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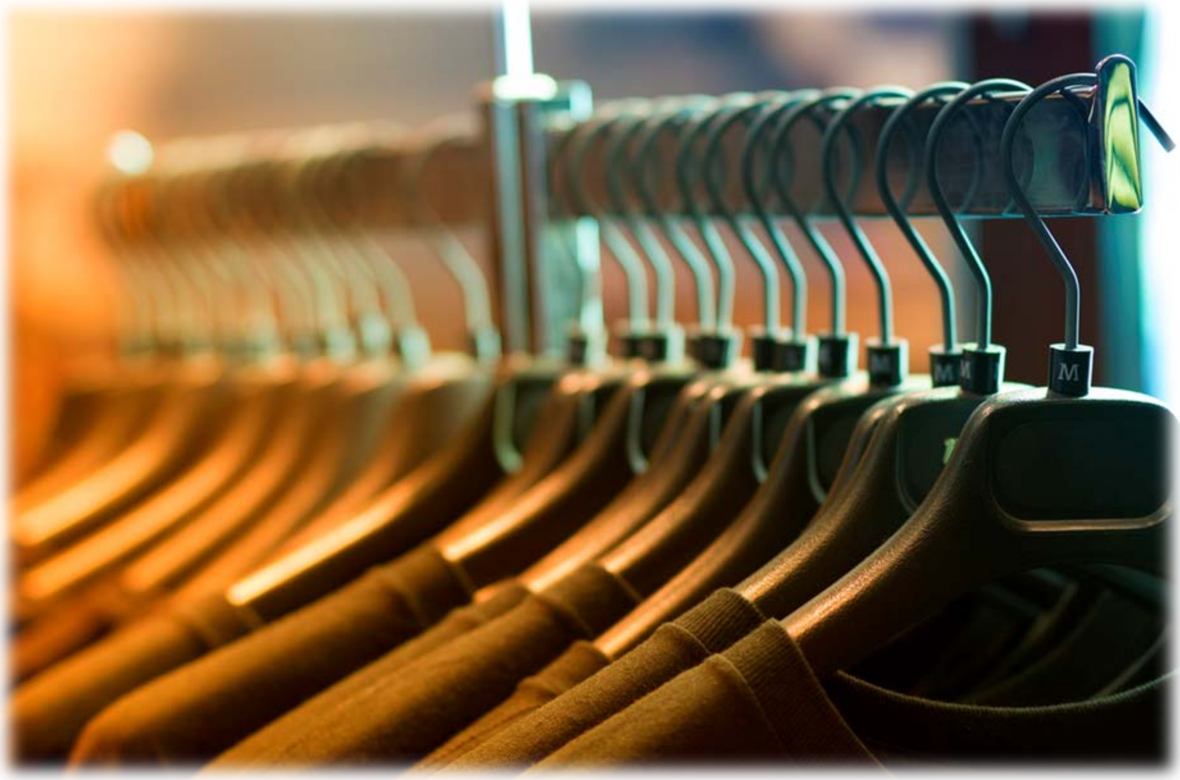

The Environmental Performance of High Value Recycling for the Fashion Industry

LCA for four case studies

Master's thesis in Industrial Ecology

THEODOROS SPATHAS

Department of Energy and Environment
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MASTER'S THESIS 2017

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Abstract

The fashion supply chain is being challenged by a rising global population, increasing wealth and consumerism in the emerging markets, and the phenomenon of fast consumption in the developed world. Enormous strains are put on natural resources to keep up with consumer demand and solutions are needed for the massive waste flows downstream.

Currently the main solutions for garments that cannot be reused are landfill, incineration for energy recovery, and downcycling. The latter is the recycling of garments into lower value products, such as insulation or wipers. Landfill and incineration cost money and these options do not deal with the natural resources issue since they do not displace the virgin fibre textiles industry. Downcycling does displace virgin fibre production, but applications have low profitability. High value recycling or "garment to garment recycling" is the concept of recycling used garments and textile waste into new garment products. This concept can reduce some of the pressure on virgin resources, while at the same adding value to waste to make recycling profitable for companies.

This research assessed the environmental performance of two garment to garment recycling systems and one scenario as well as one downcycling system, in comparison with their equivalent ones made from virgin materials. The approach was based on life cycle assessment, and the impact categories chosen were climate change, acidification, eutrophication and water consumption. The study included primary data from different processes in the life cycle, including mechanical and chemical recycling, textile collection and manual and automated sorting.

In the two systems featuring mechanical recycling and high recycled input percentage, the recycled yarns had lower impacts than the virgin product in all impact categories. This was attributed to replacing the virgin cotton production and virgin PET input, in favour of recycled ones. In the other two cases, the impact reduction was smaller, with the exception of the large reduction in water consumption for the chemical recycling case, where wood pulp was replaced with recycled cotton garments for viscose production. The biggest impact contributors identified, were production of virgin fibre, electricity production, the textile collection process, textile waste management and dyeing. Minor contributors were the recycling process itself, manual and automated sorting.

Keywords: circular economy, sustainable fashion, LCA, textile recycling, high value recycling, mechanical recycling, chemical recycling, downcycling

Preface

This work was conducted as part of an internship at non-profit consultancy Circle Economy in the Netherlands. During my work, Circle Economy was involved in exploring opportunities for textile to textile recycling, which led to three pilots with fashion brands, recyclers and textile collectors. It was a great experience, not only because I felt my work could have an impact, but also because I had the opportunity to observe more closely how businesses make their decisions regarding sustainability. Therefore, I would like to thank Circle Economy, and in particular Helene Smits, Lead of the Textiles Programme at the time, for the opportunity, and for the constant support and interest in my work. I would also like to thank Gwen Cunningham, whose help with technical aspects of the textiles industry was invaluable and Shyaam Ramkumar, whose data expertise and advice during the case studies made my work much easier.

I would also like to acknowledge the help of my supervisors Greg Peters of Chalmers University and Valentina Prado, of Leiden University (CML). From the very start of the project, Greg gave me essential advice on Life Cycle Assessment, how to structure the research, and always made time for me when I needed help. Valentina aided me with her boundless knowledge on the LCA methodology which not only saved me lots of time, but also allowed me to reach a much better understanding of the system I studied.

Many thanks to all the companies that were involved in the research by providing information and data. In particular, I would like to thank Michel Rosenquist from ReShare: Part of the Salvation Army and Alfredo Ferre, the CEO of Hilaturas Ferre/Recover. This thesis would not have been possible without them. Last but not least, I would like to thank all my friends in Gothenburg and in the Netherlands for the support, feedback and fun moments, as well as my family for being my backbone all these years.

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May 18, 2017
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1. Introduction

1.1 Environmental challenges of the textiles industry and current trends

The textiles industry is one of the most polluting industries in the world, yet one of the most deeply embedded in our society and culture. With rising population, increasing wealth and consumerism of the emerging market, and the phenomenon of fast fashion in the developed countries, enormous strains are put on natural resources to keep up with the demand (Wang, 2006). These strains have led to significant environmental impacts and social problems. What is more, overproduction and shifting consumer patterns had led to massive quantities of used and unsold textiles ending up in developing countries, while most post-consumer waste ends up as waste (Beton *et al.*, 2006, Zamani *et al.*, 2014).

The fashion industry relies heavily on the production of cotton and polyester. Both of them require natural resources such as water and oil that bring about negative environmental impacts that impact on current society and will affect future generations. For example, the cultivation of cotton, or other similar natural fibres, depends on massive amounts of water and land in regions where this land use may be competing with food production or forest preservation (Bratl).

Synthetic fibres represent the majority of textiles fibres used in apparel and the fastest growing segment of total fibre use. The most popular is polyester or “PET” (polyethylene terephthalate). PET production is expected to be double that of cotton by 2030. This will mean increased use of oil, the search for it in technically challenging deep water and arctic regions, and the use of hydraulic fracturing or fracking. Fracking has led to great controversy over the years through hydraulic damage to aquifers and water pollution (Peters *et al.*, 2015).

1.2The current textile waste supply chain system

In developed countries the annual consumption of new textiles is high (for example, 14.2 kg/person in Sweden) while significant number of purchased textile products are not even used (Palm, 2014). Post-consumer textile material flows have different fates in northern European countries. On average, 61% of post-consumer textiles in these countries is not collected and ends up in household waste. Half of this ends up in landfill, while the other half is incinerated for energy recovery (Circle Economy, 2014).

The collected fraction is delivered to sorting facilities where skilled workers sort it into different materials for reuse. Some particular types of textiles, such as vintage clothing and accessories have higher economic value and are of great importance to the sorting companies. Furthermore, depending on the quality, high quality garments can be sold in second hand shops in Western Europe, while the rest are exported to Eastern Europe, Asia and Africa. Two other large fractions complete the sorting process, the downcycling fraction and the waste fraction. Selling garments for reuse is more profitable than downcycling and companies make no profit from the waste fraction, as they need to pay for waste management.

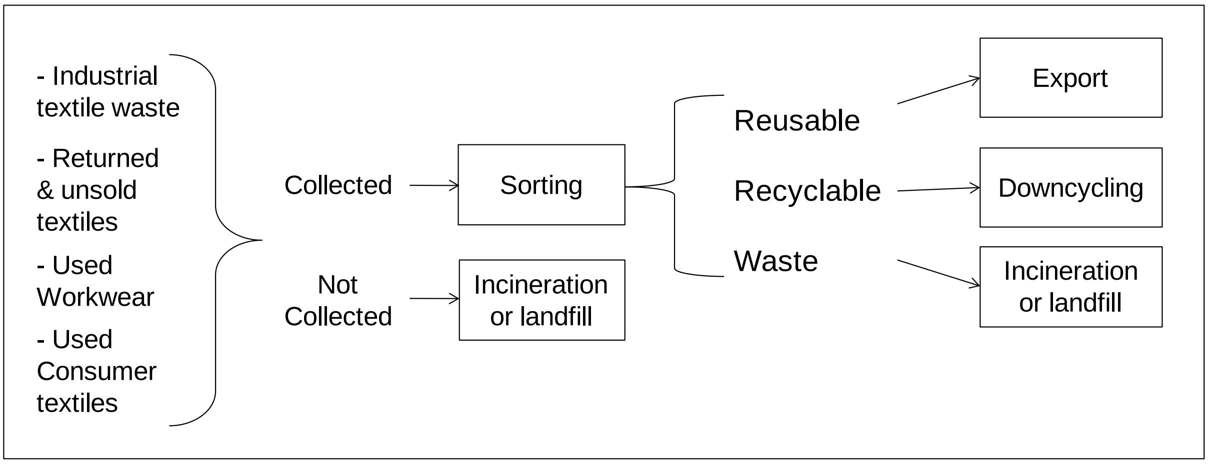


Figure 1: The supply chain of textile waste

As suggested in Figure 1, a considerable amount of what is ultimately waste is collected and sorted. In northern Europe, textiles are mostly collected from special bins located on the street for free access by everyone, in order to make it easy for citizens to donate their used textiles. However, since in countries such as the Netherlands some municipalities charge extra fees per amount of a mass or volume based charge for collection of household waste, some individuals throw their regular waste in the textiles bins, to avoid the fees. As a result, non-textile waste can amount to around 6-10 % of the total collection, according to the collection company interviewed in this study. Other sources of waste include dirty, contaminated and wet textiles, which cannot be processed. Textile bins are frequently below the ground, which can lead to rainwater leaking inside. In the Netherlands and Sweden, most of this waste in is incinerated with energy recovery.

At the moment, the practical option for the recyclable fraction is downcycling i.e. the recycling of textiles into lower value products. Some applications include wipers, where old textiles can be transformed in to cleaning products with little processing. Some other applications include insulation materials, with some examples already existing for denim insulation. Rags and other low value textiles can be turned into mattress filings and PET-based textiles can be processed into felt for the automotive industry. Finally, the option of remanufacturing exists, such as turning leather into wallets, but these applications account for a limited volume.

Generally, the application of downcycling technologies is limited by a lack of profitability and they may only have a marginal capacity to displace the virgin fibre textiles industry. Incineration with energy recovery has the benefit of eliminating some fossil carbon dioxide emissions, but both it and landfill can lead to non-biogenic carbon emissions, due to fossil-fuel based textile materials, such as PET. Besides, these technologies do not displace the environmental impacts of virgin fibre production. Finally, textile companies need to pay for landfill or incineration, while downcycling offers low revenue. For these reasons, textile waste collectors are investigating new solutions.

1.3 The concept of high value recycling

High value recycling, or “garment to garment recycling“, is the concept of recycling used garments and other textile waste into new garment products. This concept can displace some of the pressure on virgin resources, while at the same time adding value to waste to make recycling profitable for companies. There are several initiatives happening at the moment in high value recycling, including recycled denim by G-Star RAW, outerwear by Patagonia and Houdini, and closed-loop initiatives by Nudie Jeans in Sweden and Mud Jeans in the Netherlands. The concept includes using the recyclable fraction from the sorting process (Figure 3) and recycling it into new textiles instead of downcycling applications.

First step: sorting

Textile recyclers need to know the exact composition of the input material and also to have a consistent composition, on account of the existing technology. This is where automated sorting becomes important. In low volumes or at pilot scale, manual sorting based on material can be implemented. But there are two problems with this. The first is the cost and the second is the quality of the work. In terms of cost, the sorted textile wastes are raw materials and will have lower economic value than the original garments. Therefore, it does not make economic sense to use expensive manual labour for this application. In terms of quality, labels at used textiles are often faded, wrong or missing, which makes it difficult for the sorters to understand the quality of the material. To address this problem, companies have offered solutions to automate the process such as the one which is assessed in this study, which uses a near infra-red detector to identify the different textile materials. This technique is on the verge of being commercialised.

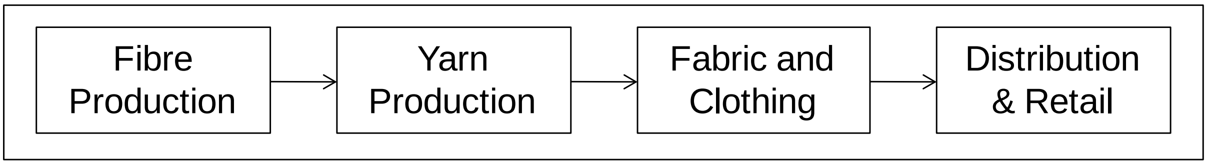


Figure 2Thetextile supply chain from raw material to retail

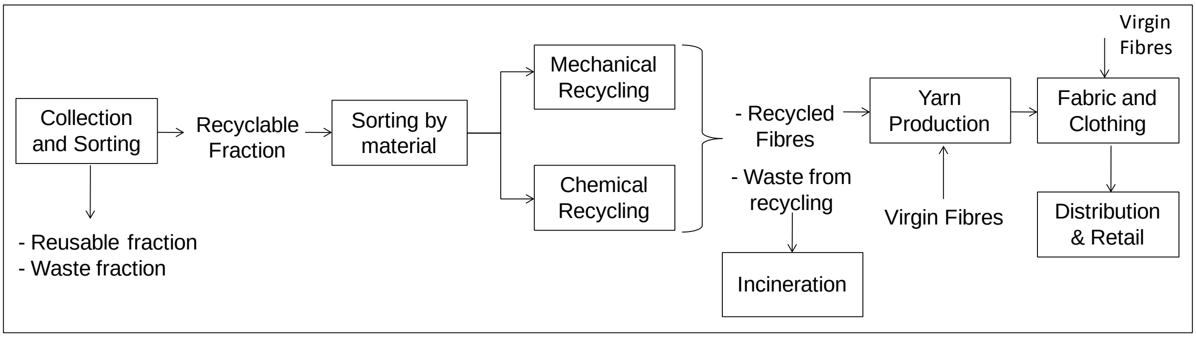


Figure 3 The High value recycling system

Second step: recycling

After the sorting step, there are different options for each material. For cotton, wool and PET, mechanical recycling is an established technology that can produce recyclates of adequate quality to be blended with virgin material at a rate of 20-30% by mass of the finished yarn. It is challenging to increase this percentage, because mechanical recycling shortens the fibres and therefore the quality of the end product.

A typical mechanical recycling process is as follows (Langley, 2006): Metal components and non-textile material are removed in a process called “cleaning”. Fabrics are then baled and cut with a rotary blade into small pieces. Fibres are then separated through a process known as ‘picking’, ’pulling’ or ‘tearing’ as fabrics are rolled on progressively smaller spiked surfaces to break them apart to remove the fibres. Finally, after-treatment methods are needed for enhancing the quality of the fibres, elimination of short fibres and dust and (if needed) blending with primary fibres (Zamani *et al*, 2014).

Compared to mechanical methods, chemical recycling is a promising new technology that may increase the recycled content of garments and enable recycling of the same materials multiple times. There are examples of these technologies such as the processes implemented by Teijin in Japan, by Worn Again in the UK, by EVRNU in the United States and most recently by Re:newcell in Sweden.

In chemical recycling, the fibres in the textiles are broken down to the molecular level and the feedstock is repolymerised (Fletcher, 2008) before passing through a spinneret to generates new fibre to be spun into yarn, ready for weaving or knitting into fabric (Payne, 2014). This process is related to the chemical recycling of polymer-based synthetic fibres. However, it results in a higher quality fibre that can have high equivalence to virgin fibre. For this thesis, the data for this technology were provided by a start-up in the field.

1.4 Research aims and goals

This thesis focuses on assessing the environmental sustainability of three high value recycling initiatives and a downcycling one. These include three mechanical textile recycling pilots and one chemical recycling concept by a start-up company. Many of the isolated new initiatives taking place at the moment have not been assessed from an environment perspective, or at least not publicly. Furthermore, as mentioned below in the literature review, there has been little research in the environmental impacts on most potential high value recycling technologies. Life Cycle Assessment (LCA) can be used to evaluate the alternative life cycles of the recycled products, providing a systems perspective that includes all the life cycle stages of a product, including collection and sorting of the textile waste.

The hypothesis to be tested in this thesis is that since high value recycling can avoid impacts from virgin resources and utilise textile waste, it can decrease the overall impact of the textile supply chain and the new system will be more sustainable. People often instinctively assume that recycling is good for the environment, but in some cases the virgin product may be environmentally preferable on account of the impacts of collection, sorting, transportation and the recycling technologies. That is why it is useful to use LCA as a methodology, since it assesses the environmental impact through entire product supply chain. By filling gaps in our understanding of the environmental impacts of mechanical and chemical recycling technologies and the potential benefits, this report will hopefully provide a more nuanced understanding on textile recycling impacts and benefits in order to bring knowledge and enable improvements in the textile industry.

The aim of the LCA is to identify the key parameters that influence the environmental performance of the alternative textile life cycles and compare them with the virgin equivalent ones. This will be accomplished by performing LCA on the production of the recycled yarns.

This LCA study was commissioned by the Dutch non-profit cooperative, Circle Economy and it was supervised by professor Greg Peters of Chalmers University of Technology (examiner), Helene Smits from Circle Economy and assistant professor Valentina Prado, from Leiden University (secondary supervisor). The practitioner is MSc. Graduate student Theodoros Spathas, intern at Circle Economy at the time of the study. This study was part of Circle Economy's "Circle Textiles" programme and the intended audience are fashion and workwear brands as well as policymakers relevant to the textiles industry.

