Textile Recycling Technologies, Colouring and Finishing Methods

Prepared by: Katherine Le, UBC Sustainability Scholar, 2018
Prepared for: Karen Storry, Senior Project Engineer, Solid Waste Services, Metro Vancouver

August, 2018

ACKNOWLEDGEMENTS

Support for this research report was made possible by Metro Vancouver and The University of British Columbia Sustainability Initiative.

I would like to express my thanks to the following individuals:

Karen Storry, Senior Project Engineer, Solid Waste Services, Metro Vancouver, for her role as my project mentor, and her continuous guidance, feedback, and insightful discussions throughout the research process;

Andrew Marr, Director, Solid Waste Planning, Solid Waste Services, Metro Vancouver, for his review and feedback on this report;

Karen Taylor, Program Manager, UBC Sustainability Initiative, for her coordination, and feedback in early stages of the writing process; along with UBC Sustainability Initiative program coordinators.

I would like to thank the following organizations and individuals for sharing their time, knowledge, and insights to support this project:

Dr. Carol Lin, Associate Professor, School of Energy and Environment – City University of Hong Kong

Dr. Jinsong Shen, Professor of Textile Chemistry and Biotechnology – DeMontfort University

Dr. Gloria Yao, Director, Project Development, and Ku Siu Ching – Hong Kong Research Institute of Textiles and Apparel Ltd. (HKRITA)

Don Bockoven, President & CEO – Leigh Fibers Inc.

Peter Majeranowski, President & Co-Founder, and Team – Tyton BioSciences LLC

Cover photo courtesy of REDRESS HK and Ecotextile News.

https://static1.squarespace.com/static/579095c1b8a79bc4629250d1/5800bd2f6a4963389100302d/5800c0bdff7c5020f07d449f/1478674282455/IMG_9877.jpg
https://www.ecotextile.com/images/stories/2015/January/Dyes_stuff.jpg

EXECUTIVE SUMMARY

Textiles are one of the largest growing waste streams in the world and are expected to continue to grow due to more frequent consumption and greater demand from "fast fashion". Along with this comes high consumption of chemicals, energy, and water, which generate significant environmental impacts globally. A logical approach to diverting existing textile waste streams is the adoption of textile recycling technologies and systems. While some textile recycling technologies have long existed and been practiced, other demonstrated methods deemed to be feasible have not been successful at commercial adoption. Barriers to widespread implementation, and established systems for recycling have been largely associated with economic viability, quality, and performance requirements. In more recent times, the shift towards implementing textile recycling, new business models to achieve this, and related materials and process innovations, have begun to emerge.

This report was produced as part of the Metro Vancouver Regional Scholars Program and the University of British Columbia Sustainability Scholars Program. The objectives of this report are to provide research knowledge regarding mechanical and chemical textile recycling technologies commercially available and under development for prevalent fibres used in industry (polyester, nylon, cotton, wool), and potential impacts of dyes and finishing chemicals on recycling processes.

The research methods applied to this work included a literature review from available industry and government reports, academic research, and interviews with industry and researchers in the field. New and emerging innovations in fibre materials, dyes, and chemicals are highlighted.

Enabling factors that address knowledge and technology gaps for greater implementation of recycling technologies have been identified:

- Coordination across the supply chain to stimulate the adoption and development of textile recycling systems.
- Automated textile waste sorting and fibre identification to support requirements of existing recyclers and contribute to the development of emerging fibre-to-fibre recycling technologies.
- Traceability systems and information/knowledge of materials and chemicals used in production processes, to contribute to safer chemistry and products, and additional efficiency for recycling processes.
- Funding and partnerships among stakeholders, for technology expansion and growth of textile recycling systems.
- Increased awareness among industry and consumers.

Related technology outlook and expansion for the future, based on topics explored in this report are summarized as follows:

- Increased adoption of mechanical recycling and textile waste diversion for fibre-to-fibre, and other end-use applications to serve other industries (flocking and nonwovens), and implementation or organization of operations where geographically feasible. **Short-term**
- Development of automated sorting technologies and systems. **Short to Medium term.**

- Expansion and improvement of polyester recycling operations, owing to its large share in global fibre production and consumption in textiles. **Short to Long-term**
- Continued support in the development of fibre-to-fibre cotton, cellulosic, and polycotton blend recycling technologies **Short to Medium-term**
- Development of separation and recycling of fibres blends, or processes that can incorporate blends i.e. nylon/elastane, cotton/elastane etc. **Medium to Long-term**
- Evaluation of how hazardous chemicals can be eliminated in textile processing operations, and where emerging methods or materials can be scaled up and implemented (enzymes, bio-based precursors etc.). **Medium to Long-term**
- Traceability of chemicals used in textile processing, understanding of impacts during usage (human exposure, washing/drying), and characterization in how they may interfere with recycling processes. The monitoring of environmental impacts and efficiencies of new recycling technologies adopted is also necessary. **Long term**

GLOSSARY OF TERMS

apparel: products made from fabrics, designed to be worn (i.e. clothing, shoes, accessories).

circular economy: an economic system where resources are kept in use for as long as possible, with maximum value extracted from them whilst in use, followed by the recovery and regeneration of new products and materials at the end of each service life. *(WRAP UK)*

closed-loop recycling (textiles): processes where discarded textiles are converted back to new yarn and fabrics to be used for subsequent apparel/garment production.

colourant: a substance that is applied to impart colour to a material or surface, such as a dye or pigment.

downcycling (textiles): a process whereby textile materials are converted into products of lower value (or inputs for such products), that do not fully utilize the material properties. *(Oakdene Hollins, 2014)* Examples include insulation, or fill materials.

dye: an organic (or inorganic) molecule used to impart colour to textile fibres. Dyes are classified based on their mode of application. They are either soluble or undergo an application process by which the crystal structure may be temporarily modified (absorption, solution, mechanical retention, ionic or covalent chemical bonds). Dyestuffs include substances that can be used as a dye. *(Ammayappan, 2016; ETAD –The Ecological and Toxicological Association of Dyes and Organic Pigment Manufacturers))*

fast fashion: an approach to supplying (creation, manufacturing, marketing) apparel based on low production cost, and fast production time by mass production. It enables fashion trends and styles to be widely available to consumers at low cost.

finishing (chemical): this process involves the addition of chemicals to textile materials to impart improved functions or desired characteristics.

natural fibre: textile fibres of plant, animal (protein), or mineral based origin. Man-made cellulosics/fibres are also classified as natural fibres.

open-loop recycling: (see downcycling)

pigments: coloured, black, white or fluorescent particulate organic or inorganic solids, that are insoluble or physically and chemically unaffected by the substrate in which they are incorporated. Pigments applied to fibres require binding agents for attachment. They modify colour by scattering or absorbing light. *(ETAD –The Ecological and Toxicological Association of Dyes and Organic Pigment Manufacturers; Kumar, 2018)*

post-consumer waste: waste arising from products that have reached the consumer and been used.

post-industrial waste: (pre-consumer) waste that arises from industrial, commercial establishments, and do not reach consumers.

recycling: the process of taking a product or material, breaking it down to make a material that is more valuable (upcycling), of equal value (recycling), or lower value (downcycling).

sustainability: the ability to meet the needs of social or economic development without compromising the ability of future generations to meet their own needs. *(Brundtland, 1987)*

synthetic fibre: man-made textile fibres produced from chemical substances (petroleum, coal).

upcycling (textiles): a process whereby textile materials are converted to products of equal or greater value.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1.0 INTRODUCTION

The textiles and apparel industry is one of the largest and fastest growing global industrial sectors, owing to increasing population, the rise in consumption, the diverse applications of textiles, and greater productivity in mass production processes. With a 1.3 trillion USD annual revenue in 2016[1], the global clothing industry is the largest consumer of textiles.[2] Annual production has nearly doubled since 2000, surpassing 100 billion units in 2015 with apparel consumption expected to rise 63% by 2030. This increase is partly due to the burgeoning fast fashion industry, which relies on shorter production cycles and style turnaround, often at lower prices, enabling a larger selection and choice for consumers.[3]

As a resource and energy intensive industry, the apparel sector's presence is far-reaching with associated environmental, economic, and social impacts across the value chain. Total fibre production in the global textile industry had increased by nearly 20% to 103 million tonnes between 2011 and 2017.[4] The textile and apparel industry is expected to increase its CO_2 emissions by more than 60% (roughly 2.5 billion tonnes per year) by 2030 while also experiencing a 50% increase in freshwater consumption from 79 million cubic metres in 2017.[5] The ecological footprint of the industry, specifically the impacts of textile and associated chemical waste, remains as both a continuing global challenge and an opportunity to drive innovative change in processes, products, and sustainable development for the future.

Across the industry, there is increasing awareness of the global impacts of the current linear system of take-make-dispose. This extends from raw materials extraction and production inputs, to distribution and usage, and results in large volumes of generated waste, degradation of the environment, ecosystems, and overall, uncaptured economic opportunities.[3,5] In recent decades there has been a growing push for calls to action among stakeholders and policy makers, which have led to and continue to drive developments in improved practices and innovative technology. The overarching intention is to shift from a linear to a regenerative circular system in which products and material usage are kept and maintained within closed-loop cycles and associated waste, energy, and emissions are minimized and gradually designed out.[3] Such practices extend from resource extraction and material production through to business models, design principles, and consumer perception and engagement.

Addressing the environmental challenges faced by the apparel industry from a material resources standpoint entails materials and process technology developments and advancements at all stages, from raw materials production to managing and designing out waste streams. With a reported 87% of all end-of-use textiles going to landfill and incineration, textile waste has become a growing global challenge and concern.[3] Textile recycling technology is a key enabler in transitioning to a circular system, specifically with the establishment of fibre-to-fibre streams. In addition to this, consideration of the impacts associated with chemicals from the dyeing and finishing processes used to make textiles for clothing must be addressed. Post-production waste management and clothing usage and disposal have resulted in contamination of major waterways, notably from manufacturing waste in the countries where production takes place, or post-consumer waste in landfills. Dye and finishing chemicals have also been cited as having the potential to impede textile recycling methods.[6]

The objective of this report is to identify and advance knowledge of closed-loop (fibre-to-fibre) textile recycling technologies, colouring and chemical finishing processes, as well as future developments. The information in this report is intended to be shared among researchers, industry professionals, and policy makers to increase the understanding of available technologies and current barriers and opportunities, encourage exploration into alternative solutions and strategies, innovative technologies, and to inform technology feasibility and future development.

1.1 Scope and Methodology

This report explores the recycling technologies for polyester, nylon, cotton (to regenerated cellulosics), and wool, as they are the most commonly used fibres in garment manufacturing. Emphasis is placed on advancements in fibre-to-fibre recycling technologies. Issues pertaining to current dyeing techniques and possible impacts during recycling are explored, and alternative and emerging innovative techniques are outlined. The following topics are presented:

- Summary of existing textile recycling technologies (mechanical and chemical)
- Identification of existing and emerging textile recycling technologies of prevalent fibres
- Summary of existing dyeing techniques, and chemical classes in use of potential concern used in dyeing and finishing processes
- Identification of alternative and novel colouring techniques, technologies for decolourization, and finishing chemistries adopted commercially and under development
- Identification of key enablers for textile recycling adoption, and greater sustainability in the textiles and apparel industry

In this work, both ‘open-loop’ and ‘closed-loop’ technologies, are considered. Open-loop recycling, refers to the process by which textile materials are broken down (shredding, deconstruction, etc.) into lower value input products, or used in products for other applications (insulation, fill, industrial rags, low-grade blankets, etc.).[6,7] The new application does not recover and utilize the full value of the material. Closed-loop recycling includes multiple loop processes whereby the textile material is recycled and used in an equivalent product.[6] Chemical recycling technologies for fibres and textiles are often considered to be closed-loop processes, given the potential to regenerate recycled materials of near-virgin or virgin quality.[6] While mechanical and chemical closed-loop recycling technologies may be applied to materials multiple times, material properties may be degraded during the process (shortening fibres, decreased material properties).[6]

The research methodology utilized in the report included a literature review of available industry reports, news sources, and data, technical research in the field, as well as qualitative methods through interviews with technology providers and researchers. Owing to both the proprietary nature or limited data available on some of concepts explored, there are still several gaps identified from the topics presented. This work is intended to serve as an informative piece to present the existing knowledge base of textile recycling technologies, colouring and finishing methods.

2.0 BACKGROUND

Global demand for textile materials is expected to continue to rise due to population growth, improvement of living standards, rapidly changing fashion trends as a result of increased style turnaround and shortened garment life cycles, coupled with lower prices.[8,9] With this comes the generation of textile and associated chemical waste streams. While still comprising a small proportion of total global waste streams (total of 1.9 billion tonnes annually[3]), textile waste is one of the most rapidly growing waste streams. This is due to low rates of utilisation and recycling, resulting in high throughput levels; with approximately 83.5 million tonnes of waste produced annually (2015), and expected to increase by 62% by 2030.[3,5] From the lifecycle standpoint, the apparel industry is considered as one of the most polluting due to the high volume of resources used, resulting in ecological impacts.[3,8,10] In recent times, there have been emerging concerns regarding microplastics release into marine environments, with the majority of suspected microplastics comprising synthetic fibres, which enter potable water systems, or are captured in municipal wastewater treatment plants.[11,12] It has been estimated that 34.8% of primary microplastics release into world oceans are derived from the laundering of synthetic textiles.[13]

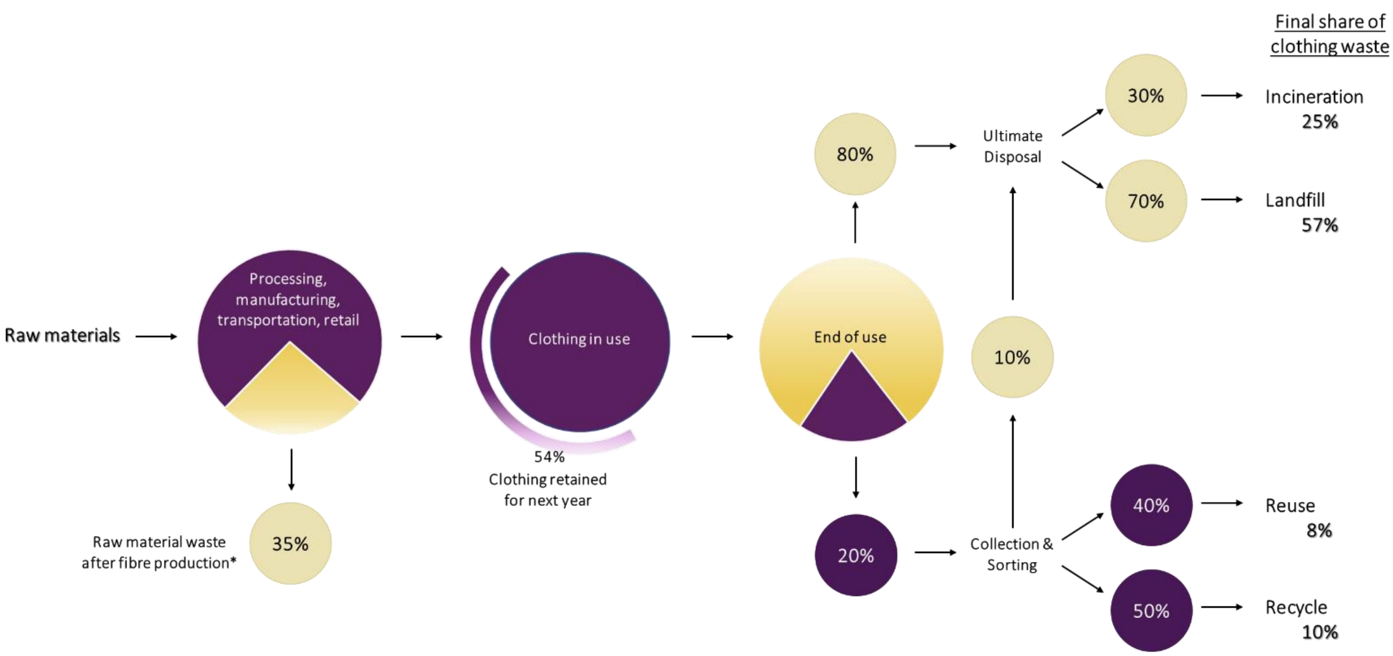

Figure 1: Apparel material waste flows from raw materials to end-of-life (estimates). *Reproduced from [5]*.

The raw materials, use, and end-of-use phases within the apparel industry value chain, were identified as areas in which greater sustainability improvements are needed.[i] It is estimated that 87% of materials used to produce clothing is landfilled or incinerated, thereby representing a 100 billion (USD) annual cost in lost opportunity.[3,14] In addition to this, only 20% of clothing is estimated to be collected for reuse or recycling,[5] and less than 1% of textile materials used to

[i] Based on the Global Fashion Agenda and The Boston Consulting Group's performance Pulse Score, developed based on the SAC Higg Index to track overall sustainability from key environmental and social impact areas

produce clothing undergoing closed-loop fibre-to-fibre recycling.[3] Figure 1 displays estimated apparel material waste flows from raw material production to end-of-life. Accordingly, the End-of-Use phase, in coordination with other phases across the industry value chain is a key enabler in advancing industry efforts towards a circular economy.

