The technological challenges and opportunities of implementing the principles of circular economy in the fashion industry

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Abstract

Background: Nowadays, since it has become clear what big of a polluter the fashion industry is, researchers are investigating the use of circular economy in the fashion industry. Circular fashion is about closing the loop of materials used in the fashion industry. In this way, massive amounts of waste and greenhouse gas emissions can be reduced by recycling and alternatively reusing textiles waste. The last couple of years, multiple studies focusses on the (technological) challenges of implementing the principles of circular economy in the fashion industry.

Method: This review tries to identify the technological challenges and opportunities a fashion enterprise encounters when implementing the principles of circular economy. The Scopus database was searched. (technolog*) AND (fashion OR clothing OR textile) AND ("circular economy" OR "circular fashion") were used keywords. Articles were included if they investigated the technological challenges of implementing the principles of circular economy in the fashion industry.

Results: 27 studies were included in the review. There identified technological challenges should all be tackled in the design phase or in the afterlife phase of the fashion industry. In the design phase, these challenges are concerning all design technicalities to think about, the use of technology to reduce post-consumer and post-industrial waste, and the use of innovation to produce 'new' types of raw materials. In the afterlife phase, these challenges are concerning the collecting and sorting process, the flaws of the current recycling options, and the possibilities of new recycling options.

Discussion: The findings of this review indicate that further research should be done to investigate how to put innovative textile-to-textile recycling methods into practice at a commercial scale. Because at this moment, there is no effective recycling method that can separate and recycle raw materials out of textile waste and reuse it in the spinning process of new textile yarns. This study identified the technological challenges that should be tackled to achieve circularity, and highlighted the opportunities that can be worthwhile to invest in. To implement circular economy in the fashion industry, other challenges than technological challenges should be taken into account as well. Moreover, further research should be done to find effective recycling methods, with economic return to invest in, which can be put into practice at a commercial scale.

Key words: Circular economy, fashion industry, textile, technology, challenges, opportunities, recycling

1. Introduction

The documentary ‘’The True Cost’’ has caused a lot of fuss about what is actually going on in the fashion industry. It showed the downside of the, what looks like, beautiful fashion industry and called it the most pollutive industry after the oil industry. Since then, people are (even) more aware that this industry has to change. The energy consumed by the fashion industry is phenomenal. At this moment, the total greenhouse gas emissions (GHGE) from textiles production is 1.2 billion tons annually (Morrissey et al., 2020). This is more than the emissions of all international flights and maritime shipping put together. Besides the extremely high total greenhouse gas emissions the fashion industry produces, global (fast) fashion companies like H&M, Zara, Urban outfitters, and Nike produce 92 million tons of solid waste due to overproduction each year. Since the non-sustainable practices of these fast fashion chains, such as burning clothes that do not sell are made public, they feel the pressure to change (Napier, 2018). At this moment, most of this excess clothing waste is burned or put into landfills instead of being reused or recycled (Koszewska, 2018). To reduce these massive amounts of waste, among other things, the principles of circular economy should be put more to use in the fashion industry.

Although there are some studies dealing with the challenges of implementing the principles of circular economy in the fashion industry in general, there is no extensive study about the technological challenges and opportunities. Some studies discuss one specific technological challenge to create sustainability in the fashion industry (Sandvik et al, (2018) and Yousef et al, (2020) and Rapsikeviciene et al, (2019)). However, no studies are done that connect all these technological challenges and create a complete overview that also highlights the newest technological innovations as opportunities to achieve circular economy in the fashion industry. To address this gap, a comprehensive systematic review of literature will be done. As a result, the main technological challenges for the implementation of circular economy in the fashion industry will be identified. Next, for these challenges, together with the related opportunities, an advice will be given to fashion enterprises on how to tackle the technological challenges best and what opportunities are out there worth investing in. This research will provide a clear and complete overview of all technological challenges a fashion enterprise might encounter when implementing the principles of circular economy, by looking at the critical technical challenges in the design phase and, in the afterlife waste management reuse and recycle phase. Moreover, this research gives an advice on the technological possibilities that are available.

2. Background

The concept of circular economy is a trending topic of which critics claim that it has different meanings to different people. The study of Kircher et al (2017), where the concept of circular economy is conceptualized by analysing 114 different definitions, explains that circular economy is an economic system that replaces the 'end-of-life' concept by reducing, alternatively reusing, recycling and recovering materials in production, distribution and consumption processes, the 3Rs, (Kirchherr et al, 2017a). The 'end-of-life' concept, also known as linear economy, uses raw materials to be processed into products that will be thrown away after use. In circular economy, the so called loops of these manufactured products are closed, to prevent them from being thrown away, and instead are recycled after the first 'phase' of usage (PBL, 2019). The aim of circular economy is to accomplish sustainable development, which seeks to meet the needs and aspirations of the present without compromising the ability to meet those in the future (World Commission on Environment and Development, 1987). Moreover, it seeks to simultaneously create economic prosperity, environmental quality, and social equity for generations today and for those in the future. The definitions vary from focusing on raw materials to system change. When focused on raw materials, circular economy is mostly concerned about the reduction of raw material used, maximum reuse of materials and product used, the recycling of high quality materials, and the combustion of material using energy recovery (Kirchherr et al, 2017b). According to Korhonen et al (2018), definitions that focus on system change often emphasize three elements:

- Closed cycles: material cycles are closed. So, there is no such thing as waste, because every remaining product can be used to make a new product. Toxic substances are eliminated from the main product and residual flows are separated into a biological and a technical cycle. Producers take back their prior manufactured products after being used by the customer and repair them to create a new and useful life for a new customer.
- Renewable energy: the energy used in circular economy to create new life for old products should be renewable by nature instead of fossil energy, to reduce the usage of raw materials in the renewal process.

- <u>Systems thinking</u>: every actor in the economy (businesses, people) takes part in a complex system, which are widely interconnected to create opportunities and consequences. One player influences all other players, so all consequences must be taken into account when choices are made which affect both long-and short term (Ellen MacArthur Foundation, 2015a)

The fashion industry is the appropriate industry to identify the challenges for implementing the principles of circular economy, because the fashion industry uses the linear model of “take - make - consume - dispose” (Franco, 2017). It produces massive amounts of textile and garments, but only uses some of it, while the rest, together with no longer used products, are burned or disposed into landfills. Together, the total amount of textile waste accounts for around 5.8 million tonnes in the European Union annually. Only 25% of all this textile waste is recycled (Rapsikeviciene et al, 2019). Moreover, the (over) production of garments and textiles has harmful ecological effects that most consumers are not aware of. Textile fibre is the raw material that can be transformed into yarns and are used to produce textile fabrics. Natural fibres are found in nature, for example cotton plants and wool. Others are chemically made by using natural polymer or synthetic polymers (Correa do Amaral et al, 2018). For the production of one normal, white t-shirt, 2700 liters water is used, and for the production of one pair of jeans, more than 8000 liters water is used (The Conscious Challenge, 2019). This shows how many natural resources the fashion industry uses for the production of clothes. The estimation has been made that 98 million tonnes of non-renewable resources and 93 billion cubic meters of water are used for clothing annually (Ho To et al, 2019). However, not only massive amounts of water and non-renewable resources are used, the production also uses a lot of energy and chemicals, dumps toxics and plastic microfibers as wastewater into rivers and oceans, and has direct CO_2 emissions (Koszewska, (2018) and Ho To et al, (2019)). This means that there are massive steps to undertake for the fashion industry to produce more according to the principles of circular economy, and reduce their negative climate impact, which at this moment is expected to double by the year 2030 (Napier et al, 2018). To completely close the loop of the textile waste, all the components of the process should be recovered through effective technologies to sustain the high quality of the product with a high recycling rate (Yousef et al, 2020). Textile should be recycled more, since this is a way to address both issues of resource scarcity and clothes waste in landfills (Sandvik et al, 2019). For efficient recycling methods to be used, technological innovation is necessary because these can make the recycling processes more efficient and can increase the number of recycling options by developing new methods.

