a regenerated cellulose fibre by dissolving of the cellulose in a solvent, followed by solution spinning. Examples include viscose fibres, Lyocell fibres (NMMO as solvent) and Ioncell™ fibres (IL as solvent).

- Chemical recycling exploits chemical processes to break down the fibres, which means that the polymers that make up the fibres are either modified or broken down, sometimes to their building blocks. This can be done by chemical or biological methods (e.g. with enzymes). After chemical recycling the polymeric molecules would need to be built-up again to be able to form a new polymer and fibre. An example of chemical recycling is degradation of polyester to its building blocks and polymerizing of these building blocks to a new polyester.

Note that the methods described here are often only suitable for monomaterials, fabrics made of 100% single fibre type. Therefore, to create new outlets for non-rewearable textiles, often a combination of separation and recycling technologies is needed. Insights into which technologies are available could enable Sympany to create new valorisation opportunities for the 5 non-rewearable textiles categories mentioned above.

The main research question for Sympany is as follows:

How can the mentioned 5 non-rewearable textile categories be recycled in the most sustainable way, in high-value applications, but at the same time in a scalable and economically viable manner?

This research question is further specified by the following sub-research question, and addressed in the next section:

Which treatment options are available for each of the 5 textile categories, and more specifically the Mixed Sweater fraction?

Figure 7 ***Pictures of Mixed Sweater fraction (by Sympany)***

Sympany provided WUR with more detailed information on the Mixed Sweater fraction:

- Composition
  The composition of the Mixed Sweater fraction is never constant. It contains a range of haberdashery (buttons, zippers, labels etc) and all textile fibres available (polyester, polyamide, elastane, acryl, cotton, viscose, wool). It is estimated that approximately 10 wt% originates from wool, 45 wt% of cotton and 45 wt% from synthetic fibres.
- Volume
  In 2020 around 115 tons of Mixed Sweater was sorted at the facilities in Assen. This is approximately 6% of all sorted textiles.

3.3 Recycling of the Mixed Sweater fraction

Today, there is a lot of interest in developing new processes that can convert non-wearable post-consumer textiles into new textiles. Now, textile recycling (i.e. conversion of post-consumer waste to new fibres and finally garments) is still in its infancy stage and will be a key challenge for the coming years. Major technical problem is caused by the blended materials, with the Mixed Sweater fraction as example. It is important that besides new textiles, also other outlet channels for the collected textiles are being studied, like insulation material or building material. This paragraph describes the various recycling options for the Mixed Sweater fraction of Sympany.

- Mechanical recycling

Mechanical recycling of post-consumer textile to new yarns is most feasible for monomaterial streams of e.g. cotton, wool or possibly acrylics. The blended nature of the Mixed Sweater fraction makes it less suitable for mechanical recycling to new fibres for spinning or weaving to a new fabric.

According to Sympany there are two options for the Mixed Sweater fraction in combination with mechanical recycling:

  - Reuse of the fabric by removal of buttons and zippers, followed by cutting into cleaning cloths.
  - Reuse of the yarns/fibres by the removal of buttons and zippers, followed by shredding and carding to fibres. Unfortunately, these fibres have limited application possibilities, as they are not suitable to produce a new yarn for knitting or weaving as the fibres are too short. Instead, they are used to produce felted products like bags or insulation material.

An option could be to broaden the scope of felted products or nonwoven products from the shredded textiles. The Mixed Sweater fraction contains, besides natural fibres wool and cotton, also synthetics. Synthetic materials can often be melted at elevated temperatures (see also physical recycling), acting as a kind of glue to the other fibres. Possible products could be buttons for example.

- Physical recycling

Physical recycling uses physical processes to make materials suitable for reprocessing, either by melting or dissolving them.

  - In theory, the cotton fraction could be dissolved in a solvent, followed by solution spinning to make lyocell or viscose. Requirements for this cotton fraction is a high content of cotton/cellulose, as non-cellulosic components disturb the process of dissolving cellulose.
  - Physical recycling (melting) could be a suitable method for recycling of synthetic polymers, provided that the fraction is separated in the individual polymer types (polyesters, polyamides, etc.)

- Chemical recycling

Chemical recycling exploits chemical processes to break down the fibres, often to their building blocks. The synthetic fraction could be used for this, but only when further separated in the individual monomer types.

- Biological recycling

Based on this report, we define biological recycling as processes to break down the textile fibres by microorganisms or insects.

  - In theory, the cotton fraction could be removed from the other fibres by microorganisms, resulting in a cotton-free fraction of wool and synthetics. Disadvantage is that the cotton or cellulose cannot be used anymore, as it is fully degraded.
  - The wool fraction could be digested by insects like the clothes moth, resulting in a wool-free fraction of cotton and synthetics.
  - The synthetic fraction is least susceptible to biological degradation (this report).

4 Discussion and conclusions

Biological degradation of textiles is a wide-ranging problem, it is encountered in materials of different chemical composition, that are degraded by different (micro)organisms, under a variety of environmental conditions. In theory, it could be a means of removing textiles from the environment by a natural manner. This can only happen if fabrics are not protected by antimicrobial or insect resistant finishes. In addition, the current fibre mix consists largely of synthetic materials, and to a lesser extent of natural polymers that are susceptible to biological degradation. As long as a large part of our clothes are made of synthetic fibres, biological recycling will have very limited applicability.

Textile recycling methods can be classified as mechanical, physical, or chemical (Harmsen, Scheffer et al. 2021), and to date biological recycling of textile fabric is non existing. Specific enzymes like cellulases or proteases can be applied in recycling processes, but only on free, accessible polymers. Advantage of biological processes is that they can be very specific, drawback is that they are often slow.

Clothes moths as raw material producer could be an interesting idea, as it resembles the production of silk by the silk moth. Caterpillars of many lepidopteran species (i.e. the order of insects that includes moths like the silk moth and the clothes moth) can digest keratin and build silk feeding tubes or cocoons for their protection. Whether the cocoons of the clothes moth can be used to produce a silk-like material needs to be further investigated. These moths feed on keratin, a recalcitrant protein present in wool, and it is stated in literature that only insects can digest keratin. Also here, the composition of the current fibre mix is the limiting factor, as wool accounts for approximately 1% of the overall fibre production. It is possible that the moths also feed on other sources, but to produce a silk-like material they need a nitrogen source, and that is not present in polyester PET or cotton for example.

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