

Textile recycling processes, state of the art and current developments: A mini review

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Abstract

World fibre production has been rising continuously over last decades and a tremendous increase is expected in the near future. The major portion of fibres goes to the textile industry whose main output streams are apparel and home textiles. With the transformation of these textile products from a basic human need to fashion items, their lifetime before disposal is steadily declining, while at the same time the complexity of their material composition is increasing. As a matter of fact, the amount of disposed items is increasing distinctively and the issue of a proper handling of end-of-life textiles is becoming more important. The objective of this mini review is, first to give a brief overview of the already available textile recycling methods, and subsequently it will discuss innovative developments of new recycling processes in the textile recycling sector. A special focus of this review lies on the emerging field of biochemical fibre recycling processes, which could become a major step on the way to a circular economy in the textile processing chain. Owing to the high selectivity of bio-catalysts, enzymes, these processes could be used to remove a specific fibre material from multi-component textiles. As the complexity of textiles is reduced, the recyclability is increased.

Keywords

Textile recycling, circular economy, waste management, textile waste

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Introduction

In 1943, Maslow placed clothing at the bottom of the pyramid of needs, along with food and shelter, which shows the importance of clothing for human civilization (Maslow, 1943). In many industrialised countries however, clothing is now subject to fashion and style, which greatly reduces the time the clothing is used before disposal. While this rapid turnover is one of the key drivers for growth in the textile industry, this behaviour results in an overconsumption of clothing and an excessive use of resources and energy and is also significantly responsible for the generation of textile waste.

Since end-of-life clothing represents a basic human need, many people have ethical concerns to dispose of them. As a consequence, separate collection for end-of-life clothing was established long before other collection schemes. The purpose of the collection usually is the re-use of the clothing, but since not all end-of-life textiles are fit for re-use, other forms of recovery and recycling have to be adopted.

End-of-life textiles often consist of multi-material fibre compositions, these make recycling more complicated since the different types of fibres would need to be separated, which is often difficult or outright impossible. Subsequently, these end-of-life textiles are then often used for energy recovery, which of course is not an efficient handling of resources. Enzymatic hydrolysis of specific fibres in multi-material, end-of-life textiles could become a cheap and fast method to remove certain fibre materials

out of these multi-material textiles, therefore this kind of hydrolysis process could be an alternative to thermal recovery in certain cases.

Facts and data

Textiles mainly consist of fibres. The term fibre is a morphological term for materials characterised by their fineness, flexibility and high length to cross-sectional area (Krieger et al., 2009). While fibres can consist of a wide range of materials, they are usually classified as either man-made fibres or natural fibre, as seen in Figure 1.

Natural fibres are both the hairs and wools of animals, and fibres from planted crops, such as cotton and hemp. The term man-made fibres refers to the process of manufacture and not the chemical composition of the material. For example, while cotton and viscose both are fibres consisting of cellulose, cotton is a crop fibre and therefore classified as a natural fibre, and viscose is a man-made fibre produced by the viscose process (Woodings, 2001).

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Figure 1. Categorisation of fibre types (Krieger et al., 2009).

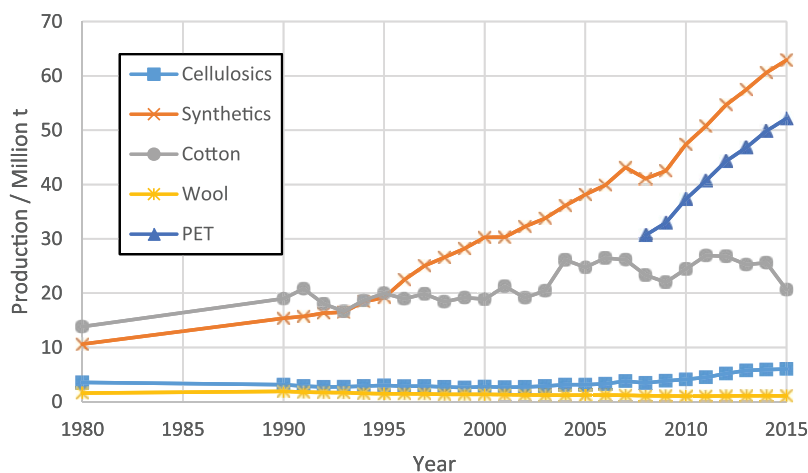


Figure 2. Global fibre production from 1980 to 2015 (CIRFS, 2016).

