CHAPTER
9

Textile Recycling Technologies

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Introduction

The globalised textile production with scattered value chains can be quite non-transparent, untraceable and unsustainable from the environmental and social points of view (Kumar et al., 2017; De Brito et al., 2008) Various environmental impacts are caused at different textile production stages, for example, by the use of chemicals, high consumption of water and energy, generation of solid and gaseous wastes, fuel consumption for transportation and use of non-biodegradable packaging materials (European Parliament, 2022; Lee, 2017; Choudhury, 2014). Social responsibility challenges of the global textile industry are related to poor labour conditions, for example, insufficient wage levels, excessive working hours, insufficient health and safety conditions, as well as forced and child labour (Annapoorani, 2017; Padmini and Venmathi, 2012; Holdcroft, 2015; Donato et al., 2020). In recent years many brands have started managing the environmental and social sustainability of their supply chains (Pederssen et al., 2018).

Furthermore, textiles are consumed in an unsustainable way due to mass production and wasteful fast fashion (European Commission, 2022). Textiles are discarded with less use time compared to earlier decades, and, on average, Europeans use nearly 26 kg of textiles, and discard 11 kg of textiles, annually (European Parliament, 2022). According to the new *EU strategy for sustainable and circular textiles* (European Commission, 2022), the priorities in the future sustainable textile system rely on long-lived textile products, which contain recycled fibres and are recyclable. This longevity will be supported by easily available reuse and repair services

(European Commission, 2022). In the linear model, *discarded textiles*, i.e., textile products unwanted by the user for one reason or another, generate a vast waste problem, as most of them (87%) are still either incinerated or landfilled (European Parliament, 2022). In a circular economy, however, discarded textiles are *not waste* per se, but there are many ways to use discarded textiles, leading to environmental and socio-economic benefits (Filho et al., 2019).

Both the European waste hierarchy (Directive (EU) 2008/98/EC) and circular strategies (Potting et al., 2017) are emphasising the prevention of waste and reuse (Figure 8.1). If discarded textile products are clean, unbroken and still visually attractive, they can be *reused* as products. Options for such include second-hand shops, physical and on-line flea markets, various digital platforms and applications, and charity organisations. Textile products having some damage, but are not fully worn out, should be *repaired*, or they could be *repurposed* or their materials can be utilised in *remanufacturing*. All of these activities should be prioritised over recycling.

However, when textile products are not suitable for reuse and materials cannot be utilised in any other way, their materials should be *recycled*. Currently, the majority of textile recycling is focusing on lower-value applications and, thus, referred to often as downcycling. According to Ellen MacArthur foundation (2017) only less than 1% of discarded textiles are recycled back into raw materials of textiles. For lowering the environmental impact of textiles, it is important that recycled textile materials are used to replace virgin raw materials (Dahlbo et al., 2017).

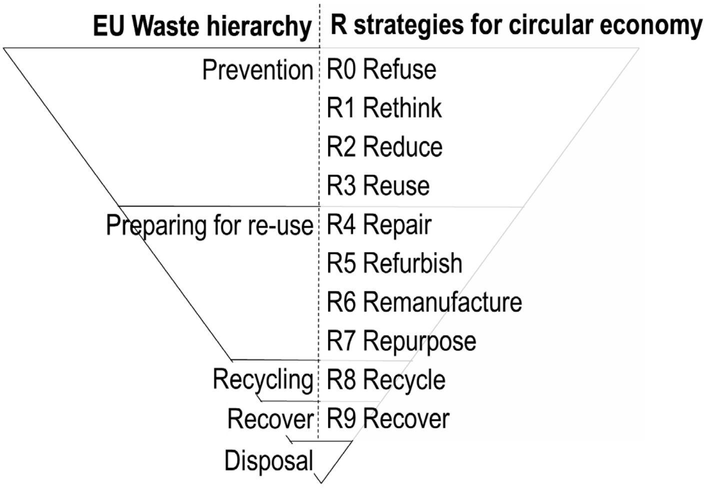

Figure 1. Circular economy strategies (Potting et al., 2017) are emphasising two priority categories of EU waste hierarchy (Directive (EU) 2008/98/EC)

In the EU, the separate collection of discarded textiles will be mandatory by 2025 (Directive (EU) 2018/851), and according to the *EU strategy for sustainable and circular textiles,* activities supporting sustainability and circularity of textiles in general will be implemented in the coming years (European Commission, 2020, 2022).

