mistra future fashion

white paper on textile recycling

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preface

complexity in the circular textile value chain leading to misunderstandings and conflicting messages

The reason for writing this white paper is that information circulating about textile recycling contains conflicting messages that can be difficult to follow and interpret. Misunderstandings can arise from confusing what exists today with what is possible tomorrow and in the further future.

Misunderstandings can also be the result of too opportunistic marketing claims in a time when material circularity by some is seen as the key for reaching a sustainable future. The authors foresee that many interventions are needed for a sustainable textile industry. Recycling is part of the solution but so is prolonging the use of clothing and reducing the environmental impact in textile production, from fibre to final garment, which carries 80% of the climate burden, and practically all of the burden regarding water use and emissions of toxic chemicals (Sandin, Roos, Spak, Zamani, & Peters, 2019). For material recycling to be part of the solution, the energy, water and chemical use of collection, sorting and recycling technologies must be efficient enough, and emerging technologies and supporting infrastructure must be developed further. Correct information is a prerequisite for this to happen.

Thus, this white paper aims boldly to provide a neutral and scientific state-of-the-art compilation of information on existing and emerging textile recycling technologies, environmental gains and losses of textile recycling, and important factors influencing the future of textile recycling: challenges of upscaling, geography, logistics, etc. Much of the content is relevant for any actor with an interest in textile recycling globally, but there is a specific focus on the Swedish and Nordic context.

A condensed version of the content of this white paper is found in:

Roos, S., Sandin, G., Peters, G., Spak, B., Schwarz Bour, L., Perzon, E., & Jönsson, C. (2019). Guidance for fashion companies on design for recycling. Mistra Future Fashion report number: 2019:08 Stockholm, Sweden.

This is a first version of the white paper. Readers are welcome to provide all sorts of input to the authors:

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1. introduction

Circular economy is a term for a society that produces no waste, but restores and regenerate products, components and materials at their highest utility and value at all times. The European Union launched in 2015 an action plan for the Circular Economy (European Commission, 2015) to stimulate Europe's transition towards a circular economy. Efficient material recycling technologies are a prerequisite for the circular economy to be environmentally sustainable. It should be noted that there are also bio-based materials where fibres such as wool, cotton and viscose that are naturally circular and reproduced via the photosynthesis, however, these aspects are not discussed in this white paper.

figure 1 shows some examples of material reuse and recycling in the textile value chain, from Sandin & Peters (2018). The material flows are divided into reuse of textile products, closed-loop recycling (textiles are turned into new textiles), open-loop recycling (non-textile material is turned into textiles / textiles are turned into low-grade products) and finally energy recovery.

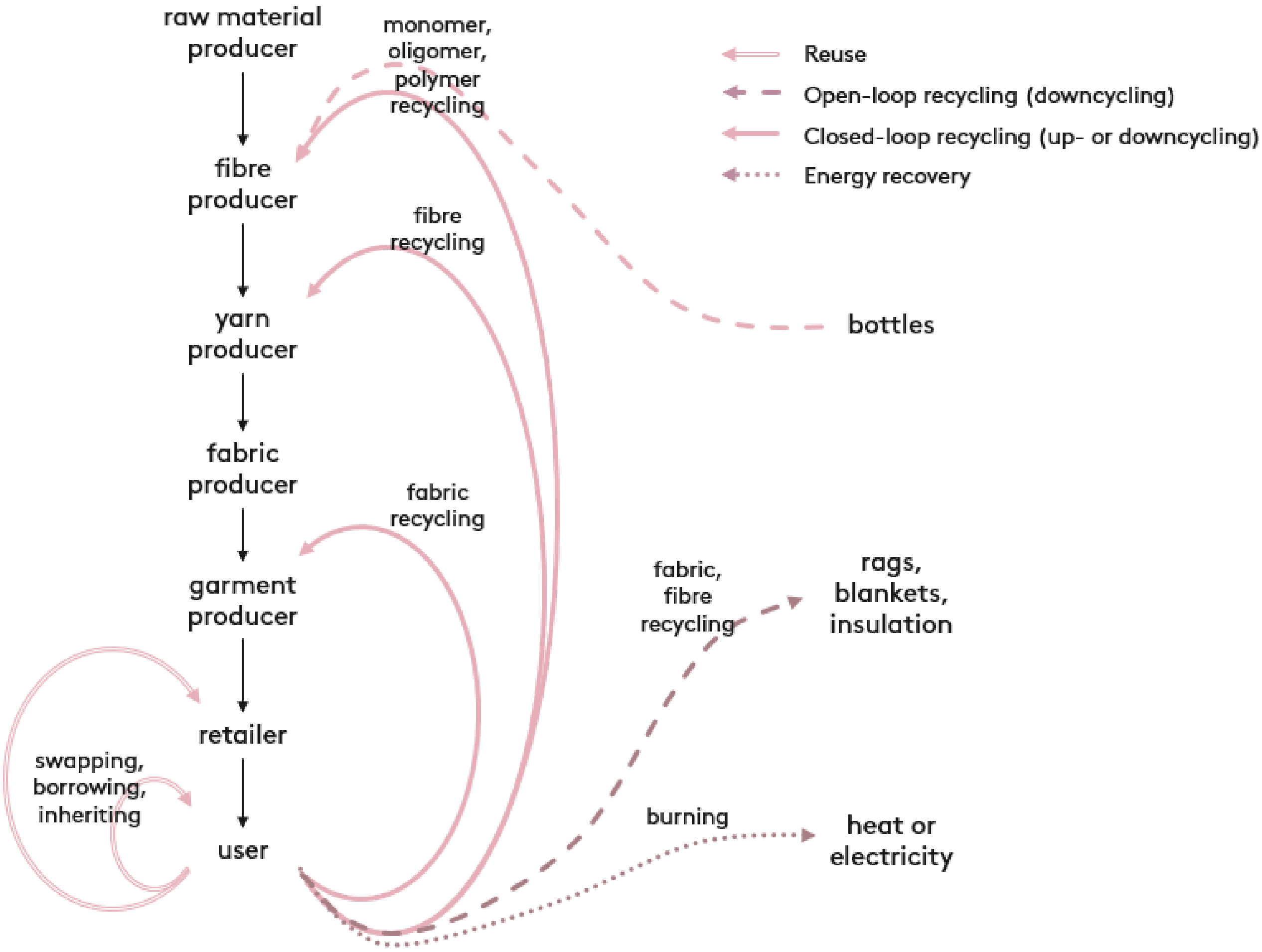


figure 1 Examples of material reuse and recycling in the textile value chain. From Sandin & Peters (2018).

1.1. how much do we know about textile waste flows today?

Textile waste supports a diverse industrial ecosystem of actors attempting to deliver environmental benefits and value to customers. Therefore, attempting to assess the flows of used textiles is a challenging task. National governments keep statistics on financial flows between industry sectors, but not necessarily material flows. The European Union collects data on waste management, but this does not include material flows between textile reuse and recycling organisations, which is not always "waste" (Fisher, 2018). Occasional reports on these flows are available in Scandinavia, usually produced by consultants to government institutions (Belleza & Luukka, 2018; Brismar, 2014; Elander, Sörme, Dunsö, Stare, & Allerup, 2014; Palm et al., 2014; Schmidt, Watson, Roos, Askham, & Brunn Poulsen, 2016; D Watson, Trzepacz, & Gravgård Pederson, 2018; David Watson & Palm, 2016). Since there is no central Scandinavian registry for such information, the writers of these reports were forced to rely on estimates from a variety of sources. Typically, they rely on the interpretation of high-level national trade statistics, interviews with recycling sector actors about their business operations, and physical sampling and sorting of municipal solid waste. The documents we collected on textile flows vary in intent and scope, and are also subject to uncertainties and missing data. Therefore, it is impossible to present a consistent temporal recycling trend, nor an absolute closure of mass annual balances based on available data. These caveats should be borne in mind when reading the table in appendix 1 and the remainder of the introduction to this report.

1.2. where does it go?

1.2.1. a detailed picture – the Nordic region

More detailed data is available on Nordic used textiles than for larger regions. The most complete Nordic overviews of the management of textiles wastes is provided by Schmidt et al 2016 and Watson et al, 2016, and both reports borrow heavily from Palm et al 2014. This means the basic data is primarily from 2010 (the Swedish textile consumption data is from 2008). figure 2 summarises this data, and indicates that the majority of textile waste is incinerated or sent to landfill.

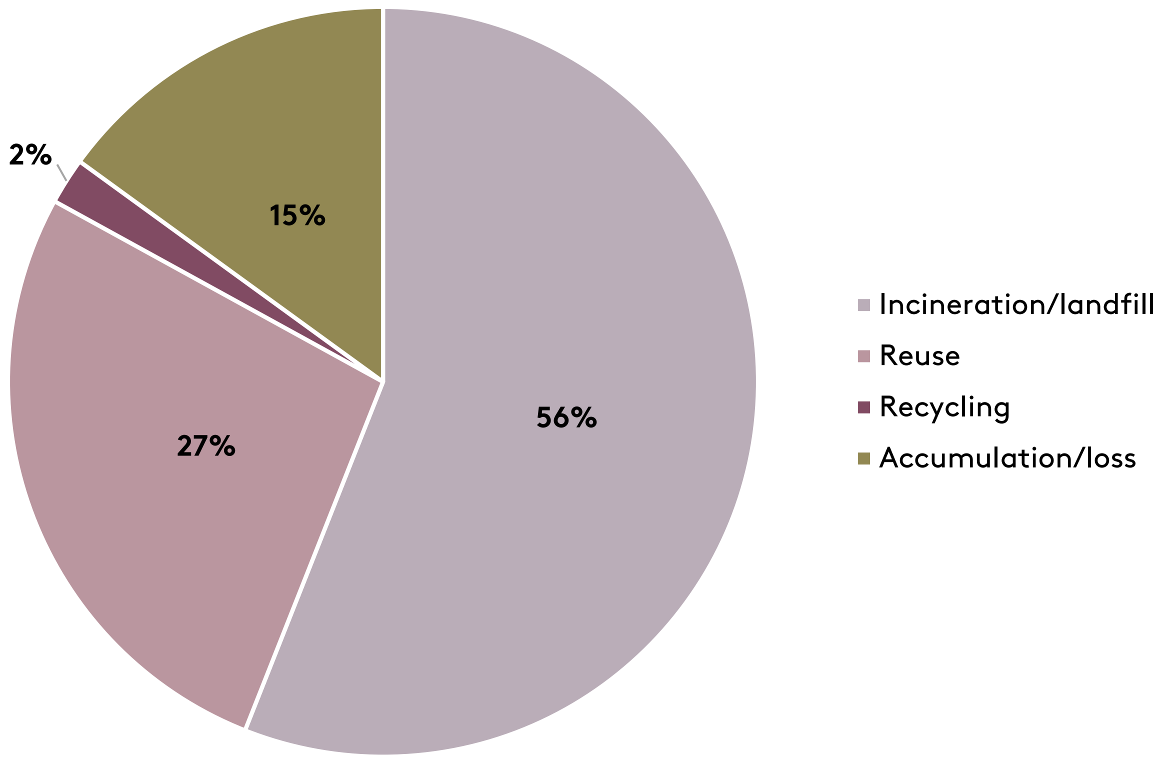


figure 2 Overview of fates for Nordic textile waste, 2008-2011 (Palm et al, 2016).

Incineration is the main destination for Nordic textile waste and typically occurs in the country originating the waste. On the other hand, reuse is a highly international affair. Roughly a quarter of the material is reused in some way. Of the reuse that occurs, a large majority (73% in the Nordic and Swedish data shown in Schmidt et al, 2016 and updated in Belleza and Luukka, 2018, respectively) is a consequence of export to other countries rather than reuse in the country of origin. As shown in table 1, Poland is the dominant importer and reuser of Nordic textiles, followed by other eastern European countries, but there are significant sorting operations in these countries, which then send used textiles to ultimate destinations in the Middle East, Africa and Asia. In particular, while Lithuania, Bulgaria and Estonia account for about a third of Nordic exports of used textiles, two thirds of these inflows is distributed to places including Pakistan, Iraq and India (Watson et al, 2016).