Man-made fibres are further classified by their chemical composition into natural polymers, such as the already mentioned viscose fibre, synthetic fibres, such as polyester and polyamide fibres, and inorganic fibres, such as carbon and glass fibres.

Since the 1980s, global poverty is on the decline (Roser and Ortiz-Ospina, 2018) and the Gross Domestic Product (GDP) is growing worldwide (World Bank, 2018), while in the same timeframe the global population rose to 7.2 billion and the life expectancy is also steadily increasing (Haub and Kaneda, 2014). These factors contribute to a rising demand in clothing, since more people need textiles for a longer timeframe, and owing to the increased wealth, clothing is changing from a basic human need to a fashion product in many parts of the world. In turn, the rising demand for clothing resulted in a rising demand for fibres, thus fuelling the world fibre production.

In Figure 2, the global fibre production from 1980 to 2016 is shown. While the production of the natural fibres, cotton and wool, remain relatively stable, the production of cellulosic fibres almost doubled in the last 10 years from about 3 million tonnes to about 6 million tonnes. Synthetic fibres are on a steady rise, they started at around 10 million tonnes in 1980, to 63 million tonnes in the year 2015. The

most important synthetic fibre for clothing production is Polyethyl-enterephthalat (PET), which contributed by far the most to the total fibre production (CIRFS, 2016).

While most of the clothing sector is split between PET and cotton, there are some specialised applications left for other fibre materials (IHS Markit, 2016). Examples would be polyacrylonitrile, which is a fibre often used for socks and sweaters because of its wool-like characteristics; aramid fibres, which are often used for firefighter clothing and military applications (KERMEL, 2008); polypropylene fibre additives for concrete in the construction sector (IFGAsota, 2017); or fibres for fibre reinforced materials, where a wide range of different materials can be used (Rosato and Murphy, 2004).

End-of-life textiles

According to the Waste Framework Directive of the European Parliament (European Parliament and Council of the European Union, 2008) the waste management legislation and policy should abide by the waste hierarchy. The waste hierarchy starts with waste prevention on the top, followed by the preparation for re-use. If preparation for re-use is not possible, the next step would be recycling, which is followed by energetic recovery.

Only if none of the above methods can be applied, disposal on a waste dump should be considered.

Prevention and preparation for re-use

While on the one hand the prevention of waste is at the top of the waste hierarchy (European Parliament and Council of the European Union, 2008), the business model of the fashion industry on the other hand is based on a rapid change of clothing and setting new trends annually to sell a high amount of new clothing. This of course results in a reduced lifetime for clothing. For example from 1998 to 2005 the mean useful life of apparel was reduced by 35% (Korolkow, 2015).

A change of the trend in textile waste generation is unlikely without a change in consumer behaviour. Campaigns to inform the population, education in primary school for simple textile repairs, such as sewing buttons back on, and the implementation of eco-labels for textiles with a longer life-time could be considered (Tojo et al., 2012).

In industrial application, textile rental companies can be a valuable asset in preventing textile waste. Textile rental companies rent textiles, such as work clothing, bed sheets and towels, to businesses. After using, the businesses send the textile back to the rental company where the fabrics are washed and if needed repaired. It is in the interest of the rental company to re-use any textiles as often as possible and therefore the consumption of textiles is reduced (Salesianer Miettex, 2015).

While for businesses textile rental is already common practice, similar services for private consumers are currently limited to the renting of clothing for specific occasions, such as weddings, carnival and balls, but there are efforts to expand on this further. An Austrian start-up for example is currently working on a rental service for ethically produced baby clothing (Students Impact Initiative, 2018).

For any kind of textile re-use, the end-of-life textiles have to be collected separately from the residual waste. If textiles are intended for the use in the second-hand market, they need to be clean, dry and not worn. Since its character as a basic human need, many people have moral concerns regarding the disposal of clothing. Therefore, separate collection is widely accepted. In Germany for example, already 75% of textiles are collected separately and most of these textiles were turned in at collection containers (Korolkow, 2015).