Textile recycling is still very underdeveloped, and successful textile recycling companies are rarer than we have hoped for. There are a number of research activities ongoing for textile recovery, recycling and waste valorisation, and some interesting commercial actors have already emerged. In principle, there are various recycling methods for all main textile fibre, with their own strengths and weaknesses (Kamppuri et al., 2019; Heikkilä et al., 2020). Possible fibre-to-fibre recycling methods are demonstrated for most textile fibre types on a lab scale. However, in practise, recycling of textiles is not a simple task. Textile products are usually not made of a single fibre type, but blends. And, in addition to fibres, textile products also contain other types of materials not suitable for the textile recycling processes. Furthermore, used textile materials can be worn out and contaminated, which makes recycling even more difficult. Sorting and quality assessment are essential stages especially in the processing of mixed textiles from households, which is the most challenging flow to sort and recycle into secondary raw materials for high-value applications. Other textile flows, i.e., side-streams of textile manufacturing processes from the textile industry and unsold items from textile retail, on the other hand, are easier to process, as the material composition is better known and fibre quality is intact (Kamppuri et al., 2019).

This article reviews different recycling possibilities for various kinds of textile materials. Sector 2 focuses on the recovery of discarded textile materials and their pre-processing into secondary raw materials for the textile industry, and Sector 3 on different recycling methods. The main focus is on fibre-to-fibre recycling processes. Sector 4 contains a short summary and a few words about the future.

2. Textile recovery and pre-processing of textile materials for recycling

Discarded textiles need to be collected and sorted so that they can be forwarded into an appropriate utilisation route. Textile products that will be recycled also require more detailed sorting based on the identified fibre type, as well as pre-processing before the actual recycling process is used. The recovery of discarded textiles and pre-processing steps used for recyclable textile fractions are illustrated in Figure 2, and processes are explained shortly in the following paragraphs.

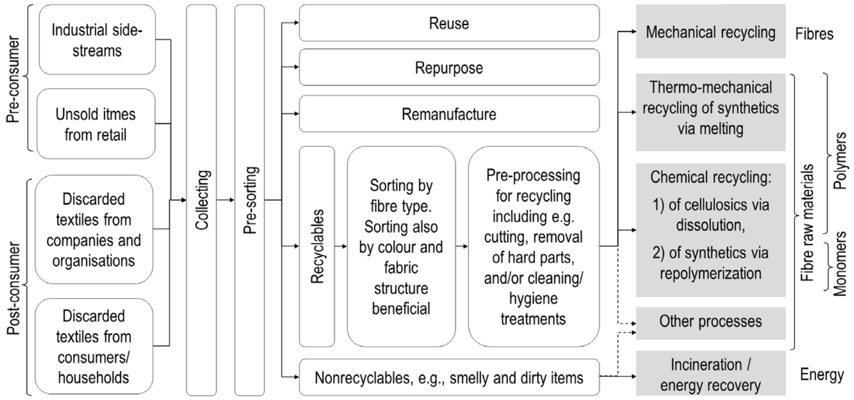

Figure 2. A simplified illustration of the recovery of discarded textiles, pre-processing for textile recycling and recycling routes

There are two main sources for discarded textile flows: (1) *pre-consumer,* i.e., industrial side-streams (sometimes referred to as *post-industrial*) and unsold items from retail, and (2) *post-consumer* (sometimes referred to as *post-consumption*), i.e., discarded textiles from companies/organisations (e.g., hospitals and restaurants) and consumers/households (Fontell and Heikkilä, 2017; Heikkilä et al., 2019; Heikkilä et al., 2020). Textile (waste) flows from these different sources vary in their qualities and quantities. Planning the separate collection of different flows may be challenging. Currently, in the EU members states, there are several different collection systems in operation. In Finland, for example, the collection of household wastes is, for most waste fractions, the responsibility of municipal waste management companies, while the collection and management of waste originating from companies and organisations is the responsibility of commercial waste management companies. This is applied for textile (waste) flows as well, at least for now. France, on the other hand, has adopted the extended producer responsibility (EPR) system for textiles. In the EPR system, producers have a significant responsibility to collect and treat the discarded products. There can be various ways to build up the EPR system, which is why the EU strategy for sustainable and circular textiles proposes harmonised EPR rules for textiles in Europe (European Commission, 2022). When the separate collection of discarded textiles begins in the EU (by the year 2025), there can be slightly different schemes to organise the activities, including combinations of the above-mentioned models.