A technological problem that makes the recycling process of textile more challenging is the sorting and separation process. For the textile to be properly recycled, people should know how to dispose their textiles (post-consumer waste) separating clothes from non - clothes, and how to separate different kinds of materials. Technological or pre-consumer waste, which is the waste caused by the manufacturing process of textiles, should be separated by trained manufactures, depending on the type of material or fibre. For instance, linen, cotton, polyester, wool and polyamide (Leon et al, 2016). Consumers can be educated on how to dispose their textiles in a correct way. However, technologies can be useful to make the sorting process more effective by automatically sorting different types of textiles and enable the deconstruction to reuse or recycle fibres.

Technology, or the lack of technology, creates multiple challenges for the fashion industry to implement circular economy. To achieve circularity in the fashion industry, the loop of textile used for garments should be closed. To realize this, some critical technological challenges should be tackled as will be explained in this article. These critical challenges can be tackled mostly in the design phase of the production process or in the afterlife phase. This is because the main factors likely to influence the practical and economic viability of textile and clothing recycling in the future are concerning product design and development, technological possibilities and disposal and recycle practices (Koszewska, 2018). It will only be possible to achieve true circular economy when materials can flow through technical and biological systems when sustainability requirements are implemented at the beginning of a product's design phase (Franco, 2017). Only if this is done right, materials can be recovered and recycled in the afterlife phase of the products, enabling circularity to be established. In the design phase, everything about how the product will look, what fabrics will be used and how the product will be produced is decided upon. This is a crucial phase to think about sustainability and circularity. If designers do not do this at the design phase, there will be no or less options for recycling in the afterlife phase. Here, used products are sorted and divided. Good quality products can be reused or recycled, however, most of the products will be disposed into landfills (Sandvik et al, 2018). To do this properly, technologies which can enhance the production of more sustainable goods are crucial. However, at this moment, efficient textile-to-textile recycling and sorting methods are yet to be investigated further and put into practice at a commercial scale. Therefore, the challenges should be tackled in these two phases. The challenges for the textile and fashion industry will refer to the reduction of toxic substances, material intensity, energy intensity, improvement in the recycle practices, maximization of the use of renewable resources, increasing service intensity and the extension of product durability (Koszewska, 2018).

3. Methods

Since there is a limited number of studies in this area, a systematic literature is done to amplify the literature available and offers the right avenues for future research direction. By combining the literature available about technological challenges and opportunities and use this as a base for a complete overview, an addition is made to the available knowledge. This knowledge can be used by different kinds of stakeholders in the fashion industry who want to tackle the technological challenges and use the technological opportunities concerning circular economy in the fashion industry to improve the sustainability in the production processes and move towards more circularity. The restriction was made for the systematic literature review regarding year of publication to be between 2010 and 2020, since the latest technological challenges and opportunities are most relevant. The language of the articles should be in English. No restrictions were made for study design, because of the expected limited number of studies in this area. The applied search strategy contained the terms (technolog*) AND (fashion OR clothing OR textile) AND ("circular economy" OR "circular fashion"). The aim was to include studies focusing on technological challenges for fashion enterprises when implementing the principles of circular economy. Relevant literature was identified using Scopus database (data search on 21th of March 2020). Together 1473 papers were found. Four criteria were used for the exclusion of studies. These were (1) duplicates, (2) not relevant for fashion enterprises, (3) not about circular economy, and (4) not about technological challenges and opportunities. The screenings are done based on title, abstract and full text. If a title seemed relevant based on the screening criteria, the abstract was screened based on the same criteria. If the abstract met the screening criteria as well, the full text was read to check the complete relevance of the article for the study. Based on these screenings, articles were included or excluded. After the first screening round, 73 papers met the eligible criteria. The others are excluded based on their title. After the second screening round, 34 papers met the eligible criteria. The others are excluded based on their abstract. After the third screening, 24 met the eligible criteria. Others were excluded after reading the full paper. After a fourth screening round, 3 papers were added. These papers were added based on the references in the already included papers. The final number of included studies is 27. See figure 1 for a flowchart showing the literature search progress.

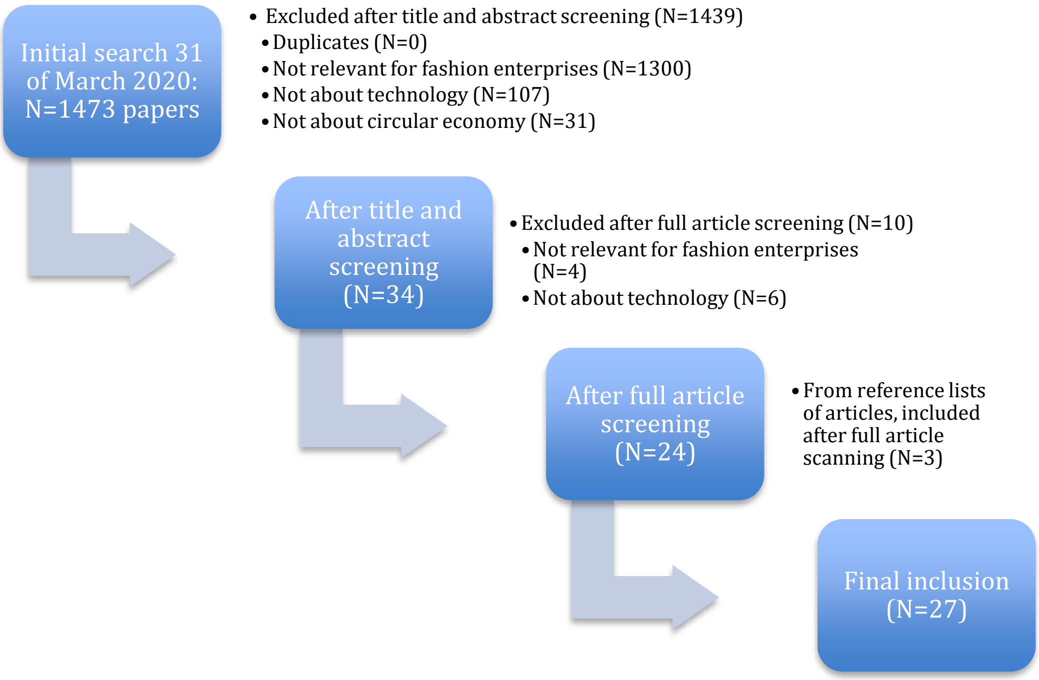

Figure 1: Flowchart of the literature search process

4. Results

In the following table you will find the summary of the results found in the included articles. The table contains a summary of the method used in the different studies, the mentioned challenges, the phase the named challenges belong to, and the main results.