1.5 Case studies

Four different case studies, each including the recycled and the virgin production alternative, were part of the study, as listed below. The three first case studies (Downcycling, Denim, Mixed) represent actual recycling pilots performed by Circle Economy and its partners. They were chosen in this thesis to reflect on the potential environmental benefits of mechanical recycling, both in downcycling and high value recycling operations. Most of Circle Economy's pilot partners were actively involved in this research sharing their energy and material flow data. The partners include Spanish mechanical recycler Hilaturas Ferre / Recover and Dutch textiles collector ReShare: Part of the Salvation Army. **These are real-life cases, but some data is coming from assumptions and generalisations.**

As mentioned above, chemical recycling is a promising technology for textile recycling with limited existing literature regarding its environmental performance. For the purpose of this research, I contacted a relevant start-up in the field and created a high value recycling concept, which I named "Viscose case". The start-up helped us in the description of the technology and contributed with relevant data for the Life Cycle Assessment. The Viscose case included an automated sorting step for the post-consumer garments. During the writing this thesis, I had not seen any published LCA study assess the environmental performance of this technology.

- **Downcycling case**

Post-consumer uniforms are mechanically recycled into yarns for blankets.

- **Denim case**

Unsold denim garments are mechanically recycled into yarn for denim.

- **Mixed case**

Post-consumer garments are mechanically recycled into yarns for garments.

- **Viscose case**

Post-consumer cotton garments are chemically recycled into viscose yarns for garments.

These case studies represent different perspectives within the fashion and textiles industry, such as the high-end fashion brand (Denim Case), the innovative start-up (Mixed Case), the textiles collector (Downcycling) and the recycling companies. In terms of textile materials, they focus on cotton and PET, because these are the prominent materials in the industry at the moment. Both chemical and mechanical recycling technologies for cotton are assessed, while only mechanical recycling for PET. Future research could include chemical recycling for PET and relevant new recycling technologies for cotton, synthetic materials, wool etc.

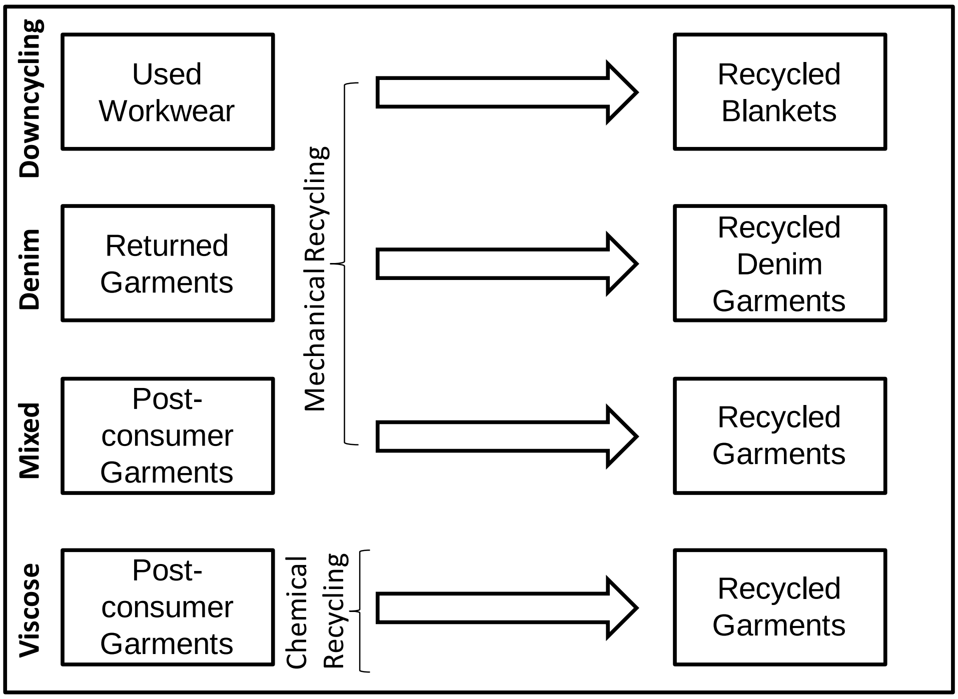


Figure 4: The textile recycling case studies

2. Literature Review

2.1 Reuse and recycling of end-of-life textiles

Woolridge *et al* (2005) performed an LCA on reuse of donated garments from the UK in comparison with producing virgin material. The report showed that “for every kilogram of virgin cotton displaced by second hand clothing, approximately 65 kWh is saved, and for every kilogram of polyester around 90 kWh is saved”. This took into account the extraction of resources, manufacture of materials, electricity generation, clothing collection, processing and distribution and final disposal of wastes. It was concluded that reusing garments consumes only 1.8 % of the energy needed from virgin materials for polyester and 2.6 % for cotton, leading to significant reduction in environmental burden. (Woolridge *et al.*, 2005).

The potential for energy and material savings of textile recycling was described by Bartl. He contends that recycling processes are useful because of the high energy and resource demands of fibre manufacturing. The paper argues that reuse is the best option when suitable, because the energy required for collection and sorting is negligible in comparison to the energy intensity of apparel production.

Downcycling means recycling waste into products of lower value than the original products. Bartl proposed that collected textiles which are not suitable for reuse, may be downcycled into products marketed towards the bitumen industry. However, he also argued that downcycling saves much less energy than reuse of the waste derived fibres. (Bartl).Due to its age, this paper does not take into account for the high value recycling technologies that are emerging today and also does not account for the business loss for collectors due to downcycling.

In their study on three different recycling processes of cotton bed sheets, Pesneh and Perwuelz (2011) found a decrease in the water consumption and eutrophication potential of the bed sheet life cycle in comparison with virgin production. This reduction was attributed to the avoidance of cotton cultivation. The same study indicated that mechanical recycling has lower impact on the global warming indicator than chemical recycling and energy recovery. They excluded the life cycle stage of waste collection, the location of the recycling step and location of the production of virgin material and other external parameters. Two parameters that affected the environmental impact the most were the energy mix of the particular nation and the location of the virgin material production.

LCA on different waste disposal options for textile waste

A study that compared the environmental impact of recycled cotton yarns versus conventional cotton yarns was performed in 2007 by Aitex, a textile industry research association that was set up by the Valencian regional government in Spain. The LCA compared recycled yarn of 80-20 % cotton – polyester fibre composition with 100 % virgin cotton, and showed over 17 % savings in greenhouse gas emissions (Aitex, 2007). Water use savings were much higher, since the recycled yarns consumed almost 8 times less water than the virgin yarns and led to almost 5 times less waste water effluent. Finally, the recycled yarns avoided all impact from fertilisers due to the avoidance of cotton production and did not need dyeing.

However, it needs to be mentioned that in terms of quality, yarns produced from 100 % recycled material cannot be compared in function with the 100 % virgin material when it comes for use in apparel (Aitex, 2007). For this reasons, in recycled collections of various fashion brands such as H&M and G-Star Raw, recycled content rarely exceeds 20 %, since brands do not consider recycled yarn to be of comparable quality.

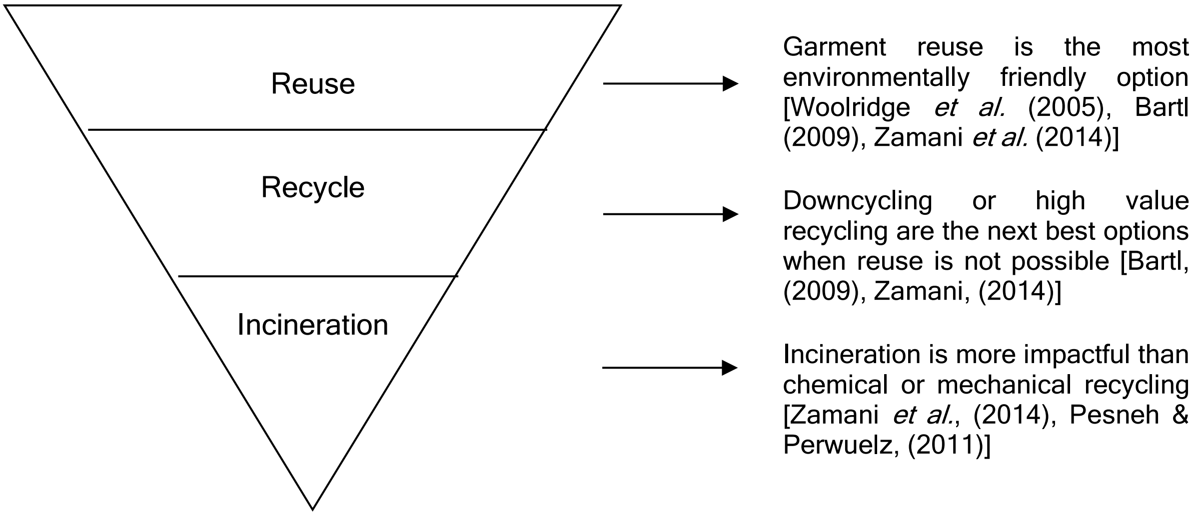
Life Cycle Assessments for textile waste recycling options

Zamani *et al.* (2014) performed an LCA on different types of textile waste recycling, including material reuse of adequate quality, chemical recycling of polyester and cotton polyester separation with NMMO. This study did not include impacts from the collection of textile waste. The authors concluded that emergent textile recycling technologies had less global warming potential than incineration, which is the dominant textile waste management option in Sweden. Furthermore, the energy intensity of cellulose/polyester separation and production of cellulose/polyester fibres from primary resources exerted a strong influence on the potential savings these technologies (Zamani *et al.*, 2014).

A cradle to grave carbon footprint and energy demand comparative LCA (excluding use phase) on bio-based PET, recycled PET, PLA (polylactic acid, a bio-based polyester) and man-made cellulosics (cellulose fibre produced from wood pulp)was performed by Shen *et al.* in 2012. The study showed that recycled (partially) bio-based PET has the lowest impact, recycled PET is second, partially bio-based PET follows, and virgin (petrochemical) PET has the highest impacts. PLA and man-made cellulose fibres were found to have lower impact both than bio-based PET and petrochemical PET. The study suggested that for open-loop recycling, the choice of allocation method plays an important role in the impacts of the recycled products (Shen *et al.*, 2012).The results of the study indicated that “both recycling and bio-based alternatives are important ways of reducing the energy requirements and GHG emissions” (Shen *et al*, 2012).

2.2 Summary from literature review and current research gaps

The literature discussed so far in this thesis (Pesneh and Perwuelz (2011), Zamani *et al.*, (2014), Aitex, (2007), Shen *et al.*, (2012)) indicates that by avoiding virgin fibre production in the textiles supply chain and replacing it with recycled fibres several environmental benefits can be achieved. These include a limited reduction in CO_2 emissions, significant decreases in water consumption and decreases in acidification and eutrophication. Furthermore, in terms of the best options for dealing with the textile waste in terms of climate change and energy use, the literature suggests the hierarchy described in the figure below:



Garment reuse is the most environmentally friendly option [Woolridge *et al.* (2005), Bartl (2009), Zamani *et al.* (2014)]

Downcycling or high value recycling are the next best options when reuse is not possible [Bartl, (2009), Zamani, (2014)]

Incineration is more impactful than chemical or mechanical recycling [Zamani *et al.*, (2014), Pesneh & Perwuelz, (2011)]

Figure 5: Summary of the alternative options fortextile waste.

The conclusions made by Pesneh and Perwuelz (2011)showed that mechanical recycling has less impact on climate change in comparison with chemical recycling and energy recovery. Zamani *et al.* (2014) showed that emergent textile recycling technologies (chemical recycling of polyester and cotton/polyester separation with NMMO) were less carbon intensive than incineration and that chemical recycling influences strongly the potential savings these technologies (Zamani *et al.*, 2014). Therefore, both studies concur that mechanical and chemical recycling technologies are better options than incineration.

While Aitex (2007) and Pesneh & Perwuelz (2011) accounted for losses during recycling processes, neither of these studies took the differences in function of the final product into account. Mechanical recycling produces fibres of shorter length, therefore at the moment can only be used as a small percentage of the total fibre mass in quality apparel products. Chemical recycling on the other hand, promises to displace the virgin fibre production even further, since the recycled fibres are of virgin quality and can be used at far higher percentages. The latter can be the case, unless there is damage at the molecular level which is carried from the previous use to the next (Palme *et al.*, 2014).

In summary, the main literature and research gaps so far concern: apart from the above-mentioned textile recycling publications, little literature exists on the environmental impacts of textile to textile recycling technologies such as mechanical and chemical recycling. The preliminary research conducted so far shows potential for environmental impact reduction through the recycling of textile waste. However, more detailed environmental assessment of recycling technologies will be necessary in order to deal with the uncertainty and lack of knowledge that exists currently on this topic. Part of the goal of this thesis is to shed light to these issues and inform discussion.

Table 1: Research gaps in the field of high value recycling

Literature Gap	Direction for this study
Environmental impacts of chemical recycling technologies and the potential benefits.	LCA for chemical recycling of cotton.

Detailed study on the contribution of collection and sorting of textile waste to the total impact of textile recycling.	LCA on collection and sorting companies.
Assessment of the impact of automated sorted technologies that aspire to enable recycling in the future.	LCA of automated sorting.

By filling gaps environmental impacts of mechanical and chemical recycling technologies and the potential benefits this report will hopefully provide a more nuanced understanding on textile recycling impacts and benefits in order to bring knowledge and enable improvements in the textile industry.

3. Methodology and System Description

3.1 Life Cycle Assessment

The environmental assessment tool that will be used for the answer of the research questions is Life Cycle Assessment (LCA). According to Finnveden *et al.* (2009), “Life Cycle Assessment is a tool to assess the environmental impacts and resources used throughout a product's life cycle, i.e., from raw material acquisition, via production and use phases, to waste management”. LCA enables this study to identify the environmental impact hotspots of textile recycling through its analysis of the whole life cycle. It also helps compare different available options.

LCA is a four step iterative process which main functions are defined by ISO14040 as:

- *Goal and Scope Definition*, the product(s) or service(s) to be assessed are defined, a functional basis for comparison is chosen and the required level of detail is defined;
- *Inventory Analysis* of extractions and emissions, the energy and raw materials used, and emissions to the atmosphere, water and land, are quantified for each process, then combined in the process flow chart and related to the functional basis;
- *Impact Assessment*, the effects of the resource use and emissions generated are grouped (classification) and quantified into a limited number of impact categories which may then be weighted for importance (characterisation);
- *Interpretation*, the results are reported in the most informative way possible and the need and opportunities to reduce the impact of the product(s) or service(s) on the environment are systematically evaluated.

Many input parameters are required in LCA and many of these parameters are uncertain; therefore, a sensitivity analysis is an integral in order to test the robustness of the study’s results. Sensitivity analysis can be performed by changing critical input parameters (Baumann & Tillman, 2004), in order to identify their influence in the results.

Software

The software used for the modelling of the textile recycling technologies, case studies and the impact calculation is GABI Education (2016).

Multifunctional processes and allocation

Different products’ life cycles are interlinked and sometimes a few products or functions share the same processes. The question becomes how to express the environmental burden of those processes in relation to one function only. This is called an allocation problem. (Baumann & Tillman, 2004). There are three basic cases where allocation problems can be encountered: Multi-output processes, that result in different products, such the output of a combined heat and power plant. Multi-input processes, such a waste management processes that treat different inputs. Furthermore, open loop recycling, i.e. when a product is recycled into another product, is another case, is different potential solutions to the allocation problem has been debated.

According to ISO 14044:2006, allocation should be avoided whenever possible by increasing the level of detail of the model and by system expansion. The first means dividing the unit process to be allocated into two or more sub-processes and collecting the input and output data related to these sub-processes, the second means expanding the product system to include the additional functions related to the co-products. Another way of doing this is the substitution method, i.e. defining an "avoided" process with subsequent "avoided" interventions/impacts - also known as "avoided burden approach". This is particularly important for energy substitution (coal, gas, hydro etc.) (ISO/TR 14049).

Where allocation cannot be avoided, the environmental burdens should be partitioned between the system's different functions, reflecting the underlying physical relationships. And finally, "where physical relationships cannot be established, allocation may be based on other relationships between the products, such as economic value". (Baumann &Tillman, 2004).

3.2 Scope of the LCA

Two key alternative methods can be applied in life cycle inventory analysis: attributional and consequential methods. "Attributional LCA can be used with the aim of estimating a product's environmental impact and to compare it with other products. Consequential LCA can describe the effects of changes applied within a system" (Baumann & Tillman, 2004). There is some controversy around the when an LCA should be attributional or consequential, and which data suits each style (Ekvall *et al*, 2016). This is an attributional LCA in that it attempts to account for the impacts of the current system and alternative systems. Furthermore, the intention is not to increase total textile production volumes, but to replace part of them. One may consider the alternative foreground systems as being the marginal systems in the present context, but all the background systems are described by average performance data. This study will be performed according to the ISO 14040 series of standards for LCA as described above.

Boundaries of natural and technical systems
This is a cradle to gate analysis. The collection of textile waste for each of the alternatives is considered as cradle because the material has very little if any financial value prior to that point. The study stops at the yarn production which is the gate. The reason behind this is that downstream of the yarn recycling process the supply chain does not change any further. This is consistent with the goals of identifying the difference that recycled materials make to the whole production and also to find where the recycled supply chain can be improved.

Geographical and temporal boundaries
Geographically, the research concerns the European Union where most of the processes take place, Japan for the recycled PET from bottles production and other countries for cotton fibre production (China, India, Turkey, Pakistan). The time of the study is 2016.

Impact categories
Characterisation factors for the environmental impact categories selected in this study were taken from the CML 2001-Apr. 2010 impact assessment method as listed in Table 2. This is not the current version of the CML factors. This older version from the CML impact categories was selected for the compatibility of the methodology with LCA characterisation data used in earlier studies. In these categories, total freshwater consumption was selected in some of the

case studies in order to show the impacts of reducing virgin cotton production. Due to the use of different characterisation factors for the LCA data, there was a lot of uncertainty about the contribution of different data to environmental impact in the toxicity and abiotic depletion categories. Therefore, these toxicity categories are excluded from the research.

Table 2: Impact categories for the Life Cycle Assessment

Impact Category	Unit/Indicator
Acidification	kg SO_2-Eq.
Eutrophication	kg phosphate-Eq.
Global warming, excl biogenic	kg CO_2- Eq.
Total freshwater consumption	kg

Cut-offs, major assumptions and limitations

Cut-offs and assumptions were made for the study because of relevance to the goal, contribution to mass, energy use and environmental relevance. Capital goods and personnel are not included in the system and materials that are recycled or valuable products of processes are also out of the system boundaries. In order to focus on the impacts of the inputs of recycled versus virgin materials same spinning process and delivery truck type (Euro 5) were used. Furthermore, packaging materials were excluded from the system.

Multifunctional processes and allocation

Garment to garment recycling, apart from displacing virgin fibres production, also deals with the problem of waste management. Thus, it can be concluded that both high value recycling and downcycling have two functions: 1) waste management 2) production of fibres. Here lies an allocation problem, as to how the total environmental burden should be divided between these functions. I addressed this problem through substitution as suggested by ISO: The total impact of garment to garment recycling is calculated in this research by accounting for the environmental impacts of the recycling process itself minus the avoided impacts from waste management. As described in the introduction, the most common waste management processes in Europe are incineration with energy recovery and landfill. Incineration with energy recovery, which is less impactful than landfill, was chosen in our research. This is a conservative option with regard to the benefits of recycling, because avoiding incineration with energy recovery provides less benefit to the recycling system than avoiding landfill.