The sorting of textiles may be done in different stages of the textile recovery process (Heikkilä et al., 2021; LSJH, 2020). In the case of textiles collected from households, *pre-sorting* may be used to remove textile products that can still be reused, repurposed or remanufactured and items that are non-recyclable from the stream. The *material-based sorting* will be done for recyclables, since many recycling processes may be fibre specific. To create new products, fibre composition may be important in order to obtain the desired properties. Furthermore, sorting may be based on colour, since in some cases, colours can be preserved and dyeing is not needed for the next life cycle. Manual sorting is still the dominant procedure for reclaimed textiles, however automated systems and lines are emerging for material-based sorting. Identification and sorting technologies used for textiles are described in more detail in Chapter 8 of this book.

Typically, all textile products that are to be recycled are pre-processed mechanically regardless of the recycling method, and they may also need additional processes. Cutting waste and similar industrial side-streams, for example, do not typically contain accessories, while non-sold items from retailers, for example, are already made into products and may have zippers, buttons, embroidery, tags and other components that may need to be removed prior to recycling. Also, cleaning and/or hygiene treatments may be needed (Heikkilä et al., 2020). A laundry-type process may be done for whole products, but cleaning may be done also in later stages. However, some recycling processes include the use of strong chemicals or high temperatures, which take care of the hygiene issues.

Mechanical pre-processing includes first cutting the textile products into smaller pieces, typically by using guillotine cutting. First, the guillotine cuts textiles into strips after which the direction of the cutter changes 90 degrees, forming a textile shred. In this stage, the pieces containing hard parts, such as buttons, sections of zippers etc., can be removed from shred. Further sorting is also possible at this stage: for example, linings and outer fabrics may have been separated in the shredding process. Textile materials can be recycled at the *fibre level* or at the *fibre-raw-materials level*, and processes include, for example, *mechanical*, *thermo-mechanical* and *chemical processes*. Mechanical recycling starts from the fibre shred, but for fibre-raw-material recycling, the shred can be cut or ground into smaller pieces (Kamppuri et al., 2019).

An illustration of various possibilities for textile recycling is included in Figure 2. Terminology used in this article is also explained there. It should be noted that the terminology regarding recycling processes is not fixed within the textile sector, and, for example, the thermo-mechanical process is sometimes also referred to as thermal or thermo-plastic process. More confusion may occur as synthetic fibres are plastics. In the textile context, mechanical recycling usually refers to opening the textile structures into fibres and using those fibres in making new products, while in the plastics sector, mechanical recycling refers to the melt processing. Textile processes are explained in more detail in the following sectors.

3. Recycling technologies

Fibre-to-fibre recycling, can be done at the fibre level (mechanical recycling) or the fibre-raw-materials level (thermo-mechanical and chemical recycling) to replace virgin fibres in clothing and textile production. Generally, the existing processes and machinery of the textile industry can be used for all types of recycled fibres. Secondary fibre materials obtained from textile recycling can also be used for the production of nonwovens, composites and other products. Alternative processes are available materials that cannot be easily included into textile-to-textile processes. These include, for example, many laminated and coated textiles, and some blended textiles.

Mechanical recycling is, in principle, suitable for fibre blends, while at the fibre-raw-materials level, recycling with chemical and thermo-mechanical methods are typically polymer specific. In mechanical recycling, the fibre length is reduced and the fibre strength remains unchanged: i.e., worn fibres remain worn, while fibre-raw-materials recycling enables the restoration of properties in fibre spinning, which will follow the recycling process. Fibre-raw-materials recycling at the polymer level enables the restoration of fibre length, and the fibre strength can be restored at least to some extent. However, if the polymer is broken down to monomer the level, the process enables the production of new fibres with properties similar to new ones: i.e., both the polymer and fibre properties are restored. Processes enabling restoration of fibre properties use water and/or chemicals, and therefore are expected to have a higher environmental impact compared to mechanical processing. The challenge is to find a suitable processing method for different types of material, also taking into account the environmental impact of the recycling process, and also finding an optimal high-value application into which material quality allows it to be used.