Table 1: Included studies

1st Author (year)	Article title	Method	Challenges mentioned	Phase challenges	Results
Albu (2016)	Innovative tools and practical solutions to facilitate environmental performance monitoring in leather processing	Experiment to develop innovative tools in the leather sector for pollutant monitoring	Challenge of the pollution of leather processing	Afterlife phase	The results show a method which can be used to improve the environmental performance of leather processing, by using technological solutions.
Aronsson, J. Persson, A. (2020)	Tearing of post-consumer cotton T-shirts and jeans of varying degree of wear	Experiment by using 100% cotton t-shirts and denim jeans which were treated for recycling	Challenge of recycling textile blends by maintaining the fibre lengths	Afterlife phase	More heavily worn post-consumer waste did not lose as much fibre length as less worn fabrics. The results suggest that fibres from heavily worn discarded post-consumer garments are a valuable raw material for yarn spinning
Blamires, S.J. Spicer, P.T. et al (2020)	Spider silk Biomimetics to inform the development of new wearable technologies	Systematic literature review for template working framework	Challenge of using new raw materials as the base for textile yarn.	Design phase	An objective-focused research program utilizing a cross-disciplinary toolbox of top-down and bottom-up techniques is required to develop wearable technologies from spider silk
Correa do Amaral, M. Zonatti, F. et al (2018)	Industrial textile recycling and reuse in Brazil: Case study and considerations concerning the circular economy	Scientific literature review	Challenges caused in the textile production processes and challenge of textile recycling	Afterlife phase	The reuse and recycling of textiles waste has environmental and social benefits, as well as economic benefits. For circular economy, the textile industry needs innovative production strategies and perpetuate positive experiences with the customers.

Dissanayake, G. Sinha, P. (2015)	An Examination of the product development for fashion remanufacturing	On-site studies and semi-structured interviews	Challenge of landfilling and waste in the fashion industry	Design phase	The results show that although collaboration among key players along the reverse supply chain is essential for business growth, the extent of this growth is dependent on the commitment and involvement of large fashion retailers and the fashion consumer.
Fisher, A. Pascucci, S. (2017)	Institutional incentives in circular economy transition: the case of material use in the Dutch textile industry.	Qualitative and exploratory analyses based on cases	Challenge of transition towards circular economy	Design and afterlife phase	The results show there are two pathways to transition to circular economy and circular material flows; Status Quo and Product as Service arrangements.
Franco, M.A. (2017)	Circular economy at the micro level: A dynamic view of incumbents' struggles and challenges in the textile industry	Induction-driven research design supported by case studies	Challenge of product design and manufacturing, demand and consumption, recovery process at end-of-life	Design and afterlife phae	The results show how certain collaborative supplier-buyer innovation factors, together with complex factors in product design, combine to determine the how fast, how much of circular products should be sold, taken back and recycled.
Haslinger, S. Hummel, M. et al (2019)	Upcycling of cotton polyester blended textile waste to new man-made cellulose fibres.	Experiment to recycle a cotton/polyester blend using [DBNH][OAc]	Challenge of upcycling of textile waste	Afterlife phase	The results show a efficient recycling method for cotton and polyester, however, this demands very specific processing conditions. Cellulose based, blended textile waste has the potential to serve as a feedstock for conventional fiber spinning processes.
Ho To, M. Uisan, K. et al (2019)	Recent trends in green and sustainable chemistry: rethinking textile waste in a circular economy.	Scientific literature review	Challenge of textile waste in the fashion industry	Afterlife phase	The results show the trends in the green and sustainable chemistry. The use of biological waste resources from the fashion industry to provide its own feedstock maximises creative value and minimises environmental impact. It also provides prospects for transdisciplinary collaboration to realise the benefits of a circular economy.

Koszewska, M. (2018)	Circular economy - challenges for the textile and clothing industry	Scientific literature review	Challenge of waste creation, product design and development disposal practices and recycling technologies	Design and afterlife phase	The results show the new challenges the fashion industry faces when transitioning towards circular economy. Such transition should start with waste prevention and reduction of landfilled waste. This should be done in the phases of product design and development, waste collection and sorting, and effective recycling.
Kumar Paras, M. Curteza, A. (2018)	Revisiting upcycling phenomena: a concept in the clothing industry	Scientific literature review	Challenge of upcycling of textile waste in the fashion industry	Design phase	The results identify numerous definitions and terminologies such as recycling, down-cycling, upcycling and redesign. Complex pattern and design are found to be the main challenges in upcycling. The concept of "design for disassembly" and "design for cyclability" were found to be the strategic foundation to boost upcycling.
Leon (2016)	Efficient technical solution for recycling textile materials by manufacturing nonwoven geotextiles	Experiment to recycle textile waste by shredding, aerodynamic web forming and needle forming to create nonwovens	Challenge of textile recycling	Afterlife phase	The results show that adding PP fibres in the textile blends are an important factor for the characteristics of geotextiles. For economic reasons, the ratio can be decreased, and high quality of the non wovens will be maintained.
Ma (2019)	Circular textiles: Closed Loop Fiber to Fiber Wet Spun process for recycling Cotton from Denim	Experiment to utilized dimethyl sulfoxide (DMSO) as a cosolvent with ionic liquid 1-butyl-3-methylimidazolium acetate ([Bmim]OAc) for the dissolution of the denim waste	Challenge of textile waste in the fashion industry	Afterlife phase	The results show a method of closed loop fibre to fibre recycling via a dissolution wet spinning approach by using a solvent. The solvent can be recovered and reused via distillation making this a closed loop system.
McQuillan, H. (2020)	Digital 3D design as a tool for augmenting zero-waste fashion design practice	Experimental and reflective approach by using 3D technologies	Challenge of textile waste in the fashion industry	Design phase	The results show that 3D technologies can be used in the design phase to aim for zero waste design.

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Navone, L. Moffitt, K. et al (2020)	Closing the textile loop: enzymatic fibre separation and recycling of wool/polyester fabric blends	Experiment by application of a keratinase in a two-step process with addition of reducing agent and undigested polyester fibres were recovered	Challenge of sorting and recycling textile blends	Afterlife phase	The results show a method of enzymatic recycling to recover wool and polyester from textile blends. The polyester could be re-spinned and used again in textile yarns, while the wool was completely degraded.
Nayak, R. Signh, A. et al (2015)	RFID in Textile and clothing manufacturing: technology and challenges	Scientific literature review	Challenge of using technologies in the fashion industry	Afterlife phase	The results show that RFID technologies may improve the potential benefits of supply chain management through reduction of inventory losses, increase of the efficiency and speed of processes and improvement of information accuracy. The basic of success lies in understanding the technology and other features to minimize the potential problems.
Norup, N. Pihl, K. et al (2018)	Development and testing of a sorting and quality assessment method for textile waste	Experiment by using waste to develop a new sorting method validated by a case study	Challenge of sorting textile waste for recycling	Afterlife phase	The results show a method to for a sorting and quality assessment of textiles in household waste, identifies a minimum sample size and it is shown that while the amount of clothing and textiles is small in relation to the total amount of waste, namely 2.1% in residual waste and 3.8% in the small combustibles, the potential for improving separate textile collection is high.
Ortega, Z. Monzon, M. et al (2017)	Banana fiber processing for the production of technical textiles to reinforce polymeric matrices	Experiment with banana fibers and enzymatic baths	Challenge of using new raw materials as the base for textile yarn	Design phase	In this project, banana fibres were extracted from banana trees pseudostems. They are treated in an enzymatic bath for the fibers to be able to be transformed into a yarn mixed with wool fibres. With the use of banana fibres it is possible to create a yarn with the by-product of banana fruits.