The sorting process also has two functions: separating garments/textiles for reuse and separating textiles for recycling. In order to avoid unnecessary complexity for this part of the system, I chose allocation by partitioning. I considered two ways of performing this: economic allocation and allocation by mass. In the first case, there is an argument that the sorting process is done primarily with the reuse as the main business activity. Indeed, the biggest value textile collectors get is by selling used textiles. Selling the recyclable fraction gives little income. Thus, in this case the argument is that since the reuse fraction is the reason this process takes place, it should carry the environmental burden based on the value that is created.

However, the main purpose of this study is not to assess the environmental impact of reuse, but to explore the possibilities of directing the recyclable fraction into higher value products. Thus, in this case, this part would be sold at a higher price. And it would make business sense to recycle. This also provides a more conservative estimate of the benefits of high value recycling. Thus, I used allocation by mass for the outputs of the sorting process.

Functional Unit

As mentioned in paragraph 1.5 this research is intended to provide information for decision-makers in the fashion industry, who understand and measure yarns in terms of length. For this reason, as functional unit 1 km of recycled yarn 25Nm (400 dtex) was chosen. The alternatives in each case were 1 km of recycled yarn and 1km of yarn produced from virgin materials. The colour and the composition of each yarn changes per case study as described in detail over the next chapters.

Function: Yarn suitable for textile production
Functional Unit: 1 km of yarn of 25 [1]Nm (400 [2]dtex)

3.3 Collection and sorting of post-consumer textiles

Data on textile collection were gathered through a series of interviews with a Dutch sorting company. This included data on the origin of the textiles, the energy consumed by transportation and the amount of total textiles collected and sorted per year (Table 3). The percentage of waste as seen in the table refers to non-textile material being disposed by individuals in the textile collection bins for various reasons. This waste is incinerated with energy recovery. The company performs textile collection in the Netherlands, Belgium, Luxembourg, Northern France and western Germany, but their main sorting facilities are located in the Netherlands. As a result, these facilities receive a mix of used textiles from all the above-mentioned countries.

The first step in the process is the collection of textiles from each country to a collection centre. Textiles from different provinces in the Netherlands are collected in the transhipment address, and then sent to the sorting facilities. In Netherlands this is located in the middle of the country, and for the rest of the countries, it was assumed that they are similarly located in central places. As mentioned above, textiles from the other countries are transported from the central collection places to the sorting facilities in the Netherlands.

Vans are used to collect textiles from special bins around the Dutch provinces. This corresponds to approx. 75 % of the collection, while 25 % is bought from companies, including a small fraction of door-to-door collection. It is assumed that in the other countries, the collection occurs in a similar manner.

In the sorting facilities, non-textile products from the collection are removed and sent to incineration. The rest of the textiles are sent to the sorting facilities, where skilled personnel aided by machinery sort approximately 90 tonnes a day shows the sorting fractions from the facility, of which 21 % is recyclable (Table 4).

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[1] Number metric or the ”metric yarns number” is the length of a yarn that weighs 1 gram.

[2] Decitex (or dtex) is the count grading for filament and spinning yarns recognised by all international bodies in the synthetic fibres industry. 1 dtex is the mass of yarn in grams per 10000 metres length.

Table 3: Energy and material flows for textile collection

Transportation to Collection Facilities		
Inputs		
Diesel	0.008	kg
Used Textiles	0.426	kg
Outputs		
Used Textiles	0.426	kg
Collection Facilities		
Inputs		
Used Textiles	0.426	kg
Electricity	0.008	MJ
Outputs		
Used Textiles	0.426	kg
Transportation to Sorting Facilities		
Inputs		
Used Textiles	0.426	kg
Diesel	0.017	kg
Outputs		
Used Textiles	0.426	kg
Sorting Facilities		
Inputs		
Used Textiles	0.426	kg
Electricity	0.0260	MJ
Thermal energy	0.0003	MJ
Outputs		
Wipers	0.071	kg
Shoes (Reuse)	0.028	kg
Textile Waste	0.024	kg
Textiles (Reuse)	0.208	kg
Textiles (Recycling)	0.09	kg

Table 4: Fraction of the textile sorting

Category	Article group	Percentage
Reusable	Export (different qualities)	49%
Non-reusable	Wipers	17%
	Recycling	21%
Shoes (reusable and not reusable)	Shoes	7%
Waste	Waste	6%

3.4 Mechanical Recycling

The flowchart below describes the recycling process of Hilaturas Ferre / Recover, the mechanical recycler that participated in the research, which can be summarised in three steps as shown in Figure 6. Non-recyclable pieces of garments such as zippers and buttons are removed by a partner of the recycling company in a process called “cleaning”. The cleaned material is then cut and pulled into fibres. Recycled fibres can then be blended with virgin fibres. The totally homogenized fibres are then carded, i.e. disentangled and processed into a continuous web and spun into yarn.

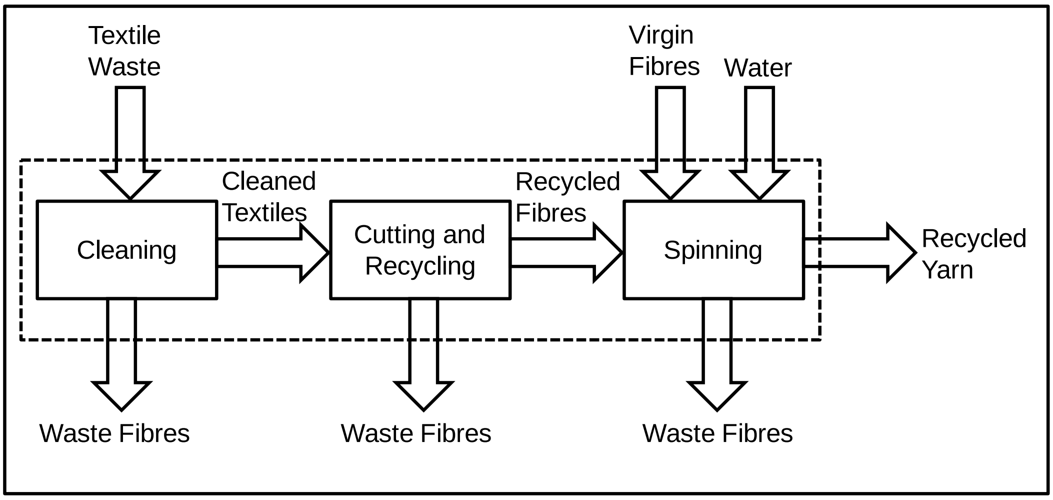


Figure 6: Process flowchart for mechanical recycling

Table 5: Material and energy flows for mechanical recycling

Pre-processing		
Inputs		
Sorted and bailed textiles	0.022	kg
Electricity	0.039	MJ
Outputs		
Clips for recycling[3]	0.014	kg
Zippers, buttons and labels (waste)	0.008	Kg
Cutting and Recycling		
Inputs		
Electricity	0.020	MJ
Clips for recycling	0.0140	kg
Outputs		
Recycled fibres	0.013	kg
Textile waste	0.0005	kg
Spinning (Recover) Parameters		
Inputs		
Water	0.212	kg

---

[3] Depends on the percentage of waste from the cleaning process.

Recycled fibres [4]	0.013	kg
Electricity	0.358	MJ
Virgin fibres[2]	0.031	kg
Outputs		
Yarn	0.04	kg
Waste short fibres	0.003	kg
Microfibres/dust	0.002	kg

3.5 Automated sorting based on material for post-consumer textiles

A near infra-red detector can be used to automate the sorting of textile wastes into different fractions based on their materials. This technique is on the verge of being commercialised. Data for this process was taken from a start-up collaborating on the thesis project. The facilities were assumed to be located in Düsseldorf, Germany, which is the target location for the factory. Energy production and other background processes were adjusted accordingly using the GaBi Education database (2016).

The garments that are fed to the machine can be categorised as either single-material or multi-material. Single-material garments are made from one type of fabric with the same material composition. Multi-material garments consist of fabrics of different material compositions, for example coats that have different fabrics as linings. Multi-material garments cannot be detected by the machine. Therefore, textile flows that are known to be only single-material are directly fed to the machine while multi-material and unknown flows are sorted manually first. The output in Table 6 is an average mix of different textiles from the first test of the machine.

Table 6 Material and energy flows for automated textile sorting by fibre composition

Automated Sorting		
Inputs		
Textiles	2011	kg
Electricity	165	MJ
Outputs		
Mechanical recycling blend	121	kg
PET recycling blend	201	kg
Viscose textiles	20	kg
Acrylic textiles	40	kg
Nylon textiles	20	kg
Poly-cotton textiles	201	kg

---

[4] Depends on the percentage of fibres. For 0.04 kg of recycled yarn, 0.4 kg of input is required, independent of whether it is recycled or not. The electricity consumption depends on the dtex, not on whether the fibres are recycled or not, or the material.

Cotton textiles	1005	kg
Textiles (unspecific)	161	kg
Polyester textiles	141	kg
Wool textiles	60	kg
Other textiles	40	kg

3.6 Chemical recycling

In chemical recycling, the fibres in the textiles are broken down to the molecular level and the feedstock is repolymerised (Fletcher, 2008) before passing through a spinneret to generate new fibre to be spun into yarn, ready for weaving or knitting into fabric (Payne, 2014). In contrast to mechanical recycling, the end product results in a higher quality fibre that can have high equivalence to virgin fibre. The data for this technology were provided by a start-up in the field.

The company uses fabric of high cellulose content to produce dissolving pulp. The market direction for the pulp is towards the commercial textile production supply chain. This dissolving pulp can be used as raw material for different products, but the main purpose is for the production of textile fibres such as viscose and Lyocell. This pulp today is made from trees (for example by Lenzing, Södraetc).The chemical recycling process is described in Table 7.

Table 7 Chemical Recycling Process

Recycling Steps	Description
Pre-treatment and shredding	The sorted textiles are shredded and non-textile components are removed with conventional shredding and separation technology
De-dyeing step	A large fraction of the dyes are solubilised in a reductive alkaline step and removed in the subsequent washing step.
Bleaching step	The remaining coloured components are bleached. After this step the material is practically white and similar to pulp in appearance.
Viscosity adjustment step	The viscosity, or degree of polymerisation, is adjusted to suit customer demands by treating the material in a specific environment
Fibre separation steps	The non-cellulosic fibres are separated from the material in two separation steps there by purifying the cellulosic pulp from contaminants.
Final washing and drying	The fibres are washed once more to remove process chemicals. The pulp is then finally dried into a dry product ready to be shipped to customers.

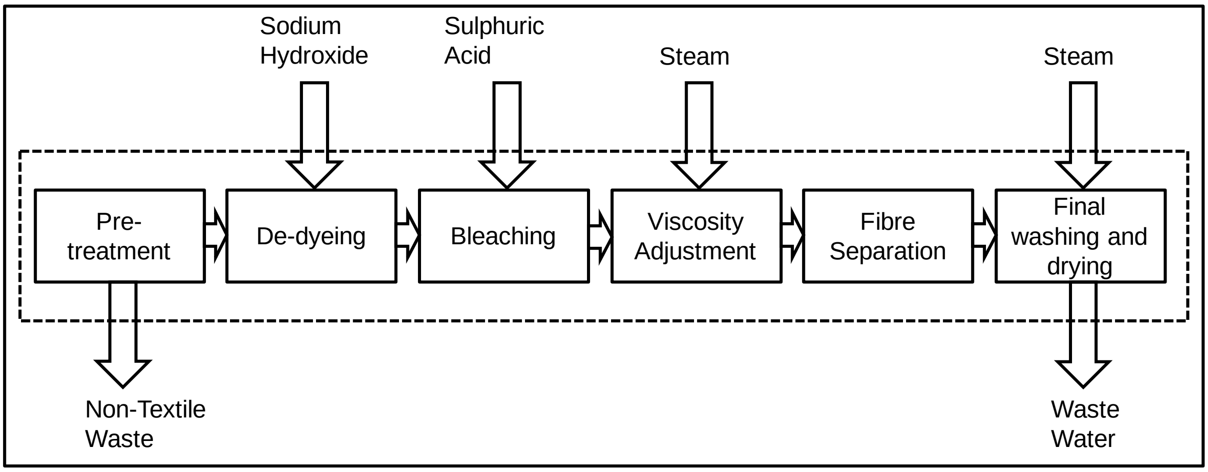


Figure 7: Process flowchart for chemical recycling

Table 8: Energy and material flows for chemical recycling

Pre-treatment and shredding		
Inputs		
Cotton-based textiles	1056	kg
Electricity	352	MJ
Outputs		
Shredded textiles	1014	kg
Waste incineration of textile fraction MSW*	42	kg
De-dying step		
Inputs		
Water	2406	kg
Shredded textiles	1014	kg
Sodium hydroxide	26	kg
Electricity	9	MJ
Outputs		
De-dyed, pulped textiles	3420	kg
Bleaching step		
Inputs		
De-dyed, pulped textiles	3420	kg
Water	114	kg
Electricity	55	MJ
Sulphuric acid	20	kg
Outputs		
De-dyed, bleached textile pulp	3581	kg
Viscosity adjustment step		
Inputs		
De-dyed, bleached textile pulp	3581	kg
Steam	178	kg
Electricity	40	MJ
Outputs		

Unfiltered pulp	3581.79	kg
Fibre separation steps		
Inputs		
Unfiltered pulp	3581	kg
Electricity	9	MJ
Outputs		
Filtered pulp	3581	kg
Waste incineration of textile fraction in MSW*	360	kg
Final washing and drying		
Inputs		
Filtered pulp	3581	kg
Water	2801	kg
Steam	867	kg
Electricity	91	MJ
Outputs		
Finished Bailer Pulp	1000	kg
Waste water to treatment	5382	kg

*Municipal Solid Waste

The chemical recycling start-up provided energy and material flows data for their process. Other energy and solvent production data were used from the database GaBi Education.

3.7 Base Case: virgin yarn production process for all the case studies

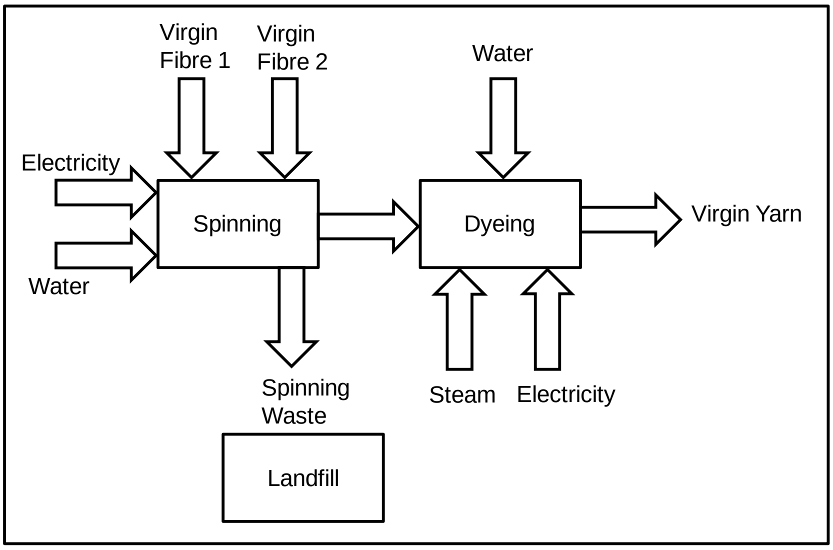


Figure 8: Process flowchart for Virgin Yarn Production

Process description

The production of virgin yarn in all case studies was modelled after the same spinning process, in order to enable comparison with the alternative recycled yarns. In this case, the virgin fibre raw materials of each case study are mixed, spun into yarn and dyed to the desired colour when necessary. The result is virgin yarn of different composition each time, ready to be sent to weaving or knitting.

Table 9: Virgin Yarn composition for each case study

Case Study	Composition (%)			Dyeing
	Virgin Cotton	**Virgin PET**	**Virgin Viscose**	
Downcycling	40	60		Yes
Denim	100	-	-	No
Mixed	61.25	38.75		Yes
Viscose	-	-	100	No

3.8 Incineration with energy recovery

As described in the Scope Section of this chapter, garment to garment recycling, apart from displacing virgin fibres production, also deals with the problem of waste management. Incineration with energy recovery, which is less impactful than landfill, was chosen in our research as the replaced waste management process. The flowchart for this process is depicted below.

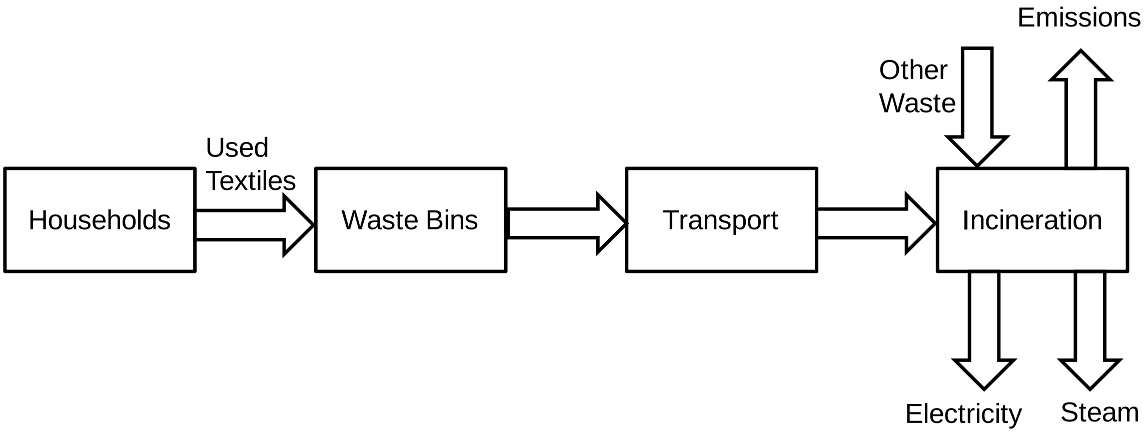


Figure 9: Flowchart for incineration with energy recovery

Incineration with energy recovery replaces energy produced in the system elsewhere, in this case, electricity and steam. Two countries were taken into account, Netherlands, where most of the research was based in and Sweden, where Chalmers University is based. The other reason for picking those countries was their very different means for producing electricity. As seen from Figure 10, Sweden has a 90 % carbon-free electricity mix, with most of its energy being produced from Hydro and Nuclear Power Plants. In contrast, approximately 80% of the Dutch electricity mix is derived from burning coal or natural (petrochemical) gas.

For steam production, data from GaBi education database was used, assuming production from natural gas which is the same for both cases. From Table 10 it seems that incineration with energy recovery in the Netherlands has negative carbon footprint and better overall performance in the other categories, which means that the energy produced by the process has lower impact than if it would have been produced by the Dutch electricity system. On the contrary, in mostly carbon-free Swedish electricity, there is an energy penalty for incineration, leading to more emissions, than if this energy was produced by the Swedish system. Due to lack of data for PET incineration and cotton incineration a process for textile incineration from the GaBi database, which includes a mix of different textile fraction was used for each case. In order to make conservative estimates for the benefits of recycling, the Dutch incineration process was used and the Swedish one is discussed in the sensitivity analysis.