3.1 Mechanical recycling

Mechanical recycling means textile structures are mechanically torn, opened and unravelled into separate fibres. The possibly unopened material pieces, fibre bundles and debris are removed during the opening process. Recyclate can be blends and mixed material, but the process may be easier to optimise for the processing of a single fibre type and one type of textile structure. The opening process can be continued until the textile is sufficiently opened and suitable for the selected further process. Unnecessary processing should, however, be avoided, as mechanical processing shortens the length of the fibres. In comparison to virgin fibres, mechanically recycled fibres vary greatly in quality as the fibre length is often short (Albrecht et al., 2003). Mechanically recycled fibres can be used in either the spinning of yarns to make fabrics and textile products for the textile industry, or for manufacturing nonwovens and composites (see Figure 3).

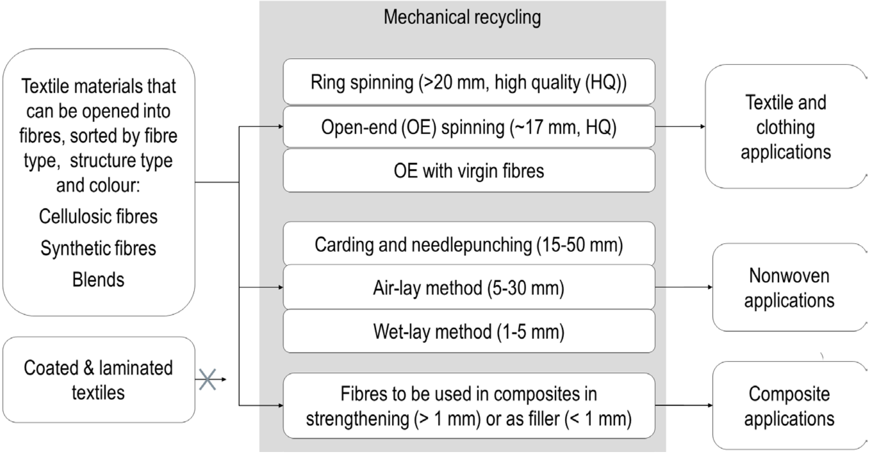

Figure 3. Simplified illustration of the possibilities of mechanical textile fibre recycling

The length of fibre has a key role in strength and durability of the yarns (Aronsson and Persson, 2020), and care must be taken to minimise the loss of fibre length. Furthermore, for good spinnability, the hard parts and textile structure residues also need to be efficiently removed from the opened fibres. The shortest fibres, less than 4-5 mm long, are lost during the processing; fibres that are 12-15 mm long provide bulk and thickness; and fibres longer that 15 mm give spinnability and provide strength and smoothness to the yarns (Klein, 2016). There are various yarn-spinning methods available, and the length of fibre is a key determinant for the method used. Ring spinning can be adjusted based on the fibre length; however, the range of 20-45 mm is considered slightly short for this method. For open-end (OE) spinning, the minimum required fibre length is 17 mm, preferably above 20 mm, and lengths ranging between 25-26 mm are considered good. It is not surprising that OE spinning is favoured for recycled materials, as the fibre length can be shorter compared to ring spinning. In many cases, recycled fibres are blended with longer fibres that have been recycled or with new virgin fibres to ensure high yarn quality (Auranen, 2018; Kamppuri et al., 2019).

Shorter fibres are suitable for nonwovens, which is a group of sheet materials manufactured directly from fibres and bonded into a consolidated structure. The shortest fibres (less than 5 mm long) can be utilised in air-laid nonwovens (i.e., dry papers) and in wet-laid nonwovens.

The air-lay and carding processes are also suitable for longer fibres (length ≥50 mm). Fibres need to be well opened for the wet-laying and carding processes, while in the air-lay process the opening quality is not as critical (Albrecht, 2003). Nonwoven technologies also enable the production of thicker products, such as insulation materials. Opened recycled fibres can be used in composites, either as reinforcement (length >1 mm) or as filler (length <1 mm) (Kamppuri et al., 2019).

Mechanical opening lines are commercially available, and companies offering opening process services and/or providing mechanically recycled fibres for spinning mills include, for example, Rester (FI), Frankenhuis (NL) and Altex Textile Recycling (DE). In order to tackle the problem of the shortening of fibres, new, softer process have also been emerging, such as the Rejuvenation process by PurFi (BE). Other companies, for example Marchi & Fildi (IT), offer yarns at least partly made of mechanically recycled pre-consumer fibres. Another example is Pure Waste Textiles (FI), which has made a *Post waste era* collection with yarns containing 20 per cent of post-consumer cotton fibres blended with other types of recycled fibres (Heikkilä et al., 2019, 2020). Nonwoven production is currently the state-of-the-art for textile recycling and commercialised for multiple types of nonwovens.