Within the Nordic region, Sweden reuses and recycles less than its neighbours. The data in appendix 1 suggest that Sweden reuses or recycles 20-24% of its textile waste (Schmidt et al, 2016; Belleza and Luukka, 2018) while the regional leader is Denmark with 37-39% (Schmidt et al, 2016; Watson et al, 2018). (Given the inherent uncertainty in the figures we report these as ranges rather than suggesting the information can demonstrate a trend over time.)

table 1 Destinations for Nordic used textiles (percentage of total flow).

	initial destination (%)	final destination (%)
Poland	27	20
Lithuania	16	3.4
Bulgaria	9.3	4.1
Estonia	8.8	4.0
Germany	8.3	2.1
Turkey	5.8	0.6
Belgium	5.0	2.2
Netherlands	3.3	2.2
Slovakia	3.0	1.9
Pakistan	2.0	7.2
Romania	1.8	1.4
Malawi	1.8	2.0
Ukraine	1.3	0.8
Latvia	1.3	1.2
Mozambique	0.6	1.7
India	0.5	3.4
Iraq	0.4	6.0
Russian Federation	0.3	2.1
Angola	0.2	1.3
Hungary	0.1	1.9
Benin	0.0	1.5
Zambia	0.0	1.3

The typical fate of used Nordic textiles is summarised in table 2 based on Watson et al (2016) use a classification of the quality of garments as part of their description of the fate of Nordic used textiles: “cream” refers to the warm and/or high value garments which represent the majority (about 53%) of the cash value of used textiles for recyclers, despite being only 10% of the total flows they handle. This is typically retained in Eastern Europe. Lighter garments of similar quality but better suited to warm climates (“Grade A and B” – 46% of the total flow) are sent to Africa, Eastern Europe and the Middle East. Only about five percent of the total cash value of the used textiles is associated with the remaining 44% of the flow: “Second Grade” garments also go to the Middle East and Asia, while the most damaged materials go to mechanical recycling, mostly in Asia, or for industrial wipes or combustion in various countries.

table 2 Estimated fate of Nordic used textile exports (Watson et al, 2016)

flow type	destination	proportion
cream	Eastern Europe	10
grade A & B	Africa, Eastern Europe, Middle East	46
second Grade	Asia and Middle East	15
industrial wipes	Global	10
mechanical recyclate	mostly Asia	8
landfill or combustion	Global	11

1.2.2. European used textile flows

Data on European waste flows is limited, but the Eurostat database provides the information shown in table 3 (Eurostat, 2018). This data excludes clothing reuse (i.e. which is not classified as a waste). Nevertheless, there is a difference of about 33% between the generation and disposal statistics. Presumably this material is exported or accumulated in growing wardrobes.

table 3 Eurostat waste textile data (tonnes, data extracted by authors)

	2010	2012	2014	2016
Textile waste generated...	**2 190 000**	**2 140 000**	**2 220 000**	**2 180 000**
...by industry	790 000	580 000	720 000	610 000
...by households	1 400 000	1 560 000	1 500 000	1 570 000
Textile waste disposed...	**1 200 000**	**1 430 000**	**1 470 000**	**1 510 000**
...to landfill	240 000	130 000	130 000	110 000
...by incineration	20 000	20 000	20 000	10 000
...for energy recovery	90 000	120 000	150 000	170 000
...for recycling	830 000	1 170 000	1 170 000	1 220 000
...by backfilling	10 000	10 000	10 000	10 000

1.3. what we talk about when we talk about textile recycling

Sandin and Peters (2018) presented a topology of textile reuse and recycling, some of which is provided in table 4. General terminology used in the textile area can be found in the Mistra Future Fashion Fiber Bible part 1 by Rex et al.

table 4 Definitions of terminology related to textile recycling

terminology	definition
closed-loop recycling	Refers to when the material from a product is recycled and used in a (more or less) identical product
downcycling	The recycled material is of lower value (or quality) than the original product.
fabric recycling	If the fabric of a product is recovered and reused in new products, it is commonly called fabric recycling (however, it can also be referred to as material reuse).
fibre (or fiber)	A single piece of a given material that is significantly longer than it is wide and often round in cross-section (made up of polymers).
fibre recycling	If the fabric is dissembled, but the original fibres are preserved, this is generally called fibre recycling.
monomer	A relatively small and simple molecule that can be linked together to form a larger molecule (a polymer).
monomer/oligomer/polymer recycling	If the fibres are dissembled, but the polymers or oligomers are preserved, this is polymer/oligomer recycling. And if the polymers/oligomers are dissembled, but the monomers are preserved, this is monomer recycling.
open-loop recycling	Refers to processes in which the material from a product is recycled and used in another product. For example when a material category (such as packaging) is recycled into another (such as textiles).
polymer (chain)	A compound made of many (up to millions) linked simpler molecules (monomers).
polymerisation	The process of linking monomers into polymers.
upcycling	The recycled material is of lower value (or quality) than the original product.
textile fibres	Fibres used for textile applications (in this report, the term "fibres" always refers to textile fibres).

terminology	definition
textile reuse	Various means for prolonging the practical service life of textile products by transferring them to new owners, with or without prior modification (e.g. mending). This can for example be done through renting, trading, swapping, borrowing and inheriting, facilitated by, for example, second hand shops, flea markets, garage sales, online marketplaces, charities and clothing libraries. In the academic literature, various forms of reuse have been conceptualised in terms such as collaborative consumption, product-service systems, commercial sharing systems and access-based consumption.
textile recycling	Reprocessing of pre- or post-consumer textile waste for use in new textile or non-textile products. In this paper, we adopt a more generous notion of textile recycling, also including the recycling of non-textile materials and products (such as polyethylene terephthalate (PET) bottles) into textile products. Textile recycling routes are typically classified as being either mechanical, chemical or, less frequently, thermal. This is in many cases a simplification of reality, as recycling routes often consist of a mix of mechanical, chemical and thermal processes.
thermal recovery	The term thermal recycling is easily confused with thermal recovery, which is when textile waste is incinerated to generate heat and/or electricity

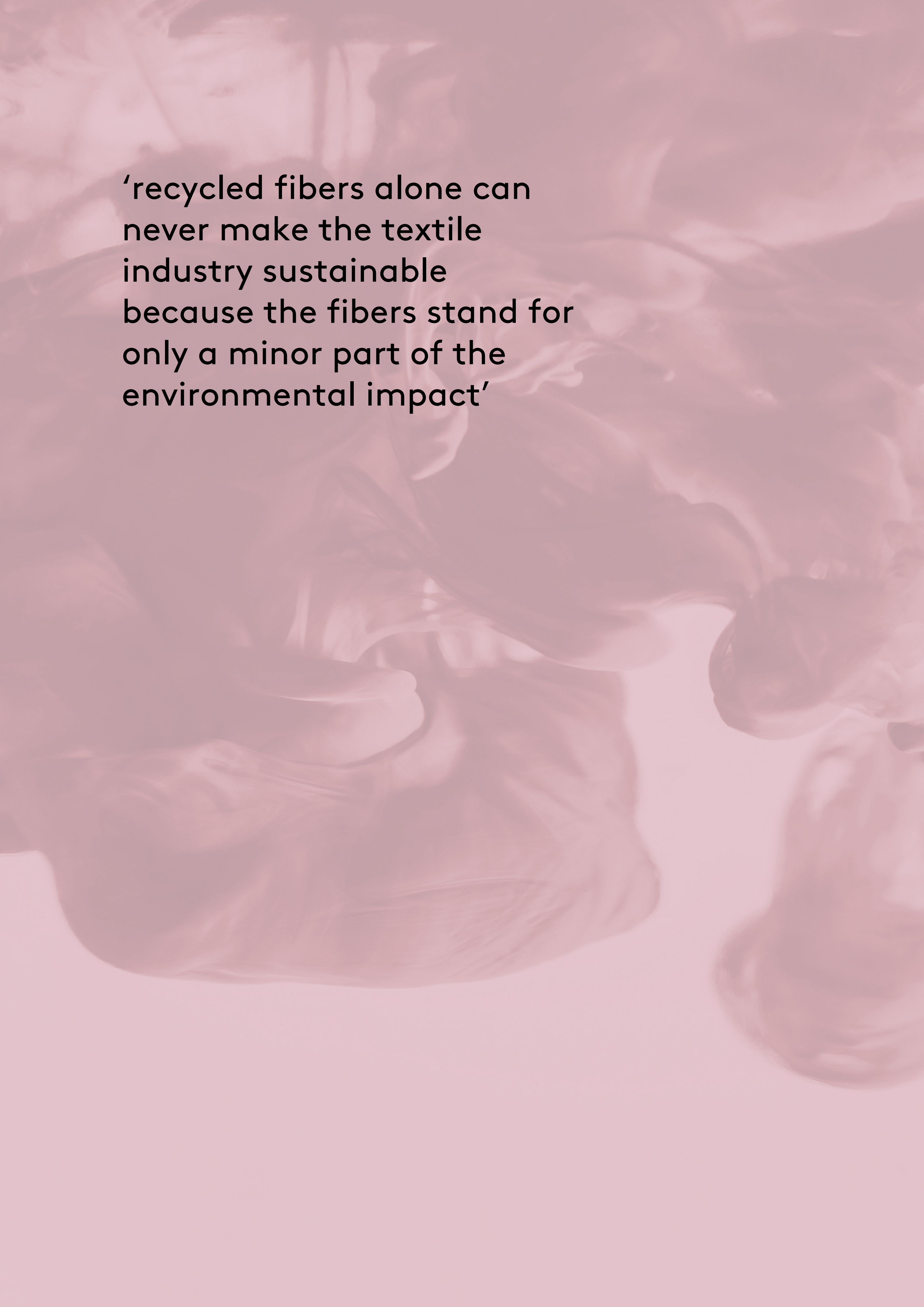
1.4. do we know what is myth and what is fact?

Some statements are easy to falsify, for example when there are clear errors in the background data. Most often however, the lack of information means that it is only possible to state that there are no facts to support a statement, which does not necessarily mean that the statement is false. table 5 lists a collection of statements that the authors have examined.

table 5 Statements related to textile recycling that to some part are myths

statement	conclusion
Recycling is better than incineration or landfilling	**TRUE, BUT NOT ALWAYS** The environmental benefits of recycling depend on what material is replaced and how much of that material is replaced and how much environmental impact that results from the recycling processes.
Reuse is better than recycling	**TRUE** The accumulated "burden" in a textile material increases with each production step, just as the economic value does. The more production steps that are replaced, the higher the environmental gain. For reuse, the burden of all production steps are replaced, which is not the case for recycling.
Recycling can make the textile industry sustainable	**FALSE** This can never be true because the fibres stand for only a minor part of the environmental impact (Sandin et al., 2019).
There are large volumes of textiles that end up on landfills if they are not recycled.	**PARTLY TRUE, PARTLY FALSE.** As described in 1.4.3, in some countries textiles are incinerated with energy recovery and in some countries they are landfilled. In the EU, it is illegal to landfill combustible waste according to the Waste Framework Directive (European Commission, 2008). National permits are being issued in some countries, however, these are regarded as offences by the EC who can issue sanctions for violating EU legislation (European Commission, 2017). In countries with poor waste management systems, where all sorts of waste end up in landfills, textiles are no exception.
When I bring my clothes to the recycling bin they will become new clothes.	**FALSE (TODAY).** Today there is no recycling of waste clothes collected in recycling bins back into new textiles to the authors' knowledge. Some of the collected garments do get recycled (see 1.4.4), but not into garments but used as insulation, industrial wipes etc.
Collected textiles are burned/landfilled anyway	**PARTLY TRUE, PARTLY FALSE, EVENTUALLY TRUE** Recycling is limited by the lack of recycling processes for handling the great variety of materials in terms of fibres, blends, dyes and finishes as well as the availability of a market with a matching demand. Today, a relatively small share of collected materials are recycled, and a substantial share still go to incineration or landfills. Eventually, after a second, third or more lives, textile material will always be thus degraded or reduced due to losses in the system so that no new product can be produced from it.

statement	conclusion
Textile waste has a negative environmental impact	**FALSE, INDIRECTLY TRUE** Indirectly, activities that create a lot of waste means that resources are not utilized optimally. Textiles are valuable materials that have gone through a number of refinement processes and have accumulated a value that is higher than the mere energy content. However, environmental impact means that there is a (measurable) change in the environment. Textile materials that are disposed into the nature risk for example releasing hazardous chemicals or microplastics into the environment and can in that way have an environmental impact. If the textile material is incinerated with energy recovery, landfilled in a controlled process, or recycled, it does not come into contact with the environment. Combustion of fossil materials to create energy contribute to climate change as do combustion of fossil fuels to create energy.
Industrial wipes made from discarded textiles are reusable	**FALSE** The multi-coloured wipes from discarded textiles are for single-use in the industry, while the wipes offered by laundries are homogeneous and branded.
Collected textiles ruin local textile production industries in Africa	**PROBABLY FALSE** A difficult statement to verify or falsify but there are at least indications that in African markets where second hand textiles are not traded, the local production has lost market shares in competition from cheap Asian textiles (David Watson & Palm, 2016).



‘recycled fibers alone can never make the textile industry sustainable because the fibers stand for only a minor part of the environmental impact’

2. environmental savings as rationale for recycling

In many sectors, material recycling is already an established practice. Securing access to and supply of feedstock has historically been the main driver. Recycled material has had lower cost than virgin, and is also increasingly seen as a more sustainable source of feedstock than virgin material. In the textile industry, recycling is much less mature and clearly the exception rather than the norm.

Textile recycling is often framed as a solution to either one of two important questions:

1. What is the best use of textile waste, environmentally and resource-wise?
2. How do we make the textile industry (environmentally) sustainable?

The first question is more limited in scope, and textile recycling is an obvious and significant part of its answer. This is about better utilising the full potential of used textiles, for example in terms of economic value or some technical property such as fibre length. Here, "better" is in relation to the current situation, in which the majority of used textiles are either incinerated with or without energy recovery or consigned to landfill after their first use cycle.

The second question is a much bigger one, which concerns the impact-reduction potential of textile recycling in relation to the total environmental impact of the textile industry. Here, recycling is but one of many possible interventions, such as more renewable energy and use of less harmful chemicals along the whole textile value chain, new business models and design strategies for prolonged use of clothing, to name a few.