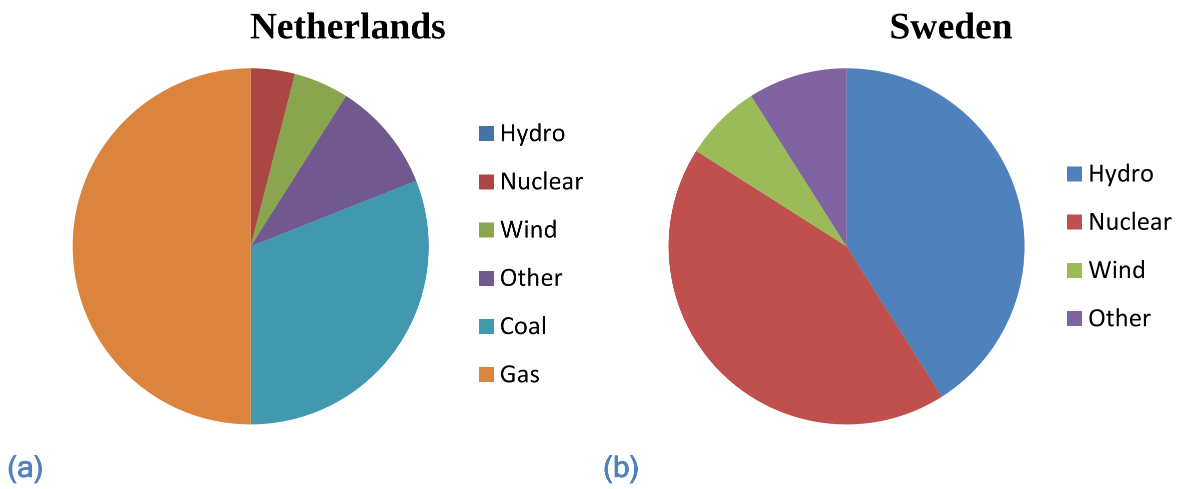


Figure 10: (a) Dutch Electricity Production by source on the left (IEA 2014) (b) Swedish Electricity Production by source on the right (Swedish Energy Agency 2015)

Table 10: Environmental impact of incineration with energy recovery for Netherlands and Sweden (per 40 g of textile waste, which is the weight of our functional unit, 1 km yarn 400 dtex).

Impact Categories	Impact Indicators	Netherlands	Sweden
Acidification	kg SO_2-Eq.	1.81E-05	3.1E-05
Eutrophication	kg Phosphate-Eq.	4.5E-06	7.5E-06
Global Warming, excl biogenic	kg CO_2- Eq.	-0.012	1.7E-03
Total freshwater consumption	Kg	-0.010	0.165

3.9 Data collection and assumptions

Textile fibre production

To ensure the robustness of the results, different data sources of were used with regard to virgin cotton production, including data from Babu *et al*, 2013 from conventional cotton from India, Cotton Incorporated (2012) and from the Ecoinvent 2.2 database. The Indian conventional cotton data were used as the main source, on the basis that this cotton is the best performer among the three, for most of the categories, and therefore a conservative choice when evaluating alternatives to virgin cotton. The Ecoinvent and Cotton Incorporated data were used to recalculate the impacts for the sensitivity analysis.

Table 11: List of characterised impacts for different types of cotton fibre 1 Kg

Impact Category	Ecoinvent	Cotton Inc.	Conv. Cotton India	Unit
Eutrophication	0.0261	0.00384	0.00289	kg PO4-Eq
Acidification	0.0445	0.0187	0.0115	kg SO2-Eq
Climate change excl. biogenic CO_2	1.94	0.268	1.32	kg CO2-Eq
Total freshwater Consumption	6.81	2.74	2.61	m^3

For the virgin production of polyester fibres, data from GaBi Education Database was used as well as LCI data from Kalliala and Nousiainen, (1999) for the sensitivity analysis. For viscose fibre production, LCA characterisation data from the Ecoinvent 2.2 database (2002) was used and for the dissolved pulp production characterisation data from Garcia et. al, 2011, as well as Ecoinvent for the sensitivity analysis.

Table 12: Dissolved pulp LCA characterised impacts

Category	Ecoinvent	Garcia et al.	Unit
Eutrophication	0.00143	0.00174	kg PO4-Eq
Acidification	0.00415	0.00555	kg SO2-Eq
Climate Change	0.44	0.415	kg CO2-Eq

Data for recycled PET (polyester) from bottles were taken from the report by Franklin Associates (2011). The recycled PET fibres were assumed to be transported from Japan where one of the companies that produces them is located, to the mechanical recycler by truck. The flowchart below explains the process of manufacturing recycled PET from used bottles.

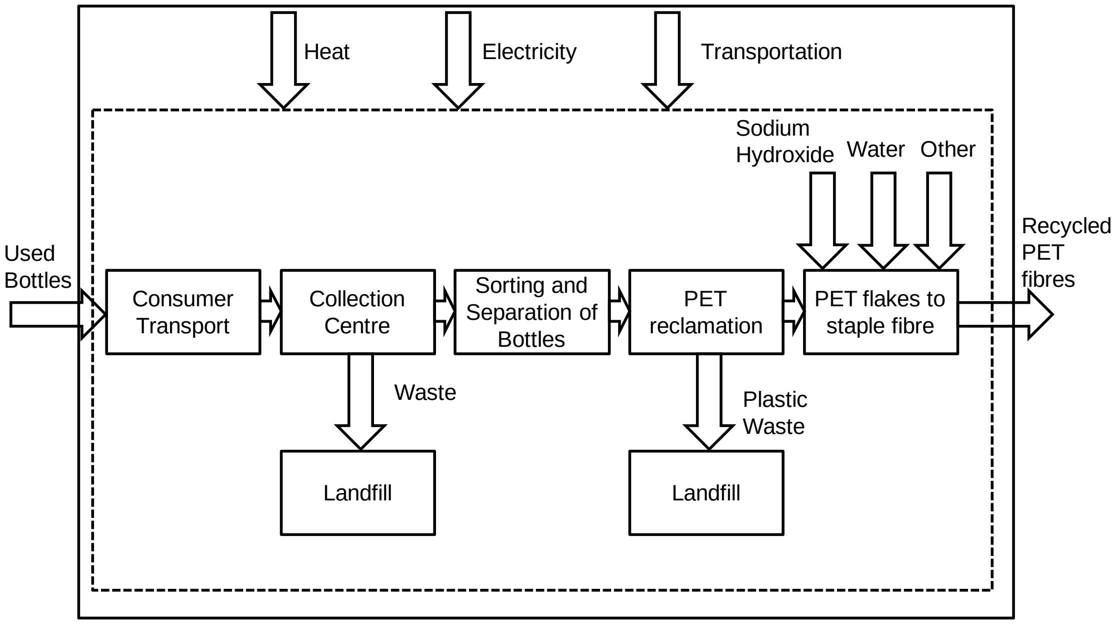


Figure 11: Process Flowchart for recycled PET from bottles

Mechanical recycling and spinning

Energy and material data for mechanical recycling and spinning processes were collected in all cases by a mechanical recycling company through a series of interviews with their technology specialist. The waste is not incinerated, and owing to lack of other information, I assumed that the treatment is landfill without energy recovery. For this project data from the GaBi database was used for landfill.

Blanket Case: collection and sorting

The process flowchart and data collection was completed through interviews with the company's management. Due to lack of data for manual sorting and safe destruction, assumptions were made for the energy use of the buildings based on data from the Dutch collection company involved. For the small baling machine, calculations where made from a Chinese product (Bobo Machine) that resembled the description of the Blanket case machine. Thermal energy produced from the incineration of the waste material was returned to the system and deducted from the energy requirements.

Denim Case: collection and sorting

I assumed that the storage in this case did not have any energy consumption. For the sorting and baling, assumptions were made about the energy and material requirements of the facilities based on the Dutch collection company.

Dyeing

With regard to dyeing, data from Roos *et al.* (2015) for the dyeing of denim yarn, which was the closest dataset available, was used. Some flows were discarded due to lack of characterisation factors, but the major material and energy flows were accounted for. A large amount of waste is produced via this method: 0.5 kg per kg of dyed yarn.

4. The Denim Case

4.1 System description for the denim system

Unsold denim garments returned from a fashion brand’s retail shops are processed into recycled fibres and blended with virgin fibres in order to produce yarn for new denim garments. The unsold garments from the brand’s storage are transported by truck to a company where they are sorted and baled in order to be sent to the facilities of mechanical recycler Hilaturas Ferre / Recover as seen in Figure 12.The baled textiles are opened and the zippers, labels and other non-recyclable material are removed. This leads to a waste up to the loss of 30 % of the original mass, which is sent to landfill. The textile fraction is recycled into fibre which is mixed with virgin cotton fibres and spun into new yarns, 25 Nm (400 dtex). The final composition of the yarns is 30 % recycled fibres and 70 % virgin cotton fibres. In the spinning process, waste is also produced in the form of microfibres and waste short fibres. No dyeing is required for the production of this yarn. The yarns are then sent to a weaving mill in Turkey for the production of new denim products. Then they are woven and the final fabric composition is 40 % recycled yarn which is used in the weft and 60 % virgin yarn. For the virgin cotton I assume that it is delivered from Turkey and a distance of 3500 km covered by truck is included in the calculations.

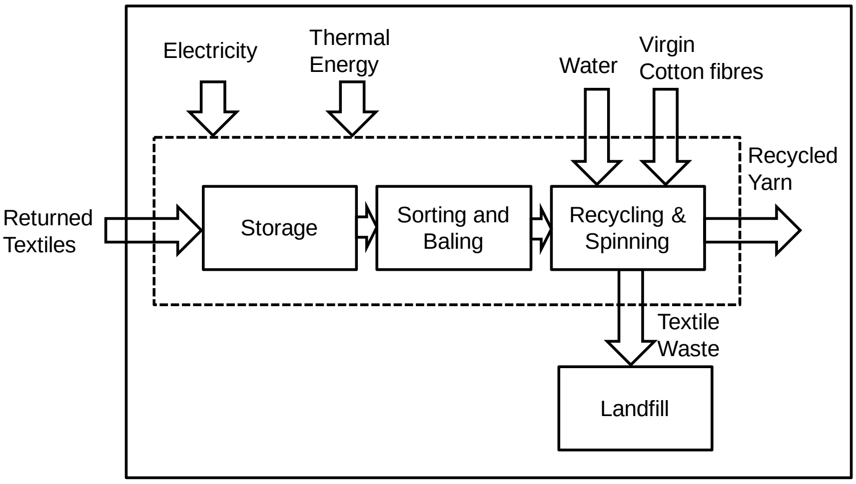


Figure 12: Process flowchart of the recycled yarn production for the Denim case.

4.2 Life Cycle Assessment for the Denim Case

Function: Provision of uncoloured yarn suitable for use in the weft of denim fabric. The weft is the weaving term for the thread or yarn which is drawn through the warp yarns to create cloth [(Burnham, 1980), Barber, 1991)] as seen in Figure 13.

Functional Unit: 1 km of uncoloured cotton yarn of 25 Nm (400 dtex).
Virgin Alternative: 1 km of uncoloured yarn of 25 Nm (400 dtex) with composition 100 % virgin cotton.

Recycled Alternative: 1 km of uncoloured yarn of 25 Nm (400 dtex) with composition 30 % recycled cotton and 70 % virgin cotton.

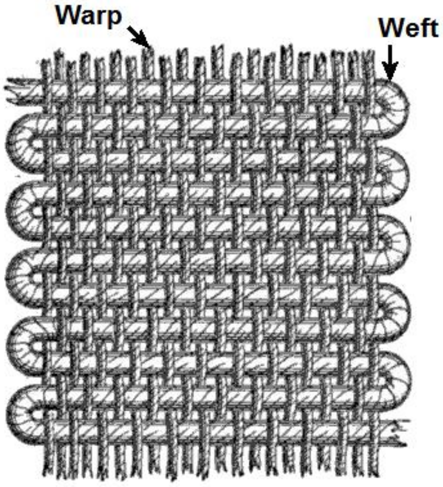


Figure 13: Demonstration of how the warp and weft yarns are creating the fabric (Wikimedia Commons)

Table 13: Yarn compositions for the Denim case alternatives

Input Materials	Alternatives	
	Virgin yarn	**Recycled Yarn**
Virgin Cotton	**100 %**	**70 %**
Recycled Cotton	-	**30 %**

Comparative analysis for the Denim Case

The LCA results for the recycled yarn and the virgin yarn equivalent of the Denim case are presented below. For the calculation of life cycle indicators of the potential impacts, the CML (2001-2010) method was used. The results reflect the potential environmental impacts per km of textile yarn 400 dtex.

Table 14: Environmental Impact Results for the Denim Case

Impact Categories	Impact Indicator	Virgin Yarn	Recycled Yarn	Difference (%)
Acidification	kg SO_2-Eq.	7.61E-04	5.87E-04	22.9
Eutrophication	kg Phosphate-Eq.	1.56E-04	1.30E-04	16.3
Global Warming, excl biogenic	kg CO_2- Eq.	1.17E-01	1.16E-01	0.6
Total freshwater consumption	kg	116.9	82.1	29.7

The recycled yarn has less 16 - 30 % less environmental impact in the acidification, eutrophication and water consumption impact categories, which is expected from the 30 % reduction of virgin cotton input. On the other hand, there is less than 1 % difference in global warming (Table 14 and Figure 14). A contribution analysis from each of the alternative explains the reasons behind this.

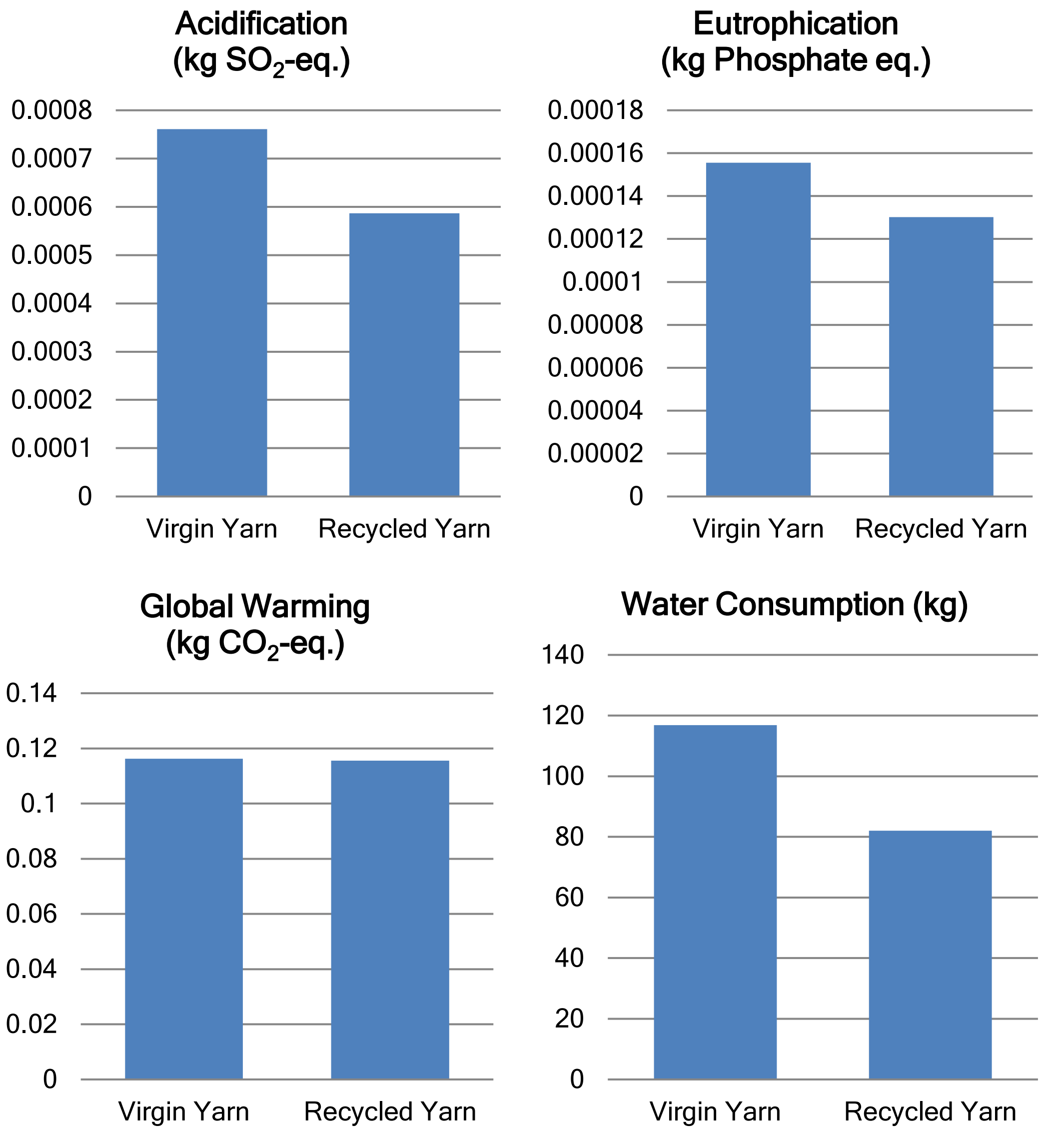


Figure 14: Environmental impact results for the alternatives of the Denim case

Contribution analysis for the Denim Case

In both cases, electricity and conventional cotton are the biggest contributors to global warming, 37 % and 50 % for the virgin yarn and 45 % and 37 % for the recycled one respectively. Most of the emissions from the electricity derive from the hard coal which is part of the grid production. In the recycled case, landfill from cleaning waste is the third contributor, with 6 %. However, as seen from Table 14, the global warming impacts are virtually the same. This can be attributed to energy required for the collection and recycling of the textiles and from emissions from the landfill.

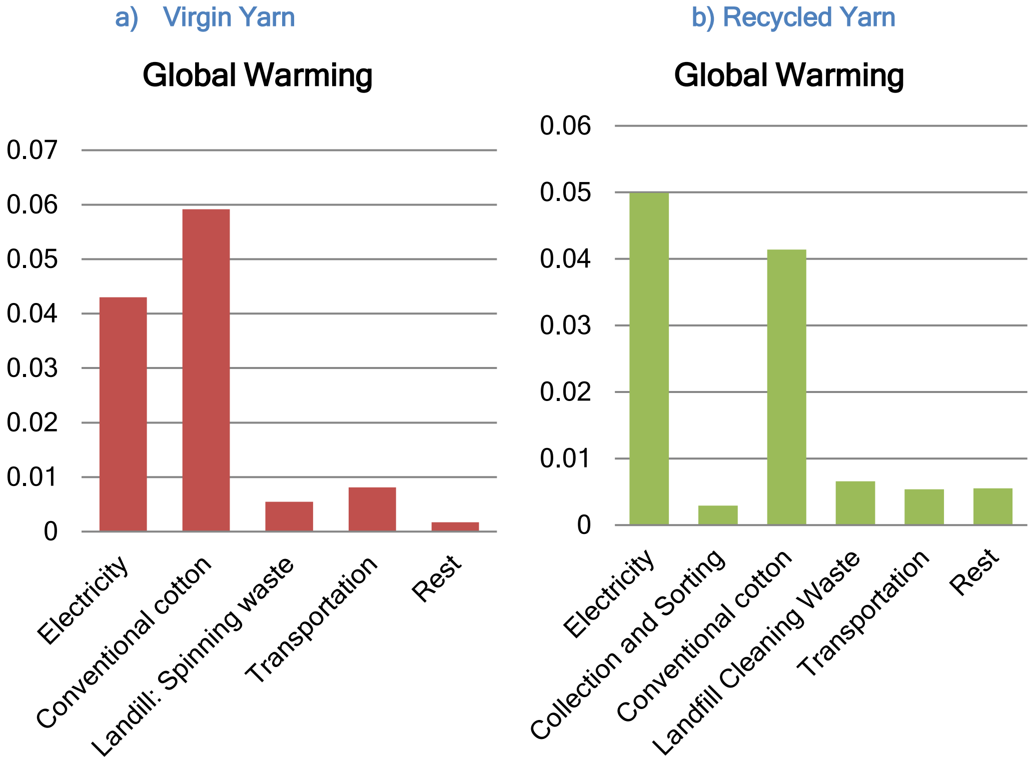


Figure 15: Contributing factors to global warming (kg CO_2-eq.) for the a) virgin and the b) recycled yarns. ”Collection and sorting” refers to the movement of textile waste for the purpose of recycling. “Transportation” refers to the movement of the rest of the materials (textile waste from spinning, virgin cotton, etc.)