3.2 Fibre-raw-materials recycling

Fibre-raw-material recycling can be applied when fibre quality, especially fibre length and strength, need to be restored. It can also be an option in cases where mechanical recycling is not possible, for example, in coated and laminated materials that cannot be opened into fibres. Some processes may also be suitable for fibre blends, even though many of these processes are fibre type-specific due to the specific chemistry used for chemical methods, or due to the used temperature for thermo-mechanical processes.

Fibre-raw-materials recycling can be done at the polymer level or by breaking them down into smaller molecules. Polymer-level recycling can be done via melting (thermo-mechanical processing) or dissolution (chemical), depending on the polymer type (see Figure 4). Thermoformable synthetics can be melted and melt-spun into fibres via thermo-mechanical recycling. Dissolution methods are suitable for cellulose-based fibres and for some synthetic fibres. Synthetic polymers can also be broken down into monomers by chemical and biochemical means, and built back to polymers to be forwarded to fibre spinning processes or manufacturing of other plastic products. These methods are referred to here as chemical recycling methods.

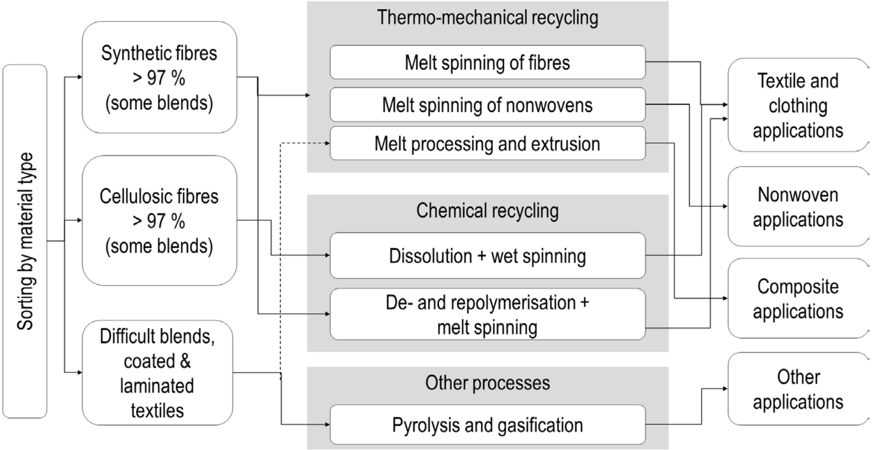

Figure 4. Simplified illustration of possibilities of fibre-raw-materials recycling

3.2.1 Thermo-mechanical recycling of synthetics – Polymer level

Thermoplastic polymers are suitable for thermo-mechanical recycling, and they can be melted and melt spun several times. Thermoplastic textile fibres include, for example, polyester, polyamide and polypropylene. Acrylic fibre decomposes close to its melting point and cannot thus be processed this way. Most of the commercially available recycled polyester fibres are currently made with melt-spinning polymer obtained from PET bottles that have been collected from consumers. However, this is not necessarily a preferred method (European Commission, 2022). Processes for recycling polyester fibres from discarded textiles have been studied (e.g., Bascucci et al., 2022) and are slowly emerging.

Challenges for using post-consumer textiles in these processes include physical and chemical changes in polymer occurring during use. More changes, for example in crystallinity and in molecular weight, may occur during thermo-mechanical processing itself. Contaminants may cause chemical reactions that lower the polyester molecular weight, and residues of other materials may weaken the fibres. It is, however, possible to maintain dyes during the process (Saarimäki and Sarsama, 2021; Heikkilä et al., 2021). Molecular weight is a limiting factor for the number of recycling cycles; however, it is possible to valorise polymer melts with additives such as by chain lengtheners (Buccella, 2013; Ozmen et al., 2019) to enable better quality for material, and flame-retarding agents may also affect the reactions during the process (Bascucci et al., 2022). Care must, however, be taken so that additives do not hinder the recyclability of materials in subsequent cycles.