After collection, the textiles have to be sorted. Reusable clothing has to be separated from not reusable clothing. Furthermore, the reusable clothing is sorted into up to 350 subgroups. The sorting process is a very labour intensive one, therefore, it is often carried out in countries with a lower cost for labour. The apparel collector ÖPULA for example, sends the end-of-life textiles they collect to Italy for sorting (Derntl, 2011).

While the separated collection of textiles requires energy for transport sorting and packing, every kilogram of virgin cotton replaced by a second hand product saves 65 kWh of energy and for polyester every virgin material replaced by second-hand

clothing saves even more energy with 90 kWh (Woolridge et al., 2006). Therefore, a big supply of second-hand clothing can have a positive impact on the environment.

Most of the currently collected second-hand clothing is shipped to developing countries. There are concerns that this practice destroys the local textile industries. While for example the Sub-Saharan textile industry is on the decline, this can also be explained with the competition of imports from Asian countries (Brooks and Simon, 2012). Another fact to consider is that a big portion of the African population cannot afford new clothing and are therefore depended on cheap clothing imports. To illustrate the importance, in the Central African Republic second-hand clothing has reached a 90% market share. One should also consider that the second-hand industry creates new jobs. In Senegal alone there exist 24,000 jobs related to second-hand textiles (Baden and Barber, 2005).

Recycling and recovery

After prevention and re-use, the next strategy in order of importance is recycling. According to Directive 2008/98/EC (European Parliament and Council of the European Union, 2008) recycling means any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material, but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations.

This definition distinguishes recycling from preparation for re-use through the word reprocess. The recycling processes can be further categorised by the degree of processing that takes place in the operation. There is product recycling, where the chemical and physical constitution of the waste materials are not changed in the operation, an example would be the use of fibres as a filler material. Then there is material recycling, where the physical but not the chemical constitution of the waste material is changed, melting of polyester textiles and subsequent re-spinning into new fibres could be categorised as such. Lastly, there is feed-stock recycling, where both the chemical and the physical constitution of the waste material is changed, de-polymerisation of fibre materials into their monomers would be the main fibre-related application in this category (Bartl, 2014).

Recovery on the other hand means any operation, the principal result of which is waste serving a useful purpose by replacing other materials that would otherwise have been used to fulfil a particular function, or waste being prepared to fulfil that function, in the plant or in the wider economy. Meaning recycling is in fact a recovery operation, for simplicity sake, the term recovery will be used in this article only for recovery operations that are not recycling operations. An example for a recovery operation would be thermal recovery in waste-to-energy power plants.

If the already discussed preparation for re-use of textiles is not economically feasible, or the clothing has damages that are not economically feasible to repair, cutting the clothing down to

cleaning and wiping rags can be a possible recycling operation. However, only textiles with a high water absorption capacity are feasible for this process, limiting the application mostly to cellulose fibres, such as cotton and viscose. In Germany, there is already a standard for the production of recycled wiping rags, where only cotton, half-linen and viscose materials that are blended with a certain amount of synthetic fibres, are considered. The rags have to be of a size above 30×20 cm and have to be free of parts, like zippers, buttons and eyelets (DIN, 2005). The recycled wiping rags are in competition with newly produced ones, which are usually designed for multiple uses, but even so, the recycled ones can be more ecologically friendly according to one producer (Irgang and Leiler, 2004). With a price of up to 2 € kg^{-1} (Affordable Wipers, 2018), wiping rags are up to twice as valuable as exporting of the used clothing, but the production itself is often labour intensive and expensive. Therefore, the production of wiping rags is limited depending on the market price of the wiping rags and the labour cost in the country where they are produced.

Pure cotton rags and certain plant fibre materials can be reprocessed to handmade paper. The process is an ancient one, however today it still has tradition, for example in India (Ideas Afresh Inc., 2004). A research group from Ghana tested different waste textile materials in combination with mulberry fibres to create quality paper that is suitable for art applications. They found that not only natural polymer fibres can be suitable for creating functional paper, but also synthetic materials, such as nylon and polyester (Opoku-Asare and Yeboah, 2013).