Sometimes the two questions are mixed up, and recycling is portrayed as the answer to the sustainability challenges of the textile industry. Commentators make the mistake of saying that the generation of textile waste is the only significant environmental problem associated with the textile industry. If this idea leads to a loss of pressure on the industry to reduce raw material consumption and the emission of pollutants, this would be a problem. It may lead to unrealistic expectations and perhaps also unwanted behaviour – if a narrow focus on recycling becomes an excuse for inaction, an excuse for preserving deeply unsustainable practices elsewhere in the textile system.

The perception of the consumers is important, when garments contain recycled fibres and garments are collected to be recycled after disposal it is easily interpreted as if the consumption of "circular" garments has a zero environmental footprint. This is a delusive perception in two ways, firstly because the fibres stand for only a minor part of the environmental impact (Sandin et al., 2019) and secondly because recycled fibres as good as never come from waste garments and garments as good as never are recycled into new garments as will be explained more thoroughly later on in this report.

This chapter aims at clarifying why we should bother with textile recycling, by exploring what we know and what we do not know about its benefits. The focus is on environmental aspects, but at the end there is also a section briefly outlining other potential benefits. As a starting point, we reviewed 35 studies[1] on the subject, covering different recycling routes, materials and environmental impacts (Sandin and Peters 2018). Below we also consider literature and perspectives not captured by that review.

2.1. retaining materials, saving resources

Production of textiles uses considerable natural resources, particularly land, water and fossil feedstocks. Obviously, Earth has a limited area of potential agricultural land on which we can grow the food and fibre we need. While the rate of expansion of agricultural land use has slowed, predictions that 2009 would see the global peak in agricultural land use on account of improved yields and slowing population growth (Ausubel et al. 2013) have proved premature, as more biodiverse, natural land is converted to monocultural agriculture. The rate of yield improvement for all crops is decreasing (figure 7 in Ausubel et al. 2013) as we approach photosynthetic rate limits. In addition to the consequences agricultural land use has for the fragmentation and elimination of the habitats of endangered species, land use is also a social sustainability issue, with projections suggesting that rising demand for land will cause increasing difficulties for the poorest of the world's people (Ibarrola Rivas and Nonhebel 2016). Cotton production demands 7% of arable land in India, and 10% in Pakistan (OECD-FAO 2018). While cotton only accounts for about 2.4% of arable land globally, it dominates the land which is highly productive on account of being capable of irrigation, and it has been estimated that fully 17% of the global impacts of freshwater extraction are associated with cotton cultivation (Pfister et al. 2009). Keeping textiles made by natural fibres, via reuse or recycling, within the economy can therefore reduce pressures on land and water resources.

Similarly, pressures on fossil resources can be reduced by retaining synthetic materials made from fossil resources, but as more fossil resources are used as energy sources across the garment life cycle than what is used as material feedstock – roughly ten times more (Sandin et al. 2019) – there are even greater fossil resource savings if energy-intensive processes can be improved or avoided. This means that there is a risk that fossil feedstock savings due to recycling of materials are offset by energy-demanding and fossil-driven recycling processes. Likewise, if bioenergy replaces fossil energy, energy-intensive processes may countervail savings of land and water resources due to recycling of natural fibres. Saving resources via recycling is thus a great potential if certain criteria are fulfilled. This means that the recycling system has to be efficient enough not to result in an overall increase in environmental impact, and it is of great important to make sure that collection, sorting and recycling use little or no fossil fuels. To explore in more detail what is needed for a recycling system to save resources and reduce pollution, let us return to the review of the 35 studies.

[1] All in all, 41 studies were reviewed, but the review covered textile recycling as well as reuse, and 6 of the reviewed studies were on reuse only.

2.2. fibre recycling replaces fibres, fabric recycling replaces fabrics

The review revealed that the main benefits of recycling arise when it prevents some other production – typically the production of a functionally equivalent material made from virgin resources – and its environmental impact (Sandin and Peters 2018). This means that the environmental benefits of recycling largely depend on *what* material is replaced and *how much* of that material is replaced. As touched upon above, the replacement of cotton reduces freshwater, pesticide and fertiliser use, and mitigates water depletion, ecotoxicity, eutrophication and other impacts. (Roos et al. 2019, FAO-ICAC 2015, Pfister et al. 2011), and if polyester is replaced, there are more likely to be benefits in terms of climate impact and fossil resource depletion (Shen et al. 2010). Apart from impacts caused by land and water use, however, most impacts of the textile industry occur in production stages subsequent to fibre production: yarn spinning, weaving and knitting, finishing and dyeing (Sandin et al. 2019). These are not prevented by monomer, polymer/oligomer or fibre recycling (see figure 1) but potentially by fabric recycling. In other words, fabric recycling can potentially mitigate more impacts (per kg recycled material) than recycling routes that to a greater extent disaggregates the recycled material. But fabric recycling may often be infeasible because the material is too worn out or because of difficulties in finding a suitable end use. There are cases where fibres can be recycled and still retain the colour in which scenario dye processes are avoided. Such situations may very well lead to large environmental savings for the newly produced fabric. To conclude, the question of what is replaced concerns both the replaced fibre type and whether other textile processes are prevented.

2.3. replacement rates

Next question for determining the environmental benefits of recycling is how much is replaced, which is measured by the replacement rate (also called displacement effect). A replacement rate of 100% means that the recycled material fully replaces an equal amount of non-recycled material, whereas a rate of 0% means that no displacement occurs, and the recycled material merely adds to a growing market. There is unfortunately a lack of evidence of how large the replacement rates are for various recycling routes, and most studies of the environmental performance of textile recycling assume rates of 100% without justification (Sandin and Peters 2018). One could think the rate is close to 100% for polymer/oligomer and monomer recycling, and lower for fibre and fabric recycling (due to inferior fibre quality). So even if fabric recycling potentially prevents more stages of textile production compared to other recycling routes, a quality not fit-for-purpose may offset some of those benefits. But as long as there is no data on actual replacement rates, this is purely speculation. A further complication is that more recycling may increase global fibre supply, thereby reduce the price and increase the demand for fibres. In other words, some of the benefits of textile recycling might be offset by increased consumption, a so-called "rebound effect" (Gielen and Moriguchi 2002). To conclude, the question of how much is being replaced concerns both the quality of the recycled material and the price elasticity of demand for textile fibres.

2.4. prevention of disposal processes

Although the environmental benefits of recycling are mainly due to prevented *production* processes, there may also be benefits (and downsides) of the prevented *disposal* processes. This largely depends on what the normal disposal practices are in the country of disposal. For example, if landfilling is the common route, as in the UK, there may be benefits in terms of less emissions of the potent greenhouse gas **methane** arising from the decomposition of organic fibres (e.g. cotton). If incineration with energy recovery is the common route, as it is in Sweden and in most of Europe, recycling may lead to less emissions from incineration – for example, less burning of oil-based synthetics translates to less emissions of CO_2 of fossil origin. And if there is an absence of formal disposal systems, recycling may prevent textile waste from entering ecosystems, for example reduce the pollution of microplastics in the oceans. The consequences of less incineration with energy recovery is complicated by the energy recovery aspect, as the recovered energy, often heat and electricity, reduces the need for other means of generating heat and electricity – which must be compensated if less energy recovery occurs. However, previous studies indicate that, at least in countries with relatively well-functioning disposal systems, environmental gains and losses due to prevented disposal are small compared to those of prevented production (Roos et al. 2019, Sandin and Peters 2018, Östlund et al. 2015).

2.5. recycling is generally preferable – if pitfalls are avoided

To summarise, there is strong support for claims that recycling in general is a preferable waste management option compared to incineration and landfilling. But there are pitfalls: (i) in case of low replacement rates, the impact of the recycling processes (including sorting and transportation) may be larger than the benefits of prevented production, causing a net increase of impact; (ii) depending on recycling route and the kind of prevented production, problem-shifting may occur: certain types of environmental impact may increase although others decrease. Östlund et al. (2015) revealed that climate impact can increase if the recycling process is powered by fossil energy and the replaced material is made by a relatively climate-friendly fibre such as cotton. Also, there are knowledge gaps, with no data on actual replacement rates and a lack of studies of certain recycling routes and materials. Moreover, some potentially important life-cycle stages (e.g. collection and sorting) and impact categories (e.g. land-related impacts) have seldom been considered (Sandin and Peters 2018), which adds uncertainty to the knowledge of the environmental consequences of textile recycling.

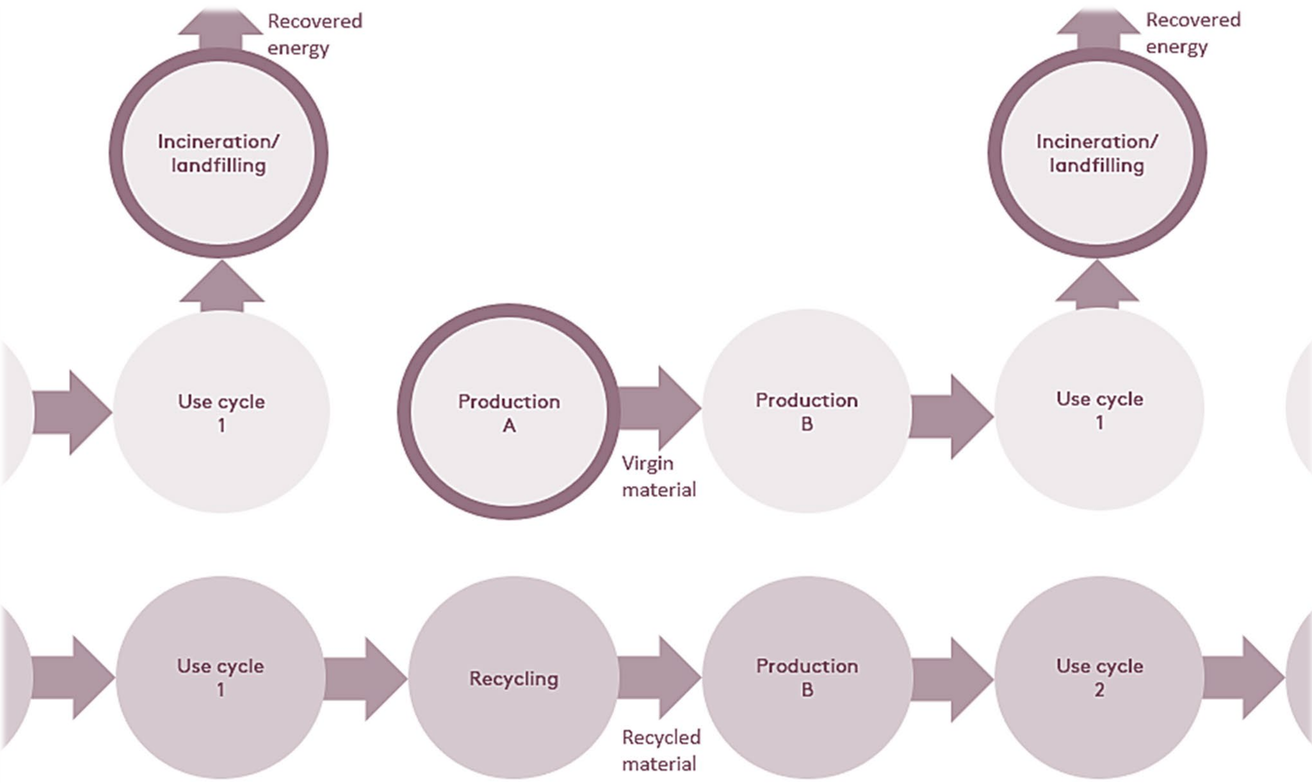


figure 3 Today's linear production and disposal system for textiles (blue circles) compared to a future circular system (brown circles).

2.6. how large are the environmental benefits?