Piribauer, B. Bartl, A. (2019)	Textile recycling processes, state of the art and current developments: A mini review	Scientific literature review	Challenge of recycling textile waste (blends)	Afterlife phase	The review identifies the current recycling options, and discusses innovative developments of new recycling processes in the textile recycling sector.
Quartinello, F. Vecchiato, S. et al (2018)	Highly selective enzymatic recovery of building blocks from wool-cotton-polyester textile waste blends	Experiment where textile waste was sequentially incubated with (1) protease for the extraction of amino acids from wool components and (2) cellulases for the recovery of glucose from cotton and rayon constituents	Challenge of recycling textile waste blends	Afterlife phase	The results show a method that can be used for the enzymatic recovery of cotton, wool and polyester in textile blends. It demonstrates that the step-wise application of enzymes can be used for the recovery of pure building blocks (glucose) and their further reuse in fermentative processes.
Rapsikeviciene , J. Gurauskiene, I. et al (2019)	Model of industrial textile waste management	Data analysis where software is used to evaluate textile scraps out of waste.	Challenge of waste management in the textile and fashion industry	Afterlife phase	The results show a model based on sustainability indicators which represents the effect of the scenarios for environmental, economic and social aspects. The 3 scenarios are; 1. zero waste when all fabric is used for product details; 2. reuse when scraps are directed to company and; 3. scraps are directed to the recycling companies.
Sandin, G. Peters, G.M. (2018)	Environmental impact of textile reuse and recycling - a review	Scientific literature review	Challenge of textile sorting, reuse and recycling in the fashion industry	Afterlife phase	The review provided strong support that reuse and recycling in general reduce environmental impact compared to incineration and landfilling, and that reuse is more beneficial than recycling.

Sandvik, I.M. Stubbs, W. (2019)	Circular fashion supply chain through textile-to-textile recycling	Qualitative exploratory research	Challenge of textile-to-textile recycling of textile blends in the fashion industry.	Afterlife phase	The results show that there is limited technology to support textile-to-textile recycling. This creates a challenge for the separation of the textile blends. By alternative design, the use of new materials, increased garment collection and collaborations can enable textile-to-textile recycling. It suggests that sorting and recycling technologies can be enhanced with digital technologies, as this would create transparency, traceability and automatisation.
Santos, P.S. Campos, L.M.S. et al (2019)	The interaction of product service systems (PSS) and corporate environmental management (CEM): Can PSS drive today's fashion industry toward more environmental sustainability?	Systematic literature review	Challenge of textile waste creation in the fashion industry	Afterlife phase	The review shows that the adoption of Product-Service Systems (PSS) can provide to industry a mechanism to increase factors such as product quality and longevity, while providing alternative consumption models that reduce environmental impact.
Sinha, P. Muthy, S.S. et al (2016)	Systems requirements for remanufactured fashion as an industry	Scientific literature review	Challenge of moving towards circularity in the fashion industry	Design phase	The review identifies the critical aspects which should be taken into account when designing according to circular economy.
Todeschini, B. Cortimiglia, M. et al (2017)	Innovative and sustainable business models in the fashion industry: Entrepreneurial drivers, opportunities, and challenges	Systematic literature review	Challenge of the design phase, consumer education, consumer expectations, and of how to align values along the supply chain	Design phase	The review identifies the trends and drivers of innovative and sustainable business models in the fashion industry. It highlights the challenges and opportunities for implementing the principles of circular economy.

Yousef, S, Tatariants, M. et al (2020)	Sustainable green technology for recovery of cotton fibers and polyester from textile waste	Experiment with nitric acid leaching, activated carbon, and green hydrophilicity solvent.	Challenge of textile blends sorting and recycling	Afterlife phase	The results show a method which can be used to recover cotton fibres and polyester from textile waste in a completely circular way. The developed technology can be a promising method for textile waste recycling with high outputs and multiple advantages over traditional methods.

The results of this review are catagorized into two subsections: the technological challenges in the design phase and the technological challenges in the after life phase. Each subsection will indentify the technological challenges a fashion enterprise might encounter when implementing the principles of circular ecnomy.

4.1 Technological challenges in the design phase

In the next four pharagraps, the technological challenges in the design phase are identified. These technological challenges in the design phase are concerning the design technicalities one should think about when trying to produce according to circular economy, technology to reduce post-consumer and post-industrial waste, and the use of technological innovations to produce new raw materials which can be used in the spinning process of textile yarns.

4.1.1 Design technicalities for circularity

The foundation of circular economy is based on the 3Rs (reducing, reuse, recycle). Therefore, it relies heavily on effective waste management. If done properly, it will influence all 3Rs significantly. However, this strongly depends on the design phase and development of the product (Koszewska et al, 2018). The design phase in the production process of textile and garments is one of the most important phases and has the most influence on sustainability or circularity in the production process of them all. Here, a designer, together with the managers, decides on all aspects of the product. For example, the fabrics used for their garments, the architecture of how an item is put together, and how and where the product is produced (Franco, 2017). The product has to be designed with multiple life cycles in mind. Only then, the product will be able to be recycled after the first 'life' (Franco, 2017). The design of products must aid the recycling of separate components at the end of the product's life. The individual parts (zippers, buttons etc.) need to be technically recycled. Other parts, like cotton or wool, must be bio-degraded and composted (Sinha et al, 2016). It is important to have a good product performance, and to make garments last longer to prevent them from ending up in landfills. This means that products should be of good quality, are made from an appealing and comfortable fabric, and have good appearance through different materials, constructions and colour finishes (Franco, 2017). The real challenge for the designers is to create optimal recycling options and sustainability and to make the product desirable for customers, since without this, the product will not sell (Koszewska, 2018). Fabrics should be used that can effectively be separated, and look appealing and are comfortable at the same time. This appears to be a challenging task, since most of the used products are blends of cotton and polyester which are appealing and comfortable; however, these materials are a challenge to recycle as it is difficult to separate different materials from each other. This clearly illustrates how challenging this process is for a designer. To achieve circular economy, designers must create new, innovative design methods to be able to accomplish both of these two goals (Koszewska, 2018). Another challenge for the designer is to think about the production processes, for instance using natural dyeing techniques, using post-consumer waste to make a new product, and to produce slow fashion instead by producing less collections each year (Todeschini et al, 2017). Products need to be produced without hazardous chemicals and dangerous substances, which will enable the safe recycling at industrial scale. At this moment, there is major contamination caused by the textile and clothing industry. The hazardous chemicals disposed by this industry include chemicals as mutagens, carcinogens and teratogens, which cause serious environmental damage through contamination of wastewater, exhaust gases and contaminate the fabrics as well (Franco, 2017). Production without these toxics will enable safe biodegradation and composting and that there is no, or as little as possible, pollution in the process while moving towards circularity (Sinha et al, 2016).

4.1.2 Technology in the design phase to reduce post-consumer waste

The design process of new, but sustainable, garments can be done with new, sustainable fabrics and processes. However, it can also be done with post-consumer waste. When developing a product by using post-consumer waste, which is textile waste generated by customers (worn out, unwanted clothing) (Koszewska, 2018), there are limited dimensions of types, colours and shapes available. This results in the fact that the design phase is a challenging process and completely different from the designing process when using traditional fashion items (Dissanayake et al, 2015).

One way of using post-consumer waste as a mean for new product design is through upcycling. Upcycling's aim is to achieve sustainability by increasing the lifespan of the product and/or its materials by reusing them at the design phase of a new product. The upcycling process has three stages: ideation, reconstruction and fitting. Since designing with post-consumer has limited options, the use of complex patterns and designs are found to be very challenging. The concept of 'design for disassembly and 'design for cyclability' should be put into practice to boost upcycling. Design for disassembly should reduce the required disassembly steps and time and depends on three important factors; (1) the selection and use of materials; (2) design of clothes and its parts; and (3) selection and use of seam, stitch, lining and trims. Design for cyclability should be considered to enhance recovery of material as much as possible. To achieve cyclability in the upcycling process, biodegradability, mono-materiality and low energy production are the three key attributes to be put into practice, as these reduce pollution and enable products to easily be recycled when only one type of material is used. As mentioned before, a big challenge for upcycling are the lack of multiple sizes, fabric types and colours. To deal with these problems, designers, or redesigners, should really devote themselves to the process of redesigning. Again, the solution can be achieved through craftsmanship and innovation (Kumar Paras, et al 2018).