Another possible fibre-recycling process is the fibre recovery. Fibre recovery means the disintegration of the textile into loose fibres, which can be spun into a yarn again. For the process, a so-called Garnett machine (Allen, 1927) is used, which consists of rotating drums with metal pins that destroy the textile structure. The heavy mechanical strain results in shorter fibre lengths than the length of the original fibres and a certain portion of dust is left in the material (Gulich, 2006). A proper sorting before the disintegration process is however needed, since a mixture of different fibre materials and colours results in low quality yarn after spinning. About 95% of the recovered fibres are in fact not respun into yarn, but are directly processed into nonwovens (Gulich, 2006). Mishra et al. (2014) created different kinds of nonwoven composite materials with disintegrated cotton waste fabrics and a virgin polypropylene matrix. They showed that the use of waste cotton does not influence the material properties in a negative way.

If the lengths of the fibres after the disintegration are too short, re-spinning into yarns is not possible. These fibres are usually referred to as flock. Flock is a term for short fibres that were produced that way intentionally (Krieger et al., 2009). While flock is usually produced intentionally out of virgin material, end-of-life textiles can be considered, such as fibres recovered after disintegration. Fibre flock can be used to adjust viscosity and flow properties in liquids or as an additive in construction materials (Reinhaller et al., 2010). Avelar et al. (2016) used short

cotton fibres, similar to flock, and combined them with biological sludge from the wastewater treatment of textile manufacturers to create briquettes for heating purposes. While this process is not a recycling process anymore, it is a recovery operation that is to be preferred over landfilling.

Thermoplastic fibres and fibres that can be dissolved in solvents can be used for fibre re-spinning. Re-spinning means that the end-of-life textiles are either molten or dissolved and afterwards, the solution or the melt can then be used for spinning just like the virgin material. Not only can end-of-life textiles be used for this process, but for example also polyester bottles. The process can be feasible for single material textiles, but has limitations for the processing of multi-material textiles.

While the 'fibre-to-fibre' process is not that common as of today, the 'bottle-to-fibre' process is common practice for polyester bottles (ecofi, 2018). Even so, virgin polyester has different intrinsic viscosity, crystallinity and opacity than recycled polyester (Gurudatt et al., 2003), which can limit the maximum recycled content in the products or could lead to further processing steps and additional additives for reaching the correct material parameters (Oromiehie and Mamizadeh, 2004).

Fibre re-spinning is also possible for natural fibres, such as cotton. For the Refibra fibre of Lenzing AG, cotton fibres and wood are recycled with the Lyocell process (Lenzing AG, 2017). The Lyocell process is a cellulose regeneration process. Cellulosic material is first dissolved in N-methylmorpholine-N-oxide (NMMO) and then pressed through a spinneret into water or an aqueous NMMO solution, where it coagulates and forms a new fibre (Liu et al., 2001).

Fibre feedstock recycling means breaking down the polymeric structure of the molecules in the textile into smaller pieces. This process can be either unspecific with thermal processes, like pyrolysis, hydrocracking and gasification, or very specific with chemical reactions, like alcoholysis, glycolysis, hydrolysis.

Pyrolysis can be used with a mixture of different textile materials without prior sorting or with multi-material textile materials, which would otherwise only be processed in waste-to-energy plants. The product of the pyrolysis contains oil and gas, which can be used as template chemicals for the chemical industry (Miranda et al., 2007).

An example for a chemical process would be glycolysis, which is the breaking down of the ester linkages by a glycol at temperatures around 200°C , resulting in oligomers or oligoester diols/polyols with hydroxyl terminal groups (Nikles and Farahat, 2005).

A special type of feedstock recycling would be the enzymatic recycling of textiles. Enzymes are biocatalysts that enable or increase the rate of chemical reactions. They are highly selective so they only act on particular substrates and produce only particular products (Palmer, 2001). Enzymes are proteins and are synthesized by living organisms. Cellulase, an enzyme involved in the cellulose hydrolysis, for example can be synthesized by multiple different organisms in both the fungi and bacteria category (Liu and Kokare, 2017).