Table 15 Denim Yarn: Contributing factors to global warming. ”Collection and sorting” refers to the movement of textile waste for the purpose of recycling. “Transportation” refers to the movement of other materials (textile waste from spinning, virgin cotton, etc.)

Virgin Yarn		Recycled Yarn	
Contributing Factor	**Contribution (%)**	**Contributing Factor**	**Contribution (%)**
Electricity	37	Electricity	45
Conventional cotton	50	Collection and Sorting	3
Landfill: spinning waste	5	Conventional cotton	37
Transportation	7	Landfill Cleaning Waste	6
Rest	1	Transportation	5
		Rest	5

Sensitivity analysis for the Denim Case

Since cotton is a major contributor in all impact categories, different datasets were used in the sensitivity analysis, to check whether the recycled yarn is still a better option. These datasets where from Ecoinvent 2.2 database which has a highest impact value for climate change, and from Cotton Incorporated (2012), which has the lowest I found in the literature. Climate change is the biggest environmental threat at the moment and carbon footprint is easily understood by stakeholders, thus the focus will be on this category.

Table 16: Sensitivity analysis of virgin cotton for the Denim case (kg CO_2-eq.).

Alternative	Cotton data		
	Babu et al. (2003)	**Cotton Incorporated (2009)**	**Ecoinvent 2.2**
Virgin	1.17E-01	6.9E-02	1.44E-01
Recycled	1.16E-01	9.1E-02	1.43E-01

By using different cotton datasets it is shown that the climate change impacts remain the same for *Babu et al.* and Ecoinvent 2.2. However, with Cotton Incorporated data, that show a more optimistic profile on the impacts of virgin cotton than the other studies, the difference is 32 % in favour of the virgin alternative. It can be concluded that the more impact the cotton production has, the more favourable the option of recycling becomes, in the case of climate change.

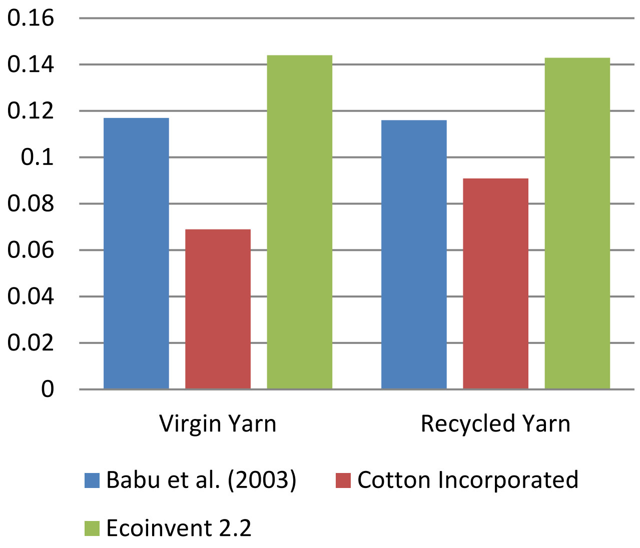


Figure 16 Sensitivity analysis for carbon footprint for the Denim Case (kg CO_2-eq.)

5. The Mixed Case

5.1 System description for the Mixed Case

This case involves recycling of the non-reusable fraction of post-consumer textiles into yarn for new garments. Post-consumer textiles from a Dutch collection and sorting company are first sorted into reusable (garments that can be worn again) and recyclable. The latter are sorted into three basic colours: white, denim and multi-colour.

The colour-sorted textiles are sent to mechanical recycler Hilaturas Ferre / Recover where they are stripped of non-recyclable pieces (17 % waste to landfill). The cleaned textiles are recycled they are afterwards blended with recycled PET from bottles and they are spun into new yarns. The final yarn composition is 70 % post-consumer yarn (87.5% cotton, 10.2% polyester and 2.2% others) and 30 % recycled PET. The recycled PET is assumed to be delivered from a company in Japan.

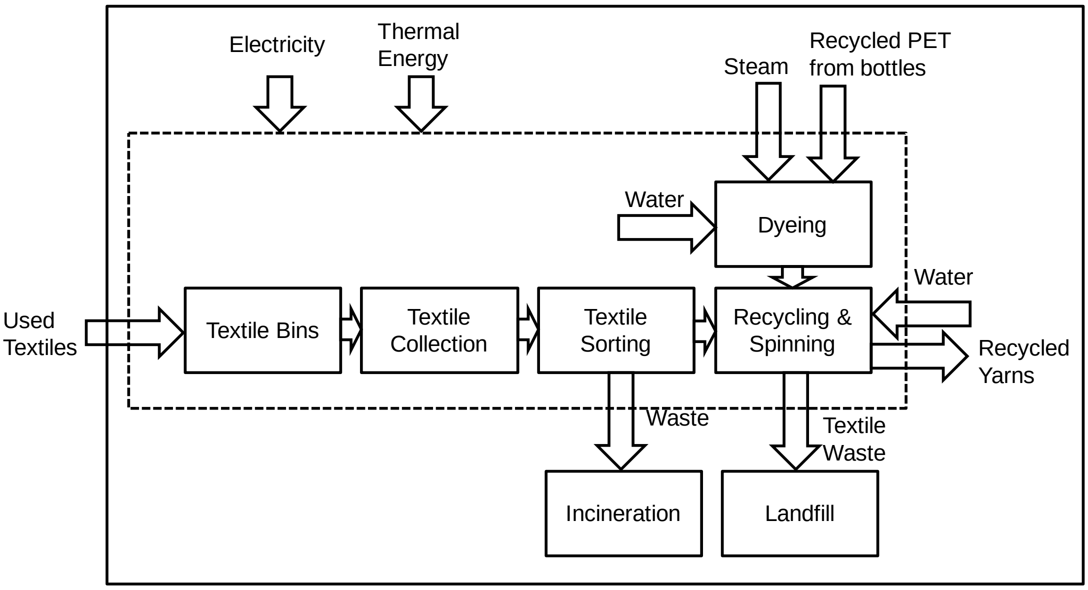


Figure 17: Process flowchart for the production of recycled yarn for the Mixed Case

By asking for colour-sorted post-consumer materials and mixing them according to the desired colour, the dyeing process that would be necessary otherwise with virgin raw materials is avoided. However, the 30 % recycled PET input requires dyeing. Finally, the yarns are transported to the Netherlands to weaving and knitting companies for the production of different types of textile products.

5.2 Life Cycle Assessment for the Mixed Case

Function: White yarn suitable for use in the production of textiles (clothing).
Functional Unit: 1 km of white yarn of 25 Nm (or 400 dtex) with composition 61.25 % cotton and 38.75 % polyester.

Virgin Alternative: 1 km of white virgin yarn of 25 Nm (or 400 dtex) with composition 61.25 % cotton and 38.75 % polyester.

Recycled Alternative: 1 km of white recycled yarn of 25 Nm (or 400 dtex) with composition 61.25 % cotton and 38.75 % polyester from 70 % recycled fibres from textiles and 30 % recycled PET fibres from used bottles.

Table 17: Yarn compositions for the Mixed Case alternatives

Input Materials		Alternatives	
		Virgin yarn	**Recycled Yarn**
Virgin cotton		**61.25 %**	**-**
Virgin PET		**38.75 %**	**-**
Post consumer material	*R-Cotton*	*-*	*87.5 %*
	R-PET	*-*	*12.5 %*
	Input	**-**	**70 %**
Bottle-to-fibre PET		**-**	**30 %**

Comparative analysis

The results from the comparative LCA for mechanical recycling of post-consumer garments into new garments versus the same process from virgin materials are listed in Table 18.

Table 18: Environmental Impacts for the Mixed case

Impact Categories	Impact Indicator	Virgin Yarn	Recycled Yarn	Difference (%)
Acidification	kg SO_2-Eq.	7.88E-04	2.72E-04	65.5
Eutrophication	kg Phosphate-Eq.	1.35E-04	6.65E-05	50.7
Global warming, excl biogenic	kg CO_2-Eq.	1.84E-01	1.22E-01	33.7
Total freshwater consumption	kg	7.25E+01	1.41E+00	98.0

For the collection and sorting, environmental impacts were allocated based on mass. Therefore, the 21 % of the recycled textile output corresponds to 21 % of the total emissions for the collection and sorting, since the other products are sold for other uses. The photochemical ozone creation was excluded as a category, due to the uncertainty of the data.

As seen from Table 18 and Figure 18, the recycled yarn has less environmental impact in all the categories. The recycled yarn shows reduction in acidification and eutrophication by 65.5 % and 50.7 % in comparison with the virgin equivalent yarn. It also has one third of the environmental impact, while the water consumption is 98.0 % less, which is expected due to the elimination of virgin cotton input.

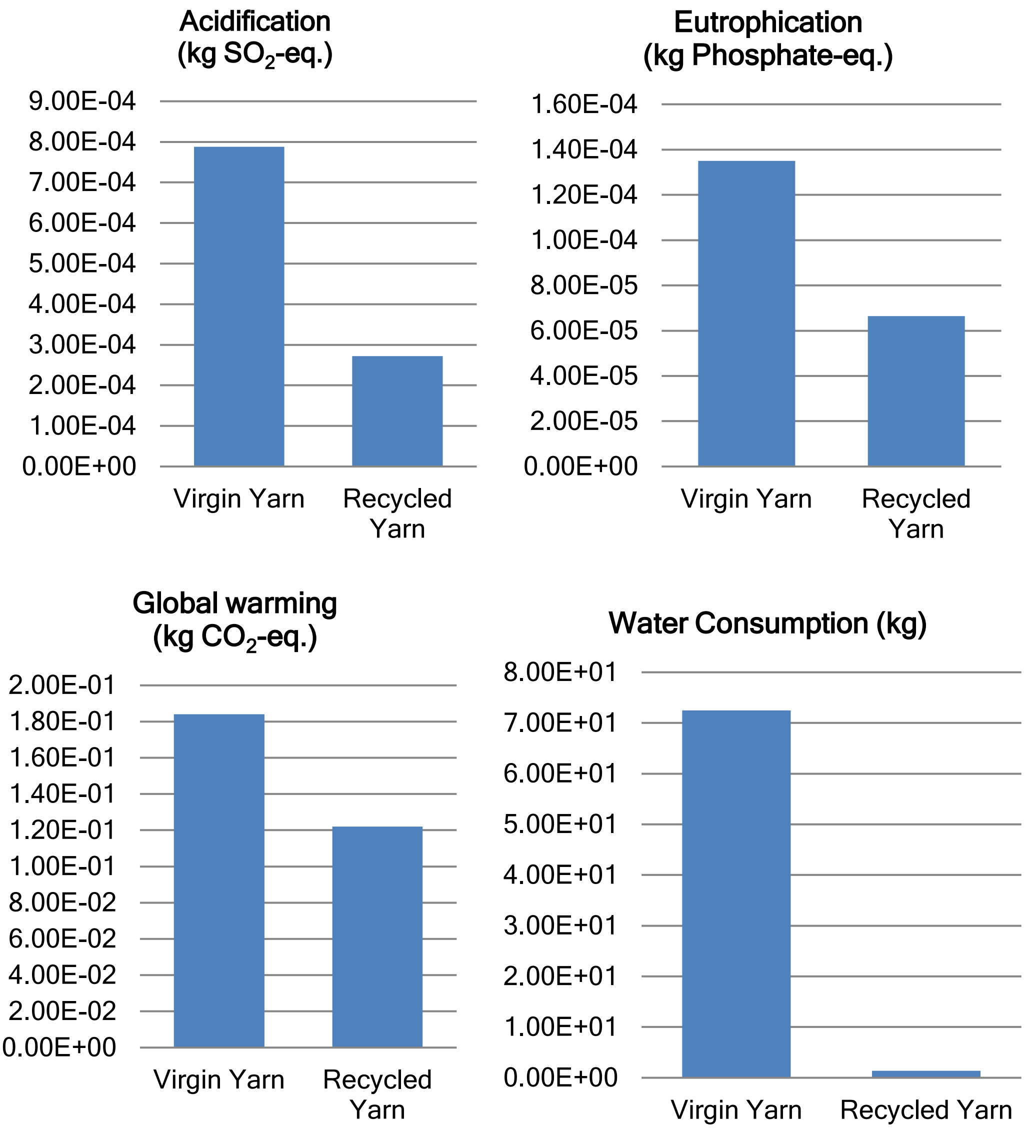


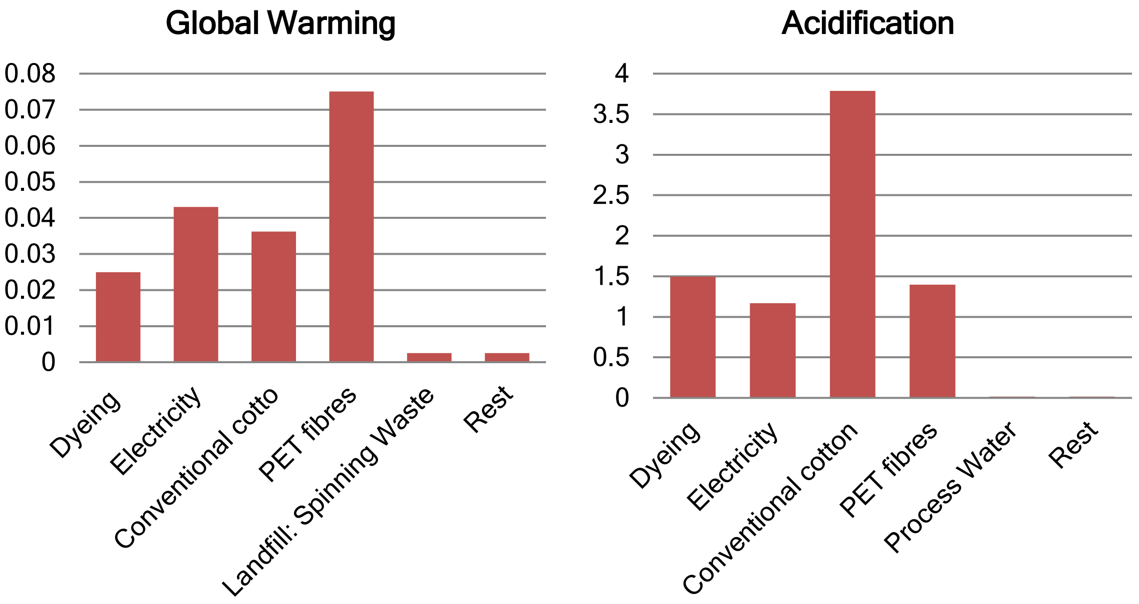
Figure 18: Environmental impacts for the Mixed case

Contribution analysis for the Mixed Case

The production of conventional cotton is the biggest contributing factor to acidification (48 %), followed by dyeing (19 %), PET fibre production (18 %) and electricity (15 %). In the recycled case, electricity (from spinning) creates the biggest impact (52 %) as well as dyeing (17 %) and recycling of PET fibres (14 %). This is consistent with the observations of Roos *et al* (2015) in relation to the production of virgin garments. However, the total impact is almost two thirds less that of the virgin yarn, attributed to elimination of virgin fibres and 70 % of which that does not require dyeing.

In the category of climate change, PET fibres dominate the emissions in the virgin yarn (41 %), followed by conventional cotton (20 %), electricity (mainly spinning) (23 %) and dyeing (14 %). In the recycled case, electricity from spinning is the biggest impact (53 %), followed by recycled PET fibres from bottle (18 %). Dyeing, collection and sorting and landfill of cleaning waste (which is 17 % in comparison with the other studies which is around 30-35 %) are the other contributing factors. The conclusions are that the replacements of PET and cotton fibres with recycled material reduces emissions, even if we include the energy required for collection, sorting and recycling of post-consumer textiles.

a) Virgin Yarn



b) Recycled Yarn

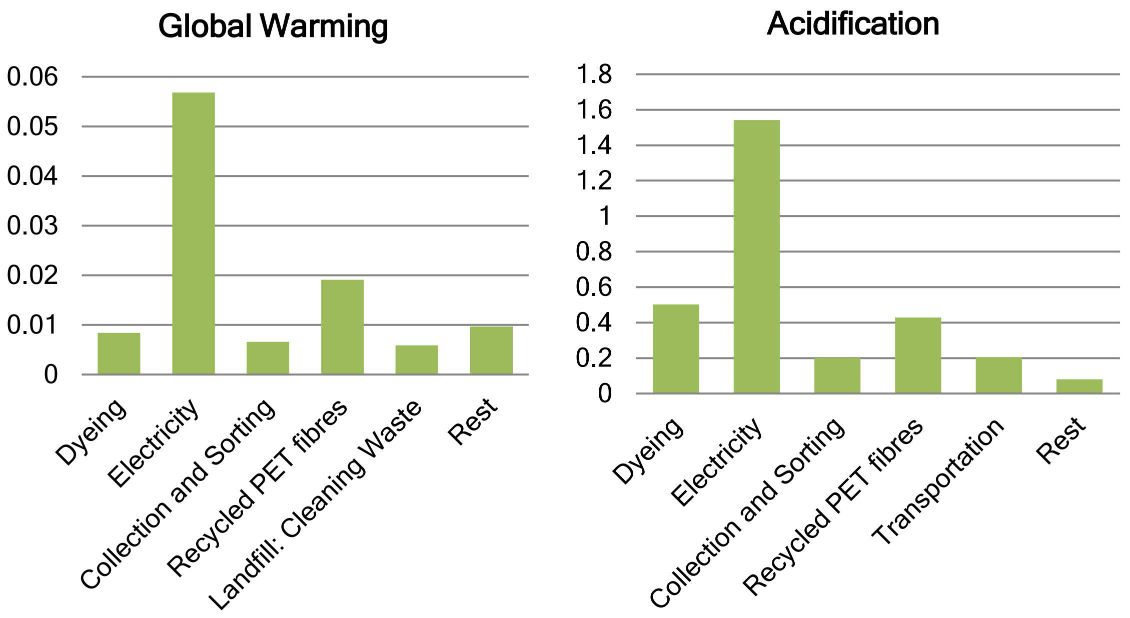


Figure 19: Contributing factors to acidification (kg SO_2-eq.) and global warming (kg CO2-eq.)for the a) virgin yarn (above) and the b) recycled yarn (below). ”Collection and sorting” refers to the movement of textile waste for the purpose of recycling. “Transportation” refers to the movement of the rest of the materials (textile waste from spinning, virgin cotton, etc.)