Another option for using post-consumer waste as a mean for new product design can be to recycle fabrics and reuse used yarns in new fabrics. The(se) challenges concerning the recycling process of post-consumer waste will be discussed in the next chapter.

4.1.3. 3D technology in the design phase to reduce post-industrial waste

The fashion industry produces a lot of post-consumer waste, which mostly ends up in landfills. However, the industry also produces a lot of post-industrial waste, which is said to be a 'side effect' of the manufacturing process of clothing; the by-product which is generated by the manufacturing process that otherwise would go to disposal (Koszewska, 2018). What is used lately as a design practice to reduce the post-industrial waste is the use of digital 3D design in zero fashion design. Zero fashion design is the process of designing garments and to minimize material waste when the product is produced (McQuillan, 2020). Its aim is to reduce the use of raw materials by using more efficient production processes. More efficient production processes can be realised through innovation to achieve sustainability (Todeschini et al, 2017). Zero waste re-design is therefore the process which solves the problem of normal fashion design; the produced waste. At this moment, the fashion industry mostly tries to reduce waste at the marker making, which is a process that can be digital or analogue, to achieve the most efficient layout of the provided garment pattern on the fabric for production. In the past, zero-waste fashion design was described as the pattern cutting process. However, most of the waste is determined at the design phase. When the focus lies only on the pattern cutting, there are problems with not overlapping patterns and 3D garments. This results in that the whole pattern cutting process has to be done again (McQuillan, 2020). A key step is that the production of waste should be avoided. To do this, fashion designers need tools to reduce production waste at the design phase because this is the step where the problem is mostly created and therefore should be tackled. One way of doing this is by using 3D software at the design process. The aim of using 3D in the design process is to completely avoid the steps of design and pattern alteration. The sketch - pattern - toile - alteration process is replaced with digital 2D/3D design, while the other steps remain more conventional fashion development processes to prevent fabrics to be wasted during this process. 3D software can allow a designer to design clothes digitally, and at the same time analyse the marker without any fabric waste, as modifications can be made online instead of during prototyping and final cutting. Using 2D and 3D processes not only speeds up the development of garment design, the 3D software also provides a higher degree of certainty for the designer that the garment designed in virtual 3D from zero-waste 2D pattern is equal to the product in real life. This process reduces the amounts of mistakes made in the process. As a result, it reduces the fabric waste. Moreover, zero-waste design by using 3D software and 2D patterns is a very efficient process which allows a designer to see what impact a choice has on efficiency and expression. The use of digital 3D tools opens up new opportunities for the application of zero-waste design practice and articulates new workflows and ways of working (McQuillan, 2020). To reduce the amounts of post-industrial waste, tools like these are necessary in every step of the design process to optimize efficiency by the use of technology.

4.1.4 The use of innovation and technology in the design phase for the production of sustainable raw materials

Fashion designers need to be highly creative to overcome the challenges of the design process by redesigning the sustainable materials and processes using technologies that are able to produce more standardized raw materials made of post-consumer waste (Todeschini et al, 2017). A way of trying to tackle this problem is to invest in technological innovation. Technology can be used for instance as a way of scaling up production, to innovate and create a new way of producing, or use technology to incorporate sustainable and environmentally friendly raw materials into the product. Besides recycled fibres, yarns can be produced by adopting any other raw materials such as bamboo, organic grown cotton, hemp, or lyocell (Todeschini et al, 2017). Additionally, creative materials like fruits, plants and other waste can be used to produce a new yarn for textile fabrics. Some examples of technological innovation to produce a sustainable yarn will be evaluated next.

One company that has created new textiles is Orange Fiber. The company Orange Fiber makes sustainable fabrics out of citrus fruits by-products, for example lemon, orange and grapefruit peels (Todeschini et al, 2017). As Orange Fiber replaces highly polluting raw materials that are normally used for the production of more common types of fabrics like non-organic cotton, wool, polyester and polyamide partially with citrus by-products, they have found a solution to tackle two problems. First, less of the highly polluting raw materials are used for common types of fabrics. Secondly, they found an alternative for the disposal of citrus waste. In Italy only, more than 700.000 tons of citrus waste are produced annually. With the production of Orange Fiber, citrus waste is reduced, and green innovation and the production of a sustainable fabric is realised (Orange Fiber, 2020). This is the perfect example of radically redesigning the textile development process by using patented technologies, and in this way succeed in producing a new sustainable product. However, these new fabrics also have their limits. As quoted on Orange Fiber's website, the fabric is mostly made for high end, luxury, premium, high fashion brands. The textiles they produce are of high quality, however, incorporating the by-product of citrus fruits is also an expensive process, making it not accessible and not replaceable for the nowadays cheap and less quality garments of the fast fashion industry. In conclusion, Orange Fiber sets an example of how to use technology in an efficient way to produce a sustainable product, however, at this point, it is not a technology that can be used to tackle the problem of the not-sustainability of the fast fashion industry.

Another way of using technological innovation as a way to transform towards circular economy are the practices of BIONIC (Koszewska, 2018). Their aim is to transform recycled plastics into a new form of raw material and textiles of high performance. The yarns of BIONIC are a hybrid of recovered marine and coastal plastics to create polymer using polyethylene terephthalate (PET) and high-density polyethylene (HDPE). They offer three yarns, varying from 40 to 100% of recycled plastic (BIONIC, 2020). By doing this, they estimated that they already pulled out 7 million plastic bottles from shorelines around the world. By using innovative technologies to create a yarn with recycled plastic, they did not only created a stronger yarn, they also helped to protect marine ecosystems (Koszewska, 2018). BIONIC created three different products named HLX, DPX and FLX yarn. Each of these can come in various forms and variations. Therefore, the three options are not limited to these three fabrics. The yarns can be mixed with different types of yarns varying from cotton, linen, wool, alpaca, bamboo, silk to cashmere. The yarns can be used for different applications varying from apparel, footwear, decor, luggage, industrial, maritime to automotive applications. For the apparel industry, BIONIC says to be the perfect collaborator. At this moment, BIONIC already works together with multiple iconic brands like H&M, Chanel, GAP, Polo Ralph Lauren and G-STAR Raw. As they are able to create a high number of different types of fabrics and options, they can collaborate with different types of brands. Even though the process is still more expensive than the production of common yarns, it increases their options and is therefore more accessible to brands, high and low-end. Brands like H&M and GAP can set an example to other fast fashion brands to enter into more sustainable collaborations and to move towards a more circular fashion industry.

A third example of a sustainable yarn that has been created for the textile industry is Banana Yarn. Banana yarn was produced under the BANTEX project. In this project, banana fibres were extracted from banana trees pseudostems as they are called. They are treated in an enzymatic bath for the fibres to be able to be transformed into a yarn mixed with wool fibres. With the use of banana fibres, it is possible to create a yarn with the by-product of banana fruits. Therefore, no resources have been employed for them to grow. Banana plants are cultivated to produce banana fruits and not fibres, therefore these being an added value (Ortega et al, 2017). However, this yarn is still being developed and has no practices in real life yet. It can become an innovative, sustainable yarn like BIONIC and Orange Fiber; however, further research is needed, and the textile yarns should be tested in the fashion industry.