Within Canada, it is estimated that approximately 500,000 tonnes of apparel waste is disposed annually. In Metro Vancouver, approximately 20,000 tonnes of apparel waste is sent to disposal, comprising 2.3% of total landfill waste, and 50% of the total textile waste generated in the province of British Columbia (BC).[7,15] In the greater Vancouver area, no closed-loop apparel recycling operations take place, and it is estimated that 20% of materials from sorter-graders are sold for recycling in foreign markets.[7,16]

In BC, apparel manufacturing is the fourth-largest manufacturing subsector based on sales, with 80% of clothing manufacturing businesses located in the Lower Mainland.[17] Within the greater Vancouver area, the apparel manufacturing sector plays an economically important role. Over 60% of the apparel manufacturing businesses in the province are involved in on-shore manufacturing.[17] From the key product lines of apparel manufacturing businesses in BC displayed in Figure 2, over three-quarters of businesses produce textile-related products (businesses surveyed may be involved in production of multiple product lines).[17]

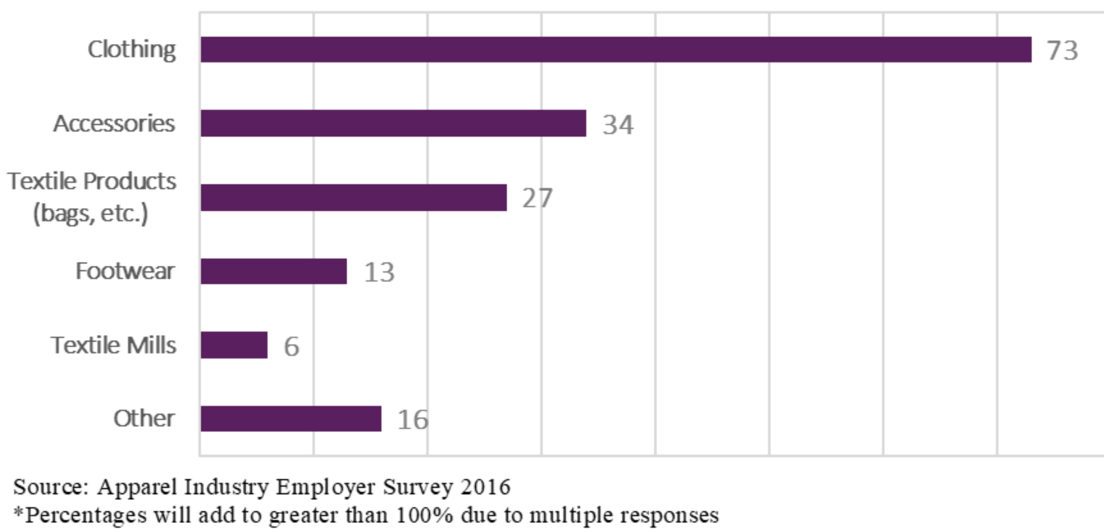

Figure 2: Apparel-related firms in British Columbia by product (%). *Reproduced from [17].*

While the overall role of the greater Vancouver area within BC is small on the global scale, combined with consumption activity from wholesale and retail apparel businesses which continues to grow, this presents opportunities to examine textile recycling technologies and current practices in the global textile and apparel manufacturing industry.

2.1 Textile Fibres

Global fibre production in 2016 was estimated to be 94.5 million tonnes, dominated by synthetic fibres (68.3%) –predominantly polyester (64%) estimated at 64.8 million tonnes, followed by cotton (22%), man-made cellulosics (6%), and animal-based fibres (1.5%- 80% wool, 20% down) (Figure 3).[18] Synthetic fibres comprise production from organic compounds derived from non-renewable sources (petroleum), and inorganic-based materials (ceramics and glass).[8] Natural fibres are derived from plants (cellulosics), animal proteins (wool, silk), or minerals (asbestos).[8] In this report, four major materials of focus identified based on the synthetics and naturals include: polyester, nylon, cotton, and wool.

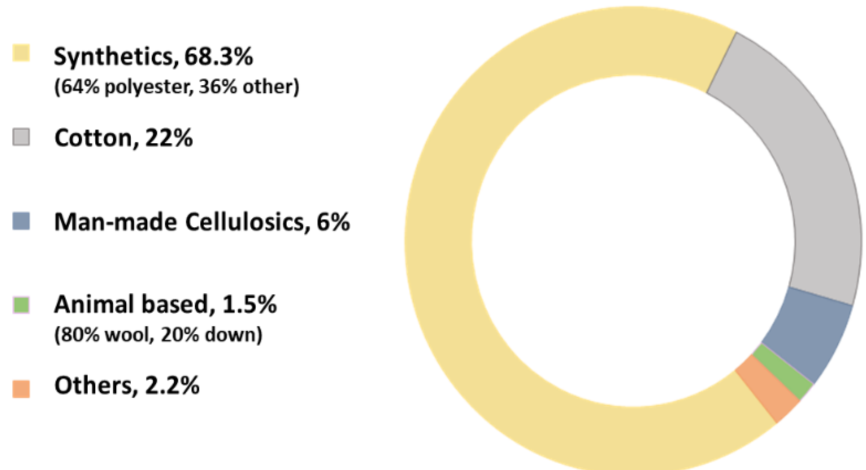

Figure 3: Global fibre production in 2016. *Reproduced from [18].*

2.2 Textile Waste

It was estimated that the total global apparel waste (83.5 million tonnes in 2015) was greater than 90% of total global fibre production (94.5 million tonnes in 2016).[5,7,18]

Textile waste streams comprise pre-consumer (or post-industrial) waste, and post-consumer waste. Pre-consumer waste includes materials arising from industrial and commercial processing of textiles or manufacturing of garments (scraps, excess inventory, damaged or defective materials, samples). Post-consumer waste includes end-use of products, such as recalled inventory, items returned or disposed of by the consumer. Figure 4 depicts general material and common chemical waste streams during apparel manufacturing and use.

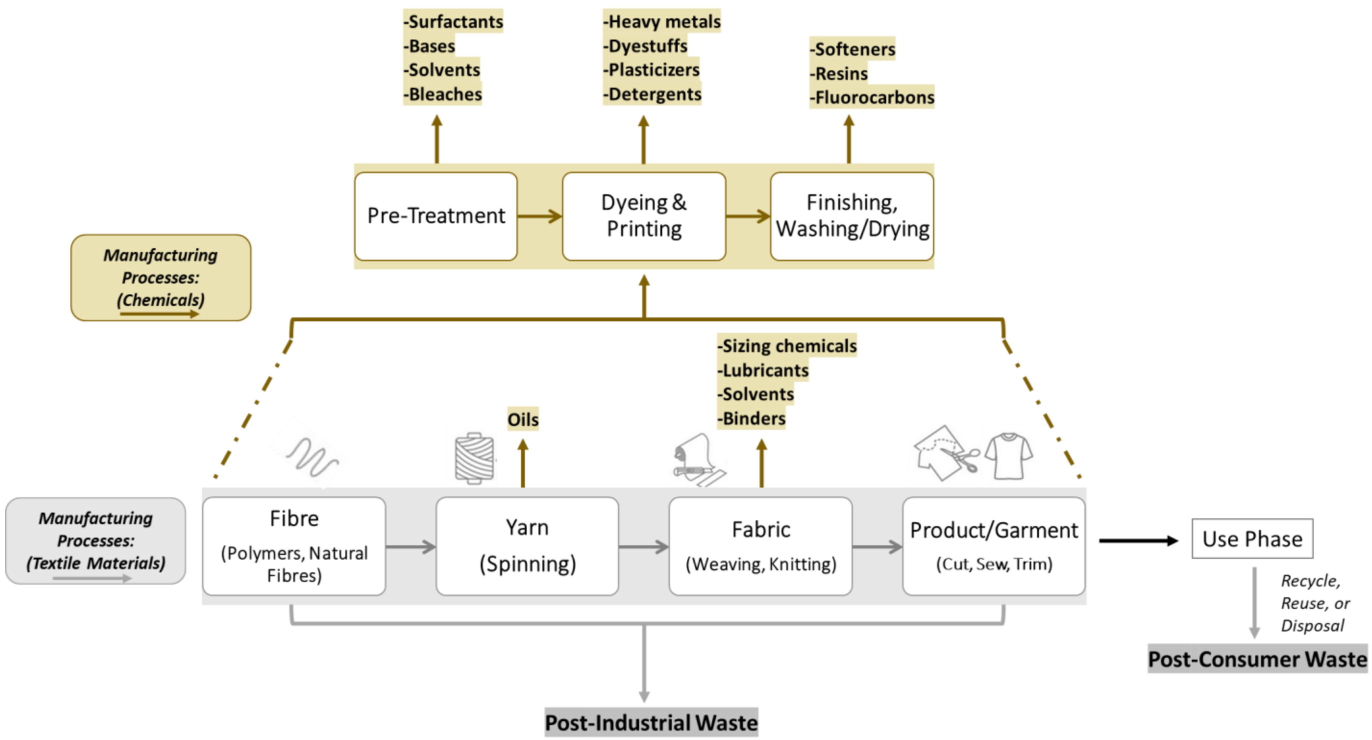

Figure 4: Material and chemical waste flows during apparel manufacturing and use. *Modified and reproduced from [19,20].*

2.3 Textile Recycling Processes

Textile recycling processes have long existed, but have been greatly influenced by factors such as high prices, volume, and availability of virgin raw materials, which have limited the ability to be integrated as established and economically viable operations.[6] Processes such as re-spinning of post-industrial and post-consumer materials, pulping of cotton and linen, and non-woven material production have existed for centuries, with variations of such operations currently practiced.[6]

In recent times, there has been great interest in increasing the reuse and recycling of textiles, notably further developing textile recycling processes, because of an increased awareness of the impacts of the existing linear supply chain of the apparel industry. Reuse refers to the utilization of product in its original form, and recycling refers to the conversion of waste into product.[21] Recovery of materials and energy, specifically through the application of recycling technologies offer potential for greater value creation within the textiles economy, and would greatly contribute to the vision of a circular economy model proposed by the Ellen McArthur Foundation –a restorative, regenerative, and distributive system by design, in which value is circulated among stakeholders, from producers to consumers in the system.

Four categories of recycling technologies exist and include, primary, secondary, and quaternary approaches, summarized as follows:[21,22]

<u>Primary:</u> recycling material in its original form for recovery of equal value
<u>Secondary:</u> processing post-consumer product usually by mechanical means into product with different physical and/or chemical properties (mechanical recycling)
<u>Tertiary:</u> processes such as pyrolysis and hydrolysis, in which waste is converted to basic chemical constituents, monomers, or fuels (chemical recycling)
<u>Quaternary (recovery):</u> waste-to-energy conversion processes such as incineration of solid waste, or utilization of heat generated [ii]

Specific to textile materials recovery, common processes include mechanical and chemical methods. Table 1 summarizes typical process inputs and outputs of the recycling types.

	MECHANICAL	**CHEMICAL**
Process	Downcycling High Value Recycling	High Value Recycling
Input Fibre	Plant Based Animal Based Petroleum Based	Plant Based Petroleum Based
Output	Non-Wovens New Yarn	New Yarn

Table 1: Mechanical and Chemical Recycling of Textiles. *Modified and reproduced from [11].*

[ii] *Note: For the purposes of this report, incineration with energy recovery has been termed a quaternary form of recycling. However, this report acknowledges that according to the internationally-recognized 5Rs Waste Hierarchy, it is a form of recovery, not recycling.*

Mechanical processes are categorized as a secondary recycling approach. Processes include: cutting of sorted fabrics for use as wiper rags, shredding and pulling of textile materials into fibres, re-bonding or respinning into new yarns or fabrics, melting and re-extruding, reblending (may include proportions of virgin material) or respinning to produce new yarns and threads, or textiles.[6,8] Chemical processes are categorized as a tertiary recycling approach, and include processes in which the chemical structure of the material is either broken down partially or fully (depolymerization), followed by re-polymerization to virgin material, or through the dissolution and melting processes, from which the material is drawn or extruded into re-usable fibre.[5,8]

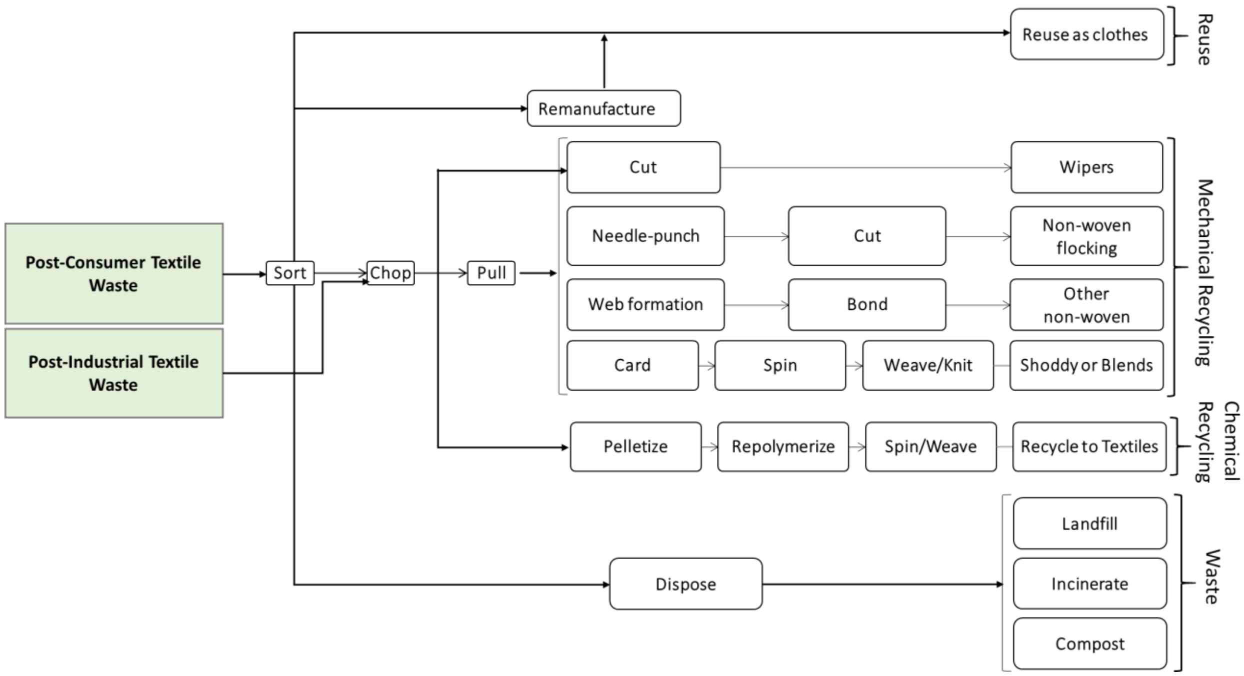

Figure 5: Overview of possible post-industrial and post-consumer textile waste flows. *Reproduced from [23].*

For the diverse range of fibres produced globally, limited options for recycling are available for textiles and apparel. Figure 5 presents an overview of reuse, recycling, or waste options for textiles. While several technologies have been demonstrated, there are currently no full-scale end-of-life recycling systems within the value chain, largely due to the economic viability of scaling up processes, educational, technical, and infrastructural barriers.[24] Most present-day recovery systems for post-consumer waste textiles mainly include reuse and mechanical downcycling processes. It has been cited that current technology can result in a 75% loss of value after the first cycle.[5,25] Mechanical recycling processes for cotton and wool fibres are well established, but are low volume, and most recycled polyester fibres are derived from mechanically recycled PET bottles.[5] Chemical recycling of cellulosic fibres has been developed with ongoing advancements in technology towards scale-up, while the recycling of synthetics (nylons and polyesters) include some full-scale developments, but is limited to a few suppliers. Nevertheless, developments in demonstrated technologies are expected to be advanced in the coming decades.

Requirements for a textile material recycling chain include stakeholders involved in the various processes along the chain from the organization of collection, sorting, and to subsequent reuse, recovery, or regeneration processes of materials.[8] Efficient recycling methods require technologies to separate and manage the various textile waste streams, which includes the characterization, identification and separation of constituent components (i.e. trims, buttons, zippers, threads), fibre blends, as well as dyes and chemicals from finishing treatments, from which final fibre quality is not diminished.[7,8] In addition, to become a viable option, future recycling technologies must be less polluting, more energy efficient, and less expensive than conventional processes for virgin material production. Additionally, a means to assist the scale-up and potential lifecycle impacts of demonstrated processes to commercialization is essential. Collaborative industry efforts from raw materials, design, collection, and recovery technologies are essential to realizing the environmental, economic, and social benefits from a textiles recycling chain.

2.4 Colouring Methods and Chemicals in Textiles

An extensive amount of chemicals is used throughout the manufacturing stages of textiles, from fibre production, through to treating, dyeing, and finishing processes, often comprising 5-15% of a garment's weight.[3,6] Chemicals may be used to provide colour and impart function to textiles. To convert raw materials into textiles, it has been cited that 8,000 different chemicals are used.[20] Various chemicals have been identified to be toxic to human health and produce a multitude of effects on the environment, notably water pollution. It is estimated that the textile chemicals market is valued at 21 billion USD (2015) and expected to reach 29 billion USD by 2024,[26] with 43 million tonnes of chemicals used in textiles production annually.[3,27] The economic benefit for the industry from eliminating negative health impacts from poor chemicals management is estimated to be 8 billion USD annually by 2030.[5]

Increased awareness and concern regarding effects of chemical usage in the industry has prompted widespread efforts to create and implement chemical management practices, identification systems, standards, policies, and legal requirements.[20,28] There have also been extensive efforts towards new safe and sustainable chemistry and processes, as well as innovation around new or alternative chemicals.