In the textile industry, enzymes are already in use, but are mainly used for surface treatments, such as the removal of fibrillary matter (Buschle-Diller et al., 1994), the washing of denim jeans (Colomera and Kuilderd, 2015), as well as for bleaching (Buschle-Diller et al., 2001), desizing (Chand et al., 2012) and scouring (Csiszár et al., 1998).

Enzymes that catalyse the breakdown of polymers back into monomers can be used to process textile waste. Already in 1974 it was reported that cellulase enzymes can degrade cellulosic paper waste into short sugars with up to 92% conversion (Mandels et al., 1974). Cellulase consists of multi-enzyme complexes with mainly three different functions. Namely endoglucanase, to break the cellulose polymer chains randomly along the chain; exo-cellobiohydrolase to break cellobiose molecules off of the cellulose polymer chain from the ends; and beta-glucosidase to divide cellobiose into two glucose molecules (Singhania et al., 2017). These three enzymes work synergistically together to process long polymer chains very quickly.

In recent years, cellulase enzymes have gained increased popularity for the generation of bioethanol in biorefineries. In such a refinery, cellulosic plant matter is broken down into glucose, which is then fermented into ethanol (Chandel et al., 2012). Cellulases are now the second largest industrial enzyme produced by dollar volume in the world with various applications besides the bio-ethanol production, such as the animal feed industry, detergent industry and paper production (Singhania et al., 2017). The high interest in bioethanol production drives the demand for the development of cheap cellulase enzyme products that can be economically used on an industrial scale all around the world (Ellilä et al., 2017).

This creates an opportunity for the textile recycling industry since the cheap cellulase enzymes that are developed can potentially be used for the processing of cellulose-based textile materials, such as cotton, viscose and Lyocell (Shojaei et al., 2012). Commercially available cellulase enzymes, such as Novozymes Cellic Ctec3 (Novozymes, 2012), show the highest catalytic activity in the slightly sour milieu around pH5 at mild temperatures of around 50 °C compared with the directly competing process, the chemical acid hydrolysis of cellulose, which is best operated at temperatures of up to 200 °C, the enzymatic hydrolysis conditions are more economic for industrial application (Jeihanipour et al., 2011).

There are already three studies from 2018 that worked on their research on processes involving enzymatic hydrolysis of cellulose waste textiles. Hu et al. investigated the feasibility of cotton textile waste as a feedstock for the production of cellulase enzymes with the *aspergillus niger* fungi. The produced enzymes were then extracted from the fungi and used to hydrolyse cotton where yields of up to 70% conversion were reached (Hu et al., 2018).

Hasanzadeh et al. investigated the bio-ethanol and bio-gas production with a feedstock of denim jeans, which consisted of a blend between cotton and polyester fibres. They treated the jeans first with calcium carbonate at different temperatures to reduce

the crystallinity of the cotton, making it easier for the following enzymatic treatment to catalyse the hydrolysis. After hydrolysis, the glucose solution was fermented with yeast to bio-ethanol. Alternatively they also tried an anaerobic digestion of the pre-treated cotton to produce bio-gas (Hasanzadeh et al., 2018).

Vecchiato et al. hydrolysed viscose fibres containing flame retardant pigment. The viscose fibres were completely decomposed within 24 hours at room temperature, at about 50 °C, however the complete decomposition of the fibre was already reached after 4 hours. They have also shown that the flame retardant pigment was not damaged by the enzymatic treatment, therefore the pigment could potentially be re-used (Vecchiato et al., 2018).

Besides the cellulase enzymes that hydrolyse cellulose, which is a natural substance, it is also reported that there are enzymes that can hydrolyse man-made synthetic fibres, such as polyester, and so-called biodegradable polymers, like polylactic acid (Banerjee et al., 2014). While there are efforts to replace, for example, polyesters with polylactic acid (FIBFAB Project, 2018), biodegradable plastics have currently only a limited market share, but are expected to more than double their market value from the reported 1.8 billion dollars in 2014 to about 4.2 billion dollars in 2022 (Lamb, 2017).

Polyester can be hydrolysed with two types of enzymes, cutinases and lipases. Cutinases are naturally occurring enzymes that hydrolyse the ester bindings of the cutin, a substance occurring in plants that has similarities to polyester (Longhi and Cambillau, 1999). Lipases are enzymes that hydrolyse lipids, such as fats and waxes, for example in the human body they hydrolyse triglycerides into diglycerides (Winkler et al., 1990).