Variations between systems and knowledge gaps make it difficult to put a number on the environmental benefits of textile recycling in general, but presuming a high replacement rate and an efficient recycling technology powered by renewables, the climate benefit could be up to a few kg CO_2 equivalent per kg recycled material (Östlund et al. 2015) or roughly 10% of the climate impact of a typical garment life cycle (Roos et a. 2019). For other environmental impacts driven by energy use, the potential benefits are in the same range. For impact categories such as water depletion, for which cotton cultivation is the main contributor in the textile industry (Roos et al. 2019), the gains of recycling can be more than 90% assuming virgin cotton is replaced. For further information on the environmental gains and losses of specific recycling systems, the reader is referred to the studies reviewed by Sandin and Peters (2018), see table 6.

table 6 Available studies of the environmental impact of textile recycling*.

author and year of publication	recycled materials	fabric, fibre, polymer/oligomer or monomer recycling
Peer-reviewed studies published in academic journals		
Dahlbo et al. (2017)	Cellulosics (CO, CV, etc.), PES, unspecified	Fibre, polymer/oligomer
Esteve-Turrillas & de la Guardia (2017)	CO	Fibre
Fortuna & Diyamandoglu (2017)	CO	Polymer/oligomer
Bamonti et al. (2016)	WO	Fibre
Yasin et al. (2016)	CO	Fibre
Zamani et al. (2015)	CO, PES	Fabric, polymer/oligomer, monomer
Pegoretti et al. (2014)	CO	Fibre
Corsten et al. (2013)	PET bottles	Unspecified
Glew et al. (2012)	CO, WO	Fibre
Liang et al. (2012)	Unspecified	Fibre
Muthu et al. (2012a)	CO, PES	Unspecified
Muthu et al. (2012b)	CO, PES, CV, WO, PA, PAN, PP, LDPE, HDPE	Unspecified
Shen et al. (2012)	PET bottles	Polymer/oligomer
Intini & Kühtz (2011)	PET bottles	Polymer/oligomer
Shen et al. (2011)	PET bottles	Polymer/oligomer
Farrant et al. (2010)	CO	Fabric
Shen et al. (2010)	PET bottles	Polymer/oligomer, monomer
Woolridge et al. (2006)	CO	Fabric, fibres
Other types of studies		
Spathas (2017)	CO, PES, PET bottles, unspecified	Fibres, polymer/oligomer
Bodin (2016)	CO, PES, CV, WO, PA	Fabric
Schmidt et al. (2016)	CO, PES, WO, unspecified	Fibre, polymer/oligomer, monomer
Östlund et al. (2015)	CO, PES	Fibre, polymer/oligomer, monomer
Beton et al. (2014)	CO, PES, CV, WO, LI, SE, PA, PAN, HF, PU, PP	Fabric
Hagoort et al. (2013)	PES	Fibre, polymer/oligomer, monomer
Palm et al. (2013)	CO, PES, CV	Fibre, polymer/oligomer, monomer
Youhanan (2013)	CO, PES	Fibre, polymer/oligomer
Pesnel & Perweulz (2011)	CO, PES	Fibre, monomer
Bartl (2009)	CO, PES, CV	Unspecified
McGill (2009)	CO, PES, CV, WO, PP, PA, PAN	Fibre
AITEX (2007)	CO	Fibre
Korhonen & Dahlbo (2007)	CO, PES, CV, WO	Fibre
Allwood et al. (2006)	CO	Fibre
Fisher (2006)	CO, PES	Unspecified
Fisher et al. (2006)	CO, PES	Fibre, unspecified
Patagonia (2006)	PES	Monomer

*The table is adapted from Sandin and Peters (2018) and specifies the type of materials studied and a classification of the studied recycling routes. CO = cotton, PES = polyester, CV = viscose, PET = polyethylene terephthalate, PP = polypropylene, PA = polyamide, PAN = polyacrylic, EA = elastane, WO = wool, LI = linen, HF = hemp, SE = silk, PU = polyurethane, LDPE = low-density polyethylene, HDPE = high-density polyethylene, N/A = Not applicable.

It should be emphasised that many studies show that reuse is the preferred waste management option over recycling (Sandin and Peters 2018), in alignment with the waste management hierarchy promoted by, among others, the EU directive on waste (EC 2008). This is because reuse prevents a larger share of the textile production chain. Notably there are potential pitfalls also for reuse, such as low replacement rates and inefficient logistics (Sandin and Peters 2018).

Note that the collection of garments, by municipalities or charities or in stores, does not automatically translate to reuse or recycling. Reuse is limited by quality of collected garments and the availability of a market with a matching demand (David Watson & Palm, 2016), and recycling is limited by the lack of recycling processes for handling the great variety of materials in terms of fibres, blends, dyes and finishes (elaborated in Chapter 4) as well as the availability of a market with matching demand. So, a relatively small share of collected materials are recycled, and a substantial share still go to incineration or landfills.

2.7. non-environmental benefits of recycling

Although Filho et al. (2019) attempted to review the literature to find evidence of socio-economic advantages of textile recycling, little was found beyond examples of good practice and the jobs and economic value generated by these examples – which, generally speaking, are benefits of any economic activity rather than specific benefits of textile recycling. Local supply might become available for some fibre types if sorting facilities and secondary raw material producers and textile manufacturers are kept in Europe, adding value to local production of textiles. The Nordic Governments' Waste Group (NAG) similarly sees local job creation ("green growth") as an attractive effect of recycling textiles in the Nordic countries (Palm et al. 2015). Unfortunately, there is a lack of evidence of whether such socio-economic benefits are greater for textile recycling than for other textile value chains, or whether recycling merely moves the economic activities closer to the consumer market (assuming recycling occurs closer to the end user).

The fact that parts of textile recycling systems, especially collection and sorting, often are run by charity organisations entail socio-economic benefits. For example, such operations provide incomes for socially vulnerable and strengthen local communities, and the earned profits are often invested in social projects, locally or elsewhere (Filho et al. 2019, Baruque-Ramos et al. 2017). There are also social risks tied to textile recycling, such as poor working conditions and the involvement of illegal businesses (Baruque-Ramos et al. 2017, Kim and Kim 2016). These benefits and risks are, however, due to the setup of *current* systems, and depending on how a future large-scale recycling system is organised, the socio-economic impact may be very different.

‘any content other than the intended fibre for recycling is a contamination that reduces the yield or adds extra separation/purification steps and increases both the environmental and economic cost.’

3. overview of recycling possibilities today

The table in appendix 1 gave an overview of current textile recycling possibilities divided into reuse, closed-loop recycling, open-loop recycling and energy recovery. This chapter provides a technical overview of the recycling technologies that exist on market scale today and their respective inputs and outputs in table 7. In the following, a detailed summary for some of the most commonly recycled materials is given.

table 7 Recycling technologies existing on market scale today. The denotation “semi” is given where the new product does not contain 100% recycled material.

Textile waste recycled into new textile products			
input-material	**process**	**output**	**status**
100% PET post-consumer garments	Chemical recycling via depolymerization (closed-loop)	PET yarn	Chinese producers Jiaren/Teijin stated in 2012 that they aimed for an annual production capacity of 19 000 tonnes.
100% cotton fabric	Mechanical recycling via shredding to fibres (semi closed-loop)	Short cotton fibres to mix with virgin cotton (15-20%)	Several brands produce garments with 15-20% content of mechanically recycled fibres.
wool and wool/acrylic fabrics	Mechanical recycling via shredding to fibres (open-loop)	“shuddy” for non-woven, emergency blankets etc.	Several brands produce garments from mechanically recycled wool. Several charity organizations produce blankets from wool/acrylic fabrics.
100% cotton cutting waste	Chemical recycling to lyocell. (semi open-loop)	lyocell fibres	Lenzing produces the Refibra fibre which contains 20% pre-consumer waste fabric. There are many actors working with regenerated cellulose fibres with recycled content (viscose/lyocell/ioncell etc.) on a pilot scale.
Non-textile waste materials recycled into new textile products			
100% Nylon 6 materials (fishing nets, carpets, pre-consumer hard plastic waste etc.)	Chemical recycling via depolymerization (open-loop)	nylon 6 yarn	Several actors make up an annual production capacity of some tonnes.
100% Nylon 6,6-materials (pre-consumer waste)	Remelting (open-loop)	nylon 6,6 yarn	Several actors make up an annual production capacity of some tonnes.

100% PET-materials (PET bottles and other food contact materials, pre-consumer waste etc.)	Remelting or chemical recycling via depolymeriza-tion (open-loop)	PET yarn	Several actors make up an annual production capacity of several tonnes per year.
Textile waste recycled into new low-grade products			
Mixed textile waste	Mechanical recycling via cutting to pieces (open-loop)	industry wipes (single-use)	Several actors make up an annual production capacity of some tonnes
Mixed textile waste	Mechanical recycling via shredding to fibres (open-loop)	insulation, composites etc.	Several actors make up an annual production capacity of some tonnes
Mixed textile waste	Energy recovery	electricity and heat	Most common treatment in Sweden today.

3.1. overview of recycling possibilities today

The main material recycling routes for textiles are chemical recycling (in figure 4: monomer, oligomer and polymer recycling) and mechanical recycling (in figure 5: fibre and fabric recycling. With the same input material, recycling processes can give different outputs, which is shown for the case of cotton in figure 4 and 5.

3.1.1. chemical recycling

Applicable for:

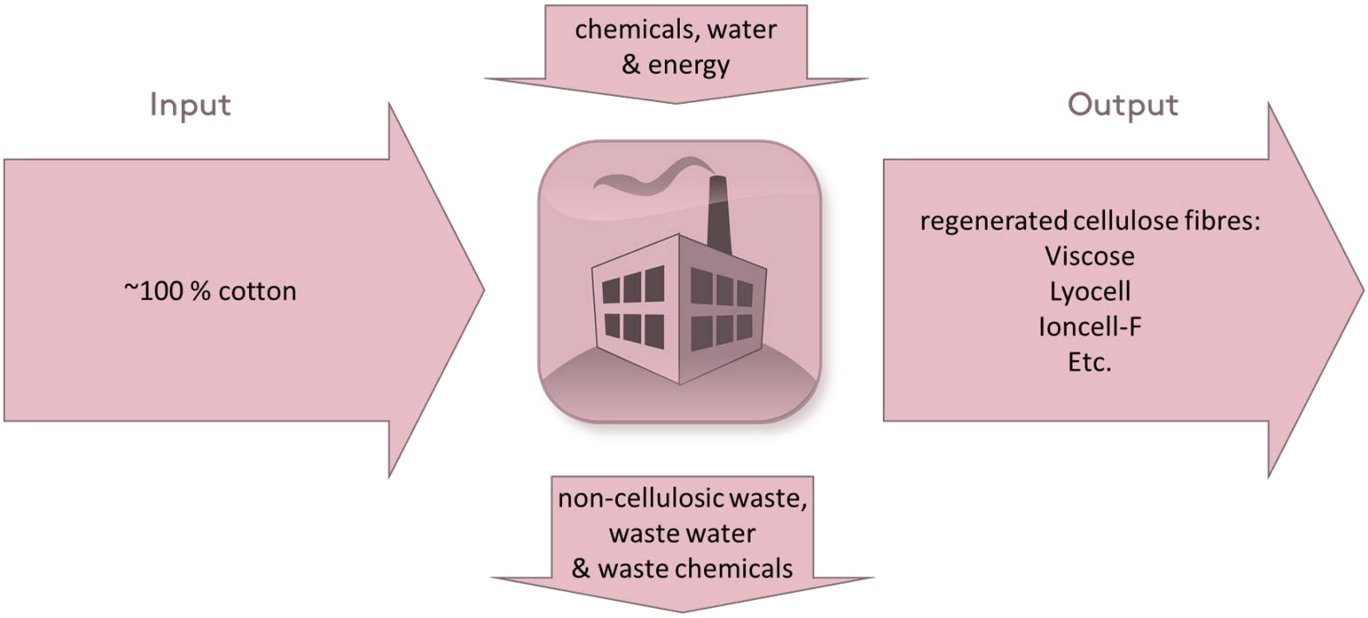
- **Closed-loop or open-loop system for pure polyester (PET) and Nylon 6 materials**
- **Open-loop system for cotton materials**

For some synthetic fibres chemical recycling by depolymerisation is a viable route. The polymer chains are broken down into monomers, which are separated and purified before being reunited into new polymers. Additives are removed during the purification (often distillation) process. The polyester polyethylene terephthalate (PET) and nylon 6 are today chemically recycled at a commercial, yet limited, scale. The polyester input material is generally post-consumer PET from food packaging materials and (pre-consumer) industrial waste. The nylon input is generally post-consumer nylon from carpets, fish farm nets and industrial waste. Recycled fibres have in principle the same properties as virgin synthetic fibres. Almost all polymers can be depolymerised in theory, however, an efficient, practical process has not (yet) been developed for all polymers, for example for nylon 6.6.

Some cellulosic fibres (e.g. cotton) can be chemically recycled by a pulping process followed by solution spinning to produce regenerated cellulosic fibres. At present, this is not a viable route for viscose and lyocell that are already regenerated cellulosic fibres. figure 4 shows a schematic picture of the process for chemical recycling of cotton (4a) respective nylon (4b) which is contrasted to mechanical recycling of cotton in figure 4. Additives are partly removed during the process. Chemical recycling of cotton produces regenerated cellulose fibres that in principle have the same properties as other regenerated cellulose fibres. The only such fibre commercially available today is a fibre blend with 20% recycled lyocell fibres from cotton and 80% regenerated fibres from virgin forest fibres (REFIBRA™).

A common feature of both synthetic and cellulose fibres is that the chemical recycling process gains higher efficiency the purer the input material. Any content other than the intended fibre for recycling is a contamination that reduces the yield or adds extra separation/purification steps and increases the cost in both environmental and economic terms.