The fourth and last example, that also still requires further development, is the use of spider silk for the development of wearable technologies. Wearable technologies incorporate electronic devices in fashion garments to provide added functionalities (Todeschini et al, 2017). These garments are predominantly not sustainably designed and produced. Most of these wearable technologies are made from synthetic polymer fibres derived from petrochemicals. The manufacturing process, the waste production, and the fixedness of the fibres in ecosystems, as a result from the production from these synthetic polymer fibres, have negative effects on the environment. The main advantage of developing polymer fibres is that massive quantities can be produced for a great variety of purposes at a relatively low cost (Blamires et al, 2020). However, the problem with creating these materials is that it is extremely environmentally harmful due to the handling and disposal of the solvents used during spinning and fixing, and the energy input required to treat and fix the materials. Therefore, it is necessary to find sustainable, organic textiles which can replace these materials. Spider silk might be able to do this. Spider dragline silk appear to have greater strength, elasticity, and toughness than most natural or synthetic materials. The research of Blarimes et al (2020) found that for spider silk to be an appropriate replacement for synthetic materials, designers need large amounts of spider silk fibres with desirable qualities built into them to construct qualitative yarns on a commercially viable scale. At the same time, biological researchers thus must be able to produce large masses of extremely high quality spider silk fibres using existing DNA or polymer engineering technologies. If this development of spider silks as wearable fibres would be successful it can be a good replacement for current wearable technologies. However, further research is needed and the development is associated with major challenges. Nonetheless, this is another sustainable option as a replacement for common raw materials and therefore its implications should be investigated.

These examples show real life examples of companies that have succeeded in the development of a new sustainable yarn and of projects that still have to be developed to be put into practice. They all do not design and produce garments themselves. They provide the sustainable yarns or fabrics to fashion enterprises who want to use sustainable yarns or fabrics in their product. This shows that there are multiple opportunities for the development of sustainable textiles and yarns using technological innovation. Moreover, fashion enterprises not necessarily have to innovate and create a new sustainable yarn or fabrics themselves. There are multiple possibilities for fashion enterprises to use innovative technologies of companies like Orange Fiber and BIONIC to design sustainable, fashionable and comfortable clothing. Moreover, innovate new technologies is a possibility to do yourself, but it is not a necessity.

4.2. Technological challenges at the afterlife phase

In the next three paragraphs, the the technological challenges in the afterlife phase are identified. These technological challenges in the afterlife phase are concerning the collecting and sorting process of textile waste, the current recycling methods, and the possibilities of innovation for new recycling methods.

4.2.1 The collecting and sorting process of textile waste

After a piece of clothing has lived its first life, the biggest challenges for achieving circular economy comes to light. The aim of circular fashion is to close the loop of textile and garments. However, this process is hindered by three main barriers; (1) consumer disposal practices; (2) producer disposal practices and possibilities and; (3) recycling technologies. The first can be solved by consumer behaviour and education, whereas the other two can be solved through technologies. The problem of the second point is mainly that collectors focus on re-wearable textiles, while other textiles that need more costly recovery solutions are neglected. There is a lack of available infrastructure and besides that, there are not enough up-scaled process and know-how of how to collect and sort textiles and clothes based on their type of fabric (Koszewska, 2018). The first thing for recycling to be possible is that a piece of clothing should not be thrown away with normal household trash. In this way, the pieces of clothing will end up in landfills together with the other trash, which will make the process of recycling or reusing immediately challenging. Therefore, clothing should be collected in a correct way to enable reuse and recycling. As mentioned before, consumers should be educated and taught how to dispose textiles in the correct way to enable efficient sorting and collecting of textile waste. In reality, not all clothes are collected to be recycled correctly. Typical end-of-life options for textile and clothing are reuse (repair, resale), recycling (up-cycling, down-cycling, high value recycling), incineration (without energy recovery but with thermal energy generation, and landfill disposal. Of the total of clothing and textile waste, only 20% falls under the two first categories, reuse and recycling. The other 80 % of the textile and clothing is disposed into landfills or is incinerated (Koszewska, 2018). It is clear that a higher percentage should be reused or recycled. For recycling to be possible, it is crucial to dispose the garments in a correct way. Likewise, it is important how the products that are disposed are sorted in the right way. At this moment, the sorting processes of clothing and textiles is mostly done manually. This is both costly and labour intensive (Sandvik et al, 2018). Moreover, it can be very difficult to identify each fibre type incorporated in a piece of fabric. For textile-to-textile recycling to be possible, which is necessary to close the loop of clothing and textile, this sorting process should be automated. A technology that would enable the sorting process to be automated must be able to identify different types of fibres by scanning the surface, whatever the type of textile is, and sorting it by fibre type. The technology should also be fast and cheap. There are already multiple projects that focus on the automatization of the sorting process (Yousef et al, 2020). For instance the “Textiles for Textiles” business project founded by the EU or the sorting and fiberization machine created by the Circle Economy’s textile sorting project (Fisher et al, 2017). However, these technologies do need a big investment and will therefore not make it a cheap process, and thus no overall good replacement. At times when there is such an investment, one way of making such scanning technology for efficient sorting more valuable, is incorporating this with a chip or ID-code through RFID. Radio frequency identification (RFID) is a technology for remotely storing and reading information from which RFID tags are located on or in objects (Nayak et al, 2015). For this to be possible, textile products will need for instance a chip or ID-code which can identify the materials and chemicals used completely. This will enhance later life recyclability and circularity (Sandvik et al, 2018). These technologies can inform sorters and recyclers about the fibres and chemicals used in each piece of textile or clothing which makes the process easier. RFID for the sorting process is a valuable opportunity which can support the process of guiding the fashion industry towards more circularity. It is not used in practice in the sorting process yet, however, it is used in other steps of the production process of textiles such as inventory management, production control and retail management. The use of RFID has some challenges, but in these processes the use of RFID has made these processes more efficient (Nayak et al, 2015). Especially, when RFID is used in the early stages of the production of textiles, and the products have a chip which can also tell what fibres and chemicals are used, the use of RFID can be very useful for the sorting process of textiles as well. Such digital receipts, made and used through RFID or through something else, can change the way of making clothes through better documentation and transparency. It will aid transparency along the supply chain since producers, as well as recyclers, know the production process a piece of clothing has followed. Moreover, information is more accessible. Such technology will reshape the supply chain and it is an opportunity to enhance recycling (Sandvik et al, 2018). Sandvik et al (2018) discusses how technologies should offer some essential functions. It should improve traceability, transparency, standardization, and the ability to connect different stakeholders or processes. Concluding, the use of technology can offer some major opportunities for the collect and sorting processes to make these more efficient and therefore enhance the chances for recyclability. As mentioned before, the best way to enable recycling of clothing is through correctly disposed clothes. However, there are new studies which try to improve the sorting methods, also through the sortation of household trash. Norup et al (2018) established a method for sorting and quality assessment of textiles in household waste. The method shows that the potential for improving separate textile collection is high. Testing on clothing and household textiles from residual waste (31 kg) and small combustibles (about 241 kg) showed that nearly 61% of and nearly 78% of textile in residual waste, and 83% of and 85% of textiles in small combustibles, could be reused or recycled. It is said to be easier to assess reusability than recyclability, since the possibilities of reusing a products only depends on the condition of the product, whereas the recyclability depends on the its condition as well, but also on the product type, how it has been made and its fibre composition. This method could be used as a mean to minimize clothing in household waste but should be investigated further (Norup et al, 2018).

4.2.2 Current recycling options

Textile recycling refers to the reprocessing of pre- or post-consumer textile waste for use in new textile or non-textile products (Sandin et al, 2018). The processes can be categorised by the type of processing that takes place, namely product, material and feedstock recycling. Product recycling is the process where the chemical and physical construction of the waste is not changed in the process, for instance the use of textiles as filler materials or fibres. Material recycling is the process where only the physical construction of the waste is changed, for instance melting polyester textiles so it can be re-spinned into new fibres. Feedstock recycling is the process where both the physical and chemical construction of the waste is changed, for instance e-polymerisation of fibre materials into their monomers, which means breaking down the polymeric structure of the molecules in the textile into smaller pieces (Piribauer et al, 2018).