Table 19 Mixed Case: Contributing Factors to Climate Change

Virgin Yarn		Recycled Yarn	
Contributing Factor	**Contribution (%)**	**Contributing Factor**	**Contribution (%)**
Dyeing	14	Dyeing	8
Electricity	23	Electricity	53
Conventional cotton	20	Collection and Sorting	6
PET fibres	41	Recycled PET fibres	18
Landfill: Spinning Waste	1	Landfill: Cleaning Waste	6
Rest	1	Rest	9

Table 20 Mixed Case: Contributing Factors to Acidification. "Collection and sorting" refers to the movement of textile waste for the purpose of recycling. "Transportation" refers to the movement of the rest of the materials (textile waste from spinning, virgin cotton, etc.)

Virgin Yarn		Recycled Yarn	
Contributing Factor	Contribution (%)	Contributing Factor	Contribution (%)
Dyeing	19	Dyeing	17
Electricity	15	Electricity	52
Conventional cotton	48	Collection and Sorting	7
PET fibres	18	Recycled PET fibres	14
Process Water	0	Transportation	7
Rest	0	Rest	3

Sensitivity analysis for the Mixed Case

The PET fibres dominate the greenhouse gas emissions in the virgin yarn case, and overall these emissions are higher than the recycled alternative. To test the robustness of the results, LCI data from another PET production process with a more optimistic view on the final impacts were used. The results were then recalculated in order to test whether the recycled yarn is still a better alternative.

Table 21: Sensitivity Analysis for contribution of PET to climate change in the Mixed case per km of yarn

Alternative	PET dataset	
	GABI Database (2016)	**Kalliala and Nousiainen, 1999**
Virgin	1.84E-01 kg CO_2-eq.	1.49E-01 kg CO_2-eq.
Recycled	1.18E-01 kg CO_2-eq.	

Table 21 shows that even when compared with the more optimistic data for PET fibre production, the recycled yarn remains a better alternative in terms of climate change impact.

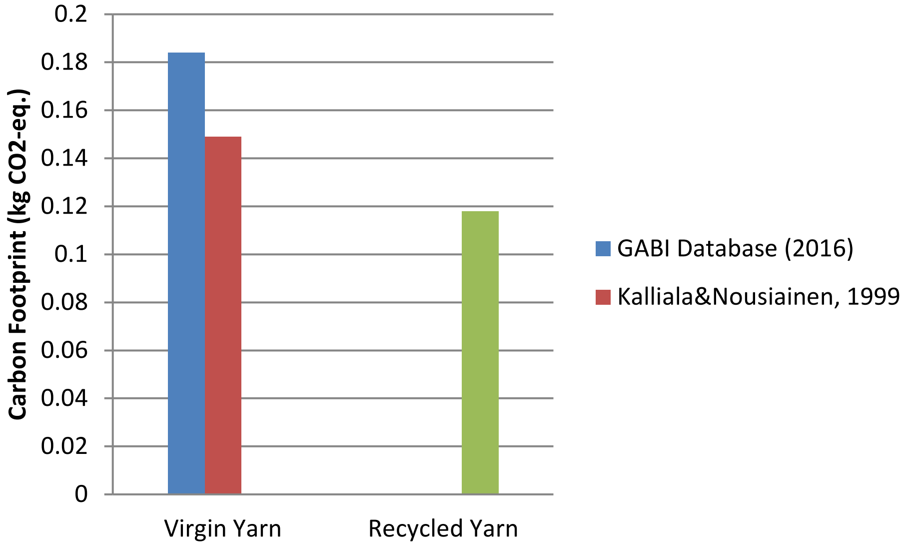


Figure 20:Sensitivity analysis for contribution of PET to climate change in the Mixed case per km of yarn

6. The Viscose case

6.1 System description for the Viscose Case

Cotton-based textiles are recycled into viscose yarn in order to produce new garments. Used textiles are collected from special bins by a company in the Netherlands and they are sorted on reusable and recyclable items. The recyclable materials are further sent to an automated material sorting company in Germany, where they are sorted on cotton, which is the preferred material for the Viscose process.

The sorted cotton textiles are sent to the chemical recycling facilities where they are processed into dissolved pulp as described in Chapter 3. The pulp is sent afterwards to another company in Germany which produces viscose fibre. Finally, the fibres are sent to be spun into recycled viscose yarn.

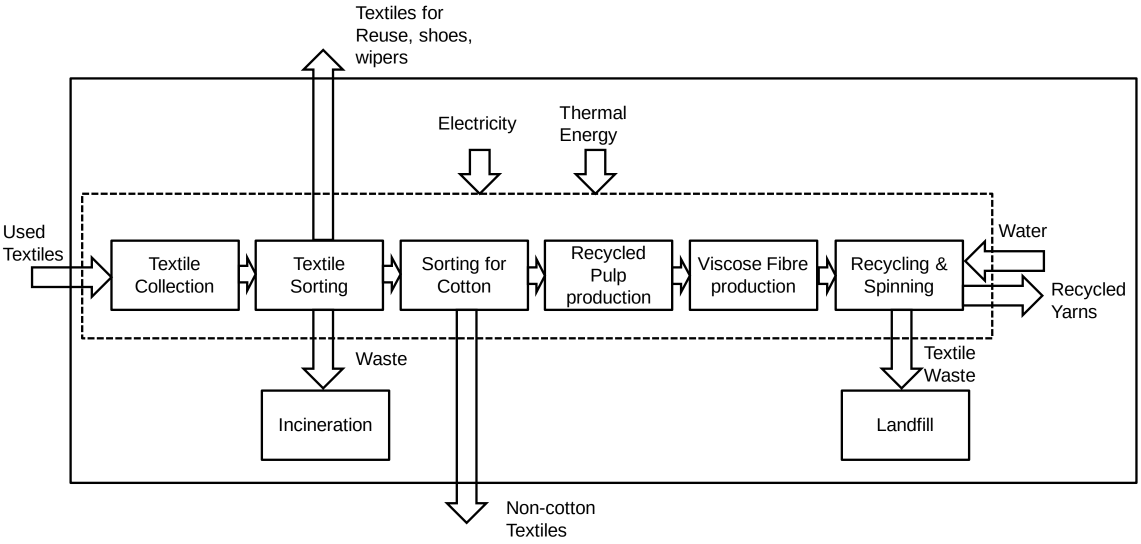


Figure 21: Process Flowchart of recycled yarn for the Viscose case

6.2 Life Cycle Assessment for the Viscose Case

Function: viscose yarns suitable for garment production.
Functional Unit: 1 km of viscose to be used for the production of garments.

Virgin Alternative: 1 km of uncoloured viscose yarn produced by 100 % chemically recycled post-consumer cotton garments as raw material.
Recycled Alternative: 1 km of uncoloured viscose yarn produced from 100 % dissolved wood as raw material.

Comparative analysis

In the Viscose case, the production of viscose from recycled cotton garments as raw material versus in comparison with the virgin production from dissolved pulp is assessed. The results are listed in the table below for 1 km of yarn 400 dtex.

Table 22: Environmental Impacts of the Viscose case

Impact Categories	Impact Indicator	Virgin Yarn	Recycled Yarn	Difference (%)
Acidification	kg SO_2-eq.	3.47E-03	3.31E-03	4.6
Eutrophication	kg phosphate-eq.	6.86E-04	6.35E-04	7.4
Global warming, excl biogenic	kg CO_2-eq.	3.01E-01	3.98E-01	-32.2
Total Freshwater Consumption	Kg	1.36E+01	3.51E+00	74.1

From Table 22 and Figure 22, acidification and eutrophication impacts are comparable, having 4-8 % difference. With regard to climate change, the virgin yarn equivalent has one third less impact than the recycled yarn, will the water consumption is reduced by 74.1 %, due to the elimination of virgin pulp which requires 186 m^3 per kg.

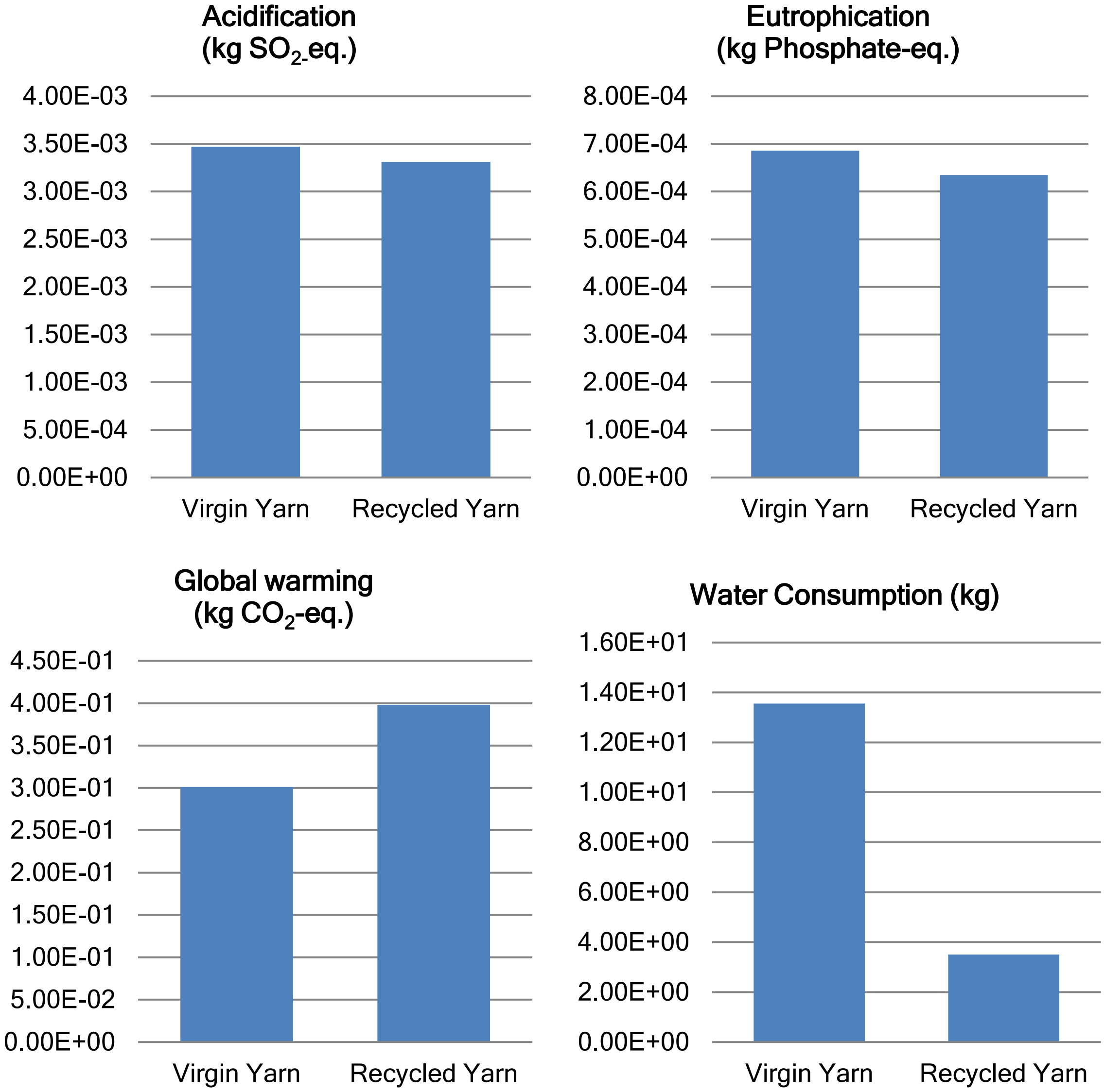


Figure 22: Environmental impacts of the Viscose case

Contribution analysis for the Viscose Case

From the contribution analysis for climate change shown in Figure 23 and Table 23, viscose fibre dominates the impacts in both cases (71 % and 56 % respectively), but the collection and sorting process in the recycled yarn (23 % contribution) seem to be the reason while the impacts are higher. On the other hand, the recycled pulp process has less impact than the dissolved pulp process.

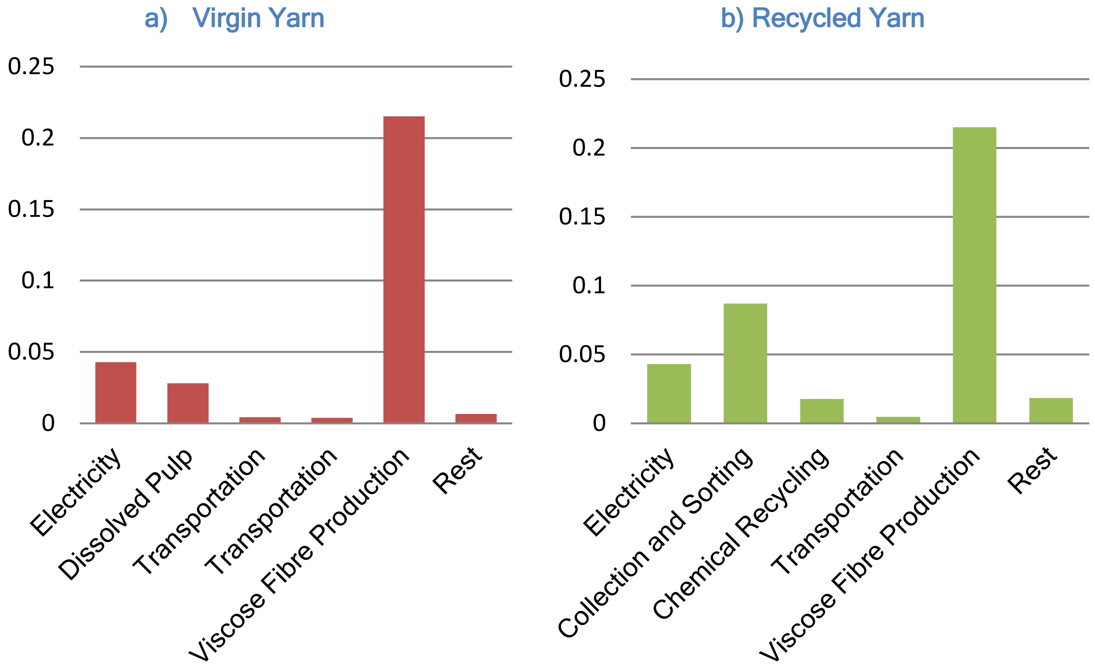


Figure 23: Contribution to climate change (kg CO_2-eq.) from a) virgin yarn (left) and b) recycled yarn (right) production

Table 23 Viscose Yarn: Contributing factors to Climate Change

Virgin Yarn		Recycled Yarn	
Contributing Factor	**Contribution (%)**	**Contributing Factor**	**Contribution (%)**
Electricity	14	Electricity	11
Dissolved Pulp	9	Collection and Sorting	23
Transportation	1	Chemical Recycling	5
Transportation	1	Transportation	1
Viscose Fibre Production	71	Viscose Fibre Production	56
Rest	2	Rest	5

Sensitivity analysis for the Viscose Case

In order to test the robustness of the results, the data from the production of bleached sulphate dissolved pulp from Ecoinvent 2.2 database was used. The results were recalculated with the different data in order to check whether that difference would make the recycled yarn a better choice. As seen below (Table 24) the results are comparable in both cases.

Table 24: Sensitivity analysis for the dissolved pulp production on the Viscose case

Impact Categories	Impact Indicator	Virgin Yarn	Virgin Yarn Ecoinvent	Recycled Yarn
Acidification	kg SO_2-eq.	3.47E-03	3.36E-03	3.31E-03
Eutrophication	kg Phosphate-eq.	6.86E-04	6.65E-04	6.35E-04
Global warming, excl biogenic	kg CO_2-eq.	3.01E-01	3.03E-01	3.98E-01
Total freshwater consumption	kg	1.36E+01	1.36E+01	3.51E+00

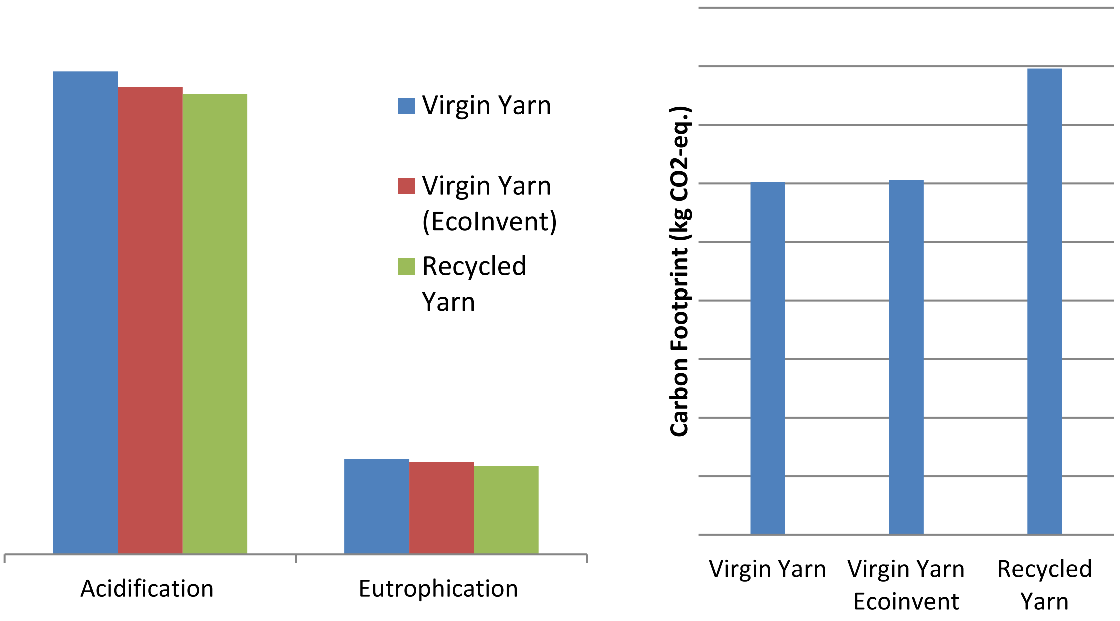


Figure 24 Sensitivity Analysis for the Viscose Case. Acidification and Eutrophication (left) and Carbon Footprint (right)

7. The Downcycling Case

7.1 System description for the Downcycling Case

Used uniforms are recycled into yarn for blanket production. The uniforms are collected by ReShare: Part of the Salvation Army and transported to the facilities of a social enterprise, by truck. This enterprise is responsible for the sorting of the garments based on material, finish and colour. In order to avoid the risk of the clothes being used by unauthorised individuals, they are destroyed by the organisation manually by tearing them apart and removing badges, logos etc., which leads to 5-10 % waste on average. The garments are sent to the collector's facilities to be baled in small presses (200-300 kg bales). The baled textiles are then sent to the facilities of Spanish mechanical recycler Hilaturas Ferre / Recover by truck.