4a



4b

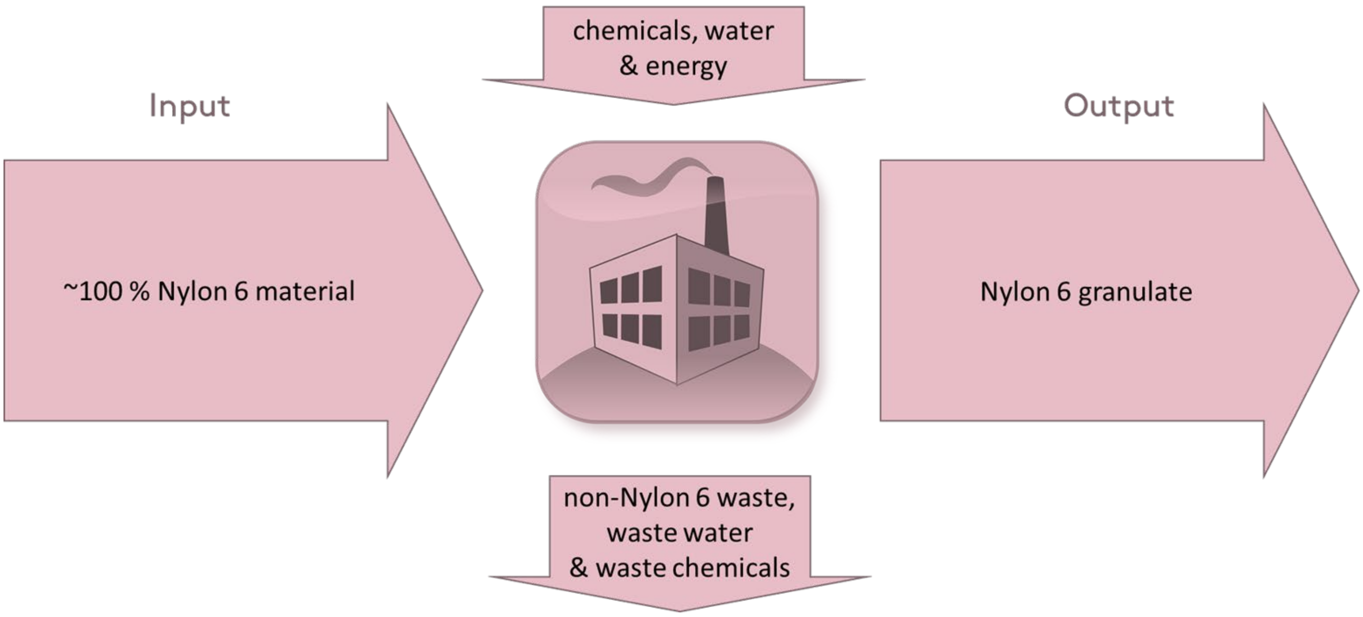


figure 4 Chemical recycling of cotton (3a) gives regenerated cellulose fibres that in principle have the same properties as other regenerated cellulose fibres from forest- or plant-based resources. Chemical recycling of Nylon 6 (3b) gives PA6 granulate that have the same properties as virgin PA6.

3.1.2. mechanical recycling

Applicable for:

- **Closed-loop or open-loop system for pure synthetic materials**
- **Open-loop system for all textile materials**

Mechanical recycling is either performed by 1) melting synthetic fibres producing granules that are used for spinning new fibres (thermomechanical recycling), or 2) tearing fabrics to recover the fibres (mechanical processing). The remelting method does not tolerate any contamination in the form of certain surface treatments, dust or dirt. Fibre blends (e.g. nylon 6 and Nylon 6.6) and polymers that are not possible to melt (e.g. elastane) cannot be recycled this way.

In the second case, the textile material is first freed from metal and plastic parts such as zippers and buttons. Subsequently, the material is cut into smaller pieces that are fed into a textile tearing machine which opens up the textile structure and releases the fibres. When recycled to yarn, the textile fibre mass is carded and may also pass through additional steps to remove short fibres. A so-called sliver is produced, which is processed into a yarn by for example ring spinning or rotor (open-end) spinning. In mechanical recycling by tearing, the fibre properties are retained with the exception of fibre length. By colour sorting the feedstock, re-dyeing can be avoided, reducing the environmental impact of the textile product manufacturing process. figure 5 shows a schematic picture of the process for mechanical recycling of cotton, though this process can be applied for basically any textile material. In reality, mechanical recycling is a very important route for blended fibre qualities.

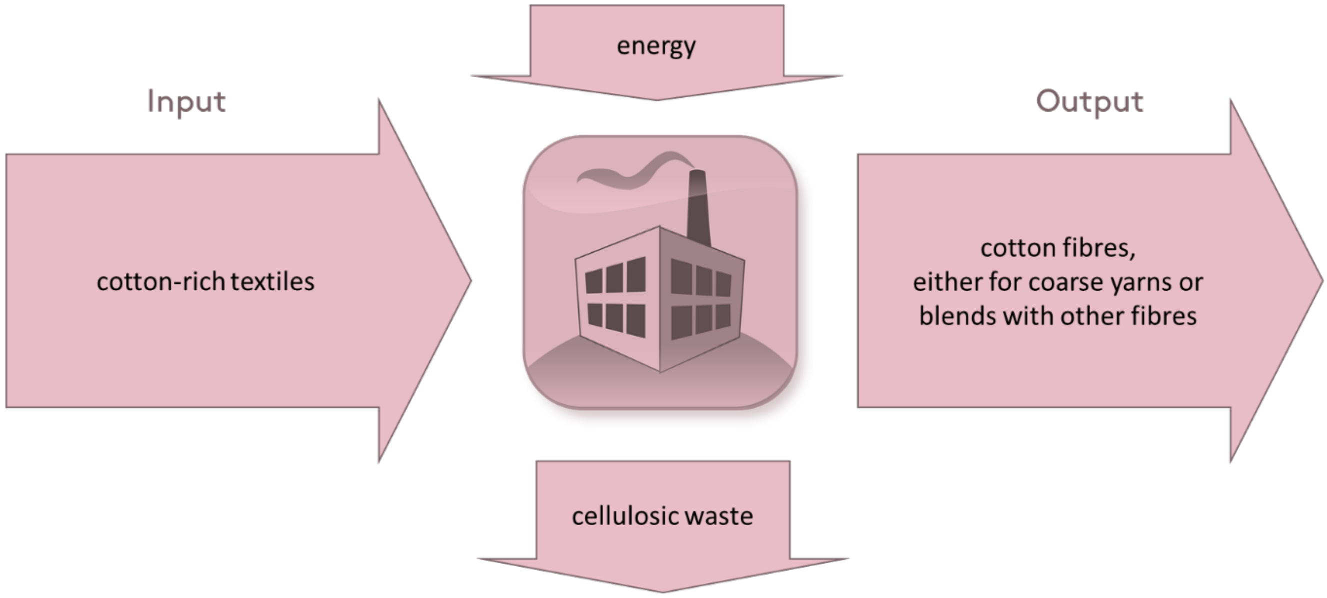


figure 5 Mechanical recycling of cotton produces cotton fibres with shorter-fibre lengths, making end-uses such as coarse yarns or blends with other fibres feasible. The figure shows the cotton case, but the same process can be applied for basically any textile material.

4. overview of future recycling possibilities

4.1. the collected textile volume and properties now and in the future

The most common textile fibres today are cotton and polyester, where cotton globally represents about 25% and polyester 50% of the fibres produced. Although it is known, at a very detailed level, the volumes and origin of produced fibre, this does not mean that we know exactly how these fibres will return once discarded. Textile is a very complex material stream, where yarns are often made up of several different fibre types and the resulting fabric constructed by different methods such as knitting and weaving. Thus, a single technology will not solve the global need for efficient textile recycling, much due to the fact that textile destined for material recycling is largely made up of these mixed yarns and fabrics. In order to utilize the potential of end-of-life textile in the best possible way, a range of recycling technologies must be applied, mechanical as well as chemical. The goal with recycling research is to leave today's situation, which is characterized by low recycling rate and fairly low-value recycled products, to instead achieve high recovery rates and high-quality products. It is imperative to demonstrate the potential of new material to reach the goal of resource efficiency and increased recycling whilst guaranteeing economic and environmental sustainability. In recent years, the need for, and potential of, textile recycling has become apparent with many initiatives ongoing.

figure 6 possible routes for collected textiles.

4.2. textile recycling technologies for the future

On a conceptual level, the situation for textile materials can be explained using figure 8. To enable efficient recycling producing a secondary raw material of high quality, it is necessary to start from the very beginning, looking at how and where textiles are collected. In order to supply the future recycling industry with an appropriate feedstock, among other things the textile must be kept dry to avoid deterioration due to e.g. mould and rot. A further prerequisite for optimized value capture is efficient and material specific sorting of textiles destined for material recycling, this in order to supply the different processes with suitable feedstock.

In this schematic, the recycling technologies have been divided into three categories; chemical recycling, thermomechanical recycling and mechanical recycling. Looking at the synthetic fibres such as polyester, this is a polymer which theoretically would be possible to melt and re-spin into new fiber. In reality however, the postconsumer materials are degraded by laundry and UV-exposure and contain contaminants in the form of foreign particles and dust that make this an unviable option. For batches of high grade, pure polyamide the thermomechanical route may be an option.

Another possibility for synthetics is chemical recycling. There are different approaches to chemical recycling where solvent-based dissolution and filtration processes are used to separate and extract the desired components. Polyester can be chemically recycled into a fiber with characteristics completely comparable to virgin material. However, the process available today can only handle some very pure polyester fractions; thus, current research is working intensively with developing new, more robust processes. For chemical recovery, regeneration, of cotton it is possible to produce a regenerated cellulose fiber like lyocell or viscose, but it is not possible to recycle the cotton fiber in the same way as in the case of polyester. A lot of resources are being spent today on finding environmentally preferable and energy efficient processes for regeneration of cotton and other cellulose-based materials. So far, there is no commercial production of chemically recycled textile except for recycled polyester (Teijin Ltd, Japan).

The simplest and least energy-consuming recycling technique for both natural and synthetic fibers is mechanical recycling. Globally, mechanical recycling is an established, commercial

figure 7 recycling techniques and their outputs.

process for the production of more low- end products such as shuddy wool or insulation. When discussing mechanical recycling in Sweden, the aim is producing materials and products of significantly higher quality, including recycled yarn. The quality of the recycled fiber-mass depends on the input material, which means that origin and use phase of the textile has a large influence and also that the sorting process is of significant importance for final result. It is important to point out that the quality of raw materials is controlled by input material. It is therefore of great value to demonstrate applications of recycled material, as this directly affects the process upstream, and points to the need for efficient and specific the sorting process in particular processes.

A resource efficient system would make use of an exchange of materials between textile, plastic, composite and nonwoven applications. As the fabric is used and exposed to wear, it breaks down, which may make it inappropriate for the original product, but suitable for another product type. Development of new, innovative recycling methods, where the highest possible material value is utilized, is a prerequisite for optimal handling of textile for recycling.

The first thing that comes to mind when talking about mechanical recycling of textiles is probably the recycling of textile fiber into new yarn. In the cases where this is possible, it is the route to take given after a positive environmental and financial analysis. However, considering the large proportion of mixed fiber found in industrial waste as well as post-consumer materials, this is not always a viable way. Alternative solutions are then to investigate applications in other material categories. As an example, some elastane-containing polyamides can produce high-quality plastic components, whereas other textile fibers can be used as fiber reinforcement in thermoplastic materials. Recycled textile materials also have a high potential as raw material in the production of nonwoven products. When considering value, these uses can sometimes account for a higher price index than the original textile fiber itself.

In mechanical recycling of textile fibers, the textile material is processed in a textile shredder. In this process, metal and plastic parts such as zippers and buttons are first removed. Subsequently, the material is cut into smaller pieces that are fed into the shredder. The first step is an opening of the textile structure using a cylinder with coarse spikes. Here, opening of the textile structure and exposure of fibre begins. In cases where the opening is insufficient, the textile is returned to the opening step to go through this process step for one more cycle. When opening is sufficient, a number of process steps follow where fiber is exposed during passage through cylinders with finer spikes, usually 6-9 such cylinders are used. The final material can subsequently be further processed to any of the aforementioned material categories. At mechanical processing, the material is subjected to tearing causing the fibres to decrease in length. Natural fibers and synthetic fibers are affected to a different extent, but the construction of the textile also has a major influence on the final result. Of course, the aim of this process is to maintain fiber length to the greatest extent possible to enable the production of high-quality recycled yarn. When recycled to yarn, the textile fiber mass is carded and may also pass through additional steps to remove short-fiber material. A so-called sliver is produced, which is processed into a yarn by ring spinning or rotor spinning, for example.

In regard to recycling by melt spinning of textile post-consumer materials, trials have been carried out at RISE IVF (former Swerea IVF)[2]. Studies have been conducted in regard to melt spinning of polyester material as well as polyamide-based materials. It is theoretically possible to melt spin textile produced from these polymers; however, this recycling method imposes very high requirements on the purity of incoming materials. For example, the method does not tolerate contamination in the form of certain surface treatments or dust and dirt. Feedstock must be free from elastane or other blends and as for the polyamide itself, the material used for melt spinning cannot be a mixed grade polyamide. This means that it is not possible to melt spin blends of, for example, PA 6 and PA 6,6 to fiber. At present, it is difficult to use this technology to recycle textiles into new textile fiber. In addition, in order to use this technology new, efficient and specific sorting technologies are a necessity. A problem with melt spinning is the color of the output material, since it is not possible to remove pigments of the feedstock.

[2] Mistra Future Fashion, Spill till Guld

‘open-loop recycling that can exchange materials between textile, plastic, composite and nonwoven applications adds to the potential to be resource-efficient, both economically and environmentally.’

5. deep-dives into commonly described challenges of textile recycling

5.1. from bench to factory – challenges of scale

A technology's stage of maturity can be described in terms of its technology readiness level (TRL) on a 1 to 9 scale. TRL 1 means that the basic principles of technology have been observed, TRL 9 corresponds to mature technology proven in operational environment[3]. From being a NASA tool for assessing space technology, TRL has become much more widespread and is for example used as an innovation policy tool in the EU (Héder, 2017). Many of the emerging technologies for textile recycling described in Chapter 4 exist at a bench or pilot scale, corresponding to TRL 4-7, with further technology development necessary to reach full maturity. Apart from technical problems that must be solved in this process, there are other challenges of scaling up and competing with existing systems for end-of-life treatment and production of virgin fibres.