The main reason to recycle textile, is to reduce the enormous waste streams from the fashion industry. However, the increasing demand for fashion and textiles does not only increase waste streams, it also increases the demand for raw materials. Synthetic materials like polyester can keep up with this demand. However, the cotton production has stabilized around 25Mton/year (Aronsson et al, 2019), which means that the cotton production cannot keep up with this growing demand. There is a need for alternatives to virgin cotton. Some studies have shown the possibilities for the use of lyocell and viscose as an alternative. However, the simplest and most energy efficient alternative is the recycling of mechanically disintegrated fibres that can be turned into yarn again (Aronsson et al, 2019). Every kilogram of virgin cotton replaced by a second hand product saves 65 kWh of energy and for polyester every virgin material replaced by second-hand clothing saves even 90 kWh (Piribauer et al, 2018). For this to be realised, effective recycling methods should be put into practice which can recycle textiles and keep the fibres lengths intact to maintain the quality.

There are some well-established technologies to recycle textile, but in reality, this mostly means down-cycling (Sandin et al, 2018). Here, products are recycled and used as a resource for products and materials of lesser quality and reduced functionality. This is due to the fact that technologies of this time cannot efficiently separate and recycle garments that are produced. Since a lot of clothes are produced in the fast industry, the quality of the fibres is even harder to maintain. Fast fashion, which is low-cost, low quality garments which are produced at high speed at low-wage countries, is bought more and more by consumers and therefore there is more and more post-consumer textile waste. In the Netherlands, the Nordics and the United Kingdom around 61% of post-consumer waste ends up in household waste and therefore is disposed into landfills or gets burned. Of the other 39%, 16% is recycled, or downcycled (Fisher et al, 2017). The products are used as a resource for a ‘second life’, for example cleaning towels, fillers, or geotextiles. However, after this ‘second life’, these products do still end up in landfills or are incinerated. In this way, even though post-consumer products are recycled, there is no circular flow of materials since product do not find their way back into the textile or garments industry (Fisher et al, 2017). This can be explained by the fact that the currently available technologies are not able to determine the exact composition of mixed fabrics loads, for instance when a fabric is made from cotton mixed with polyester. This makes the separation of different types of fibres out of a mixed fabric an impossible task (Franco, 2017). Moreover, the textiles that are disposed, mostly get disposed way before the end of their technical service life (Sandin et al, 2018). This means that in reality, clothes that are disposed often have not lived their longest life and still have potential for usage.

There is great potential for the increase of recycling technologies. Especially for materials as polymer, oligomer and monomer. However, also the recycling of these materials is hindered by a lack of technologies for sorting and separation into pure enough fractions (Sandin et al, 2018). The main three technologies that are available and used for downcycling are thermal practices, chemical treatment, and mechanical recycling. Thermal practices burn the textile to generate heat and energy. Chemical treatment is mostly used as a waste pre-treatment to improve the digestibility of cotton based textile, to enable later use as a feedstock for biofuels and other biogas containing products. Mechanical recycling is the process of cutting and shredding fabrics to be used as blankets, stuffing, geotextiles or fillers (Correa do Amaral et al, 2018). However, all these recycling options do not close the loop by reusing the textile back into the textile industry.

According to multiple literature studies, and as seen in practice, there are currently no efficient technologies to support textile-to-textile recycling, which is the process of closing the textile loop by recycling textile and use it as new raw materials on a commercial scale. The development of such technology struggles with some challenges concerning the sortation process and the recycling of the fabrics. According to Sandvik et al (2018) these four main challenges are 1) the separation of blends; 2) the separation of additives and trims; 3) restoring quality; and 4) the sustainability of all processes. The separation of blends is a challenge as most garments contain different types of materials that should be recycled through different methods. This makes the separation process a difficult task. Apart from the blends, additives and trims also need to be separated from the garment, for instance, zippers, buttons, and chemicals. These additives and trims make the sorting and recycling process even more complicated. Especially when there is a lack of knowledge about what chemicals and other hazardous substances are used in the production process, the process is even harder (Sandvik et al, 2019). Concerning the challenge of restoring the quality, technologies should be developed which can maintain the quality of the fibres after the garments have been used and washed by consumers. At this point, the quality of recycled fibres are not of good enough quality to be reused as yarn for new textiles. The quality is not sufficient and therefore the recycled textiles can only be down-cycled into pillow stuffing. The last challenge for sorting and recycling fabrics is the sustainability of all processes. This is more concerning economic environmental viability. Recycled textiles must be able to match the prices of current production and emissions and resource usage should not exceed the emission levels and resource usage of the production of clothing (Sandvik et al, 2019). Moreover, three of the four main challenges can be tackled through technologies. However, technologies are expensive and huge investments are needed to develop such technologies. This is another type of challenge which should be tackled through other types of interventions, not technology.

4.2.3 Innovation for recycling technologies

At this point, there are no effective textile-to-textile recycling methods on a commercial scale that can efficiently recycle textile fibres and reuse these fibres again as new recycled textile yarns of good quality. However, there are options to do this and research had been done which investigates the possibilities for new technologies. For textile-to-textiles recycling to be possible, fibres re-spinning should be possible. Fibre re-spinning is the process of melting or dissolving end-of-life textiles and afterwards, the solution or the melt is used for spinning in the same way as the original virgin material is spinned (Piribauer et al, 2018). This is rather easy when materials contain one type of fibre. However, most fabrics these days, especially in the fast fashion industry, textiles are produced with blended, non-recyclable, low-cost materials. Blends are often dyed and finished with hazardous chemicals, which make the sorting, separation, reprocessing and reuse incredibly challenging if not impossible (Franco, 2017).

Some other studies tried to tackle the challenge of the variable composition of different types of fibres, dyes which are used and chemicals used during the final process of the textile and garment production. The study of Ho To et al (2019) drafts a biological process for recycling through the use of substrate in biorefineries. This variation of used raw materials increases the level of complexity of recycling processes and reduces the opportunities for new products (Novone et al, 2020). The biological process uses enzymes to degrade the biodegradable textiles from a piece of fabric after it has been shredded into tiny pieces, so degrade cotton for example into glucose, whereas the non-biodegradable textiles such as polyester are recovered for textile application after the so-called enzymatic hydrolysis. The purified cotton can be turned into value-added chemicals and materials via chemical processes and fermentation. The recovered polyester, PET, can be used as a recovered raw material for new PET yarn. To make sure the PET yarn is of good quality, they mixed the recovered PET yarn with PET from plastic bottles. The results show the yarn is indeed of good quality and is suitable for applications in the textile and fashion industries. The proposed biorefinery strategy is capable to recycle more than 70% of the textiles including 100% cotton, 100% polyester, jeans and cotton-polyester blend fabrics. Overall, this biorefinery is a technology which can enable a closed-loop recycling method for PET fibres recovered from polyester while reusing the purified cotton as other value-added chemicals, which would establish circularity of a part of the textile industry (Ho To et al, 2019). The study of Navone et al (2020) proposes an effective recycling technique for wool fabric blends. The researchers try to tackle the same challenge as Ho To et al (2019), the difficulty of the separation process of different types of fibres and of closing the loop of fashion waste. For effective recycling, it is necessary to separate different types of fibres from each other. As mentioned before, the process of correctly separating and collecting the fibres is a major technological challenge for recycling and the avoidance of landfilling. The recycling process of wool blends needs separate technologies that do not affect the nutritional value of the material. Again, an enzymatic treatment of wool/polyester fabric blends is done to selectively degrade wool fibres (instead of cotton fibres as in the study described before) while recovering the synthetic polyester fibres. Moreover, this can be a first effective recycling method for wool blends when more research for such methods is done. A third study used enzymatic hydrolysis methods to find an environmentally friendly tool for the reduction of textile waste. It is a method similar to the study of Navone et al (2020), namely creating a recycling method for wool blends. However, this study included wool blends with not only wool and polyester, but with cotton as well. The hydrolysis of wool- and cellulose (cotton fibres) fibres in this study led to yields of approximately 95% and 85%, respectively. The results showed that the purity of the recycled polyethylene was very similar to pure PET which allowed recycling to be possible. The recovered wool and cellulose fibres can be reused in blended textiles, enabling circular economy (Quartinello et al, 2018).