In the Safer Chemistry Innovation in the Textile and Apparel Industry report by Safer Made (commissioned and initiated by Fashion for Good and the C&A foundation), chemicals on major industry restricted substance lists were evaluated, organized into 46 classes of chemicals, and six broad chemical groups, summarized below. Based on the six chemical groups, newly identified chemicals can be classified accordingly in the future.[20]

- Amines
- Dyes and residuals
- Halogenated Chemicals
- Metals
- Monomers
- Solvents and process aids

It has been identified that chemicals found in textile materials have potential to impede recycling processes;[6] however, the knowledge base surrounding chemicals problematic for recycling is limited, and specific impacts have not been characterized. In the current system, information regarding chemicals and quantities present in textile materials is not generally passed on to potential recycling companies. It would be greatly beneficial to advance the knowledge gaps in this area by improving traceability and the identification of chemicals in textile materials, with concurrent work in the examination and identification of substances which have been found to interfere with recycling technologies.

3.0 TEXTILE FIBRE PRODUCTION AND RECYCLING

Textile fibre recycling of polyester, nylon, cotton and wool are discussed in this section, with a general focus on fibre-to-fibre (f2f) recycling, and overview of technologies for fibre blend recycling. Examples of current mechanical and chemical recycling stakeholders are highlighted. Table 2 summarizes options for mechanical and chemical recycling developed to commercial scale or demonstrated, for fibres of interest.

Fibre	Mechanical Recycling		Minimum Input Composition, %	Chemical Recycling		Minimum Input Composition, %
Polyester	**Closed-loop**	✓	100 (f2f)*	**Closed-loop**	✓ *, **	70-80 [11] /100* No requirement** (i.e. various polycotton blend ratios)
	Other applications (open-loop or downcycled)	✓	Varied * (mainly post-industrial)			
Nylon	**Closed-loop** **relatively low volume*	✓	100 (f2f)* Must be same type (6 or 6,6)	**Closed-loop**	✓ * (only for Nylon 6)	100*
	Other applications (open-loop or downcycled)	✓	Varied * (mainly post-industrial)			
Cotton	**Closed-loop**	✓	100 (f2f)*	**Closed-loop**	✓ *, ** (regenerated cellulosic, not 100% recycled cotton product)	100 * No requirement** (i.e. various polycotton blend ratios)
	Other applications (open-loop or downcycled)	✓	Varied * (mainly post-industrial)			
Wool	**Closed-loop**	✓	>80 (f2f)*	**Closed-loop**	X	N/A
	Other applications (open-loop or downcycled)	✓	30-100* (application dependent)			

Table 2: General Summary of Available Recycling Options for Polyester, Nylon, Cotton, and Wool.

** commercial scale*
*** developed/demonstrated*

3.1 Polyester

3.1.1 Summary

Polyester accounts for most of synthetic fibres produced globally (64%, 2016), and is the most widely consumed fibre.[18] Polyethylene terephthalate or PET is the most common subclass. The raw material components of PET are generally derived from petrochemicals, with main applications for fibre and packaging production, and a small proportion for film applications (Figure 9).[11] Polyester is characterized by its strength, crease-resistance, and lower water uptake (dries quickly). The environmental impacts of polyester are significant, with recent studies of microplastic release in aquatic systems which have characterized and reported the presence of substantial amounts of polyester (majority) among synthetic microfibres and particles collected from wastewater treatment facilities.[12]

Polyester is produced by condensing monoethylene glycol (MEG) and purified terephthalic acid (PTA) or dimethyl terephthalate (DMT).[6] To form fibres, PET pellets are heated, forming fibres and melt-spun into filament yarns. Yarns may be texturized to resemble cotton or wool yarns.[29] To form fabrics, yarns are knit or woven. Approximately 7% of total polyester fibre production is derived from recycled polyester materials.[18]

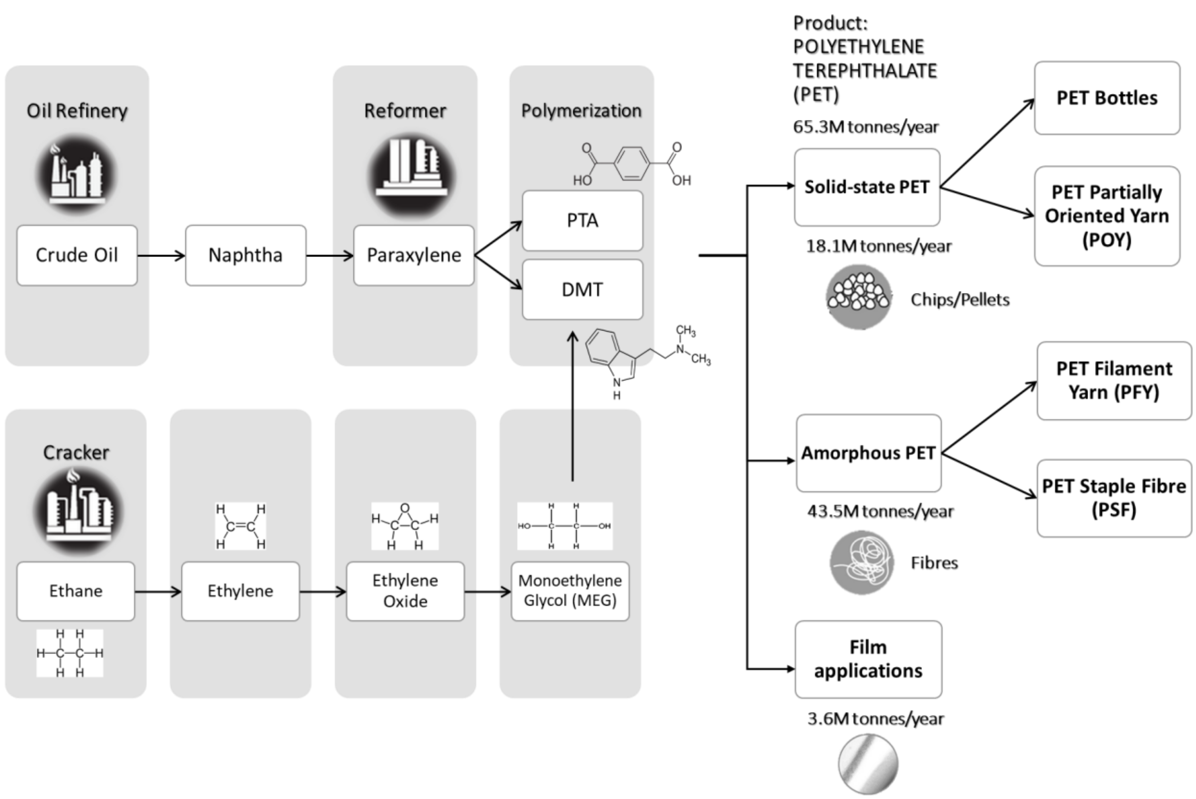

Figure 6: Virgin polyester production methods. *Modified and reproduced from [30,31]*.

3.1.2 Polyester Recovery and Recycling

The grades of PET polymers differ in terms of physical properties, which ultimately affects recycling, and designates the intended applications. The intrinsic viscosity (IV) is an important physical property that is a measure of the polymer molecular weight, and is related to the material's melting point, crystallinity, and tensile strength.[32] PET bottle resin has a higher IV and crystallinity, whereas fibre grade PET for textiles and technical applications range from low to high IV values (Table 3).[11]

	Application	Intrinsic Viscosity Value
Fibre Grade	Textiles	0.40-0.70
	Technical	0.72-0.98
Bottle Grade	Water bottles	0.70-0.78
	Carbonated soft drink grade	0.78-0.85
Film Grade	Biaxially oriented PET film	0.60-0.70
	Thermoforming sheet	0.70-1.00
Engineering Grade	Monofilament	1.00-2.00

Table 3: Intrinsic Viscosity Values of Different PET grades. *Reproduced from [11].*

3.1.2.1 Mechanical Recycling

Mechanical recycling of polyester consists of a re-melt process (or melt recycling). The process consists of the following main steps:[33]

-Collection, sorting, separation, and removal of contaminants or non-target materials
-Reduction of size – crushing, grinding, shredding, or pulling
-Heating/re-melting, and extrusion into resin pellets
-Melt extrusion into fibres
-Processing of fibres to fabric

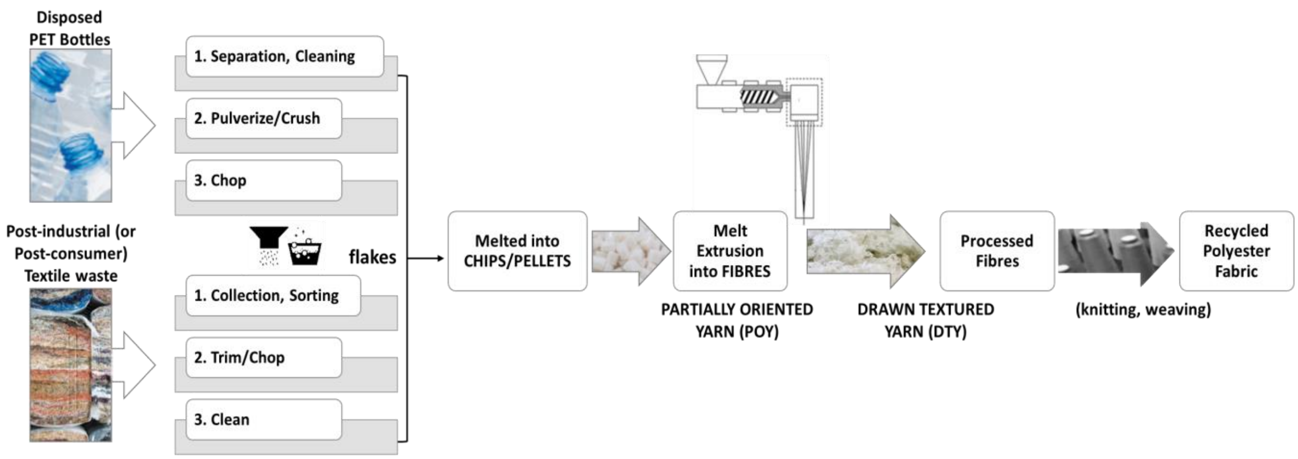

Figure 7: General route for mechanical recycling of polyester. [33-35]

The PET recovered from mechanical recycling is often used in lower value applications, due to the loss of physical properties, degradation, and contamination during use cycles and processing. Post-consumer PET bottles (generally higher IV value) are most often recycled into PET yarns (lower IV values) and is a successful example of open-loop recycling. From 2015, the market of recycled PET spun into yarns from plastic bottles, apparel materials increased by 58%.[20] The reverse process is not commonly practiced, due to low prices and high production capacity for virgin PET resin, thereby resulting in a very low incentive to invest in technology to upgrade lower IV materials to meet higher value specifications. Polyester from post-industrial waste or post-consumer PET bottles most often undergo fibre-to-fibre mechanical recycling, and ease in recycling by this route is due to the waste material properties being relatively close to 100% PET.[36] However, maintaining quality of respun polyester is a challenge in mechanical recycling, along with decolourization and loss of mechanical properties, as cheaper recycled polyester materials are known to have yellowing problems when respun from mechanical recycling routes.[36] Varied material composition or contamination from post-consumer textile waste would be more difficult to mechanically recycle back into polyester fibre.[36]

Other options for the mechanical recycling of pre-consumer and post-consumer PET textile waste generally include end uses for filler materials or nonwoven materials, for furniture, mattresses, insulation, or automotive lining.[23]

3.1.2.2 Chemical Recycling

Chemical recycling pathways for PET have been demonstrated and include processes which break down (depolymerize) the polymer into its components (monomers, oligomers, other intermediates). Various end products may be formed based on the chosen process and depolymerization additives.[33] Chemical treatment in the recycling process may also facilitate the separation of PET from other materials, such as blended fibres (i.e. elastane or cotton), or dyes and chemical finishing, as well as the creation of other end products of equal value.[33] For fibre-to-fibre recycling, the desired end products to reproduce virgin quality PET resin are the main monomer constituents of PET: ethylene glycol and purified terephthalic acid (PTA) or dimethyl terephthalate (DMT).[33] The most common depolymerization methods include: hydrolysis, methanolysis, glycolysis, or hybrid routes.[6]

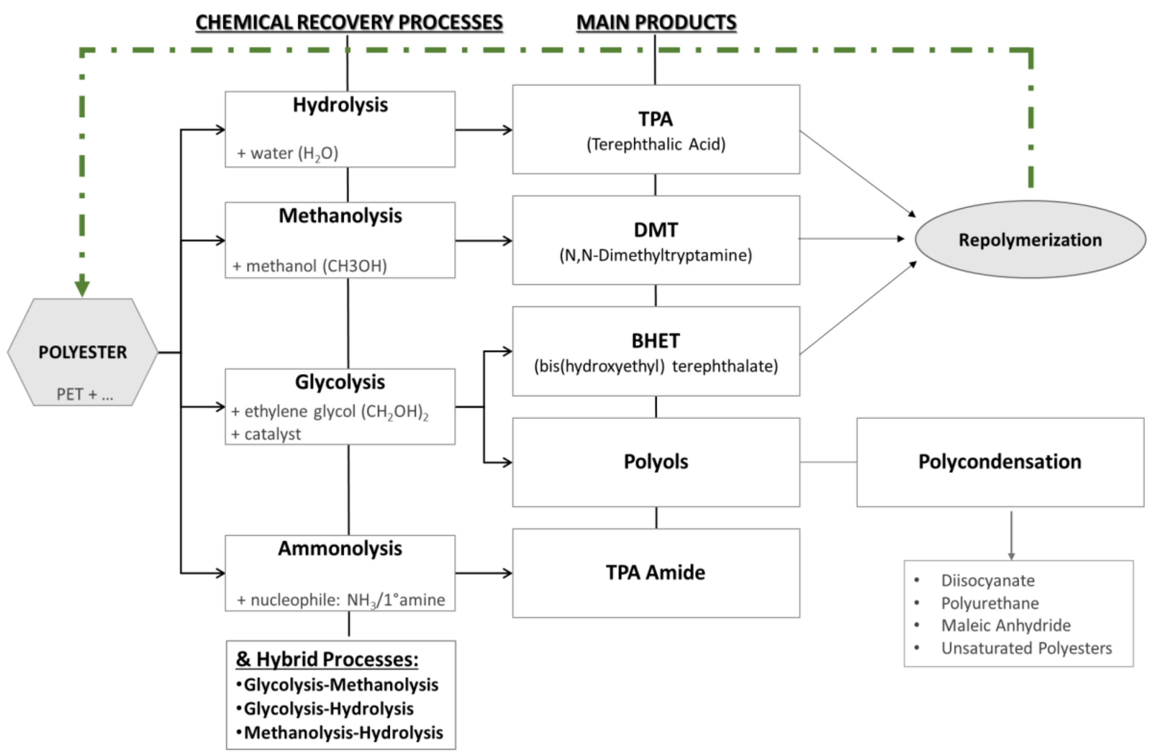

Figure 8: Overview of different approaches for chemical recycling of polyester (monomer products repolymerized to polyester). *Modified and reproduced from [6,33]*.

Obstacles to the practical application for polyester chemical recycling include, blended fabrics (i.e cotton, elastane blends); the use of polymers, dyes, additives, and processing agents in textile materials. Difficulties in separating such substances may result in significant degradation of the polyester during the recycling processes applied or require the application of a more advanced process for their removal. Other issues have included economic feasibility compared to the cost of producing virgin fibre, and environmental impacts of applying new chemical processes to recycle polyester fibres.