The thermo-mechanical recycling process is excellent for industrial textile side-streams. Companies, such as Nurel (ES), Racidi (IT) and

Fulgar (IT), offer fibres made from remelted PA from production. There are industrial examples for thermo-plastic recycling and upgrading of used synthetic polymers, for example, Cumapol's (NL) processes for polyester. Development work for these processes is ongoing, and fishing nets, for example, have been successfully thermo-mechanically recycled (Mondragon et al., 2020), but those are also suitable for other plastic processes.

Thermoplastic materials can also be used for making composites, where they can be either as fibres or as matrix. Composite can also be made of a cellulosic-synthetic fibre mixture, where the synthetic man-made fibre(s) are melted around cellulose-based staple fibres (e.g., CO or man-made cellulosic fibres (MMCF)) (Kamppuri et al., 2019). Thermo-mechanical methods have shown to be also very promising for the recycling of technical textile materials into high-quality plastic and composite materials (Saarimäki and Sarsama, 2021; Heikkilä et al., 2021).

3.2.2 Chemical recycling of cellulosics – Polymer level

Cellulose-based fibres, such as cotton, flax, viscose and lyocell, can be dissolved and spun into MMCFs. Impurities, such as silicates and metals, can be chemically removed from grinded fibres, and a coloured fraction can be bleached. Cellulosic fibres are dissolved, and the cellulose solution is pressed through h0oles in a nozzle into a spinning bath, where fibres are formed by precipitation. The dissolution and spinning processes vary slightly, but in principle, they are the same methods used for making primary fibres from wood-soluble pulp. The chain length of the cellulose molecules of cotton is higher than that of the dissolving pulp (de Silva, 2017), so the wear of fibres is typically not a problem in cotton recycling.

Typically, raw materials entering the chemical recycling process should have high-cellulose-fibre contents (between 97% and 98%) to reach MMCF; however, methods for higher-mixing-ratio blends are developed actively. Dissolution may be used for the separation of blends by dissolving the cotton and filtering other fibres out from the cellulose solution (De Silva, 2014). Filtration may, however, increase the cost of the process. Some fibres that are dissolved with cotton are also more difficult to remove, for example, elastane. Regarding colour preservation, it has been demonstrated that the colour of fibres can be saved during chemical recycling (Ma et al., 2020). If needed, colour and fibre-finish removal steps may also be included into recycling processes (Wedin et al., 2018).

Recycling of cotton has been demonstrated with the main commercial MMCF processes, i.e., viscose (e.g., Wedin et al., 2018) and lyocell processes (e.g., Haule et al., 2016; Björquist, 2018), and emerging processes, including cellulose carbamate (Paunonen et al., 2019), Biocelsol (Vehviläinen et al., 2018, as cited in Vehviläinen et al., 2020), Ioncell technologies (Asaadi, 2016) and mixed solvent process (Ma et al., 2019).

Traditional MMFC companies, like Lenzing (AU) and Kelheim (DE), have introduced products utilising recycled pulp as raw material, but within the last ten years, new companies have also been founded around this business, including, for example, Renewcell (SE), Infinited Fiber Company (FI), Evrnu (US) and SaXcell (NL).

3.2.3 Chemical recycling of synthetics – Monomer level

Various chemical recycling methods have been developed to recycle synthetic fibres, such as polyester, nylon and acrylic. In the process, the polymer chain is broken down into monomers or other molecules, and then re-polymerised into a polymer of preferred length. Such repolymerisation methods are commercially available, for example, for polyamide and polyester. Polyamide 6 can be recycled via ring closing repolymerisation (Alberti, 2019); polyamide 6.6 by glycolysis and amino-glycolysis processes (Datta, 2018); and polyester, for example, via glycolysis (e.g., Sert, 2019). Other process alternatives include alcoholysis, hydrolysis, aminolysis and ammonolysis (Raheem, 2019).

Monomer-level recycling processes typically involve cleaning, colour removal and separation of different molecules obtained in a depolymerisation process. Therefore, purity and quality of the polymers can be restored. Many of the processes are not economically viable yet, however, especially if extensive cleaning steps are used to recycle slightly contaminated textiles. The environmental impacts of such processes may also not be known. Chemical recycling methods open new possibilities for upcycling and making products similar to those made of new polymers. Processes are principally the same as are used for plastics recycling; however, additive chemistry and contaminants of textile waste are somewhat different compared to typical plastics products, such as packaging materials or bottles. Therefore, cleaning and pre-processing might be different (Kamppuri et al., 2019).