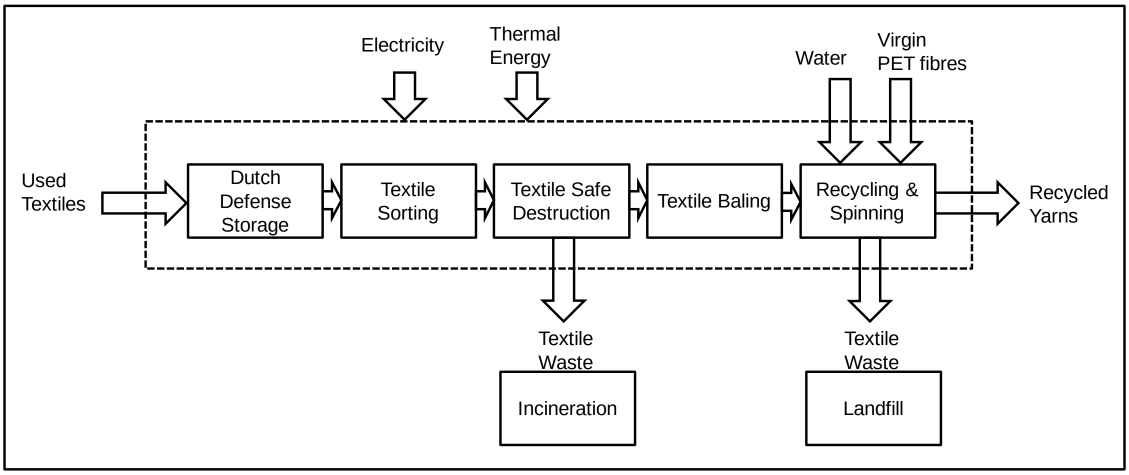


Figure 25: Flowchart of the recycled yarn production for the Blanket Case

Non-recyclable pieces such as zippers and buttons are removed by a partner of the recycler in a process called "cleaning", which leads to the loss of approximately 35% of the total mass. This waste is sent to landfill. The cleaned uniforms are then recycled into cotton fibre (10% waste in process), blended with virgin polyester fibres, carded and spun into yarn containing 80% recycled fibres and 20% virgin polyester. The yarns are woven into blankets by a partner of the recycled. For the virgin polyester, it is assumed that it is transported from Turkey and a distance of 3500 km covered by truck is included in the calculations

7.2 Life Cycle Assessment for the Downcycling Case

Function: Yarn suitable for use in the production of sleeping blankets.
Functional Unit: 1 km of green yarn of 25 Nm[5] (400 [6]dtex) with composition 61.25 % cotton and 38.75 % polyester.

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[5] Number metric or the "metric yarns number" is the length of a yarn that weighs 1 gram.

[6] Decitex (or dtex) is the count grading for filament and spinning yarns recognised by all international bodies in the synthetic fibres industry. 1 dtex is the mass of yarn in grams per 10000 metres length.

Virgin Alternative: 1 km of green yarn of 25Nm (400 dtex) with composition 40 % cotton and 60 % PET.

Recycled Alternative: 1 km of green yarn of 25 Nm (400 dtex) with composition 40 % recycled cotton and 60 % polyester (1:2 virgin : recycled).

Table 25: Yarn Compositions for the Blanket case alternatives

Input materials		Alternatives	
		Virgin yarn	**Recycled yarn**
Virgin cotton		40 %	-
Virgin PET		60 %	20 %
Post consumer material	*R-Cotton*	-	*40 %*
	R-PET	-	*40 %*

Comparative analysis for the Downcycling Case

The LCA results for the recycled yarn and the virgin yarn equivalent of the Blanket case are presented below. For the calculation of the potential impacts, the CML (2001-2010) method was used. The results reflect the potential environmental impacts per km of textile yarn of 400 dtex.

Table 26: Environmental impact results for the Downcycling case

Impact Categories	**Impact Indicator**	**Virgin Yarn**	**Recycled Yarn**	**Difference (%)**
Acidification	kg SO_2-eq.	7.5E-04	2.56E-04	65.9
Eutrophication	kg phosphate-eq.	1.20E-04	7.13E-05	40.6
Global warming, excl biogenic	kg CO_2-eq.	0.22	1.40E-01	36.4
Total freshwater consumption	kg	48.3	1.43	97.0

The comparative characterisation results show that the recycled yarn has less impact in all categories. The biggest reduction is shown in Acidification (65.9 %). Global warming is 36.4 % less and water consumption is reduced by 97.0 %, which is expected due to the elimination of virgin cotton fibre. The impact contribution of each process to the life cycle of the yarn production will be analysed below.

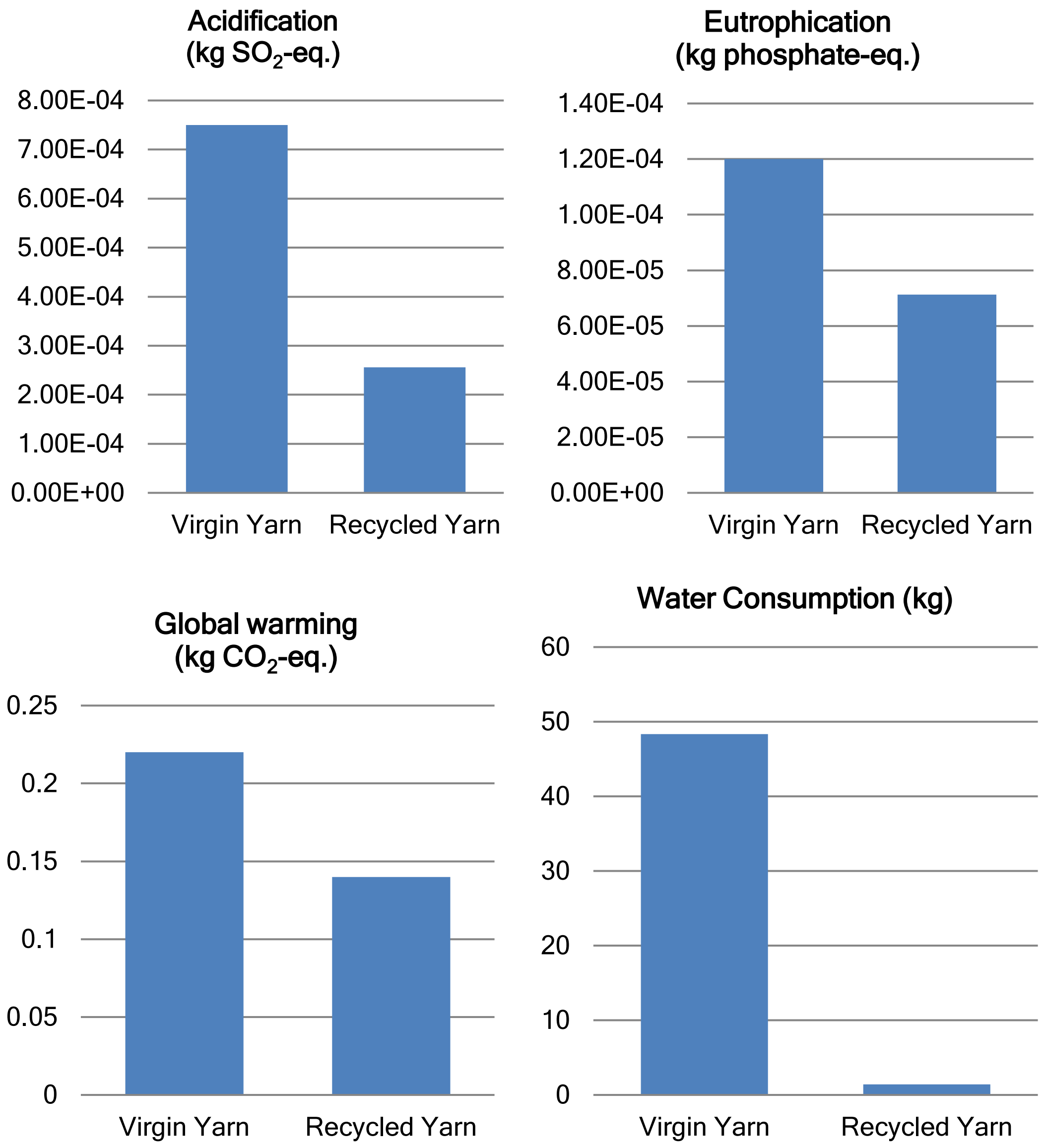


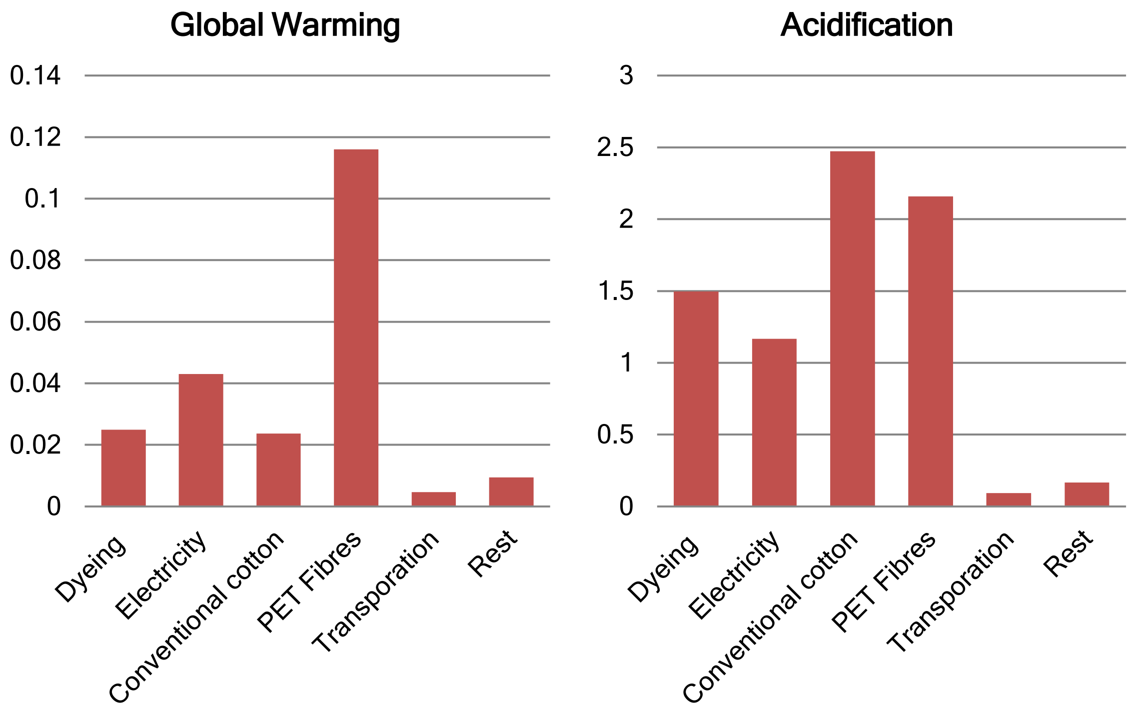
Figure 26: Results for selected impact categories for the alternatives of the Blanket case

Contribution Analysis for the Downcycling Case

The PET fibre production is the biggest contributor to climate change for the virgin yarn (52 %), which the dyeing, electricity and conventional cotton following (Table 27). On the other hand, electricity contributes most to the environmental impact of the virgin yarn, as well as the PET fibres and the landfill of cleaning waste.

It can be concluded that the reduction of PET fibres in the case of the recycled yarn has led to the biggest reduction in greenhouse gas emissions. In the data collection process, I used a generous estimate of the energy consumption of the collection process, and it is still a minor contributor to climate change, compared to the other processes. Therefore, in this case it is not a critical parameter. Finally, the avoidance of dyeing and cotton production also led to reduction in emissions.

a) Virgin Yarn



b) Recycled Yarn

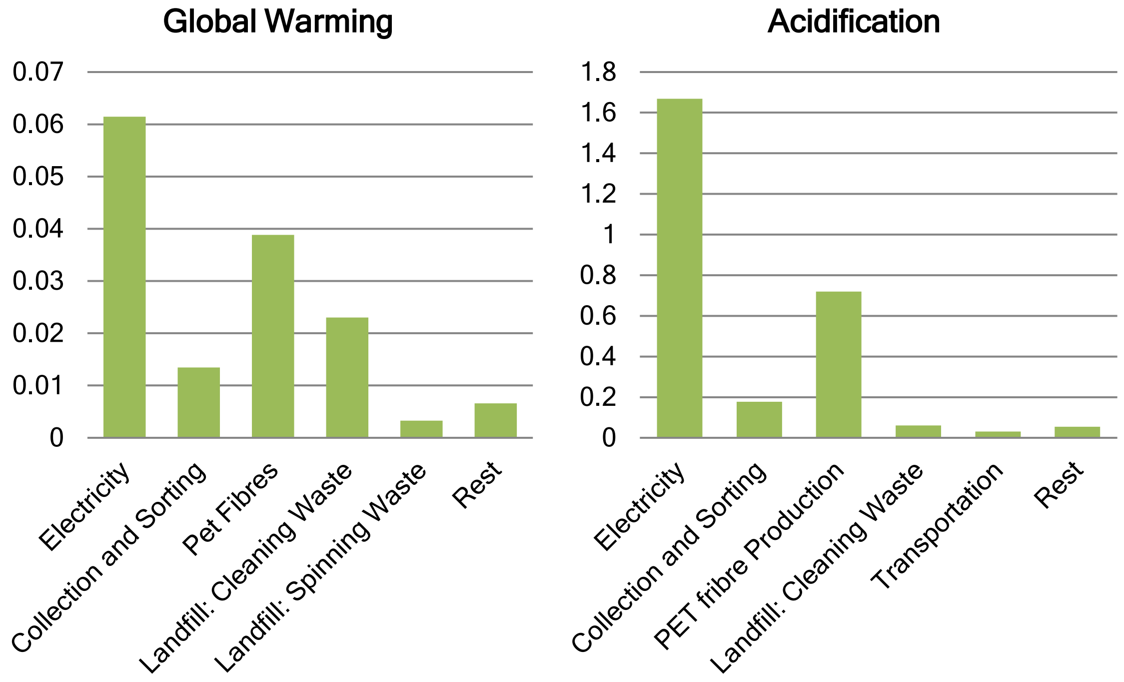


Figure 27: Carbon Footprint contribution (kg CO_2-eq.) for a) virgin yarn (above) and b) recycled yarn (below).
* ”Collection and sorting” refers to the movement of textile waste for the purpose of recycling. “Transportation” refers to the movement of the rest of the materials (textile waste from spinning, virgin cotton, etc.)

Table 27 Downcycling: Contributing factors to Climate Change

Virgin Yarn		Recycled Yarn	
Contributing Factor	**Contribution (%)**	**Contributing Factor**	**Contribution (%)**
Dyeing	11	Electricity	42
Electricity	19	Collection and Sorting	9
Conventional cotton	11	Pet Fibres	26
PET Fibres	52	Landfill: Cleaning Waste	16
Transportation	2	Landfill: Spinning Waste	2
Rest	4	Rest	5

Table 28 Downcycling: Contributing Factors to Acidification * ”Collection and sorting” refers to the movement of textile waste for the purpose of recycling. “Transportation” refers to the movement of the rest of the materials (textile waste from spinning, virgin cotton, etc.)

Virgin Yarn		Recycled Yarn	
Contributing Factor	**Contribution (%)**	**Contributing Factor**	**Contribution (%)**
Dyeing	20	Electricity	62
Electricity	15	Collection and Sorting	7
Conventional cotton	33	PET fibre Production	27
PET Fibres	29	Landfill: Cleaning Waste	2
Transportation	1	Transportation	1
Rest	2	Rest	2

The acidification impacts are almost three times lower for the recycled yarn production than for the virgin one. As seen from

Table 27 and Table 28, conventional cotton and PET fibres are the biggest contributors for the virgin yarn (33 % and 29 % respectively), as well as dyeing (20 %). By eliminating these and reducing the PET fibres, there is reduction in impact. Electricity production is the biggest contributor of the recycled yarn (62 %), mainly due to electricity production from hard coal, according to Spanish electricity data from the GABI database.

Sensitivity analysis for the Downcycling Case

The production of virgin PET fibres seems to be the biggest contributor to all impact categories. The energy and material flows data for the virgin PET fibres were taken from the GABI database. In order to test the robustness of the results, the impacts were recalculated using a different dataset for PET fibres (Kalliala and Nousiainen, 1999) which accounted for fewer emissions per kg of fibre. The goal was to identify whether the recycled choice is still a more sustainable choice, even if the virgin PET fibres have less impact.

Table 29: Sensitivity analysis on PET data for the virgin yarn

Impact Categories	Impact Indicator	Virgin Yarn (GABI)	Recycled Yarn	Virgin Yarn (Kalliana & Nousiainen)
Acidification	kg SO_2-eq.	7.5E-04	2.56E-04	8.1E-4
Eutrophication	kg phosphate-eq.	1.20E-04	7.13E-05	1.7E-4
Global warming, excl biogenic	kg CO_2-eq.	2.2E-01	1.40E-01	1.68E-01
Total freshwater consumption	kg	2	1.43	1.24

The results from Table 29 show that even with less impactful PET fibre production, and with keeping the same production as before for the recycled yarn, the latter is still a better option in terms of environmental impact, with the exception of water consumption, where there is a trade-off.

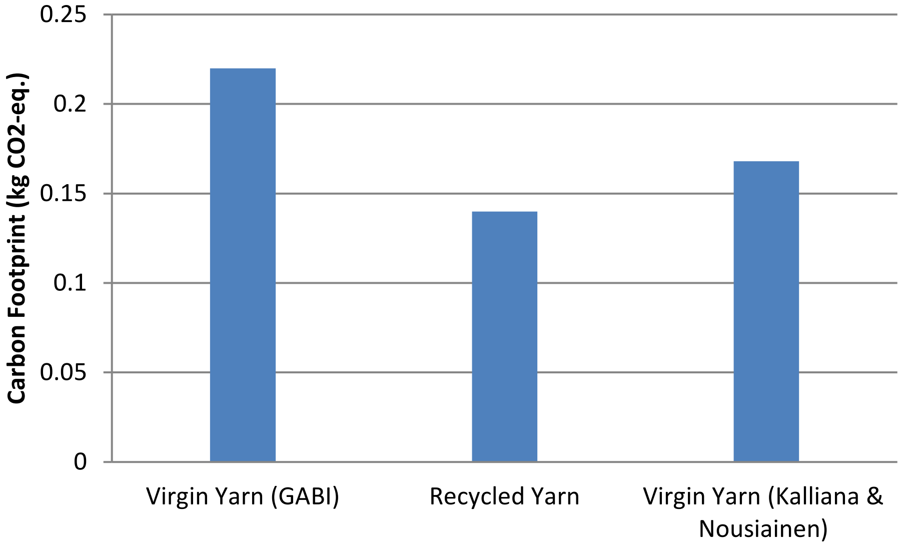


Figure 28: Sensitivity analysis for Carbon Footprint for the Downcycling Case

8. Sensitivity analysis for textile waste management replacement

As mentioned in Chapter 3, garment to garment recycling has also the function of managing some textile waste flows. For the case studies of this thesis, it was assumed that it replaces incineration with energy recovery in the Netherlands where the case studies were based. In this chapter, I show how the results would differ in terms of carbon footprint, if we took into account incineration with energy recovery in Sweden.

The graph below shows the comparison between the carbon footprint of the virgin yarn, the recycled yarn, and the recycled yarn including the replacement of incineration for Netherlands and Sweden. The same functional unit is used as the other case studies, i.e. 1km of or 25 Nm (400 dtex). The differences between the recycled yarn with or without the incineration were minimal in terms of climate change and negligible if compared with the difference with the virgin yarn for each case study.