3.1.3 Current Recycling Stakeholders

Table 4: Polyester - Mechanical Recycling Stakeholders

Company	Feedstock/Input, Requirements	Product/Output	Description or Processes
Hyosung [37] (South Korea)	Post-consumer PET bottles	Regen™ polyester yarn, 100% recycled	Mechanical recycling
Polylana [38] (USA)	Recycled polyester (rPET) materials (i.e. rPET flakes made from bottles)	Polylana® staple fibre (patent pending)	Polylana® modified polyester pellets mixed with rPET flakes, proprietary staple fibre created, spun into yarn. The fibre blend can be dyed at low temperatures, blended with various natural and synthetic fibre materials.
RadiciGroup [39] (Italy)	Post-consumer PET bottles	r-Radyarn® r-Starlight® yarns	r-Radyarn®: continuous PET filament, with dope dyed, bacteriostatic, UV stabilized versions
Seaqual [40] (Spain)	Waste recovered from the ocean weekly (boats and fisherman from the Spanish Mediterranean Coast involved in project)	100% recycled polyester thread	From the ocean waste collected, PET plastic is collected for conversion, while other waste materials are sent to their respective recycling chains The output recycled fibres can be blended with fibres from other brands.
Sinterama [41] (Italy)	Post-consumer PET bottles	NEWLIFE™ polyester yarn, 100% recycled	Dyeable from 98°C (low temperature) with standard polyester dyestuff, along with different fibres while maintaining mechanical properties.
Stein Fibres [42] (USA)	Post-consumer PET bottles, post-industrial textile waste	Infinity Polyester, 100% recycled polyester fiber. <u>2 Streams:</u> Gold (100% post-consumer PET bottle flake) and Silver (at least 30% post-consumer bottle flake, remainder is post-industrial reclaimed PET)	Largest producers of polyester fibrefill and non-woven fibres in North America. <u>Distribution (relevant to Canada):</u> Charlotte-Toronto, and Montreal-Vancouver
Teijin [43] (Japan)	Post-consumer PET bottles	ECOPET™ staple fibre, spun yarn, fibre product	Mechanical recycling
Toray [44] (Japan)	Post-consumer PET bottles, post-industrial textile waste	ECOUSE™ fabrics	Mechanical process blends recycled PET pellets with cotton, to spin to thread for ECOUSE™ products.
Unifi [45] (USA)	Post-consumer PET bottles, post-industrial textile waste	Repreve® yarns (wide product range): staple and filament fibres Flake and resin products	Mechanical recycling 80/20 post-industrial/post-consumer waste.[36]

Table 5: Polyester - Chemical Recycling Stakeholders

Company	Feedstock/Input, Requirements	Product/Output	Description or Processes
Far Eastern New Century Corporation (FENC) [46,47] (Taiwan)	Post-consumer PET bottles	TopGreen® recycled fibre	Chemical recycling, back-to-oligomer. Depolymerization by glycolysis of PET to BHET oligomer, which is filtered and repolymerized into PET (96% material efficiency). The polymer is spun into filament fibre. Process solid waste disposed in incineration facility with electricity recovery (43% recovery rate).
	Post-consumer PET bottles, Agro-waste (haulm and husk)	TopAgro™ (bio-based) fibre	Sintering technology converts the plant waste to ash form (nano-inorganic materials). Ash is combined with recycled PET flakes and chemically recycled.
Ioniqa [48] (The Netherlands)	Post-consumer PET bottles, textiles, carpets	PET raw material	Chemical recycling process that allows for impurity and colour removal from plastic feedstock, as well as chemical recovery.
Jeplan [49] (Japan)	Post-consumer PET bottles, textile waste	BHET flake, PET resin, yarn, fabric	Subsidiary company: PET Refine Technology Non-PET clothing or materials separated and sent for recycling by other technologies. Depolymerization to recover BHET (likely glycolysis), decolourization, and polymerization to PET.
Loop™ Industries [50] (Canada)	Post-consumer PET waste (any)	Loop™-Branded PET plastic	Patented zero energy depolymerization technology. Waste is converted to constituent monomers: PTA and MEG without heat or pressure. Purification step: dyes, additives, and impurities are removed. Repolymerization of monomers to Loop™ plastic.
Moral Fiber [51] (formerly Ambercycle) (USA)	PET bottles, post-consumer textiles	PET raw material/feedstock (PTA), PET fibre	Chemical/Biological Process: Engineered microbes to metabolize plastic waste material to generate PTA as feedstock for polyester production.
Polygenta [52] (India)	Post-consumer PET bottles	Filament yarn (50-300 denier), chips	ReNew™ patented technology. Chemical process (glycolysis) converts waste to liquid esters (recycled esters equivalent to virgin), glycol is also recovered. Proprietary decolourization process is performed to remove impurities.
Teijin [53] (Japan)	Post-consumer apparel material accepted from their Eco Circle program. Minimum: 80/20 PET/cotton, 90/10 PET/nylon, and 80/20 PET/rayon blends[36]	ECO CIRCLE™ fibres, textiles (apparel, interiors, household goods, industrial materials)	ECO CIRCLE™ recovery system comprises a chemical process to recover DMT, and decolourization process (heat and solvent) to remove dyes and impurities.

3.2 Nylon

3.2.1 Summary

Nylon is a widely used synthetic polymer material for various applications and is also the generic term for polyamide-based materials. Nylon-6 and Nylon-6,6 comprise approximately 85% of nylon material used.[33] Main commercial applications for nylon include, fibre, packaging/films, carpet, and component parts most commonly found in the automotive industry.[54] Nylon is characterized by its high strength, elasticity, wrinkle-resistance, and higher moisture regain than polyester.[3] While nylon production holds a lower proportion than polyester in annual synthetic fibre production, it requires more energy to manufacture, and nearly three times as much as conventional cotton.[55] Dyeing nylon is not suited to natural or low-impact chemical dyes, and is thereby another contributing factor to the environmental impact from its production process.[56] Nylon derived microplastic pollution in aquatic environments has been found to originate from nylon fishing nets (with total fishing net waste accounting for 10% of ocean waste), and synthetic textile fibres from laundering. [56]

Nylon-6 is produced from the ring-opening polymerization of a single monomer, Ɛ-caprolactam –forming polycaprolactam (Figure 9). "6" is denotes the 6 carbon atoms that comprise caprolactam.

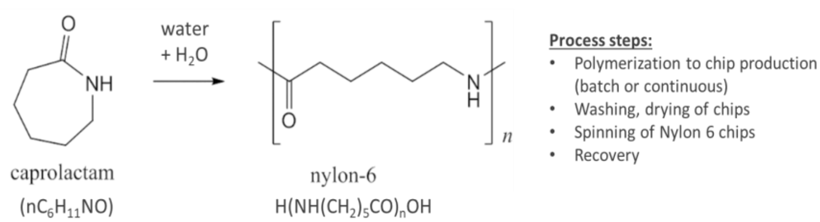

Figure 9: Polymerization of Nylon 6 (general process). [57,58]

Nylon-6,6 is produced by combining two monomers – adipic acid (AA) and hexamethylene diamene (HMD) acid (or HMDA), with water, also known as a polycondensation reaction (Figure 10). "6,6" denotes the 6 carbon atoms in each of the two monomers (AA and HMD) which comprise the polymer.

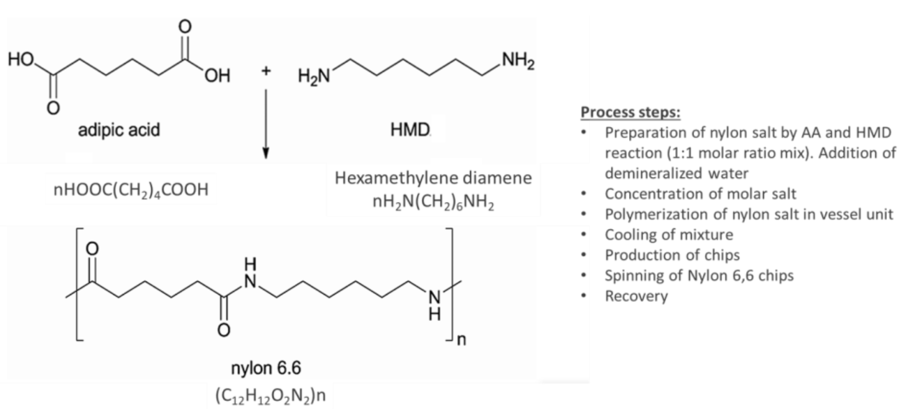

Figure 10: Polymerization of Nylon-6,6 (general process). [58,59]

Nylon-6 fibres exhibit high elasticity and lustre and are commonly used for carpet fabrics and rope.[60] Nylon-6,6 is characterized as being more wear resistant and durable than Nylon-6, with a slightly higher melting temperature.[61]

3.2.2 Nylon Recovery and Recycling

The closed-loop recovery of Nylon-6 has been widely used in the carpet industry, through combining mechanical and chemical (depolymerization) processes.[61] Chemical or monomer recovery systems are applied to volatized caprolactam after spinning operations during Nylon-6 fibre formation.[62] The depolymerization of Nylon-6,6 is more complicated, since it is composed of two different monomers and often requires a larger volume of reagents, which may be potentially more damaging, and produce more waste product.[6,63] Chemical recycling of Nylon-6,6 is not performed commercially, and monomer recovery systems are not feasible given that the processing of the compound does not yield large volumes of residual monmers.[61,62] Nylon-6,6 is commonly recycled mechanically from pre-consumer fibres.[61,64]

3.2.2.1 Mechanical Recycling

The process for the mechanical recycling of nylon may involve the following steps (outlined in Figure 11):

-Cleaning process to remove impurities
-Shredding and grinding
-Melting into chips/pellets from which they can be used in new applications
-For fibre production: the recycled chips are melted and respun into filaments

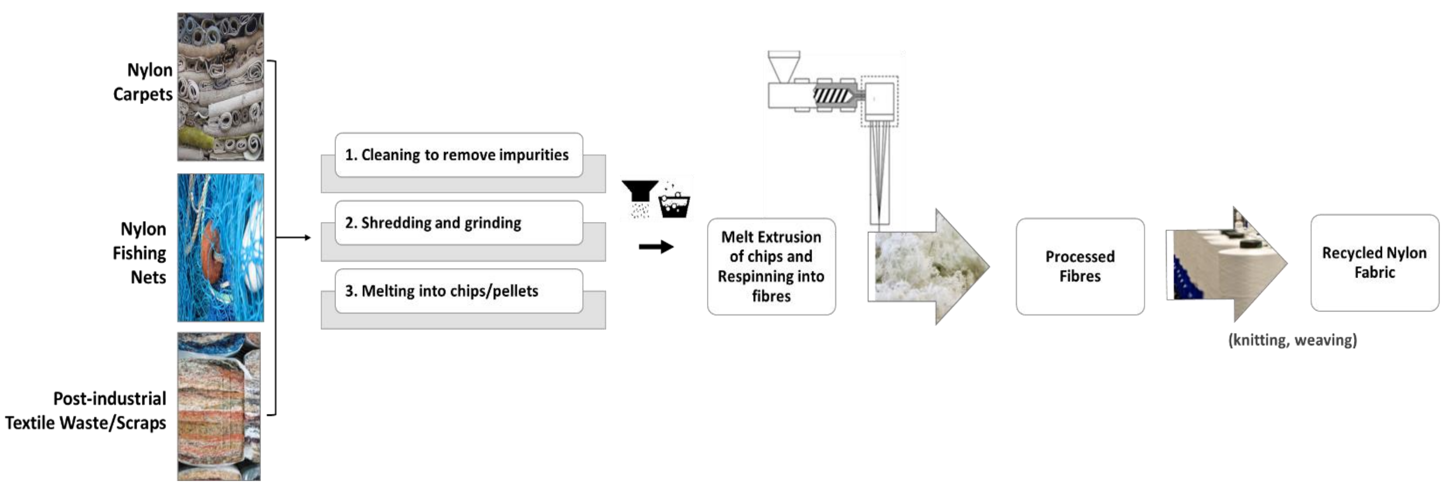

Figure 11: General route for mechanical recycling of nylon.[35,65-67]

Due to its lower melting temperature (compared to PET), nylon is highly susceptible to contamination by microbes, bacteria, and nonrecyclable impurities remaining in the material, and thereby requires a cleaning process prior to recycling.[24]

3.2.2.2 Chemical Recycling

Chemical recycling of nylons (6 and 6,6) includes a depolymerization process followed by distillation to obtain and recover their monomeric constituents: caprolactam (for Nylon-6), and HMDA and adipic acid (for Nylon-6,6).

Various chemical processes have been demonstrated and developed, and are summarized in Figure 12. Barriers to their widespread adoption have included high costs, challenging materials issues, multiple processing steps requiring high operational knowledge, which are thought to pose difficulties for technology transfer.[6]

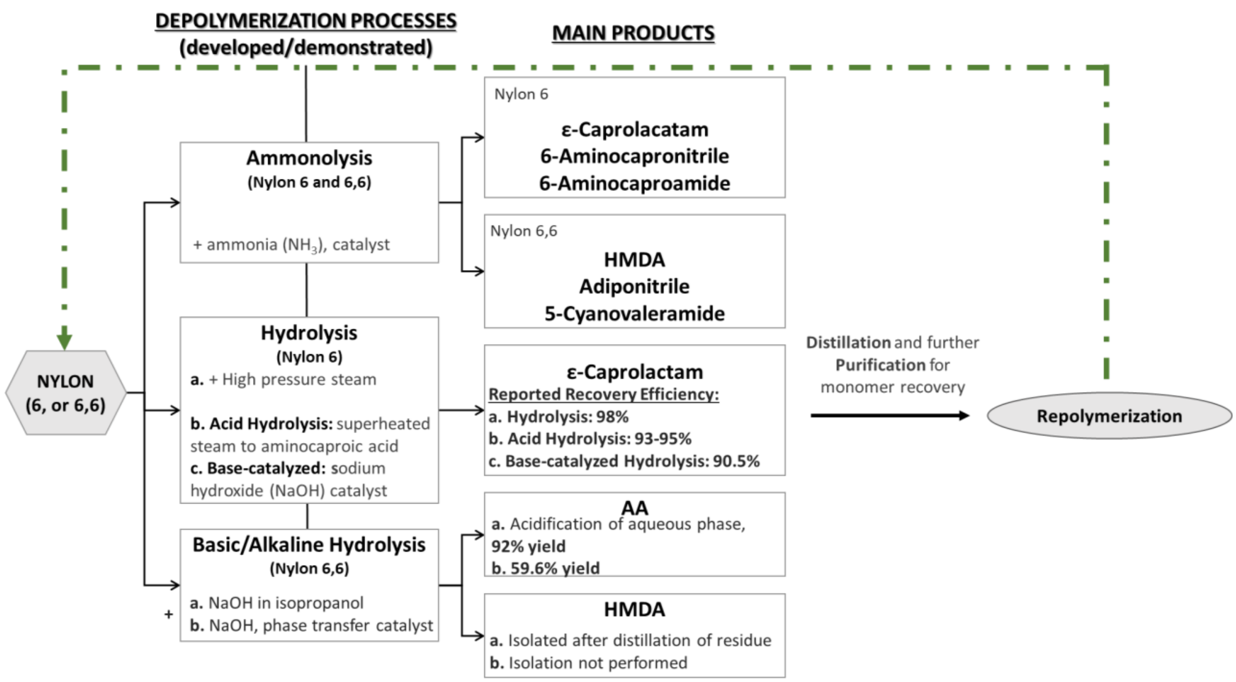

Figure 12: Overview of different approaches for chemical recycling of nylon. *Produced from* [68].

Current chemical recycling operations for both Nylon-6 and Nylon-6,6 (to a lesser extent) include the ammonolysis method, created by DuPont (Figure 13), and patented processes for Nylon-6 chemical recovery by TORAY - CYCLEAD™, Aquafil, and Hyosung.[6,18]

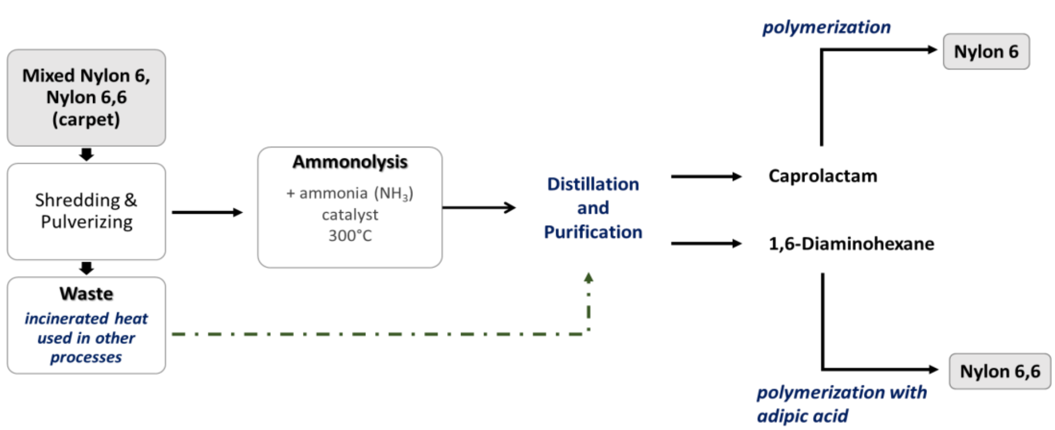

Figure 13: Overview of DuPont ammonolysis chemical recycling process for nylon. *Reproduced from* [69].

3.2.3 Current Recycling Stakeholders

Table 6: Nylon - Mechanical Recycling Stakeholders

Company	Feedstock/Input, Requirements	Product/Output	Description or Process
Chainlon [70] (Taiwan)	**Nylon 6 and 6,6** Post-industrial, and post-consumer textile waste	Greenlon® Re recycled yarn (40, 70, 400 denier)	Mechanical recycling process (recycled chips melted and spun). Energy savings: 8.5%; CO_2 reduction: 76.7% (combined physical recovery and polymerization); Waste water savings: 100%
ECOALF [71] (Spain)	**Nylon 6** Discarded fishing nets	Recycled yarn used in ECOALF apparel	Waste fishing nets are collected from the ocean (Spain and Thailand) and mechanically recycled. The Ecoalf Foundation works to facilitate recycling of other plastic waste (PET bottles, used tires)
Fulgar [72] (Italy)	**Nylon 6,6** Post-industrial textile waste	Q-NOVA® filament (99% recycled) Properties: excellent breathability (EN ISO 62), and dyeing quality	Fugar partners with producers to recycle Nylon 6,6 waste materials (mechanically) from main production cycle which would have otherwise been disposed. CO_2 reduction: 80%, Water savings: 90%
Nilit [60,73] (Israel)	**Nylon 6,6** Post-industrial textile waste.	NILIT® ECOCARE Yarn	Preferred feedstock: partially oriented yarns (POY), 80-90% (w/w) of waste material in the mixture for melt-spinning. Process not limited to Nylon 6,6, other nylons may be recycled by the process.
Toray [74] (Japan)	**Nylon 6** Post-industrial textile waste Discarded fishing nets	Reycyclon™ yarn (Patagonia)	Mechanical recycling process for off-spec yarns generated from their virgin nylon production process. CO_2 reduction: 80%
Unifi [75] (USA)	**Nylon 6** Post-industrial textile waste	PREPREVE® Nylon Filament fibre	Proprietary chip extrusion and texturizing process.