One challenge of scaling up concerns the fibre properties: properties achieved at bench scale can be difficult to repeat at full commercial scale (Röder et al., 2009, 2013). There may also be technical difficulties in achieving sufficiently low energy use and efficient chemical recycling to make the process environmentally and commercially viable. Related, it can be difficult to know whether the process can become environmentally and commercially viable in large scale – it can be difficult to quantify the environmental performance of an existing bench- or pilot-scale process, but it is an even greater challenge to quantify its potential future performance in a hypothetical large-scale operation[4]. Another technical obstacle when scaling up chemical recycling processes may be the potentially large volumes of by-products. One example is viscose production which yields large volumes of salt, about 1.3 tonnes sodium sulphate per tonne viscose fibres[5], which must be sold or deposited somehow. It can be feasible to dispose of this up to a certain scale, but beyond this it may become an obstacle for upscaling.

Another challenge of scaling up is the competition from existing systems and processes for end-of-life treatment and production of virgin fibres, which have been fine-tuned and optimised over many years with an invaluable accumulation of know-how. For example, viscose fibres have been produced for more than a century, and polyester fibres for almost 80 years. Expectations of the market (business-to-business buyers, end users, etc.) shaped by existing systems may also constitute obstacles, for example expectations on the supply and quality of fibres or how a textile supply chain is organised. A parallel can be made to emerging dye technologies: to save water

[3] https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf
[4] See Peters et al. (2019) for a recent attempt to quantify the environmental performance of an emerging recycling technology.
[5] Ecoinvent, 2018. Ecoinvent 3.5 dataset documentation viscose production – GLO. Available at: https://www.ecoinvent.org/login-databases.html.

and chemicals, a designer may want to use textiles made using spin dye (applied on yarn) instead of the regular vat dye (usually applied on fabric). The designer must then work with one or a few types of yarn, instead of hundreds as he/she is used to, as each spin-dyed yarn must be produced in large volumes to make it economically viable. Changing to spin dye is thus an obstacle in relation to ordinary practices. In other words, existing systems and practices create lock-in effects that may hamper the scale-up of emerging, competing solutions.

Looking more into economic obstacles and lock-ins, a change of status quo can be a threat to the profit of those dominating the textile industry today, so they may be uninterested in adopting or supporting new solutions for recycling. Another obstacle for attracting economic interest is the fact that a typical time period for an emerging technology to reach widespread market diffusion is from one to several decades (Hall, 2004). These business risks may hamper possibilities to attract the venture capital needed for scaling up emerging solutions.

Another issue of scale is the possible limitation in feedstock availability. One example is the use of discarded textiles from large-scale laundry services (e.g. bed sheets from hospitals and hotels), which have known fibre and chemical content and often also documentation on the number of washes the material has gone through. Such a controlled, well-known and (relatively) easily recyclable feedstock is a prerequisite for some recycling processes, but the volumes are limited – laundry services discard about 800 tonnes of textiles per year in Sweden, which is about 0.5% of all discarded textiles (Peters et al. 2019). Related, many existing textile recycling processes use another source of well-known material: pre-consumer textile waste, often from one's own manufacturing of textiles from virgin feedstock. To increase the availability of such a waste stream, the manufacturing from virgin feedstock must increase – which countervails the environmental rationale behind recycling. Similarly, some recycled fibres must be blended with virgin fibres in order to make fabrics of sufficient quality. This entails that production of virgin fibres must co-exist and possibly expand in tandem with the expansion of recycled fibres. On the other hand, a certain percentage of recycled fibres in all fabrics can also be an opportunity for expanding the market share for recycled fibres – for example as a legal requirement similar to the reduction obligation quota system for transportation fuel distributors in Sweden, which requires them to gradually increase the share of biofuels in gasoline and diesel[6]. But overall, the demand on having controlled and well-known materials as input to the recycling process, and the shortcomings in terms of handling the complex bulk of post-consumer textile waste (see Chapter 4), put limits on the availability of feedstock and therefore the potential scale of recycling operations.

Although a certain recycling process has limitations in scaling up, and thus limitations in terms of contributing to solving the sustainability challenges at a global level, it can still be a viable option in small scale – both in terms of economics and sustainability. The question on what a suitable scale is for a production system can have many answers. For example, the suitable yield for an agricultural activity depends on the parameters considered and the time perspective. Optimisation of the mass of biomass produced per hectare is often very different compared to optimisation of the maintained biodiversity or the provisioning of ecosystem services. Likewise, optimisation of the biomass production next year or in 10 years can be very different compared to optimisation of the accumulated biomass production in 100 years – short-termism may, for example, lead to losses of fertile soil and thereby undermine the opportunities for long-term sustainable yields.

[6] http://www.energimyndigheten.se/nyhetsarkiv/2018/ny-foreskrift-om-reduktionsplikt/

A few examples of obstacles to scaling up are given above. In short these can be technical ones (e.g. fibre quality, energy and chemical use, by-products), financial ones (e.g. competition from existing systems, business risks and challenges in attracting venture capital), or relate to access to or availability of feedstock. Having these obstacles in mind and understanding the criteria that need to be met enables a development of a sustainable recycling system.

5.2. from Kristinehamn to Matsuyama – challenges of geography

Several challenges of textile recycling relate to geography. Many of these boils down to the difference between using a diffuse or a concentrated source of feedstock. Recycling relies on diffuse sources: collecting and sorting discarded textiles from thousands of factories or millions of users. In contrast, virgin production relies on concentrated sources: pumping oil from the ground, harvesting cotton at farms. Besides, used textiles are heterogenous and have unknown content: manifold and often unknown fibres treated with manifold and unknown dyes and finishes (see Chapter 5.5). In contrast, the resources extracted to produce virgin fibres are homogenous and of known content. The challenge is to overcome the geographical obstacles of using diffuse sources of feedstock – to collect, sort and control the discarded textiles in a way that makes the recycling system technically, environmentally and economically competitive compared to production systems based on concentrated feedstock sources.

One aspect of a diffuse source is the increased need for transportation: the transportation to collect textiles may more than counteract the benefits of avoiding virgin production (this is further explored in Chapter 2). The Renewcell plant located in Kristinehamn and the Teijin plant in Matsuyama will have different transportation burden depending on where they source their waste textiles. Another aspect of using a diffuse source is the many legal and organisational differences between and within countries. For example, legal requirements on producers and retailers to know and (upon request) disclose the chemical content of products can hamper the use of recycled material as a feedstock. Under the EU legislation REACH, Europeans have the right to to be provided a list of hazardous substances contained in a product within 45 days of asking a manufacturer or a retailer, and the business-to-business (B2B) customer should be informed immediately on delivery (European Commission, 2006).

Further, collection and sorting systems of different countries must to a certain extent be harmonised, to have the capacity to produce the sufficiently pure, large and consistent feedstock streams required by a large-scale fibre producer. There are even differences within countries – in Sweden, for instance, the municipalities are responsible for collecting and treating household waste and different municipalities have different solutions for textile waste. Not only municipalities collect discarded textiles, but also retailers through dedicated recycling bins, and charities involved in the second-hand market. There are often different wants and needs among these actors. A second-hand retailer wants clean and not too worn-out clothes – the 10% of best quality, the "cream", can be sold in domestic market and is often what enables charity organisation to generate a profit on textile collection (David Watson & Palm, 2016). In contrast, a fibre recycler wants materials with known fibre and chemical content and preferably mono-materials (see Chapter 4). A challenge of collection and sorting is thus to harmonise the demands of different actors, which can vary between and within countries, in order to retain as much value as possible for each discarded piece of textile. Differences in actors and systems may also make it challenging to transfer a solution for textile recycling that works in one country, to another country.

Differences in waste treatment between countries may also constitute an environmental risk if more textiles are to be collected for recycling and reuse, as more or less all textile materials eventually will be burned or landfilled (e.g. because the polymer chains are too short for further recycling). So if recycling and reuse entails that more textiles are transported from countries with well-developed waste treatment systems (e.g. state-of-the-art incineration with energy recovery) to countries with less-developed waste treatment systems (e.g. non-functional collection, non-existing sorting and leaking landfills), there is a risk that the benefits of using the material for a longer time are offset by poor waste treatment at its end-of-life.

Geographical aspects can also be used as an advantage in textile recycling. One such example is the Prato province of Italy, which is the home to wool recycling dating back to the 12th century (Arthur, 2018). These operations are based on trust – producers and consumers know the origin of the recycled material, and they know that if wool scrap is collected it will be recycled. Geographic proximity is used as an advantage. However, a challenge is that not all operations in the textile value chain are nearby. In the case of wool recycling in Prato, the grazing of sheep and the making of yarn takes place locally but confectioning (cutting and sewing) is often made abroad, for example in Portugal. The leftover scrap from confectioning is sent back to Prato for recycling. To make this economically viable, the scrap is sent to Prato once there is a full container, which can take years (Jönsson et al., 2016). So there may be long and costly lead times due to the small volumes of scrap produced. Another reason for why the sewing factory must send a certain volume of scrap is that recyclers can seldom work with small volumes. The same is commonly the case also for collection of post-consumer textiles in stores: a certain volume must be sent per batch to make it an interesting source of feedstock for recyclers – once again, an effect of used textiles being a diffuse source of feedstock.

Above we list some geographical challenges of textile recycling, related to distances and transportation, and differences in legal requirements and the wants and needs of actors – often these stems from the fact that textile recycling relies on diffuse sources of feedstock. This is not an exhaustive list, and the challenges may not be issues for all recycling solutions and for all countries.

5.3. collecting used textiles – too much transport?

An important question is whether transports involved in the collection of discarded textiles counteracts the environmental gains of recycling. This potential risk was emphasised in Chapter 2, and it is also connected to the chapter above on geography and the use of diffuse sources of feedstock, but it deserves a chapter of its own.

Let's explore how far used textiles can be transported for recycling to make sense from an environmental point of view. First, we need to know the environmental benefits of recycling – let's focus on climate impact, as this is one of the main issues of transportation. In Chapter 2, it was concluded that variations between systems and knowledge gaps make it difficult to put a number on the environmental benefits of textile recycling in general, but the climate benefit can be up to a few kg CO_2 eq. per kg recycled material. To simplify, let's assume the climate benefit is 2 kg CO_2 eq. per kg recycled material that replaces non-recycled material, and if the replacement rate is assumed to be 50% the benefit is about 1 kg CO_2 eq.

Next, we compare the benefit of recycling with the impact from collection. Discarded textiles can be collected in three principal ways: A, the final user transports the discarded textile directly to a civic amenity site; B, the final user transports the discarded textile to some point of collection (e.g. a recycling bin in a retail store), from which a truck transports the textiles to a civic amenity site; or C, the final user discards the textile as household waste, which then is collected together with other household waste and transported to a civic amenity site by means of a garbage truck. Let's explore options A and C, as B can be expected to be somewhere in between.

For option A, assuming an average car with well-to-wheel emissions of 258 g CO_2 eq. per km[7] and that 10 kg of waste[8] is transported to the civic amenity site, the transport can be about 40 km (20 km in each direction) before its impact equals the impact-reduction from recycling.

Option C[9] is in many ways a more complex option transport-wise: a garbage truck starts and stops many times per collection round, gradually increasing its payload. Rose et al. (2013) conducted an LCA accounting for these complexities, on the operation of a garbage truck with a 8.3 t payload[10]. With a normal duty cycle[11], they found emissions to be 6-8 kg CO_2 eq. per km travelled. Assuming the lower number (as most data is at least 7 years old) and trucks loaded to about 75% of full capacity (6 t), this corresponds to about 1 g CO_2 eq. per kg and km. The distance travelled by the truck to collect waste can thus be up to 2 000 km before the impact of transporting discarded textiles offsets the savings from recycling. Although this is based on some rough estimates, this indicates that collection by garbage trucks is not an issue climate-wise.

The above calculations presume rather efficient recycling technologies and that discarded textiles are recycled once collected, which is seldom the case today. Collected textiles are today often incinerated with energy recovery, with lower climate benefits. On the other hand, depending on sorting operation, some collected textiles may enter the second hand market, with higher climate benefits (presuming a sufficiently high replacement rate). In the future, emissions per km transportation will be lower, making collection less important, but the impact of virgin fibre production may also be lower, diminishing the benefits of recycling – which effect will be greater is difficult to know. Nonetheless, if users are to drive to the civic amenity site by themselves, a distance shorter than 20 km can be seen as a rule of thumb for the travelling to make sense from an environmental point of view. With garbage trucks, the distance is not an issue. Thus, to integrate the collection of textile waste with the ordinary collection of household waste seem to be the better option climate-wise. On the other hand, if some other collection setup is executed in a smart way, it can be located in places users visit in any case, similar to collection of bottles and aluminium cans in grocery stores. In other words, the collection system and the user logistics must be accounted for when developing a sustainable recycling system.

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[7] This is based on an average combustion engine car sold in Europe in 2017, whereof 165 g CO_2 eq. is from tailpipe emissions (ICCT 2018).