For both types of enzymes it has been shown that commercially available products can potentially hydrolyse polyester (de Castro et al., 2017). The yields are currently low, but there are efforts to enhance the polyester hydrolysis ability by, for example, fusing of the cutinase enzymes to binding molecules (Ribitsch et al., 2013).

It was also reported from Yoshida et al., that they found a new bacterium that produces two new types of enzymes that would be suitable for the polyester hydrolysis. Their experiments with the produced enzymes showed that they could hydrolyse 50% of their polyester substrate in about 50 days (Yoshida et al., 2016).

A major problem for all these polyester hydrolysis processes is that the big protein molecules cannot penetrate into the polyester material, therefore the hydrolysis mostly happens on the surface of the material limiting the speed of the reaction significantly. Also, the duration of the hydrolysis processes as seen in the previous examples is in the scale of months, making it difficult to develop economical processes. Recycling of polyester with enzymatic hydrolysis therefore is currently not feasible.

There are also enzymes that could potentially hydrolyse polyamides and polyacrylonitriles, but these hydrolysis processes have similar limitations to the enzymatic polyester hydrolysis process. The biggest two of which would be the limited catalytic activity and that the attack of the substrate by the enzymes is

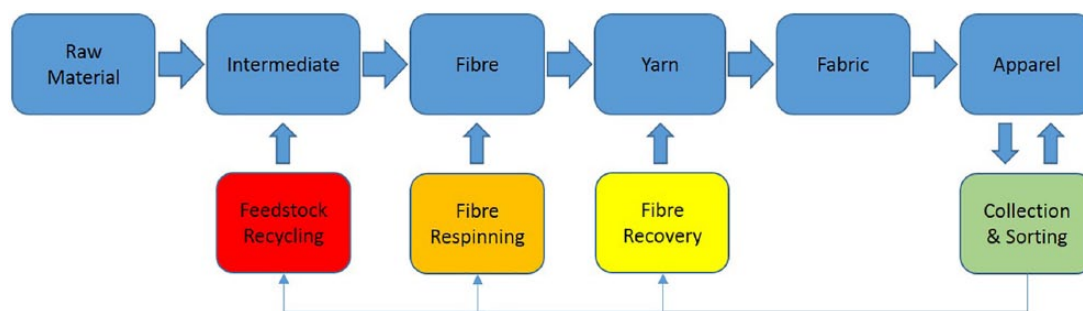


Figure 3. Textile processing chain and recycling processes.

limited to the surface of the substrates (Guebitz and Cavaco-Paulo, 2008).

Instead of using enzyme mixtures, it is possible to use the living organisms that produce enzymes that degrade the textile waste. Two noteworthy processes would be composting and vermin composting. While composting, different kinds of bacteria and fungi degrade the organic waste to a very nutrient-rich soil conditioner. Vermin composting speeds the process up by adding living creatures, such as earth worms. Both processes do not result in a product along the textile processing chain, but they can close the material cycle indirectly by generating new nutrient rich-soil, for example for the cotton production (Aishwariya and Amsamani, 2012; Mohamed Abdalla et al., 2012).

In Figure 3, the recycling processes discussed in this section are shown and where they interact with the textile processing chain. Re-use after collection and sorting is of course the most efficient processes. While the monomers created by feedstock recycling can result in a similar quality to virgin material, almost the whole textile processing chain has to be repeated. Fibre recovery on the other hand, results in low quality fibres, but the remaining processing chain is much shorter.

Multi-material textiles in the circular economy

To reach the goal set by the European Commission in their action plan for the circular economy (European Commission, 2015), textile to textile recycling processes have to be implemented. From the previously discussed recycling techniques mechanical fibre recovery, fibre re-spinning and chemical feedstock recycling seem to be the best suited techniques since they have the potential to create new products with a similar quality to the virgin material. However, all three recycling strategies have a big problem with multi-material textile waste.