In a study from January 2020, researchers found a possibility to recover cotton fibres and polyester from textile waste by using a completely sustainable, new method tested on denim fabrics. It was evaluated based on the principles of circular economy, recycling rates, economic value, greenhouse gas emissions estimates and sustainability of the consumed and recovered materials, and they concluded that the developed technology can be a promising textile recycle technology with high outputs and good economic value (Yousef et al, 2020). Since the chemical nature of cotton and polyester is different, it is possible for them to be separated efficiently. However, this demands very specific processing conditions. The study of Yousef et al (2020) together with the study of Haslinger et al (2019) have both presented data that shows that cellulose based blended textiles (mixed with polyester) have potential to be recycled separately, and can become a feedstock for the ordinary fibre spinning process. Whereas the study of Haslinger et al (2019) did not present possible options for the recycling of the PET in the mixed blends, the study of Yousef et al did find a way to efficiently recycle the PET.

This shows the potential for the future of recycling. When more research is done and more options are presented, we might be able to implement such recycling methods at a commercial scale. Commercialization will require the development of efficient, reliable techniques for sorting and material identification to be able to deal with a heterogeneous substrate such as textile waste. Overall, there are some good prospects for the future of closing the loop of textile by using textile-to-textile recycling technologies. However, such reliable technologies and techniques for the commercialization of recycling methods must be investigated more thoroughly and it will need big money investments. The economic return of recycling technologies can be up to 1,629$/tone of waste (Yousef et al, 2020). However for investors, like banks, efficient recycle technologies can be a tricky investment since there is some lack of knowledge about the returns of this investment (Fischer, 2017). Hence, government funding and subsidies as well as Cradle 2 Cradle fundings can create opportunities to realise such automated sorting and recycling technologies. Cradle 2 Cradle (C2C) is a Fashion Positive Program which sees waste as a feedstock for the development of new products through up-cycling. In this project there are specific contracts with the fashion companies that deal with large collections of garments and investments of millions of euros. These contracts are the base for projects which can completely be up-cycled after use (Fischer et al, 2017). Moreover, an investment of time and money is necessary until these technologies can be put into practice at a commercial scale.

5. Discussion and conclusion

The aim of this research was to answer the question of what the technological challenges and opportunities for fashion enterprises are when implementing the principles of circular economy. This research identified the main technological challenges and opportunities by using a comprehensive systematic literature review. However, there are more challenges when implementing the principles of circular economy. For instance, consumer behaviour and practices and supply chain management to align values along the supply chain. These challenges have not been highlighted in this research but must be taken into account when implementing the principles of circular economy. The results of this review indicate that furter research should be done to completely tackle the technological challenges encourtered when implementing the principles of circular economy in the fashion industry. The first thing should be to study the recycling methods that would be able to reuse recycled raw materials back into the spinning process of textile yarns, since such methods are not available in practice on a commercial scale at this moment. The second would be to study what textile-to-textile recycling methods are best to invest in to achieve circularity, since such technologies require high investments and need to have a sufficient return. The third would be to study how to put these textile-to-textile recycling methods into practice at a commercial scale so the recycling methods can be used broadly, since this is a crucial step when wanting to achieve circularity. These three points are the gaps that are not itensively studied at this moment, but should be studies to achieve circularity.

The fashion industry is an extremely polluting industry due to enormous amounts of excessive waste, high greenhouse gas emissions and the use of toxic chemicals and other hazardous substances. By moving towards more circularity in the fashion industry, we can reduce all these polluting factors. However, the transition towards more circularity in the fashion industry, knows some critical technological challenges that have to be tackled before being able to achieve circularity. These technological challenges can be tackled in the design phase and in the afterlife phase of the production process, because for circularity, materials need to be recovered at the end of the product life cycle. This is only possible when the products are "designed for cyclability" and "designed for disassembly". In the design phase, designers should create garments that are able to be recycled, and the use materials can have a second life. This appears to be a major challenge since there are only limited options when using old pieces of fabrics for upcycling, the use of mixed blends fabrics makes the separation process at this point in time nearly impossible and the sketch - pattern - toile - alteration process produces massive amounts of waste. Even though the design process for circularity is a challenging task, there are some technological opportunities designers can use to close the fashion and textile loop. The first technological opportunity is to use technological innovation to create alternative sustainable raw materials for yarns instead of using more traditional raw materials like cotton, wool and polyester. Fashion enterprises could develop a sustainable yarn themselves, however, they could also collaborate with companies like BIONIC and Orange Fiber, which already have developed a sustainable yarn, and use these for the production of their collection. Another opportunity is to use 3D technologies in the design process. Here, 3D technologies can reduce the textiles waste caused by the sketch - pattern - toile - alteration process and enable the production according to the zero waste principle. Moreover, designers have to be highly creative to find alternatives to the current design practices by designing garments for multiple life cycles, using technologies which create traceability, transparency, standardization, automatization, and connections between different stakeholders or processes. For the afterlife phase of garments and textiles, the major technological challenges are the sortation and separation process and the (lack off) recycling technologies which can separate textiles blend and recycle these while maintaining the quality through fibre length. At this moment, there are no technologies for textile-to-textile recycling on a commercial scale. There are studies which have presented options for technologies that can separate different fibres from mixed blends and recycle these to be used again in the spinning process of yarns. The development and put into practice of these technologies can be an opportunity to close the loop for fashion enterprises. One major opportunity for the fashion industry can be the use of RFID in the production process. The use of RFID can create the traceability, transparency, and connections between different stakeholders or processes, by using a digital receipt that holds all information about what materials, chemicals and substances are used for the production of a garment. This creates transparency and makes it easier to disassemble and recycle materials at the end of the life cycle. However, it will need an investment of time and money until these technologies can be put into practice at a commercial scale. For investors, like banks, efficient recycle technologies can be a tricky investment since there is some lack of knowledge about the returns of this investment. Hence, government funding and subsidies as well as Cradle 2 Cradle fundings can create opportunities to realise such automated sorting and recycling technologies.

Overall, an advice for fashion enterprises would be to collaborate with companies which have created sustainable yarns when an enterprise does not want or has not succeeded in creating such a sustainable yarn or fabric themselves. The main advice for managers or stakeholders would be to find investors to invest in technologies to achieve traceability, transparency, standardization, automatization, and connections between different stakeholders. Such technologies can be for instance 3D technologies to achieve zero waste, RFID throughout the entire chain to ease the recycling process at the end of the product life cycle, recycling technologies to tackle the difficulty of separating mixed blends of textiles, and innovative technologies that uses alternative raw materials as the base for sustainable yarns and textiles. Since these technologies require investments that are hard to find for small initiatives, policy makers can step in by offering subsidies and funds to fashion enterprises which want to produce according to the principles of circular economy. Circular fashion is better for the environment, and additionally/moreover, closing the loop by recovering raw materials is also economically viable since it can have returns of 1.629$/tone of waste. Therefore, investments in technologies should be done so the technological challenges for implementing the principles of circular economy can be tackled and we can move towards more circularity in the fashion industry.

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