Table 7: Nylon - Chemical Recycling Stakeholders

Company	Feedstock/Input, Requirements	Product/Output	Processes
Aquafil [76] (Italy)	**Nylon 6** Post-industrial and post-consumer (used apparel) textile waste, fishing nets, carpets, delivered in bales. Must be 100% nylon materials, no prohibited substances	Econyl® Yarn (70% recycled nylon, 30% virgin fibre) for use in carpet flooring and textiles	The ECONYL® closed-loop process includes collection and sorting of feedstock, caprolactam monomer recovery by depolymerization, and subsequent polymerization to nylon of equivalent quality to the petroleum derivative.
Hyosung [77] (South Korea)	**Nylon 6** Post-consumer fishing nets, safety nets, nylon rope, waste yarn and chips	Mipan Regen™ Yarn (50% recycled nylon), as fine as 20 denier Properties: excellent dyeing uniformity, tenacity, finer denier, finer denier per filament	Mixed mechanical and chemical process. Process includes impurity removal from feedstock, continuous recycling process, with the recycled nylon chip for made from recaptured caprolactam.
Toray [78,79] (Japan)	**Nylon 6** Post-industrial (from Toray Nylon 6 production) and post-consumer textile waste	CYCLEAD® fibre and fabrics	CYCLEAD™ process consists of chemical recovery of liquids, waste, and caprolactam from Nylon 6 production, and post-consumer textiles, to produce recycled Nylon 6 products. Heating with cyclic amide compound solvent. Simultaneous colour removal is performed.

3.3 Cotton

3.3.1 Summary

Cotton is the most widely produced natural textile fibre, owing to its strength, lightweight, and absorbency. The staple fibres grow around the cotton seed (as seed hairs), and range from 22 to 32 mm in length, with longer fibres having higher quality. Cotton fibres contain 88-97% cellulose, with the remaining constituents which include waxes, proteins, and pectinic substances.[80] Chemicals and water usage from both crop and textile production are associated with significant environmental pollution and impacts.

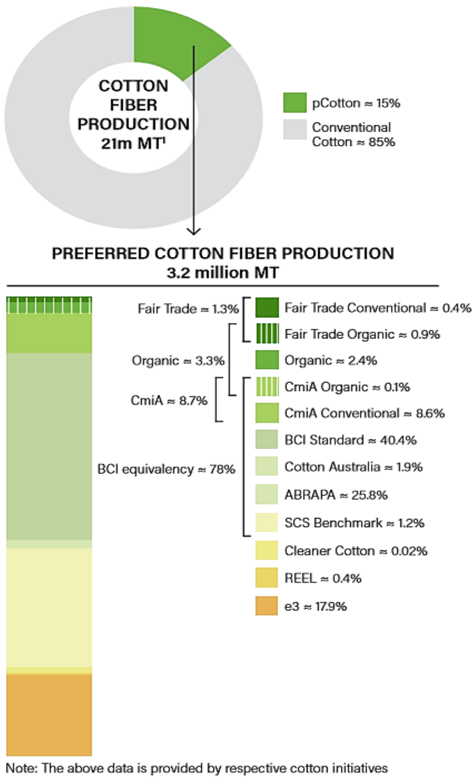

Figure 14: Cotton global fibre production.[18]

Conventional cotton production from its cultivation to harvesting, requires the use of arable land, large amounts of water, and agrochemical resources (i.e. pesticides and fertilizers).[80,81] There have been efforts towards more sustainable agricultural processes, which includes the transition to low-input organic management system cotton farms, that include sustainable practices which enable water and energy reduction, and sophisticated fertilizer usage.[29] Other combined efforts through partnerships with organizations including Better Cotton Initiative and Textile Exchange,[29] also forms part of the Preferred Cotton Fibre Production Segment (Figure 14) in the apparel industry.

The textile production process from cotton fibres to fabrics for garments requires the extensive use of chemicals and energy to reduce the level of natural impurities found in the fibre, improve dye and finishing chemical uptake, and impart functional properties to the final fabric (i.e. high absorbency and hydrophilic properties).[82] The basic steps are outlined in Figure 15.

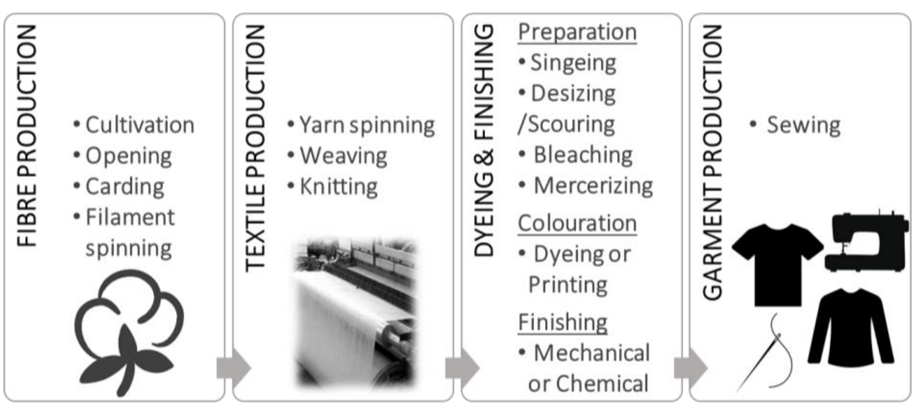

Figure 15: Cotton textile production steps from fibres to garments.[83-86]

3.3.2 Cotton Recovery and Recycling

Cotton recovery and recycling provides alternatives to both the diversion of waste from landfill, and raw material production utilizing agricultural land. The mechanical recycling of cotton from is well established and is applied to both pre- and post-consumer waste, an generally entails the respinning of recycled combined with virgin material, without additional chemicals.[3] The majority of chemical recycling processes of cotton is in developmental stage, or close to commercial adoption, and include either dissolution processes to recover the cellulosic fibres, or depolymerization processes to generate other by-products, namely regenerated man-made cellulosics.

The overall ecological advantages of recycled cotton fibres include, lower water and energy requirements (20% lower), fewer chemicals, and lower emissions generation and natural resource consumption owing to the elimination of farming operations associated with conventional cotton production.[87]

3.3.2.1 Mechanical Recycling

The general process of mechanical recycling of cotton for apparel applications involves the respinning of waste fibres. Given that the mechanical process breaks the fibre, quality and strength are reduced and therefore, the recovered staple fibre must be blended with either virgin cotton fibres or other fibres to impart both increased strength, and to provide colour matching, thereby eliminating the need for re-dyeing. Other applications that utilize pre-consumer and post-consumer cotton as feedstock materials include a variety of nonwovens used for insulation, automotive felts, oil sorbent sheeting. The main challenge cited for widespread commercial adoption of closed-loop respinning lies in facilitating logistical support to increase volume of material collected and processed.[6]

The process flow diagram in Figure 16 details the options for mechanical recycling of cotton to produce respun fibre for apparel, and blended materials for various applications.

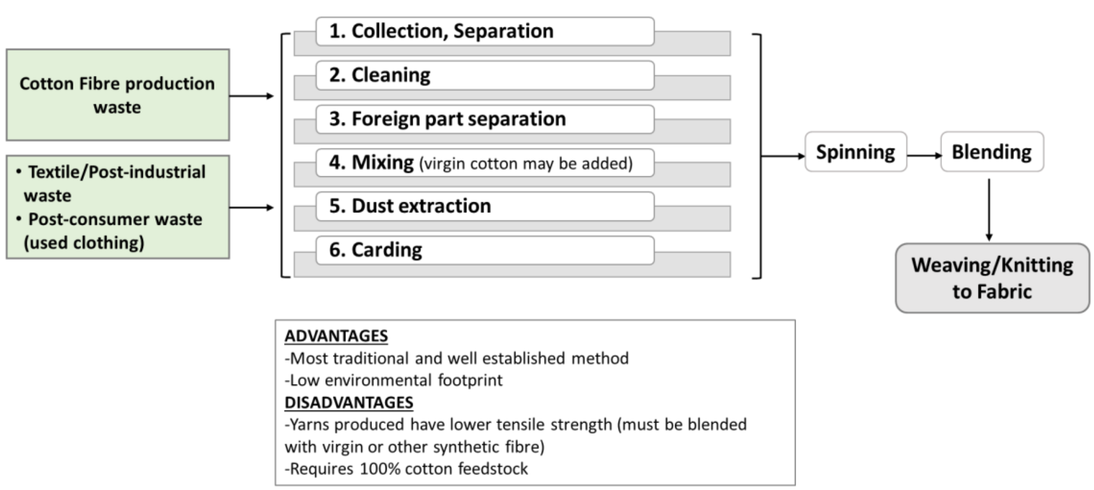

Figure 16: Overview of mechanical recycling process of cotton. *Produced from [88].*

3.3.2.2 Chemical Recycling

The chemical recycling process of cotton is based on the dissolution of cellulose. Two main routes which have been explored include: the depolymerization of glucose monomers for use in other applications, or a polymer dissolution route where the separation and regeneration of cellulosic fibres occurs by use of solvents.[88] The latter process may recover a chemically modified or pure cellulosic fibre products, which can also be incorporated as feedstock for regenerated/recycled man-made cellulosic fibres (MMCs).[87,89] Chemical processes for recycling and regenerating MMCs would also reduce the burden of toxic chemicals, namely carbon disulfide used in conventional viscose production, and enable the production of fibres with equivalent virgin quality.[90] The Lyocell (NMMO) and Ionic Liquid processes are two main chemical recycling methods which have been explored and developed. Figure 17 summarizes the different chemical-based processes for cotton fibre recycling.

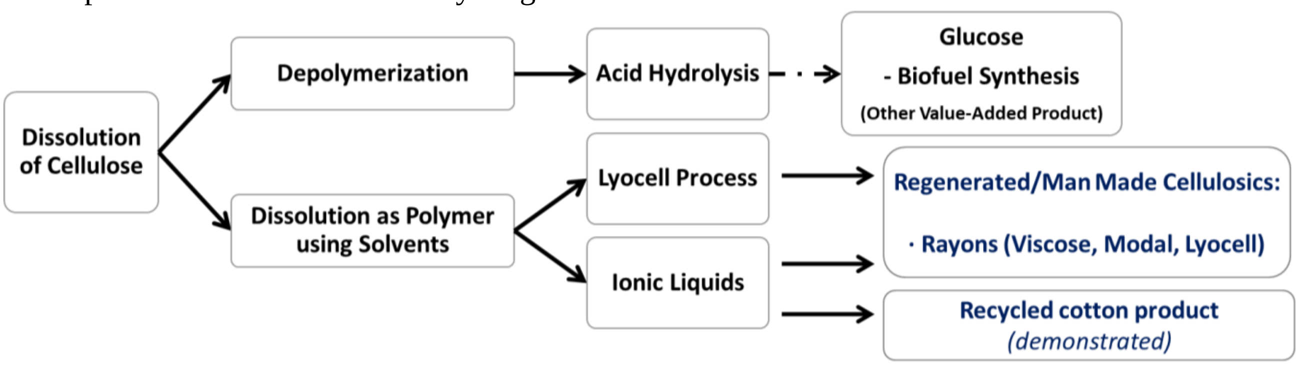

Figure 17: Overview of cotton chemical recovery processes. *Reproduced and modified from [8]*.

The Lyocell method (Figure 18) can be applied to 100% cotton fabrics for regeneration of cellulosic fibres (MMCs) using N-methylmorpholine N-oxide (NNMO) to dissolve cotton fibres (dissolving pulp). The regenerated fibres are produced by processing the dissolved pulp (cotton waste) and blending with other plant-derived pulp products (wood, flax, hemp, etc.).

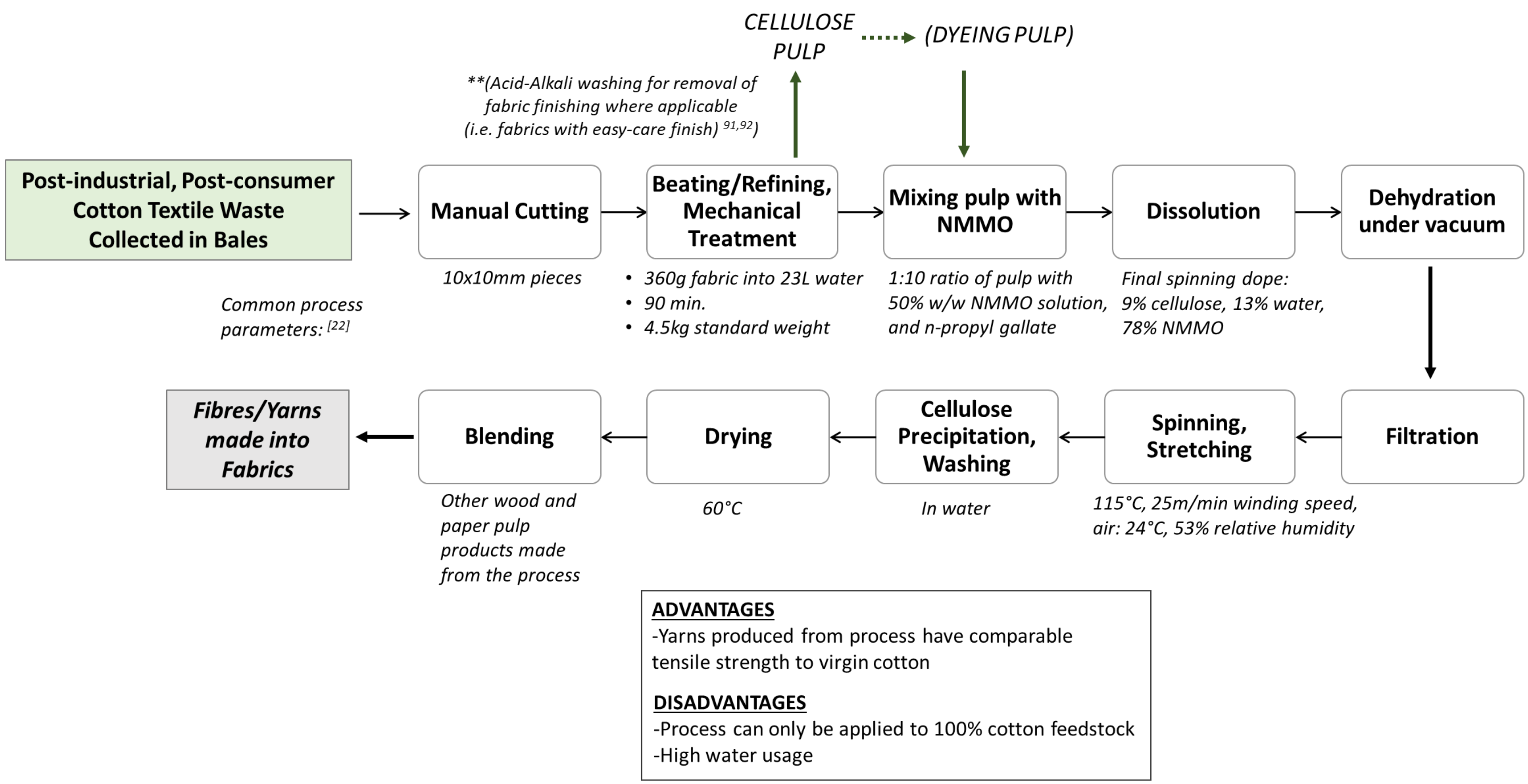

Figure 18: Overview of Lyocell process.[91,92] *Reproduced and modified from [88].*

The ionic liquid process (Figure 19) can be applied to blended cotton fabrics. Researchers from Aalto University and the University of Helsinki who developed the Ioncell-F process, applied the ionic liquid solvent, [DBNH]OAc (1,5,diazabicyclo[4.3.0]non-5-enium acetate) to chemically recycle cotton waste and produce MMCs, with the fibres exceeding tensile strength of native cotton and commercial MMC fibres.[93] Researchers from Deakin University demonstrated the use of ionic liquid, 1 allyl-3-methylimidazolium chloride (AMIMCI), to separate cotton from polyester blend (50:50 polycotton blend). While still in developmental phase, it has potential to produce 100% recycled cotton product, but may also be blended with other pulp product to produce regenerated cellulosic materials.[94]

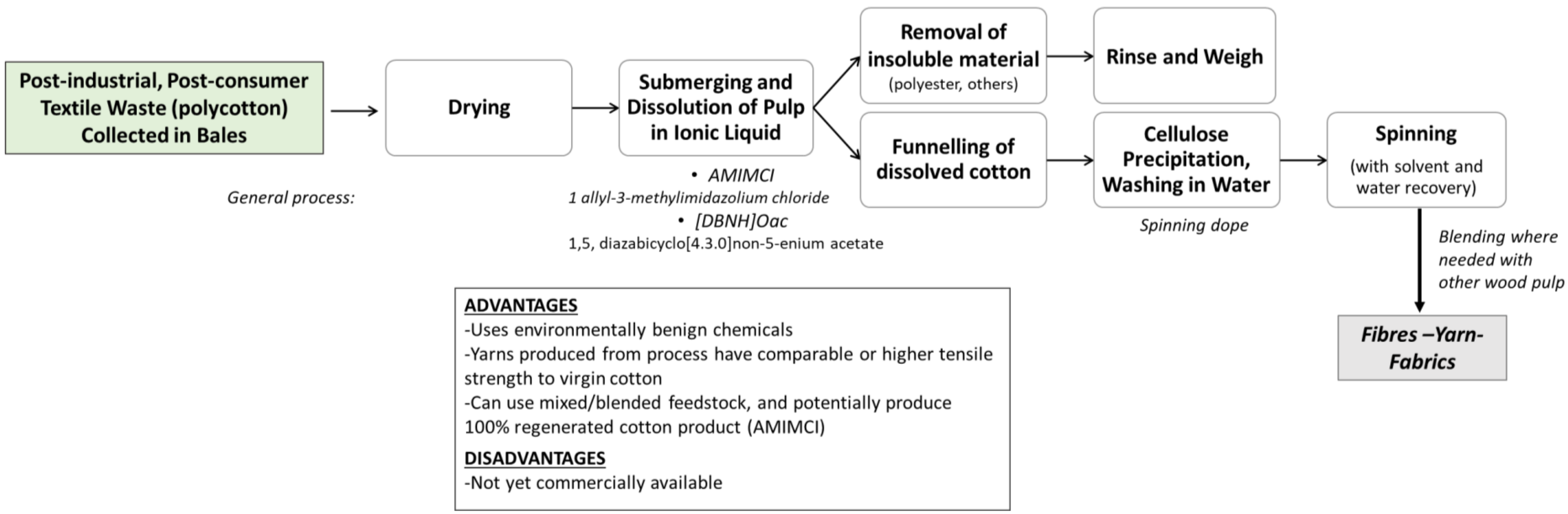

Figure 19: Overview of ionic liquid process. *Reproduced and modified from [88]*.