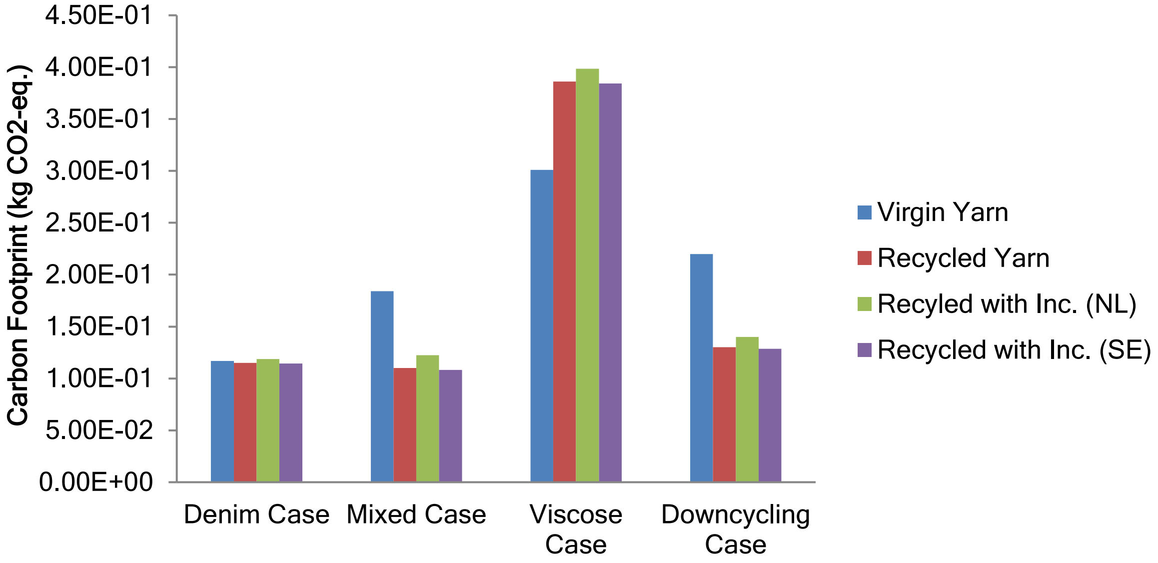


Figure 29: A comparison of each case study including incineration as a secondary function

Also, as described above, the Dutch electricity system favours the use of incineration with energy recovery as waste management, thus replacing it in our research led to all cases having higher impact, from 3 to 11 % in comparison with the base case. Predictably for the Swedish case, the impacts were slightly lower, though the difference was not higher than 1.5 %. Since different countries have different energy systems, this adds a great deal of complexity and uncertainty in the system. In conclusion, the more sustainable the electricity mix, the less are the benefits of incineration with energy recovery and the better the case for recycling. As there is a strong trend for introducing more sustainable energy in our electricity production system in Europe nowadays, this is a positive case for the use of high value recycling and downcycling in the future.

9. Completeness and Consistency Check

A consistency check is performed in order to determine whether the assumptions, methods and data are in accordance with the goal and scope of the LCA. A completeness check ensures that all relevant information and data are available and complete. The data sources and the accuracy of the information are described in detail in Chapter 3.

In terms of consistency, the goal of this LCA was to identify impact hotspots in the recycled yarns life cycle by comparing with equivalent ones from virgin materials. This is an attributional LCA in that it attempts to account for the impacts of the current system and alternative systems. It is used with the aim of estimating a product's environmental impact and to compare it with other products. Background data were collected from LCA Databases (GABI, Ecoinvent) and relevant literature when necessary. Most of the data from the foreground recycling processes in study were gathered from primary sources.

The time of the research is 2016 and the majority of the data correspond to the demands of the study, being collected the same year. This is true for used textiles collection, sorting, mechanical recycling and chemical recycling, which primary data were collected in 2016 from companies which participated in this study. Similarly, background data from the Gabi Education database (2016), such as energy production, electricity, waste management etc. are consistent with the time boundaries.

Data were representative of the geographical boundaries of the study, which is mostly the EU, as well as other countries for some specific processes, for example cotton fibre production. Whenever possible, data from the specific country were used, such as in electricity consumption and whenever not, EU aggregated data for processes such as landfill or incineration was used.

Due to limitations of the GaBi education database, data from an older version of the Ecoinvent database were included. This was not a problem for viscose production, in the respective case, since it was a comparative study. Furthermore, the impacts of virgin fibre production according to data from Ecoinvent were also compared with those using data from literature, in the sensitivity analysis.

The data cover specific technologies in the field of textile recycling and therefore, especially for chemical recycling, which is a very innovative one, I cannot claim that they are representative for the whole industry. For the automated sorting by material, another innovative technology I used data from a start-up in the field, thus this data is also not representative for the whole industry. This affects the comparison in the sense that there are no generic data available for the recycling technologies, since they is little LCA research been performed for them. This means that I cannot take into account all the recycling technologies in the market, but rather the ones that are included in this case study. This is consistent with the fact that this is an attributional study as mentioned above.

The majority of the data are consistent with the goal and scope of the study and more than 95 % of the necessary data has been collected. An explanation of how I dealt with incomplete processes can be found in Chapter 3. In total, I can conclude that the research is sufficiently complete and consistent for the purposes of this work, with the overall data quality being sufficient enough to support the results and conclusions of the study.

10. Discussion

10.1 Results from comparing environmental performance of recycled yarns with virgin yarns

The aim of the study was to identify the key contributing factors to environmental impact for the recycled yarns by comparing them with their virgin alternatives. In the denim case (30 % recycled cotton, mechanical recycling, Table 14 and Figure 14), the recycled yarn has 16 – 30 % lower environmental impacts in the acidification, eutrophication and water consumption impact categories. On the other hand, the global warming impact differed by less than 1 % (Table 14 and Figure 14). In the mixed case (100 % recycled PET-cotton blend, mechanical recycling, Table 18 and Figure 18), the recycled yarn has less environmental impact in all the categories. The recycled yarn shows reduction in acidification and eutrophication by 65 % and 50 % in comparison with the virgin equivalent yarn. It also has one third of the climate change impact, while the water consumption was 98 % less.

In the viscose case (100 % recycled cotton, chemical recycling, Table 22 and Figure 22), acidification and eutrophication reduction is less than 10 %. With regard to climate change, the virgin yarn equivalent has one third less impact than the recycled yarn, will water consumption is reduced by 74 % in the recycled yarn. In the downcycling case (80 % recycled PET-cotton blend, mechanical recycling, Table 26 and Figure 26) the comparative characterisation results show that the recycled yarn has less impact in all categories. The largest reductions are shown in water consumption (97 %), with acidification following (65.9 %). Global warming is 36 % less. The total results are summarised in Table 30.

Overall, in two of the cases featuring mechanical recycling and high recycled input percentage (80-100 %), the mixed and the downcycling ones, the recycled yarns had strong advantages in water consumption (97-98 %) and acidification, eutrophication showed over 50 % reduction. In both cases, climate change impact was approximately one third less. The differences in the three first categories can be attributed to replacing the virgin cotton production with recycled cotton, and the global warming reduction can be attributed to the reduction of virgin PET input, in favour of recycled one.

In the other two cases, the impact reduction was smaller for most categories. The denim case showed some limited reduction (16-30 %) in acidification, eutrophication and water consumption categories, which was expected, since there is only 30 % recycled cotton and the rest is virgin. The rest of the differences were negligible. In the viscose case, acidification and eutrophication impacts decreased less than 10 %, while global warming increased by one third, due to the collection and sorting process. An exception was water consumption, with 74 % reduction in the recycled alternative.

Table 30 Overview of Results: Green: Impact Reduction >10 % Grey: Impact Reduction <10 %. Red: Impact Increase

Case Studies	Recycled Composition	Acidification	Eutrophication	Water Consumption	Global Warming
Denim Case Mechanical Recycling	30 % Recycled Cotton	23 %	16 %	30 %	0.6 %
Mixed Case Mechanical Recycling	100 % recycled PET-cotton blend	65 %	50 %	97 %	33 %
Viscose Case Chemical Recycling	100 % recycled cotton	4.6 %	7.4 %	74 %	-32 %
Downcycling Mechanical Recycling	80 % recycled PET-cotton blend	61 %	40 %	98 %	36 %

10.2 Key contributing factors to environmental impact

Virgin fibre content

Conventional cotton fibres are significant contributors to acidification in the virgin yarns, with 48 % in the Mixed case with 61 % virgin cotton and 33 % in the downcycling case with 40 % virgin cotton. In terms of global warming, cotton has less contribution than electricity in all the above mentioned studies, more specifically 50 % for the denim case, 20 % for the mixed case and 11 % for the downcycling case. In the recycled yarn of the denim case, which includes 70 % virgin cotton, a similar pattern can be noticed for climate change: conventional cotton contributed 37 % in this category. Finally cotton contributes significantly to water consumption. Its replacement in the respective cases, led to reduction in water consumption up to 98 %, which is expected, due to the water-intensity of the crop cultivation. For 1 kg of cotton fibre, 2610 m^3 are required according to the data used in this thesis.

On the contrary, the percentage of PET fibres has a bigger effect on climate change, which is also expected, since it is produced from fossil fuels. They dominate the emissions in the virgin yarns in the mixed case, with 41 % and 38 % virgin PET content, as well as the downcycling case, with 52 % contribution, having 60 % virgin PET content. PET fibre production has less contribution to acidification, 18 % for the mixed case and 29 % for the downcycling case. In the downcycling case, the only recycled yarn which includes a percentage of virgin PET (20 %) it had 26 % influence on climate change and 27 % on acidification.

The results are consistent with the overall findings as presented in Table 30. Introducing recycled cotton, led to reduction in acidification and water consumption in all the relevant cases (Denim, Mixed and Downcycling). Increasing the percentage of recycled PET reduced the climate change impact in the Mixed case and Downcycling case where it was used (33 % and 36 %). Combined benefits in acidification where noticed in the Mixed and Downcycling cases which featured 80-100 % recycled cotton-PET blend. On the other hand, the 30 % recycled cotton content in the denim case, led to up to similar percentage impact reduction in comparison with the virgin equivalent.

Finally, in the viscose case, where the virgin content was pulp, it contributed 9 % to climate change, which was dominated by the viscose production in both recycled and virgin yarn. Thus, it is not possible to clearly conclude how replacing with recycled fibre affected the results. This fibre had highest impacts than any other in this research. From the contribution analysis for climate change shown in Figure 23, viscose fibre dominates the impacts in both cases with 71 % for the virgin yarn and 56 % for the recycled one.

Electricity production

Electricity production followed the virgin fibres production in environmental impact for the virgin yarns and in most cases dominated the environmental impacts for the recycled life cycles. In the mechanical recycling case studies, electricity was delivered from the Spanish grid which relies on coal, a carbon-intensive fuel for electricity generation. From the contribution analysis, in the virgin yarns, electricity contributed 15 % in the mixed and downcycling case to acidification. In the recycled yarns, they dominated the impacts for the same cases ranging from 43 % to 62 %. With regard to global warming, the impact of the virgin yarns ranged from 11 % to 37 % and for the recycled yarns they dominated all categories from 42 % to 53 % with the exception of the viscose case. It can be concluded that electricity plays an important role in the recycled life cycles, being approximately 50 % of the impact.

Collection, transportation, sorting and automatic sorting

Transportation does not play a significant role in most of the cases, as it contributes to less than 10 % to climate change and acidification, apart from the viscose case, where it contributes 24 %. The acidification impacts range from 1 % to 8 % in all cases and the climate change is the similar, 2 to 9 %, with the exception of the viscose case where it is 24 %. Manual sorting and automated sorting has negligible impact to this, thus for improvements, one needs to look into the efficiency of logistics. Finally, the automated sorting helps in reducing the costs or sorting by material and had negligible impact on the environment.

Textile waste management

The mechanical recycling technologies produce quite some textile waste, because they cannot process parts of the clothes with non-textile material, such as badges, zippers and buttons. The result is that these need to be manually discarded, by cutting along a significant part of the garment. The contribution to climate change ranges from 6 % for cleaning waste in the mixed case with 17 % cleaning waste to 16 % in the downcycling case, where more than 35 % of the material is being discarded.

Dyeing

In two of the case studies, the mixed case and the downcycling case, the virgin yarn required dyeing which was avoided or reduced in the recycled cases, due to proper mixing of the used textiles by the recycling company. Dyeing contributed approximately 20 % to acidification in the virgin yarns, whose avoidance or reduction led along with other contributing factors to the over 60 % decrease in this impact category.

10.3 Influence of recycling on the impact of the entire supply chain

What are the benefits of a textiles supply chain based on recycled materials in comparison with business as usual? The system boundaries for this research end at the yarn, because the rest of the supply chain is assumed to remain the same. However, in order to understand the magnitude of the benefits of sourcing recycled material for garment production, it is important to assess them taking the whole supply chain into account, including use, fabric production and other processes. For this purpose, I used data from an LCA for a pair of jeans (Levi Strauss & Co, 2015) which assessed the entire life cycle of the garment, including consumer care and end-of-life. According to the study, fibre production is equal to 9 % of the total climate change impact, and 37 % of the eutrophication impact. Thus, in this case, the overall climate change reduction would be very small, since the only different variable is the virgin fibre production, which is replaced by recycled fibre. On the other hand, since reduction in eutrophication impacts were noticed up to 50 %, the benefits of recycling would be more visible in this impact category.

10.4 Methodological limitations and further insights

LCA by default does not cover economic or social impacts. For example, chapter 1 describes how automatic sorting by material enables the recycling process, by reducing the cost of sorting for companies, which at the moment does not make much business sense to do. However, these financial benefits which can lead to impact reduction are not visible with the LCA methodology. Moreover, the approach of this research was attributional, thus it did not assess the potential impacts of garment to garment recycling being implemented on a large scale.

Another issue I noticed during the research was that costs of an LCA study for many companies, especially SMEs, are often prohibitive. The collection of primary data and creation of the case studies in this report was achieved only through the network a non-profit organisation and through participation of two academic institutions, Chalmers University and Leiden University. In order to disseminate these insights for commercial application, other solutions are needed, such as the development of general models with easy guidelines that cover different cases of garment to garment recycling.

Fashion companies, in particular designers and business employees, often do not have training in environmental impact assessment or similar methodologies (Clancy et al, 2015). Thus in most cases it is useful to translate environmental impact categories in values that they can understand, for example, km driven by car for CO_2, or number of showers for water consumption. Actions like this can help grow the impact of LCA and bring these cases into light. Finally, of vital importance is the presentation of sound business cases so that more environmentally-friendly processes can be realised.

10.5 Literature comparison

Even though there have been few publications in the area of LCA and textile recycling, there are some insights to be gained for the comparison of this study and the earlier ones, discussed in the literature research section of this report. The results of this study concur with Brantl, on the fact that recycling processes are useful because of the high energy and resource demand of the virgin fibre industry. This was evident in the case of virgin PET and cotton production. Specifically the PET fibre production was the biggest contributor in carbon emissions in most of the cases that it was included.

Pesneh and Perwuelz (2011), in their study on three different recycling processes of cotton bed sheets, found a 15 % decrease in the water consumption and 10 % eutrophication potential of the bed sheet life cycle in comparison with virgin production, due to the avoidance of cotton cultivation. However, in our study, the advantages in water consumption for the recycled yarn were much higher, while eutrophication reduction was up to 50 % in one case study. Furthermore, our study includes the life cycle stage of waste collection which was excluded from the above-mentioned research.

An earlier LCA was performed on mechanical recycling by Aitex in 2007. This study confirmed that electricity from spinning is the biggest contributor to climate change and that the results led to less water consumption. However, it did not include collection and sorting impacts or transportation of raw materials. Overall, taking into account the literature gaps identified in 1.5, this study provided knowledge into chemical recycling of cotton, investigated the contribution of sorting and collection to the total impact and assessed the impact of automated sorting, which was found to have negligible impact.

11. Conclusions and Recommendations

Garment to garment recycling can be one of the ways to address the fashion supply chain problems regarding pressure on natural resources upstream and the massive waste flows downstream. This research assessed the life cycles of four such case studies in comparison with their equivalent ones made from virgin materials. The impact categories chosen were climate change, acidification, eutrophication and water consumption. From the contribution analysis, the most impacting stages of the recycling process were identified. The study included primary data from different processes in the life cycle, including mechanical and chemical recycling, textile collection and manual and automated sorting.

From the results, in two case studies featuring mechanical recycling and high recycled input percentage, the recycled yarns had the potential to reduce impacts including acidification, eutrophication and water consumption. In both cases, climate change impact was approximately one third less. The differences in the three first categories can be attributed to replacing the virgin cotton production with recycled cotton, and the global warming reduction can be attributed to the reduction of virgin PET input, in favour of recycled one. In the other two cases, the impact reduction was smaller, with the exception of the high reduction in water consumption for the chemical recycling case, were wood pulp was replaced with recycled cotton garments for viscose production.

From our analysis, the biggest impact contributors identified were virgin fibre content, electricity production, the textile collection process, textile waste management and dyeing. Minor contributors were the recycling process itself, manual and automated sorting. In comparison with the total supply chain, the recycled life cycles brought environmental benefits with regard to eutrophication categories, but minimal reduction in climate change, since apart from the displacement of virgin fibre production, the rest of the supply chain remains the same.

This study focused on cotton and PET based garment recycling, primarily because these are the most widely used fibres in the industry. LCAs for recycling other materials such as wool, acrylic could be performed in the future. Further research could be directed towards chemical recycling of polyester as well, since this study included chemical recycling of cotton. Due to lack of adequate data, toxicity impacts were not assessed, which is something that could be further researched.

Since electricity played an important role in the recycled products/fibres life cycles, contributing to approximately 50 % of the carbon footprint, improvements in energy efficiency and investment in renewable energy are necessary to curb the impacts of these yarns. Concerning textile collection, more efficient route planning could both help reducing carbon footprint and also cut costs for the companies. Municipalities in the Netherlands have increasingly stricter regulations regarding atmospheric pollution in the city centres, where population density is usually higher. Thus, electrification of the fleet at least in these areas, or alternatives such as bike collection, whenever possible, are some options to be considered.

Automated sorting of used textiles by material enables the garment to garment recycling process, because it cuts down costs, thus reducing the economic barriers, while the impacts are negligible. Finally, mechanical recycling can lead up to 50 %textile waste in some cases, due to non-textile materials such as buttons and zippers that are removed manually by cutting a large part of the garment. This could be avoided by investment in better cleaning technologies, and then recycling of these waste materials.

There has been a debate in the recent literature regarding mechanical and chemical recycling and in which circumstances each of the two is a better option. Mechanical recycling is considered in general to have less energy consumption. However, due to the shortening of the fibres, an inevitable consequence of the process, the end quality is sufficient for 20-30 % recycled content in the final product. There are exceptions such as in our study, which included a pilot with 70 % mechanically recycled content from a start-up in the Netherlands. However, this concept is new and still has to prove itself to the consumers. On the other hand, chemical recycling has the potential to create fibres with can be used up to 100 % in the final product, thus really displacing virgin production. Finally, for downcycling, mechanical recycling proves to be a good option, as the quality requirements are lower, thus it can displace a higher amount of virgin fibres.

Garment to garment recycling leads to new products from textiles which were previously considered waste. Thus, it replaces waste management processes, such as incineration and landfill. For the case studies of this thesis, it was assumed that it replaces incineration with energy recovery in the Netherlands and weal so calculated how the results would differ in terms of carbon footprint, if I took into account incineration with energy recovery in Sweden. Incineration with energy recovery as waste management in the Netherlands has net benefits in climate change, since it replaces the Dutch electricity system which is mostly fossil-fuel based. Replacement of incineration in the Netherlands, subtracted some of these net benefits from our cases, leading to a slight increase in the climate change impact. Predictably for the Swedish case, where electricity production consists of approximately 90 % nuclear and hydro power, incineration had negative impacts in climate change. In conclusion, the more carbon-free the electricity mix is, the less are the carbon benefits of incineration with energy recovery and the better the case for recycling. As there is a strong trend for increasing the ratio of sustainable energy in our electricity production system in Europe nowadays, there is a positive environmental case for high value recycling and downcycling.

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