[8] This can be different types of waste, not only textiles. But this is of little importance if we assume that the environmental load of the transportation is allocated to each waste fraction based on mass.

[10] This was based on refuse collection vehicles operating in the Canadian city of Surrey (population 500 000), running on either diesel or natural gas, with engines corresponding to the Euro 5 classification.

[11] A normal duty cycle for one day was in this case 54 km long, had 1400 stops and lasted 9 h.

5.4. circular economy – bust or boom?

Recycling is a key component of the so-called circular economy (CE), a concept which emerged in the 1970s and has gained momentum in recent year (Geissdoerger, Savaget, Bocken, & Hultink, 2017; Suttie et al., 2017). CE has been defined as the "closing of material loops to preserve products, parts, and materials in the industrial system and extract their maximum utility" (Zink & Geyer, 2017). But there are many definitions of CE, at least 114 (Kirchherr, Reike, & Hekkert, 2017), whereof some are more comprehensive in scope. An example of a more comprehensive definition is that by Geissdoerfer et al. 2017, also emphasising the importance of energy: "[CE is a] regenerative system in which resource input and waste, emission, and energy leakage are minimised by slowing, closing, and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling." Another comprehensive definition is the one by Ellen MacArthur Foundation[12]: "a continuous positive development cycle that preserves and enhances natural capital, optimises resource yields, and minimises system risks by managing finite stocks and renewable flows." The Ellen MacArthur CE framework also emphasises that all energy flows should be renewable, material stocks should be managed by sharing, reusing, remanufacturing and recycling, renewable material flows should be managed in a way that preserves and enhances natural capital, and design should prevent negative externalities, including the reduction of damage to human utility, such as food, mobility, shelter, health, and air, water and noise pollution, the release of toxic substances, and climate change. The Ellen MacArthur framework for CE is probably the most well-known one today, although some organisations referring to the Ellen MacArthur definition as being the basis for their work does not adopt its comprehensiveness in practice.

An example of criticism of CE concerns the the so-called "circular economy rebound", which is about circular economy activities not preventing regular, linear production but instead causing increased production (Zink and Geyer 2017). This is the same risk as pinpointed in Chapter 2: the risk of a low replacement rate. Similarly, Danielzon (2018) highlights the limitations of using CE principles in the fashion industry for decoupling economic growth from material consumption and thereby achieving absolute environmental gains. She bluntly concludes that "the CE offers a weak challenge to unsustainable practices." Other criticism is often based on the notion that CE excludes some important dimension of sustainability, and as such CE has limitations in being a conceptualisation or replacement of the traditional sustainability concept. In other words, there is a risk that too much emphasis and reliance on the CE concept – in one of its narrower forms – makes one ignore or forget about important sustainability aspects. A solution to this is of course to redefine CE to be more comprehensive, one example being the aforementioned definition by the Ellen MacArthur Foundation, another being the definition proposed by Murray et al. (2017), which also encompasses human well-being (social sustainability): "an economic model wherein planning, resourcing, procurement, production and reprocessing are designed and managed, as both process and output, to maximize ecosystem functioning and human well-being."

The criticism of CE resembles many of the caveats of textile recycling discussed in this white paper. That is, a narrow focus on material circularity is not sufficient, and sometimes even

[12] https://www.ellenmacarthurfoundation.org/

counterproductive, in making the clothing industry more sustainable – one must adopt a life-cycle perspective and consider how the systems are powered, the hazardous chemicals in processes and end products(see Chapter 5.5), and other sustainability dimensions not necessarily influenced by recycling. Just as the CE concept has been expanded to encompass these other aspects, the implementation of textile recycling must be accompanied by a comprehensive analysis of sustainability consequences – adopting a life-cycle perspective and considering a broad set of sustainability indicators – and be coupled with other changes of the textile industry. Likewise, the adoption of circularity metrics by the industry (of which there are many, see (WBCSD, 2018) as a means to work with, track and assess the transition to a CE, should complement working with, tracking and assessing other dimensions of sustainability.

To further your understanding of CE, material circularity and related concepts – beyond textile recycling – we recommend CIRAIG (2015) and Ghisellini et al. (2016).

5.5. chemical content in textiles

A pre-requisite for a production of a valuable secondary raw material is that the material is "toxic free". The feed stock needs thus be having a chemical profile that can be aligned with future customer and legal demands. In addition, chemical content that may disturb recycling processes are important to track and trace enabling as resource efficient route as possible.

In the manufacturing of textiles, a variety of chemicals are used, and often in large amounts (Olsson, Posner, Roos, & Wilson, 2009). Chemicals are added either to support the manufacturing process (auxiliary chemicals) or to add function to the final textile product. Some of the textile-related substances are harmful to health and/or the environment, with properties such as sensitizing, human toxic, eco-toxic, persistent, or bio-accumulative (Swedish Chemicals Agency, 2014) (see figure 8).

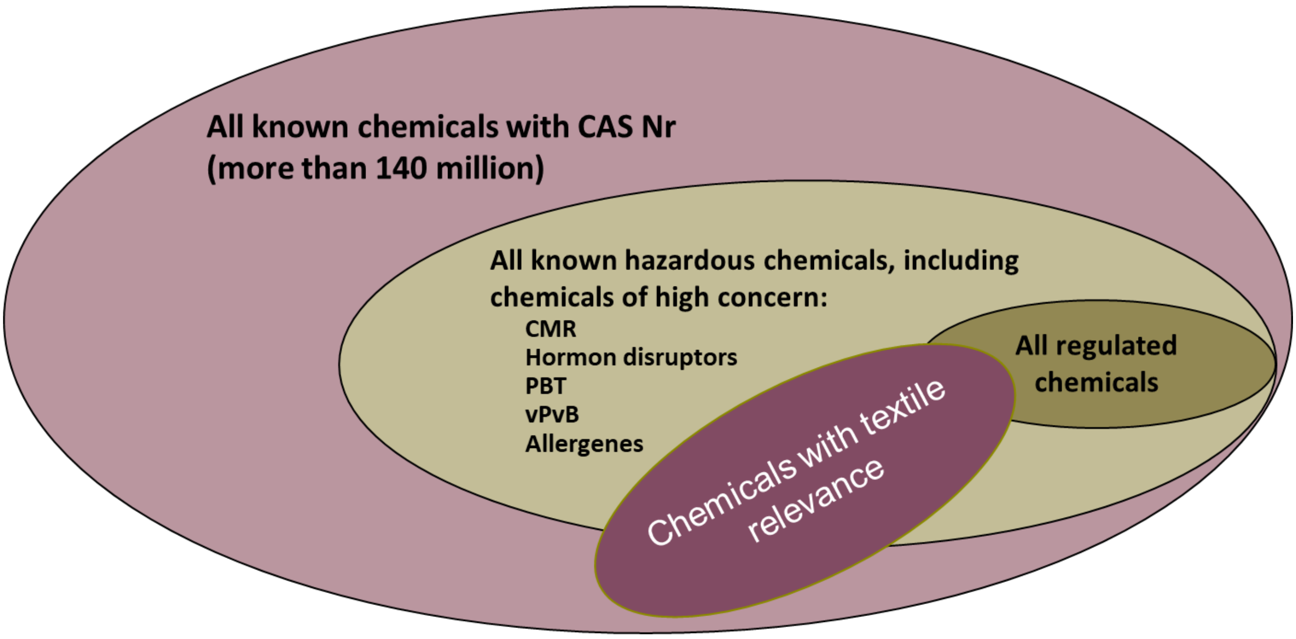

figure 8 Chemicals with textile relevance can be restricted or not as well as classified as hazardous or not.

Example of chemicals providing function to the final product can be i.e. colorants, anti shrinkle, water and dirt repellence and they may be used in fairly high amounts in the production and become a considerable content in the final product (many w%) Chemicals are also used in the manufacturing processes as auxiliary chemicals and solvents and may be used in high quantities in the process but usually are only present in low amounts in the final product. In the final textile garment or product they are more to be considered as impurities and residues.

In total, 2400 different substances have been identified to be potentially used in the textile value chain (Swedish Chemicals Agency, 2014). Approximately five percent of the identified textile-related substances are considered to be of potential risk to the environment, with only a few substances restricted under REACH (see chapter 5.6).

Most of the identified substances with very serious health hazardous properties, such as carcinogenic, mutagenic and/or toxic for reproduction, have an EU-harmonised classification and several are restricted under REACH or are included on the candidate list (substances of very high concern). When textile goods are to be recycled, it is therefore important to know which chemicals are present in them and in which levels these occur. In the case of large-scale recycling of textiles, a certain dilution effect is likely to be obtained, since for example only a subset of the bulk mass contains one or more substances in too high levels. Content of harmful substances over the tolerance limit places restrictions on the application of recycled material and it is of the utmost importance that this is under good control before the recycling process begins. For persistent chemicals and substances with persistent degradation products with potential risk to the human health and/or the environment, dilution will lead to dispersion of these chemicals. For short-lived substances, the dilution may lead to that the chemicals will not cause any problems in that concentration.

In thermal processing, chemicals from different products can be mixed and react with each other and then risk becoming more harmful than they were originally. There are several studies that have identified particularly hazardous chemicals with high relevance to various textile materials for recycling (Östlund et al., 2015; Schmidt et al., 2016). These studies, among other things, identified a number of groups of particularly hazardous substances that may in some way remain in the textile waste. These known especially hazardous substance groups for textile are:

- Per- and polyfluorinated substances
- Halogenated flame retardants
- Toxic softeners/plasticizers
- Toxic metals
- Toxic dyes and pigments
- CMR-classified biocides
- CMR-classified solvents
- Residuals or toxic degradation products such as polycyclic aromatic hydrocarbons (PAHs) and dioxins and dibenzofurans

Some chemicals affect human and the environment throughout the life cycle, and it is therefore not only in the recycling of textiles that the use of chemicals and the handling of chemicals has been recognized. In the case of material recycling and thus resale of used textiles, nowadays, hazardous chemicals can be present in the material, which may thus have to be classified as hazardous waste and instead of becoming a valuable raw material need to be handled accordingly. In light of the chemical history of the textile materials, a couple of specific aspects should be elucidated:

- How does the garment's potential chemical content affect different recycling techniques (e.g. mechanical processing followed by respiration compared to blending textile fiber into plastic melt);
- How insufficient information flow affects the possibility of utilizing old textiles as a raw material.

These aspects should result in a basis for decisions that are based on comprehensible and effective systematics, if any specific material / product segment should be sorted out from future waste streams before a certain recycling technique and clear indications of material fractions that are suitable for such recycling techniques and application areas. The focus should be on chemical content in recycled material and what impact these have on subsequent consumer products and their compliance.

- Important parts include:
- System for information sharing
- Common language and definition
- System for categorization / classification of materials intended for material recycling
- Coupling of materials / fiber categories and use area to relevant chemical content and limit values based on existing mapping of chemicals in textile
- Analysis package related to each material category for risk assessment and possibly labelling / certification system and assessment of suitable applications for recycled material

5.6. legal compliance and policy instruments

This chapter gives a snapshot of the legal situation in relation to textile recycling as of Spring 2019. It should be noted that legislation is constantly developing, and no guarantee is given that this report covers all aspects.

5.6.1. restricted chemicals

A prerequisite for the production of a valuable secondary raw material is that the material is "toxic free". Thus, the constituent chemicals in feedstock need to be aligned with future customer and legal demands. In addition, chemical constituents that may disturb recycling processes[13] must be tracked, traced and removed for cost- and energy-efficient handling.

[13] For example pigments in PES material that are to be melt spun in a second life.

Within the European Union (EU), several hazardous chemicals are restricted in textile products via regulations such as REACH[14] (European Commission, 2006), BPR[15] (European Commission, 2012) and the POP[16] regulation (European Commission, 2004). Many countries have chemicals legislation similar to the EU legislation, for example Canada and the USA. On the other hand, the legislative basis for chemicals management is lacking in many countries, especially in developing countries that dominate textiles manufacturing. Legislation *per se* is no guarantee for compliance (road speed limits does not mean that all drivers respect them). In addition, the EU chemicals legislation applies only to businesses and not to private citizens; the growing share of privately imported goods from online stores means that textile products with unknown chemicals content will eventually reach the waste collection points within the EU.

Although certain chemicals are restricted for certain textile applications, they may be allowed for others because of the value and function they bring to the to the final product. the legal differences between applications mean it is very important to know the chemical content of recycled textiles and whether it is allowed in the application foreseen for the recycled material. For example, flame retardants are allowed for some textile applications, but if these textiles are recycled the flame retardants must be removed if the recycled materials are to be used in, for example, children's wear.

5.6.2. fibre labelling

The EU regulation on fibre labelling applies to textile products as well as products and certain product components that are at least 80% textile fibre (by mass) (European Commission, 2011). Depending on the product, between 95-98% of the fibre content must be declared on the label. This is not sufficient information to enable large-scale textile recycling, since the remaining fibre content may disturb certain recycling processes, for example low levels of elastane prevent melt spinning of synthetic material. Also, the regulation does not require labelling to distinguish between fibres at a sufficiently specific level, for example it does not distinguish between Nylon 6 and Nylon 6.6 which is necessary for certain recycling processes.