3.3.3 Current Recycling Stakeholders

Table 8: Cotton - Mechanical Recycling Stakeholders

Company	Feedstock/Input, Requirements	Product/Output	Description or Process
Hilaturas Ferre [95,96] (Spain)	Post-industrial and post-consumer textile waste, 100% cotton	Recover® yarn 50% recycled cotton blended with other synthetics (i.e rPET, acrylic)	Collection and sorting of cotton textile waste globally. Waste is cut, shred, and fed into industrial spinning process to produce 50% recycled cotton blend yarn.
Gebrüder Otto GmbH &Co. [97-100] (Germany)	Post-industrial textile waste predominantly from Otto's spinning mill, 100% cotton	recot^2® fibre 25% recycled cotton with 75% virgin organic cotton, or 50% raw cotton and 50% recycled selected production waste	The recot^2®-process was developed to produce a carded yarn with comparable quality to a combed organic yarn, but with added eco-balance, achieved through the recycled cotton waste content.
GIOTEX [101] (Mexico, USA)	Post-industrial textile waste, 100% cotton	Giotex™ yarn 75-90% recycled cotton-blend yarn depending on required application, or shade request (100 custom shades)	Collection of waste, shredding to fibre, blended (for colour or strength), and spun into yarn. Giotex™ Fifty: 55/45% recycled cotton/polyester Giotex™ POP: 75/25% recycled cotton/polyester

Table 9: Cotton - Chemical Recycling Stakeholders

Company	Feedstock/Input, Requirements	Product/Output	Processes
Evrnu [102-104] (USA)	Post-consumer cotton textile waste	Regenerated cotton/cellulosic fibre Properties: can be dyed efficiently with ability to add moisture-wicking or anti-microbial properties.	Solvent used for cellulose dissolution, polymerization, and extrusion into regenerated cellulosic fibre. Evrnu proprietary technology can strip down cellulose to a pure carbon chain that is three times stronger than steel. The technology can also simulate other fibres (end-products) such as rayon, polyester.
Ioncell [105] (Finland)	Dissolving pulp, paper grade pulp from Kraft pulping process, waste paper and cardboard, waste cotton	Ioncell-F Cellulosic fibre Properties: moisture absorbing, biodegradable, high lustre, can be dyed with same processes as cotton and viscose	Ionic liquid used for cellulose dissolution. Fibre filaments produced through dry-jet wet spinning. Ionic liquid is recovered as aqueous solution, and separated from water, to be re-circulated in the process.
Lenzing [18] (Austria)	Pre-consumer, other cellulosics (beech, eucalyptus, pine, etc.)	Cotton blends TENCEL® Modal® Refibra™	Respinning of cotton with cellulosic reinforcement (classified as MMCs).
Re:newcell [106] (Sweden)	Post-consumer cellulose-based textile waste, high cellulosic content (cellulose and viscose)	re:newcell cellulosic pulp for use in recycled fibre production (lyocell process)	Cellulosic waste sorted and shredded. Decolorization is performed, turning waste into a slurry. Slurry is dried, producing pure, natural re:newcell pulp, used for textile production. re:newcell pulp found to have higher mechanical properties than wood-based dissolving pulps, as well as better dyestuff absorption.
SaXcell [107]	Post-consumer cotton waste	Regenerated virgin cellulose. Colouring may be carried out at fibre, yarn, or fabric levels.	Cotton textile waste sorted into well-defined waste stream. The waste is grinded, with removal of non-textile components, followed by chemical decolourization. Wet spinning is performed according to the viscose or lyocell processes.

3.4 Wool

3.4.1 Summary

Wool is a natural animal protein fibre that grows on sheep (other sources: goats, llamas etc.). The protein fibre is known as keratin. Wool exhibits many favourable properties in apparel, consumer products, as well as industrial textile applications. Wool has favourable thermal comfort properties, being breathable, warm, and moisture wicking. It is easily dyed and requires less washing than other fibres.[3] The relatively long fibre length of wool makes it well suited for mechanical recycling.[108] Wool accounts for up to 5% by weight of total clothing donated for recycling and reuse.[109] Wool recycling has been practiced for over 200 years, with several options for its reuse, and is considered as one of the most re-used fibres.[109] The production stages from fibre to garment, along with recycling flows during process steps are outlined in Figure 20.

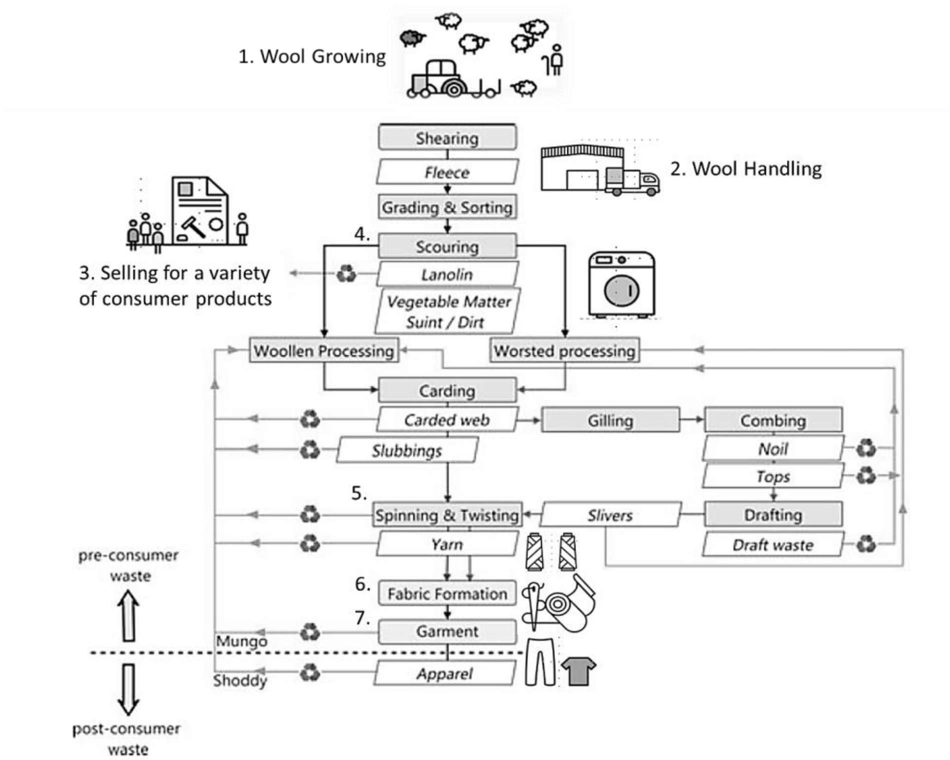

Figure 20: Overview of wool fibre processing steps with recycling flows of post-industrial and post-consumer waste. *Reproduced and modified from [109,110]*.

3.4.2 Wool Recovery and Recycling

Wool textile waste is processed from both post-industrial (pre-consumer) and post-consumer materials. The textile waste recovered from manufacturing process (post-industrial) following closed-loop steps in which waste is continuously fed into different processing steps (Figure 20).[109] Wool textile recycling is applied in commercially practiced open loop and closed loop mechanical processes. While chemical recycling of wool is not performed, there have been many research developments into recovery processes of keratin from pre- and post-consumer waste wool for other value-added applications.

3.4.2.1 Mechanical Recycling

Open Loop Recycling System (Pre-Consumer and Post-Consumer Waste): From this process, the recycled wool is mechanically pulled into their fibrous form and used as raw materials for new industrial products. Nonwoven fabrics are most commonly produced from this recovery system and used for the production of insulator pads for mattress or furniture, automotive felts and insulating materials, and oil sorbent sheeting.[23] Nonwoven products are less sensitive to impacts on properties due to shorter fibre lengths, and the products derived from this system contribute to greater sustainability owing to a substantially longer second operational life.[109] Figure 21 details basic steps in an open loop recycling system for wool, and examples of products and compositional requirements.

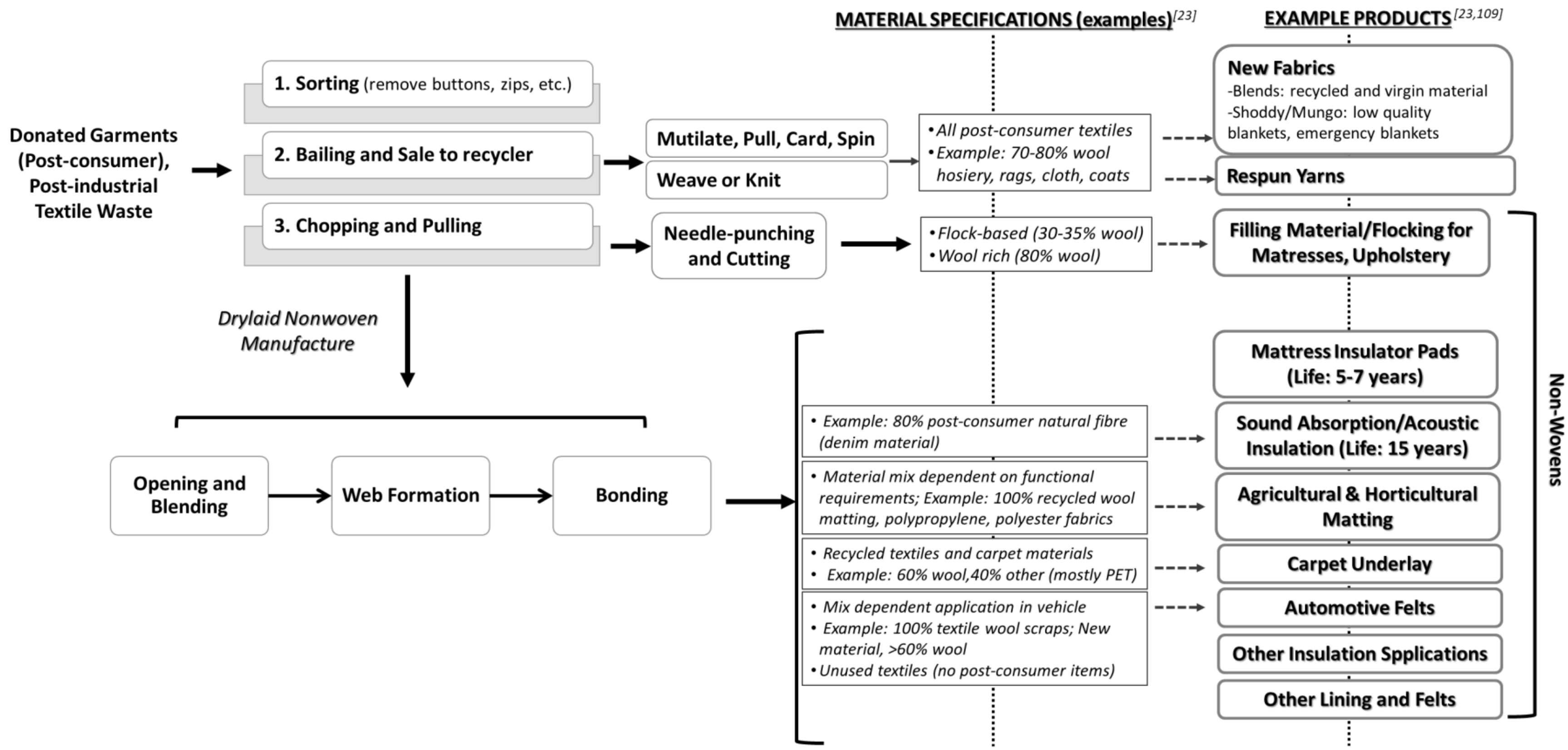

Figure 21: Open-loop recycling system for wool, with examples. *Reproduced and modified from [23,109].*

Closed Loop Recycling System (Post-Consumer Waste): During this process, garments are mechanically pulled into their raw fibre state (carding) and reused as raw material in the respinning back to yarn by conventional processes.[111] The yarn can be used to produce new high-value garments. With the impact of fibre breakage during mechanical recycling, the respun yarn will contain a blended proportion of virgin fibre, which can either be virgin wool, or synthetic fibre (reduce raw material costs in yarn manufacture[109]). The sorting of wool by colour, may also be a means of eliminating the need for subsequent dyeing processes.[109] Figure 22 summarizes the basic steps in the closed loop recycling for wool.

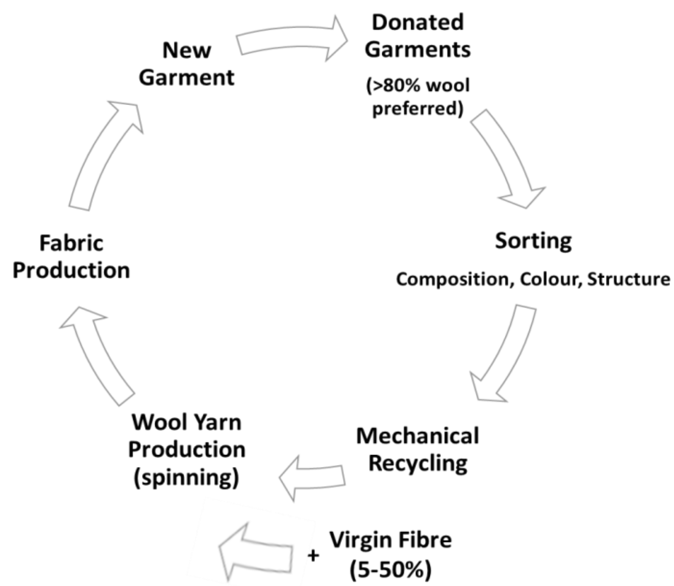

Figure 22: Basic steps in closed loop recycling of wool. *Reproduced from [109]*.

3.4.2.2 Chemical Recovery

Chemical recycling of wool textiles is not practiced, however, research and development into the recovery of keratin protein from pre- and post-consumer waste has been demonstrated for use in other applications including, biomaterials, and resins and adhesives.

Other notable research has involved the protein recovery from waste or recycled wool for use as functional treatments in wool fabric production. Work by Smith and Shen, applied extracted polypeptides (protein molecules) from low quality waste wool as a means of surface modification to the fibre surface, to improve the shrink resistance.[112] Du *et al.* successfully demonstrated an anti-felting/anti-pilling finishing process on wool fabric by a fixation treatment using keratin polypeptides extracted from recycled waste wool.[113] Improvements in softness, dyeability, and hydrophobicity were also observed in the modified fabrics.[113]

Examples of chemical recovery processes are listed in Table 10.

Table 10: Examples of Keratin Chemical Recovery Processes from Wool.[112-115]

Input	Process	Output/Product	Application
Low quality waste wool Pre-consumer Post-consumer	Alkali hydrolysis Ionic liquid Sulfitolysis Reduction Oxidation	Keratin protein	-Biomaterials, biopolymers: wound healing -Animal feedstock
Waste wool	RESYNTEX biochemical process and resin synthesis	Protein hydrolysate extraction to obtain resins and adhesives	Bio-based resins and adhesives
Low quality waste wool	Polypeptide protein extraction, surface modification of wool fibre by enzymes	Machine washable wool through an alternative shrink-resistant finishing process	
Recycled wool	Keratin polypeptide extraction, fixation treatment	Anti-felting/anti-pilling finishing	

3.4.3 Current Recycling Markets and Applications

Table 11: Wool - Mechanical Recycling Stakeholders

Company	Feedstock/Input, Requirements	Product/Output	Description or Process
Cardato, Cardato Recycled Trademarks[116,117] (Prato, Italy)	Post-industrial and post-consumer textile waste	Recycled wool yarn "Cardato" brand (at least 60% of yarn or fabric using carding process) "Cardato Recycled" (at least 65% recycled material) "Cardato Regenerated CO_2 neutral" trademark certification system for companies	Closed-loop mechanical recycling process (carding recycled waste fibre feedstock and virgin fibres). Under trademark, environmental impacts (water, energy, CO_2 consumption) from production cycle must be measured.
ECOALF [118] (Spain)	Post-industrial textile waste	Recycled wool yarn for ECOALF products.	Closed-loop mechanical recycling process (carding recycled waste fibre feedstock and virgin fibres).
Woolagain[119] (USA)	Post-consumer textile waste	Woolagain yarns with up to 80% recycled wool content. Yarns blended with acrylic or polyester.	Closed-loop mechanical recycling process (carding recycled waste fibre feedstock and virgin fibres). 31 colour shade offerings.
Christian Fischbacher Co. AG [120] (Switzerland)	Post-industrial and post-consumer textile waste	BENU Recycled Wool. Premium woven wool for upholstery fabrics that is blended with other post-consumer waste, PET bottles.	No fibre dyeing required.