While blends of different thermoplastic fibres can be melted and reprocessed into a new product, the resulting product is most likely of low quality, and the creation of something close to virgin material seems impossible. Mechanical disintegration of the multi-material textiles will also lead to mixtures of different fibre material types that cannot be separated efficiently. As already discussed, most fibre materials can be used for thermal feedstock recovery, the generation of oil for fuel, however, is not necessarily

the goal of a circular economy approach. The use of chemical feedstock recovery processes can be considered, but the use of excessive non-recoverable chemicals, high temperatures and undesirable side reactions with the secondary fibre material can make these processes potentially not ecological or outright impossible to operate. An exception here would be the emerging biochemical recycling processes, which are highly material selective and work on lower temperatures, enabling a more economic and ecological recycling process. There are already some efforts to tackle the problem of multi-material textiles with the use of biochemical processes. In the following paragraphs some of the current research projects are introduced.

A patent application published in 2017 describes a recycling process where textiles containing flame resistant synthetic fibres like aramid and enzymatic hydrolysable fibres like viscose are involved. The process consists first of an enzymatic hydrolysis of the cellulose fibres. The remaining synthetic fibres can then be mechanically separated into individual fibres. These fibres could then, for example, be used for the production of new yarns, which in turn can be woven into new textiles. Solid additives like pigments that were spun with into the viscose fibres are also released in the hydrolysis step and can be separated and potentially re-used. The glucose solution gained from the enzymatic treatment can be used, for example for the production of bio-ethanol (Müller, 2016).

The RESYNTEX project is a research project funded from the European Union's Horizon 2020 innovation programme, which aims to create a circular economy concept for the textile industry. The project involves biochemical processing of cotton into glucose, polyester into its monomers, polyamide into polyamide oligomers and wool into protein hydrolysate.

The glucose is then further processed into bio-ethanol, the polyester monomers can be used to create new polyester bottles, the polyamide oligomers can be used as value-added chemicals for certain processes and the protein hydrolysate is useful as a resin or adhesive (Delahay, 2016).

The Austrian research project Coin TEX2MAT is developing circular economy-based recycling processes for multi-material textiles. In multiple case studies, polyester/cotton textile waste both from pre- and post-consumer sources are going to be separated. The cotton is going to be hydrolysed with enzymes and the remaining polyester is going to be re-granulated and re-spun into

new fibre material. After initial tests in the laboratory scale, the whole process is going to be scaled up and an assessment of the feasibility for industrial application will be made. In another case study in the project, the recycling of polyamide blends is going to be evaluated (Plastextron, 2017).

Conclusion

The annual fibre production is expected to rise above a 100 million tonnes in the next years, while the lifespan of textile products is continuously decreasing. Without consumers rethinking their consumption habits, these trends will only be aggravated. A waste management strategy to generate awareness for sustainable action should be established to set the sails for a change in these trends. For an efficient textile waste management strategy like that, it is important that textiles are collected separately from municipal waste and therefore these schemes have to be established across the board in all western countries.

To reach the goal of a circular economy set by the European Union, end-of-life textiles have to be recycled in such a way that new fibre material with similar properties to the virgin material can be produced. While this is already a technically achievable strategy for sorted textile waste materials consisting of only one type of fibre material, multi-material textiles are a problem for recycling purposes. These multi-material textiles should therefore be avoided and a 'design for recycling' approach should be established in the textile and apparel industry.

In the cases where textiles with multiple different fibre materials are unavoidable, novel recycling concepts have to be developed that can separate the different fibre materials from each other either directly, or through selective processing of individual fibre materials into useful chemicals. Biochemical processes seem to be the most suitable solution for this task because of their high selectivity and ecological operating conditions.

Since every recycling process that is to be implemented by a private company needs to be profitable, a bonus malus system based on extended producer responsibility should be considered. A system like that could allow a profit-orientated operation of recycling processes and could therefore rise collection rates, and subsequently also recycling rates by making their implementation economically feasible. Such a system would also encourage the development and application of novel recycling techniques, like further development of biochemical recycling processes, through the potential financial gain of being able to recycle waste streams that are currently only used for thermal recovery operations. Innovative high-tech companies could rise on the market because of this opportunity, which could in turn also lead to a return of parts of the textile processing chain back to European countries, where the environmental and social standards are under European legislation.

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