5.6.3. the waste frame directive

The waste frame directive (2008/98/EC) requires that Member States adopt waste management plans and waste prevention programmes[17]. This directive has led the way for further actions towards a circular economy. The Directive introduced the "polluter pays principle" and the "extended producer responsibility" as two important policy tools. In addition, EU Member States shall apply as a priority order the following waste management hierarchy (figure 9).

[14] Registration, Evaluation, Authorisation and restriction of Chemicals
[15] Biocidal Products Regulation
[16] Persistent Organic Pollutants
[17] http://ec.europa.eu/environment/waste/prevention/legislation.htm

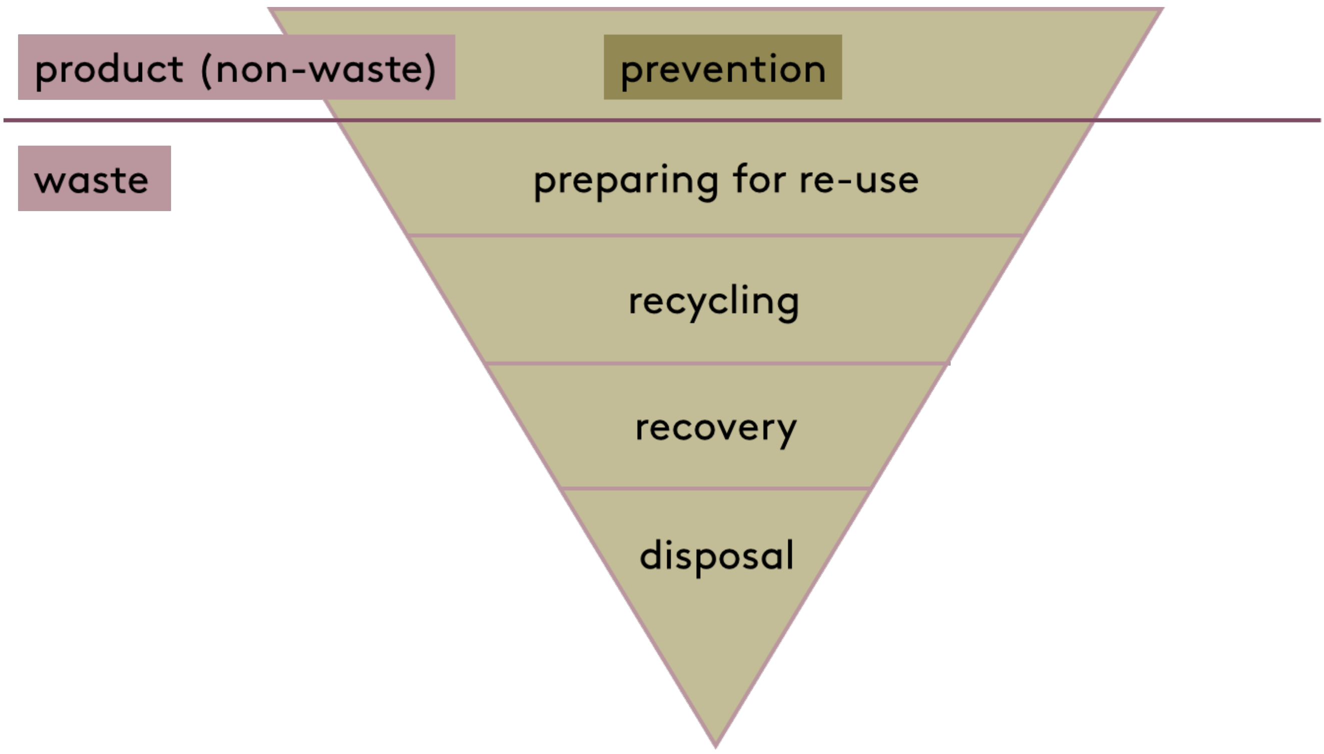

figure 9 The waste hierarchy according to Directive 2008/98/EC on waste (Waste Framework Directive).

5.6.4. policies related to the circular economy

On a EU-level, the Circular Economy Package was adopted in 2018. This package states that all member states must collect textiles separately by 2025, in addition, member states must consider by 2024 whether specific targets should be introduced in regard to reuse and recycling. In 2014, The Swedish EPA was assigned by the government to investigate how textiles should be handled in a future system. The targets that were suggested in this work relates to collection as well as reuse and recycling, stating that by 2025, the volume of textiles in the household waste shall be reduced by 65% compared to 2015. The same year, 2025, 90% of the textile volume separately collected shall be prepared for reuse and recycling in alignment with the waste hierarchy. In the EPA report, the route to reaching these goals were left open. In January 2019, however, the Swedish government stated, in the January-agreement, that an EPR for textiles will be implemented by 2025.

In a communication (European Commission, 2018) from the Commission to the European Parliament, the council, the European economic and social committee and the committee of the regions, the implementation of the circular economy package in regard to options to address the interface between chemical, product and waste legislation is addressed. This communication highlights the need for information systems, innovative tracing technologies and strategies to share information along value-chains.

5.6.5. extended producer responsibility (EPR)

EPR is a policy tool for encouraging and enabling recycling, in which producers are given financial and/or physical responsibility for treating and disposing of post-consumer products. In the EU, EPR is currently mandatory for some product categories but not for textiles. France introduced EPR rules for textiles in 2008 (David Watson et al., 2015) and as stated above, in Sweden the government has decided to work towards implementing EPR for textiles (Socialdemokraterna, 2019).

‘environmental benefits of recycling largely depend on ***what*** material is replaced and ***how much*** of that material is replaced.’

6. conclusion

This white paper has highlighted how textile recycling is often framed as a solution to either one of two important questions:

1. What is the best use of textile waste, environmentally and resource-wise?
2. How do we make the textile industry (environmentally) sustainable?

Recycling is a key component of the so-called circular economy, commonly defined as the "closing of material loops to preserve products, parts, and materials in the industrial system and extract their maximum utility" (Zink & Geyer, 2017). However, as many as 114 different definitions are known (Kirchherr et al., 2017), whereof some are more comprehensive in scope. We recommend that circular economy is seen as a means to achieve sustainability, and not as a goal in itself.

The condensed information is found in Roos et al. (2019).

6.1. design for textile recycling

Some current opportunities for using recycled materials in new fashion products, and guidance for assuring that fashion products are designed to be recyclable at end-of-life, are provided for the most commonly used fibre types: polyester, cotton and nylon.

6.1.1. opportunities for using recycled materials in new fashion products

Table 9 summarizes today's opportunities for using recycling products in new fashion products. Supplier dialogue is one of the essential actions.

table 8 Opportunities for using recycled materials in new fashion products.

material type	opportunities for using recycled materials
generic	• Make use of recycled material, see to that it is certified recycled content (e.g. GRS[18]) to avoid green-washing. • In the dialogue with the supplier(s): o discuss the rationale behind choosing the specific quality, is it a suitable material for the application?

[18] Global Recycle Standard, a certification standard for recycled content

	◦ dialogue regarding chemicals content, compliance and suitability for the application.
polyester fibres	• Make use of recycled polyester (chemical or mechanical recycling).
cotton fibres	• Make use of recycled cotton (mechanical recycling).
nylon 6	• Make use of recycled nylon 6 (chemical or mechanical recycling).
nylon 6.6	• Make use of recycled nylon 6.6 (mechanical recycling).
trims	• Use your own production's waste fibres for trims to your garments.

6.1.2. design fashion products to be recyclable at end-of-life

table 10 summarizes today's opportunities for designing recyclable products at end-of-life. Supplier dialogue is one of the essential actions.

table 9 Opportunities for designing recyclable products.

material type	opportunities for using recycled materials
generic	• Avoid finishing with e.g. water repellent coatings and anti-bacterial treatment. • Create monomaterial design (unless this shortens life length of product)
polyester products	• Use 100% polyester (PET) in fabric, membranes, coatings and trims. • Collaborate with a polyester yarn producer: ◦ check with producers of virgin fibre regarding which additives and dyestuffs may be present, to avoid a potential problem for the recycling process and ensure the recycler can use your products as input. ◦ engage with one of the few polyester fibre-to-fibre recyclers that exist on an industrial scale, e.g. Teijin/Jiaren.
cotton products	• Use 100% cotton and/or regenerated cellulose in fabric and accessories • Collaborate with a cotton yarn producer: ◦ encourage the expansion of pilot plants that are available for post-consumer textiles, e.g. Re:newcell.
nylon 6 products	• Use 100% Nylon 6 in fabric (other names are polyamide 6, PA 6)

	• Accessories should if possible also be made of nylon 6 – check all items on the request
	• Nylon 6.6 is NOT the same fibre, in terms of recycling it is rather a contamination.
	• Collaborate with a nylon 6 producer:
	    o check with producers of virgin fibre regarding which additives and dyestuffs may be present, to avoid a potential problem for the recycling process.
	    o engage with one of the few nylon 6 fibre-to-fibre recyclers that exist on an industrial scale, e.g. Aquafil.

nylon 6.6 products	• Today, post-consumer nylon 6.6 (polyamide 6.6, PA 6.6) waste is not recyclable into textile fibres. Consider replacing this fibre until this situation changes.

6.2. current status for textile recycling

To establish textile recycling on a larger scale, we should not judge the future based on the current situation. There is a great potential for environmental benefits from textile recycling if high recovery rates are achieved and high-quality products are produced. Therefore, we recommend viewing textile waste not only as a resource that should be "returned" to the textile value chain alone. Open-loop recycling that can exchange materials between textile, plastic, composite and nonwoven applications adds to the potential to be resource-efficient, both economically and environmentally.

For use of recycled materials in textiles, some examples are provided for the main fibre types: polyester, cotton and nylon. To ensure that fashion products are designed to be recyclable at end-of-life, the current recommendations are to create monomaterial design (unless this shortens the life length of product) and avoid chemical treatments that may disturb the recycling process or contain restricted chemicals.

Environmental benefits of recycling largely depend on ***what*** material is replaced and ***how much*** of that material is replaced. We want to stress that to maximize the environmental benefit, the first steps involve materials being used and reused, with recycling being the option when materials are discarded after a prolonged life in alignment with the waste hierarchy. In this way, reuse and recycling are not competing strategies but rather both necessary and complimentary in a circular economy.

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appendix 1

	Schmidt et al 2016 (citing Palm 2014)				**Elander et al 2014**		**Belleza & Luukka 2018**	**Watson et al 2018**	
	Denmark	**Finland**	**Norway**	**Sweden**	**Sweden**	**Sweden**	**Sweden**	**Denmark**	**Denmark**
	2010	**2010**	**2011**	**2008-10**	**2011**	**2013**	**2016**	**2016**	**2016**
								govt/bus	household
consumed textiles	**89000**	**71000**	**86400**	**132000**	**133000**	**121000**	**138000**[19]	**10130**	**75330**
incinerated/waste	33000	43300	33600	102000				9020	44532
reused textiles ("formal")	35000	13200	26400	26500	23400	23400	*29100*		26888
recycled textiles	0	8500	0	0			*4700*		4470
accumulation/loss	21000	6000	26400	3000					
not separately collected	**48000**	**46000**	**58800**	**103000**					
accumulation/loss	21000	6000	26400	3000					11040
incinerated	24000	14000	26400	100000					39900
industrial waste/landfill	3000	26000	6000						
reuse within country via friends/family ("informal")									6000

[19] This value was not shown in Belleza and Luukka (2018) but has been calculated by the authors of this report for completeness. The method for calculating this value was made consistent with both Schmidt et al 2016 and Elander et al 2016 in terms of the included textile product categories.

	Schmidt et al 2016 (citing Palm 2014)				Elander et al 2014		Belleza & Luukka 2018	Watson et al 2018	
	Denmark	**Finland**	**Norway**	**Sweden**	**Sweden**	**Sweden**	**Sweden**	**Denmark**	**Denmark**
	2010	**2010**	**2011**	**2008-10**	**2011**	**2013**	**2016**	**2016**	**2016**
								govt/bus	household
separately collected waste textiles	**41000**	**25000**	**27600**	**29000**			**38300**		**36000**
incineration/landfill	**6000**	**3300**	**1200**	**2000**			**1800**		**4632**
incinerated in country							99		2230
waste elsewhere					4500	5400	1701		2402
reused textiles	**35000**	**13200**	**26400**	**26500**	**23400**	**23400**	**29100**		**26888**
formal reuse in country	12000	7000	1200	7500	7400	8600	7800		10600
reuse sale via charity shops					5250	6000			
reuse - given away by charity					450	500			
reuse via online platform					1500	2000			1600
via second hand shops (not charity)					180	170			
formal reuse post export	23000	6200	25200	19000	16000	14800	21300		15288
informal reuse presumed after theft									1000
recycled textiles		**8500**					**4700**		**4470**
recycled in country		8500					100	100	320
recycled elsewhere							4600		4150

Mistra Future Fashion is a research program that focuses on how to turn today's fashion industry and consumer habits toward sustainable fashion and behavior. Guided by the principles of the circular economy model, the program operates cross disciplinary and involves 60+ partners from the fashion ecosystem. Its unique system perspective combines new methods for design, production, use and recycling with relevant aspects such as new business models, policies, consumer science, life-cycle-assessments, system analysis, chemistry, engineering etc.

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