3.5 Recycling of Fibre Blends: Progress in Closed-Loop and Alternative Technologies

At present, many blended fibre materials are generally suitable for open-loop recycling systems. Requirements for processes designed to recycle blended materials must be capable of handling lower grade materials, applying treatments to separate or selectively dissolve blended constituents, and removing impurities such as finishing chemicals and dyes. With ongoing developments in fibre-to-fibre recycling processes of prevalent textile materials, concurrent progress in closed-loop recycling of fibre blends will facilitate the transition to circular systems. Table 12 provides examples of current commercial, patented, or processes under development for recycling of fibre blends.

Table 12: Recycling of Fibre Blends – Stakeholders and Processes in Development (*)

Company	Feedstock/Input, Requirements	Product/Output	Description or Process
Leigh Fibers Inc. [121,122] (USA)	Post-industrial textile waste. Wide range of materials accepted.	Reprocessed fibres (i.e. shoddy) and nonwoven products for various applications (natural, synthetics, technical fibres), in addition to proprietary branded fibres.	Mechanical processing and deconstruction methods (i.e. melt spinning). SafeLeigh™: barrier fabrics and coarse yarns. Para- and meta-aramids, intrinsically fire-retardant fibres, treated recycled cottons and synthetics. [123] QuietLeigh™: acoustic insulation primarily for automotive industry, meeting flame retardancy and sound deadening standards. [123]
Martex Fiber [124-126] (USA)	Post-industrial and post-consumer textile waste	Recycled cotton or cotton-polyester materials to textile products and reclaimed fibres for various applications	Mechanical processing and deconstruction methods. All-inclusive waste services: textile and non-textile (cardboard, metal) waste collected but not processed by Martex Fiber is sent to appropriate waste streams.
Phoenix Fibers [127] (USA)	Post-industrial and post-consumer textile waste (cotton and cotton/polyester)	Cotton (denim and other fabrics) fibre conversion into shoddy for various applications.	Mechanical processing and deconstruction methods. Affiliate companies include United Fibers, Bonded Logic.
Le Relais [128,129] (France)	Post-consumer textiles waste Cotton (no VOC emission or formaldehyde release –test certified), wool-acrylic mix	Métisse® thermal and acoustic insulation materials for the building construction industry (nonwoven)	85% recycled fibre (70:15 or 45:40 cotton: wool-acrylic mix) and 15% polyester. Treatment with anti-fungus and anti-bacterial additives. The product can also be recycled at its end of life and is certified to ACERMI thermal insulation quality standards (evaluated by CSTB, France).
Chroma[130] (Canada)	Post-consumer textile waste sourced near Montreal, Quebec (<600km)	Felt products, 100% recycled material for surface coverings, furniture, soft goods.	Product contains 80% post-consumer waste, 20% recycled/regenerated polyester. Collected waste is sorted by colour, no dyeing required.

(continued)

Company	Feedstock/Input, Requirements	Product/Output	Description or Process
Aquafil [131] (Italy) * **demonstrated, reference to patent application:** WO2013032408A1	Clothing or fabrics (knit and woven) containing Nylon (Polyamide) 6 or 6,6 fibres blended with Spandex (elastomer) fibres -varied composition levels	Two separate material streams: Degraded spandex, and nylon fibres	Controlled thermal degradation and solvent washing treatment of spandex, resulting in its removal from the blended material, followed by the removal of excess solvent from the remaining nylon fibres. The solvent is recoverable. Portions of the separated material waste streams can be recycled, disposed of, or repurposed thereafter.
***Biocellection** [132,133] (USA)	Mixed post-consumer plastic waste from municipal recovery facility.	Regenerated virgin chemical intermediates for plastic or textile manufacturing.	Chemical catalyst is used to decompose plastic waste. Chemicals can be used as feedstock for plastic/polymer materials such as apparel, footwear, or automotive parts. Colour and impurities can be separated and removed. Current conversion efficiency of developed process: 70%
***CARBIOS** [134] (France)	Single-use plastic materials -PET plastics	100% bio-recycled PET granule for various biodegradable products	Biological recycling through an enzyme-based biodegradation process. Various enzymes to treat waste of different polymers to regenerate new polymers for reuse.
***City University Hong Kong, HKRITA** [135,136] (Hong Kong)	Post-consumer polyester-cotton blends	Cotton is recovered and converted to glucose to potential value-added use in other industries. Highly pure polymer residues (PET) can be respun to fibre.	Biological recycling method: Fermentation of textile waste to produce cellulase enzyme, a freezing alkali/urea pretreatment, followed by enzymatic hydrolysis (cellulase enzyme) and filtration to obtain a glucose stream from the cellulose component, and recovered PET polymer component.

(continued)

Company	**Feedstock/Input, Requirements**	**Product/Output**	**Description or Process**
***HKRITA** **[137,138]** (Hong Kong)	Post-consumer polyester-cotton blends	Two separate streams: cellulose powder from cotton, and polyester fibre. The recovery rate of polyester fibres is 98% in 0.5 to 2 hours, with maintained quality.	A hydrothermal treatment method is applied to separate and recycle blended polycotton blended textiles. Cotton is decomposed into cellulose powder, which allows for polyester fibres separation from the blends. Process inputs include heat, water, and 5% chemical (sustainable/green).
***HKRITA** **[138,139]** (Hong Kong)	Post-consumer wool, cotton, and wool-cotton blends	Sliver for yarn spinning, fabric or garment making. The processing method has minimal impact on fibre properties.	Mechanical recycling process incorporating sanitization processes that reduce 90% of microorganisms present in the waste (ISO 11737-1:2018), and a highly automated sorting system (residual metal detection, colour detection algorithm) with robotics (AGV) and intelligent conveyor control.
***Tyton Biosciences** **[140]** (USA)	Post-industrial and post-consumer cotton, polyester and polycotton blends	Dissolving pulp that can be processed into a continuous filament fibre with comparable characteristics to viscose (strength and cost). Polyester monomers of chemical equivalence to virgin monomers.	A hydrothermal treatment process is used to separate and recover the material streams. Chemicals and dyes are separated in aqueous solution. 70% of water used in process is recycled, and waste water is treated by traditional waste water management process.
Worn Again **[141]** (UK)	Post-industrial and post-consumer cotton, polyester, and polycotton blends (up to 20% other fibres and contaminants), post-consumer plastic materials (PET bottles, packaging)	Worn Again (WA) Circular Cellulosic Pulp (competitive in quality and price with virgin resources) WA Circular PET Pellets (virgin equivalent properties).	A solvent-based recycling technology for separating and recovering cellulose and PET from waste textiles. The process enables contaminant, dye, and other polymer material separation.

The emergence of innovative technologies, new and alternative materials (i.e. bio-based) will help expand the availability of options in sustainable processing and sourcing. Table 13 features developments in new fibre materials (under development/demonstrated and commercialized).

Table 13: Developments in New Fibre Materials [20]

Company	Technology/Material
Agraloop Bio-refinery	Production of natural fibre from crop waste
Algiknit	Fibres from seaweed extract
AMSilk	Synthetic silk biopolymers
Aquafil and Genomatica	Bio-based caprolactam for Nylon 6 generation
Bolt Threads	Synthetic spider silk
Invista * [142,143]	Bio-based Lycra (elastane) derived from renewable butanediol (raw material source made from dextrose, derived from corn)
Ioncell-F	Conversion of wood pulp to cellulosic textiles
Mango Materials	Production of naturally occurring biopolymer (polyhydroxyalkanoate polyesters -PHAs) from waste biogas/methane emissions, used for production of biodegradable PET products
Orange Fibre	Citrus by-product-based fibres
Pinatex	Pineapple leaf-based fibres
Qmilk	Milk-based fibres
Resyntex	Biochemical processing to produce value-added products from wool (resins and adhesives), cotton (bioethanol), polyester (bio-based plastic bottles), nylon (new chemicals)
Spinnova	Wood fibre-based yarns
Virent, with Far Eastern New Century * [144]	Plant based polyester, Bio-PET

* *commercialized*

4.0 TEXTILE COLOURATION AND CHEMICAL FINISHING

Enormous amounts of chemicals and water are used during textile production to facilitate physical and chemical processes to achieve desired properties. Dyes and chemicals applied during finishing stages of the production process may be used to impart aesthetic (colour) or functional qualities (flame resistance, water repellency, wrinkle resistance, etc.). Significant efforts have been made in the management and treatment of chemicals and effluents from the various processing routes. Many technologies have been developed and applied from fibre to finished product stages to reduce energy, effluent loads, processing costs, and improve wastewater treatment. [145]

At present, there is a lack of information and traceability of chemicals and their content remaining in textile products from usage to end of life, specifically in post-consumer textiles. Additionally, with labelling, legal requirements and regulations differing from country to country, this results in the lack of knowledge regarding potentially hazardous chemicals used in sourced textiles. In recent times, the European REACH regulation (Registration, Evaluation, Authorisation and Restriction of Chemicals) has been criticized for further aggravating the issue of hazardous textile chemicals on the environment and human health.[146] The regulation has been blamed for causing increased relocation of the European textile dye sector to Asia, where supply chains are less regulated, and rife with environmental pollution, thereby creating a loss of jobs, stifling innovation, and resulting in chemical monopolies.[146]

It has been noted that chemical coatings and dyes may comprise up to 5-15% by weight to a finished garment.[6] Additionally, in the realm of automotive textiles, it is estimated that one car may contain an average 23 kilograms of dyed and finished textiles.[146] This poses potential risks to human health, commonly through skin contact, and implications on material recovery, owing to limited understanding of the interaction of chemicals present in feedstock with process chemicals applied in recycling treatments.[28] In addition, potential pre-treatment or cleaning steps that may require more costly and toxic chemicals to achieve their removal.

4.1 Dyeing and Finishing Processes

The dyeing process involves the use of colourants to apply colour to yarn or fabrics. Colourants are substances that may include dyes or pigments. Dyestuffs are classified into natural and synthetic dyes and are most widely used in textile dyeing operations.[147] Natural dyes are derived from plants and animals, whereas synthetic dyes are typically prepared from resources such as petroleum by-products and earth minteral.[147] Natural dyes tend to be limited by the number of colours available, fastness properties, yield, and nonreproducibility,[147] therefore, synthetic dyes, which overcome these issues are more commonly used.[145]

Traditional dyeing methods can be divided into two types of methods: Exhaust dyeing (or batch dyeing) and Pad-steam dyeing (continuous dyeing). The exhaust dyeing method is most common and imparts colour to the textile material in a dye bath. As a batch process, it is suited for lot sizes from 10-1000 kg. The process requires the control of parameters including dyeing temperature, dyeing liquor, chemical additives, electrolytes, water or solvent, and mechanical agitation of the dye bath.[145] The pad-steam process is a continuous process in which the textile fabric is padded through dyeing solution, followed by steaming. During the process, dye molecules on the fibre surface migrate into the swollen fibre structure and are subsequently fixed.[145] Colour fastness properties from dyeing fabrics by this method tend to be low, along with higher effluent discharge.[145]

The interaction and fixation between dye and fibre impacts the discharge of dyes in effluent, colourfastness during consumer use, and the lesser characterized, dye removal from recycling processes at the material end-of-life stage. Sustainability of the dyeing process in industry is assessed by the ability to discharge low amounts of unfixed dyes (effluent) as drainage, with less discharge when the aggregation and chemical bonding present between the fibre and dye molecule is strong.[145] Table 14 summarizes the different dye classes on textiles.

Table 14: Dye Classes, Use on Textile Fibres and Fixation, and Associated Hazardous Substances
Reproduced and modified from [145-148].

Dye Class - Colourant/Dyestuff Type		Fibre Type	Hazardous Substances	Fixation Degree (%)	Interaction between dye and fibre
	Acid	Wool, Silk	Banned arylamines due to carcinogenic effects (from azo dyes)	85-98	Hydrogen bonding, ionic bonding, van der Waals forces
	Acid Subclass: Metal complex (Replaced banned azo dyes)	Wool, Silk	Toxic metals from heavy metal content in dyestuff	82-98	Hydrogen bonding, ionic bonding, van der Waals forces, hydrophobic bonding
	Basic	Silk, Polyacrylic	Carcinogenic dyestuff, complexing agents (quaternary ammonium compounds)	95-100	Hydrogen bonding, ionic bonding
	Direct (Azo-based direct dyes banned)	Cellulose	Salts, aftertreatment with water, toxic cationic agents	64-96	Hydrogen bonding, van der Waals forces
	Mordant	Wool, Silk	Chromium VI, some banned	95-98	Dye fixative
	Reactive	Cellulose, Wool, Nylon	Salt emissions, unfixed dyestuff in effluent require treatment, metal complexes	50-97	Covalent bonding, hydrogen bonding
	Sulphur	Cellulose	Sodium hydrosulphite	60-95	Hydrogen bonding, van der Waals forces
	Vat	Cellulose		75-95	Hydrogen bonding, van der Waals forces
	Disperse	Polyester, Nylon	Allergenic and carcinogenic dyestuff, chlorinated solvents	88-100	Van der Waals forces, hydrophobic bonding
Solvent or Pigment		Polyester, Cellulose, Nylon, Wool, Silk, Polyacrylic	Chlorinated or aromatic, aliphatic solvents, residues (binders, VOC etc.)	100	Require additional substrate compound for attachment

Better Thinking Ltd. (2006 report) categorized fibre types based on dye class applied and associated pollution discharge, upon with a derived Pollution Category ranking (1 being the lowest and 5 being the highest polluting).[149] Cotton textile dyeing processes are primarily conducted by reactive dyeing, and are found to discharge larger amounts of effluent compared to other fibres, which are associated with high cleaning costs (Table 15). In addition, reactive dyes on cotton require large volumes of wash-off (dye transfer inhibiting polymers) to remove unfixed dyes, accounting for high energy consumption, and up to 50% of the total cost for the dyeing procedure.[150] Of conventional dyeing methods, vat and sulphur dyes are considered to pose the least environmental impact. Metal complex dyes are favoured for wool fibres and are also considered to have low environmental impacts.[145]

The categorization was reproduced to also include nylon fibres and other effects from the fibre production process, in Table 15.

Fibre	Dye Class	Type of Pollution from Dye	Pollution Category	Other Chemical and Finishing Effects
Cotton	Direct	Salt Unfixed dye (5-30%) Copper salts Cationic fixing agent	1 3 5	Large amounts of chemical resources required during production. Must be treated with chemicals to absorb dyes (pre-treatment and post-treatment).
	Reactive	Salt, Alkali Unfixed dye (10-40%)	1 3	
	Vat	Alkali, Oxidising agent Reducing agents	1 2	
	Sulphur	Alkali, Oxidising agent Reducing agents	1 2	
Wool	Mordant (Chrome) (banned)	Organic acid Heavy metal salts	2 5	Preparation steps often involve harsh chemical treatments.
	Acid; Metal complex (single-stage application; dye and mordant combined prior to dyeing)	Organic acid Unfixed dye (5-20%)	2 3	
Polyester	Disperse	Reducing agents Organic acid Carriers Unfixed dye	2 5 3	Heavy metal catalysts (antimony) used in production, carcinogenic. Dyeing requires, high temperatures.
Nylon	Disperse	Reducing agents Organic acid Carriers	2 5	Production emits nitrous oxide gas.
	Reactive	Salt, Alkali Unfixed dye (10-40%)	1 3	

Table 15: Pollution Category Ranking Based on Dye Methods Applicable to Fibre Types. [145,149]

Finishing processes on textiles include mechanical and chemical methods. Chemical finishing methods may assist with reactions such as dye fixing or cross-linking agents, or impart functional properties and improved characteristics of the textiles.[147]

Common chemical finishing methods include the following:

- Colouration (dye-fixing agents)
- Easy-case (crease/wrinkle resistance)
- Water-repellency
- Moisture wicking
- Stain resistance
- Flame resistance
- Antimicrobial or odour resistance
- UV protection
- Abrasion resistance
- Antistatic treatment

Some finishing chemicals of concern outlined by the Safer Made Report[20] along with alternatives (under development and commercially available), are summarized:

Finishing Chemical/Solvent	Function	Alternative Chemicals (under development, commercially available)
Formaldehyde, other short-chain aldehydes	Easy-care, wrinkle free	-Polycarboxylic acids (PCA), citric acid (CA) and butane tera carboxylic acid (BTCA), CA/xylitol[151] have been demonstrated
Halogenated Flame Retardants	Flame retardant	-Phosphorus, or Nitrogen (melamines) based, and inorganic flame retardants on cotton, polyester, and polycotton blends -Patented atmospheric plasma/UV laser technology on viscose/flax and cellulosic textiles (MTI-X Ltd.)[152,153] Commercial: Basofil® melamine fibre, Lenzing FR® flame resistant cellulosic fibre, Zoltek Pyron® fibres, Trevira CS® (phosphorus based), Green Theme International HDF™ (high definition finish)
Triclosan and triclocarban **Nano silver**	Antimicrobial fabric treatments	-Zinc oxide nanoparticles applied to Nylon 6, polyester, polypropylene textiles[154] -Nano chitosan particles applied to 100% cotton, viscose, polyester fabrics [155] - Siloxane sulfopropylbetaine(SSPB) covalently bonded to cotton [156] -Sol-gel based surface coatings demonstrated [157] Commercial: Green Theme International HDF™, Microban ZPTech®, Noble Biomaterials, X-STATIC®
Per- and poly-fluorinated compounds	Durable water repellency (DWR)	-Silicon-based, hydrocarbons, dendritic/hyperbranched chemistry, wax-based repellents[150] -Sol-gel (Si-based) surface coatings demonstrated -PepWing (Taiwan) - Plasma treatment for water repellent finishing removal[158,159] Commerical: HeiQ Eco Dry, Beyond Surface Technologies miDori®evoPel, OrganoTex®, Chemours Zelan™ R3, Green Theme International fluorine-free HDF™
Chlorinated cleaning solvents, alkali detergents	Dry cleaning, spot cleaning, scouring	-Enzyme based textile processing – may technologies available (developmental and commercial) Commercial: Dupont Primagreen® Ecoscour, Americos Textile Enzymes, novozyme textile enzymes

Table 16: Examples of Finishing Chemicals of Concern and New Alternative Chemicals.