Chemical monomer-level recycling has been available for over two decades (Paszun et al., 1997). The first company to use this on an industrial scale was Teijin (JP). New commercial actors have recently joined this business, for example, Aquafil (IT) for the recycling of polyamide (Econyl process) and Carbios (FR) for utilising enzymatic recycling process for polyester.

3.3 Other methods

For materials that cannot be sustainably recycled by the means described in the previous chapters (e.g., various alloy materials and dirty fractions), thermal conversion processes may provide an option. In these processes, the polymer structure is broken down in thermal conversion into short-chain hydrocarbons or other molecular structures. The processes of thermal conversion are pyrolysis and gasification. They are very similar processes to each other but produce different types of finished products. Pyrolysis produces mostly liquid products containing solid carbon of 15-25% and gaseous compounds of 10-20%. Gasification typically produces approximately 85% of the gaseous final product, 10% of solid carbon and 5% of fluid. The characteristics of the raw materials entering into the thermal conversion affect the characteristics of the finished product obtained. Such products may be used by the chemical industry (Kamppuri et al., 2019).

Incineration is also a thermal process, where only thermal energy from the thermal degradation of the material is utilised. The calorific value of the polypropylene, polyethylene and polyester is high (more than 40 MJ/kg) and of the same class as the calorific value of the fuel oil. The incineration of mixed waste does not reach such high readings, as part of the thermal energy is used to dry the moisture contained in mixed waste (Kamppuri et al., 2019).

4. Summary and future prospects

In the future, circular economy textiles must be produced, used and (re)cycled in a sustainable way. While longevity and re-use of the products should be emphasised, we should also be able to deal with the textile waste and to recycle that to be used as raw material for the textile industry. *Post-consumer* materials from organisations and companies using textiles are worn, but these may be known and controlled textile flows; while discarded textiles from household and consumers are mixed, unknown and therefore the most challenging to sort and recycle into secondary raw materials that could be used in high-value applications. Mechanical recycling is applicable when products are unusable, but fibre quality is good and fibre length sufficient for the intended purpose. In order to replace virgin materials in textile products, mechanically recycled fibres must be long enough for the spinning of yarns. Spinning uses longer fibres, while shorter ones can be used for nonwoven and other lower-value applications.

If mechanical recycling is not feasible, and fibre length needs to be restored, there are options for fibre-raw-materials recycling. These include several processes at different levels. It should be noted that the more we process, the more we might cause environmental impacts. Polymer-level recycling includes thermo-mechanical melt-processing of synthetics and chemical recycling (dissolution) of cellulosics and blends. Chemical monomer-level recycling of synthetics and blends also enables restoring polymers. Most of these processes are polymer specific, but some of them are capable of handling blends as well.

Mechanical recycling is still a dominant method, while fibre-raw-materials recycling, such as chemical processes, are emerging but mostly still in pilot scale. There are multiple technological challenges related to recycling technologies themselves. Future developments are expected to focus on such chemical processes , for example, the processing of material blends (Circle Economy, 2020). Development is also needed related to textile collection systems, new identification and sorting technologies and digitalisation.

In addition to technological challenges, non-technological-affecting factors, for example, environmental law and policies also need to be considered (Damayanti et al., 2021; Dissayanake and Weerasinghe, 2021). To make recycling more efficient, we would benefit from the development of a textile classification system. Classification could be based on chemical groups and bonds that form the backbone of the polymers (Harmsen et al., 2021). However, it would be important to also understand the condition of fibre and polymer wear and tear in order to enable more efficient recycling. This is a challenge for the further development of identification technologies. In addition, recognition of contaminants including fibre finishes, would benefit recycling process control and make recycling safer. Furthermore, better understanding is needed on the sustainability of different recycling processes, since from an environmental point of view it would be beneficial to use low-impact recycling processing, such as mechanical process, instead of more water-, chemical- and/or energy-intensive processing, whenever possible.

Acknowledgements

This article was mainly based on work carried out in the Telaketju Tekes project (e.g. Kamppuri et al., 2019) complemented with a literature review carried out in the Telaketju 2 and Telavalue projects. I would like to thank the project groups from all of the Telaketju joint projects and Business Finland for the funding.

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