4.2 Potential Problematic Chemicals in Textiles for Recycling

In general, the current surveys from literature and industry of potential substances that may impede recycling have not been well characterized or reported.

Hazardous or incompatible chemicals present in textile waste sent for recycling is thought to be less problematic for post-industrial (pre-consumer) waste, especially from known producers, given that information on composition and chemicals present may be readily available. In addition, risk of chemical contamination may be reduced at the sorting stage, in cases where finishing chemicals can be distinguished (i.e water repellent finishing).[28]

During mechanical recycling, substances are thought to remain in the outgoing material produced, due to the low effects of the process on the molecular level.[28,160] Where chemical substances of concern may be present, this may continue to pose health and environmental issues during the use-phase of the product.

In chemical recycling (such as depolymerization), a large proportion of chemical constituents in the textile material is expected to be eliminated by leaching, degradation, or related distillation and separation processes performed, therefore, the risk of hazardous substances carry-over to recycled product is low.[28,160,] While some substances may remain in the material, with limited understanding of the interaction of certain chemicals in recycling processes applied, it is speculated that technical issues may arise, such as decreased dyeability or the need for an additional purification process step.[28,160,161]

Difficulties in removal of chemical finishing agents used for flame resistance, and water repellency have been cited as issues encountered during research-scale chemical recycling and processing of synthetic textiles.[162] It was found that cotton fabric containing ‘Easy care’ finishing had reduced solubility in solvent (NMMO) when the Lyocell recovery method was applied.[91]As a result, the chemical was removed by treating fabrics with acid-alkali solution prior to applying the Lyocell process.[92] The chemical bond type from dye to fibres are thought to pose challenges during textile recovery and recycling; however, removal processes have been demonstrated for various dye classes. Colourants and other contaminants have been observed to coagulate, or form insoluble impurities, which have been problematic for during spinning processes in recycling systems.[93]

Several chemical recycling methods surveyed cite pre-treatment steps in which dye and contaminants are removed. From chemical recycling technology providers surveyed (polyester, cotton, and polycotton blends), there have been no technical issues associated with dyes and chemicals present in pre and post-consumer textile materials and blends during processing.[138,140]

Ostlund *et al.* presented potential chemical substances and product types of concern, summarized in Table 17.

Chemical substance	**Product type, uses**
Biocides	Sportswear and underwear with/without odour prevention Workwear used in hygiene applications (cleanrooms, healthcare sector)
Flame retardants	Workwear, upholstery, floor covering, curtains/drapes, cotton and polycotton materials for home textiles
Fluorinated and Perfluorinated substances (short and long chain)	Workwear Outdoor textiles (water repellent coatings on clothing, equipment, tents)
Phthalates, SCCPs, heavy metals	Coated textile products Textiles with prints

Table 17: Potential Chemical Substances of Concern Used in Consumer Textile Products.[160]

A summary of processes developed for dye removal are outlined in Table 18. Other decolourization and impurity removal processes from chemical recycling technology examples provided in this report have been summarized in the previous sections.

Table 18: Examples of Dye Removal Processes from Textiles.

Company	Technology Summary	Target Fibre
Teijin (Japan)	Xylene and alkylene glycol extracting solvent is applied, and the process includes dye extraction, solid liquid separation.[163]	Dyed polyester fibre
Feyecon (Netherlands)	Polyester textile waste treated with supercritical CO_2 in a gas vessel, which decolourizes the material by dissolving the dyes.[6]	Dyed polyester
Toray (Japan)	Process utilizes an ethylene glycol-based solvent and includes thermal and organic solvent treatment to remove the polyurethane component.[164]	Polyurethane component from Nylon 6, Nylon 12 (i.e waterproof, moisture permeable function)
BASF (Germany)	Non-aqueous extraction solvent comprising a nitrogen containing organic base, ammonium salt and alkanol, is applied to remove dye from nylon.[165]	Dyed Nylon 6, or 6,6 fibres
Deakin University (Australia)	Production of ultrafine particles from waste denim and other waste textiles for subsequent denim dyeing or dyeing of other textiles.[166]	Denim jeans and other used textiles
Graz University of Technology (Austria)	Enzyme treatment (laccases), alternative to sodium hypochlorite or potassium permanganate used for shade reduction. [167-169]	Denim fading - Indigo shade reduction
Hong Kong Polytechnic University (Hong Kong)	Colour fading of reactive dyed cotton by plasma treatment. The process had similar colour fading effects when compared to conventional enzymatic processes, with added benefits of a shorter treatment time, and limited loss in fabric weight.[170]	Dyed cotton fabrics

4.3 Advances in Dyeing Technologies

Table 20: Developments in Sustainable Dyeing Technology

Industry Developments	
Company	**Technology**
Applied Separations (USA)	Super critical CO_2 technology for dyeing polyester. ***appliedseparations.com***
Debs Textile Corp. (Japan)	Air-Dye: Waterless dyeing and printing process for synthetic textiles. ***debscorp.com***
ColorZen	Cationization of cotton for dyeing (safe and efficient). ***colorzen.com***
Feyecon (Netherlands)	DyeCoo waterless dyeing process using super critical CO_2, Drydye™ fabrics (polyester). ***feyecon.com***
e.Dye Ltd. (China)	e.Dye® Waterless Colouring System™ Dope dyeing of polyester yarns. ***e-dye.com***
Green Theme International (USA)	Waterless chemistry platform for dyeing. ***greenthemeint.com***
Expert Fibres	IndiDye®: natural plant dyes for cotton and lyocell, patented dyeing technology, ultrasonic fibre dyeing process. ***expertfibres.com*** ***indidye.com***
HeiQ Materials AG (Swizerland)	HEIQ DYEFAST technology enables rapid polyester dyeing with reduced dyeing time, energy and water savings, and improved dye quality. ***heiq.com***
MTI-X Ltd. (UK)	Multiplexed Laser Surface Enhancement "MLSE®" technology for textile (natural and synthetic) dyeing and functional finishing. ***mti-x.com***
We aRe SpinDye (Sweden)	Dope dyeing process for synthetics and MMCs ***spindye.com***
U-long (Taiwan)	Dope dyeing of synthetics. ***u-long.com***
Research Developments	
Research Group	**Technology**
Clemson University, University of Georgia (USA)	Textile dyeing process using coloured nanocellulosic fibres (wood pulp)[171,172]
DeMontfort University (UK)	Laser enhanced dyeing of wool and wool blend textiles (collaboration with Loughborough University) [173,174]
	Laccase-catalyzed colouration of nylon and wool fabrics (collaboration with Jingnan University, China) [175]
Loughborough University (UK)	Digital CO_2 laser technology/laser-dye patterning as alternative coloration method for polyester fabrics[176]
University of Leeds (UK)	DyeCat Process: catalytic process allowing colour to be integrated directly into polyesters (chromophore molecule bonds to fibre)[150]
University of Nebraska (USA)	A fully recyclable reactive dyeing process for cotton, using 40% less dye, 97.5% less base, and no inorganic salts [177]

5.0 ENABLING FACTORS AND TECHNOLOGY OUTLOOK

Several enabling factors relating to process technology and supply chain will aid in stimulating development of widespread textile recycling.

Coordination across the supply chain: The global reach of various stakeholders in the textiles industry makes it an inherently collaborative environment.

-Logistics for collection and transport of materials for recycle or reuse (i.e. collection schemes, new business models) can enable a continuous supply of materials to their intended streams.

-Stakeholder buy-in would enable developmental phase technologies to reach commercial scale. As an example, provided by Tyton Biosciences:[140]
"There are many moving pieces that need to be activated together to catalyze a solution. A sanitation system needs to be ready to test or try collecting textiles as a separate stream, a party needs to be ready to either re-use or recycle that clothing (where [their technology] fits in), a textile supply chain player needs to be ready to accept those recycled materials (perhaps with some adjustments on their process) to make those materials back into fibers and yarn, and lastly a clothing brand needs to be ready to use and buy the outputs from this process."

-Information exchange regarding technology developments within the recycling system (from collectors, sorters, to recyclers) is imperative to ensure adequate knowledge of inputs and potential constraints to their system.[6] This would also enable efficient management of materials within the system, i.e. collected and sorted waste is passed onto a mechanical recycler, from which materials that may be more valuable through chemical processing can be passed along to the chemical recyclers (when technology is available).[140]

Automated sorting and fibre identification: Textile waste sorting is currently performed manually. Accurate knowledge and identification of chemical and structural composition of the textile waste stream, whether applied to mechanical or chemical recycling routes is necessary for efficient processing, and quality of feedstock and outputs.[178] The development of efficient and reliable automated sorting of textiles, as well as fibre identification will greatly complement and contribute the development of fibre-to-fibre recycling technologies and continue to support the requirements of mechanical recyclers for other material outputs. Various optical sorting technologies, namely spectroscopic-based, have been explored and are currently being developed for commercial operations. Some examples in development are highlighted:

Company/Group	Technology
Valvan (Belgium, Netherlands, UK)	FIBERSORT Near-infrared (NIR) spectroscopy, industrial scale sorting (Speed: 1 piece per second)[179]
IVL Swedish Environmental Research Institute (Sweden)	Automated sorting technology based on optical sensors that detect different fibre materials, similar technology used to sort packages[180]
Telaketju (Finland)	REISKAtex®: NIR spectroscopy, small scale identification and sorting equipment system.[178,181]
HKRITA (Hong Kong)	Automated sorting system (residual metal detection, colour detection algorithm) with robotics AGV and intelligent conveyor control (Speed: 2 seconds per sample)[139,182]

<u>Information and traceability systems:</u> The increased traceability and knowledge of materials and chemicals used in textiles and apparel during production processes (with adequate protection of confidential information among stakeholders), would contribute to safer chemistry and practices, extending into product safety and greater efficiency in subsequent recycling processes. With the various information management systems, testing and certification systems, coupled with globally dispersed industry players that operate under diverse regulations, information availability of materials and chemicals of concern may be limited or incomplete. Traceability systems integrated in the full supply chain, and development of supporting technologies (i.e. DNA, QR codes, RFID tagging) are emerging as long-term initiatives.[20]

<u>Funding:</u> Cost is a significant barrier for various industry players and emerging technologies. Funding is needed to expand existing technologies, or support collection schemes that enable the implementation and growth of textile recycling systems. For new technology solutions to scale beyond the prototype stage, public-private financing structure could help attract private funds and launch a new technology solution.[140] Partnerships among brands, government, and/or academia could help facilitate technology and infrastructure development.

<u>Increased awareness among industry and consumers:</u> Most everyday consumers are unaware that their clothing is the world's second largest polluter.[140] With the flexibility of supply chains within the textiles and apparel industry, and continuous induction of trends among consumer groups, many opportunities are available to stimulate and apply sustainable practices and solutions. This extends into design of high-quality and durable garments, fundamental change in habits of consumers, or initiatives for collection and sorting or repurposing textile waste.

Based on the enabling factors identified, outlook of the expansion and development of existing and promising new recycling technologies explored in this report are summarized:

- Increased adoption of mechanical recycling and textile waste diversion for fibre-to-fibre, and other end-use applications to serve other industries (flocking and nonwovens), and implementation or organization of operations where geographically feasible. **Short-term**
- Development of automated sorting technologies and systems. **Short to Medium term.**
- Expansion and improvement of polyester recycling operations, owing to its large share in global fibre production and consumption in textiles. **Short to Long-term**
- Continued support in the development of fibre-to-fibre cotton, cellulosic, and polycotton blend recycling technologies **Short to Medium-term**
- Development of separation and recycling of fibres blends, or processes that can incorporate blends i.e. nylon/elastane, cotton/elastane etc. **Medium to Long-term**
- Evaluation of how hazardous chemicals can be eliminated in textile processing operations, and where emerging methods or materials can be scaled up and implemented (enzymes, bio-based precursors etc.). **Medium to Long-term**
- Traceability of chemicals used in textile processing, understanding of impacts during usage (human exposure, washing/drying), and characterization in how they may interfere with recycling processes. The monitoring of environmental impacts and efficiencies of new recycling technologies adopted is also necessary. **Long term**

6.0 CONCLUSIONS

"Few industries provide a more immediate image of the pervasive impact of materials than those we turn to on a daily basis to clothe us." [29]

The textiles and apparel industry is well positioned as a global industry to address future waste management and sustainability challenges. Increased awareness of overall material waste impacts across the textile value chain has initiated and incited discussion and strategies towards the development of sustainable practices. Looking to the future, collaboration and dialogue among stakeholders is crucial.

This report has highlighted existing and emerging technologies in the industry to contribute to this overall understanding. The knowledge of present to future developments in recycling, colouring and finishing technologies, as well as their enablers is a foundational aspect in assessing and guiding the vision and transition for a circular textiles economy.

REFERENCES

[1] Euromonitor International Apparel & Footwear, "Global fashion industry statistics - International apparel," Fashion United, 2016. [Online]. Available: https://fashionunited.com/global-fashion-industry-statistics. [Accessed June 2018].

[2] Wood MacKenzie, "Product Developments in Manmade Fibres: Is Cotton Able to Compete?," in *33rd International Cotton Conference*, Bremen, 2016.

[3] Ellen McArthur Foundation and Circular Fibres Initiative, "A New Textiles Economy: Redesigning Fashion's Future," 2017.

[4] The Fiber Year Consulting, "The Fiber Year 2018: World Survey on Textiles & Nonwovens," 2018.

[5] Boston Consulting Group and Global Fashion Agenda, "Pulse of the Fashion Industry," 2017.

[6] Oakdene Hollins, "Apparel and Footwear Recycling Innovation," Sustainable Apparel Coalition, 2014.

[7] K. Storry and A. McKenzie, "Unravelling the Problem of Apparel Waste in the Greater Vancouver Area," 2018.

[8] A. Peterson, "Anna Peterson, PhD Thesis: Towards Recycling of Textile Fibres: Separation and Characterization of Textile Fibers and Blends," Master's Thesis: Chalmers University of Technology, 2014.

[9] J. J. Lu and H. Hamouda, "Current Status of Fiber Waste Recycling and its Future," *Advanced Materials Research,* vol. 878, p. 122–131, 2014.

[10] K. Niinimaki and L. Hassi, "Emerging design strategies in sustainable production and consumption of textiles and clothing," *Journal of Cleaner Production,* vol. 19, pp. 1876-1883, 2011.

[11] GreenBlue Institute, "Chemical Recycling - Making Fiber-to-Fiber Recycling a Reality for Polyester Textiles," Patagonia and Steelcase, 2017.

[12] E. A. Gies, J. L. LeNoble, M. Noel, A. Etemadifar, F. Bishay, E. R. Hall and P. S. Ross, "Retention of microplastics in a major secondary wastewater treatment plant in Vancouver, Canada," *Marine Pollution Bulletin,* vol. 133, pp. 553-561, 2018.

[13] J. Boucher and D. Friot, "Primary microplastics in the oceans: A global evaluation of sources (2017), p.21," International Union for Conservation of Nature and Natural Resource (IUCN), Gland, 2017.

[14] "Estimate based on Circular Fibres Initiative analysis on the share of materials and on a price of USD 2.8/kg for cotton yarn and USD 1.7/kg for polyester yarn," 2016. [Online]. Available: (see http://www. globaltexassociates.com/price.html). [Accessed June 2018].

[15] Tetra Tech EBA Inc., "2016 Waste Composition Monitoring Program," Metro Vancouver, Burnaby, 2016.

[16] SORT BC , "survey, June 22, 2017.".

[17] British Columbia Alliance for Manufacturing, "BC apparel Industry Labour Market Partnership, Labour Market Information Report," [https://www.workbc.ca/getmedia/41be12dd-ce11-472c-903f-1d44341fb3c9/Manufacturing_BC_Apparel_LMP_Phase_2_Final_Se, 2016.

[18] Textile Exchange, "Preferred Fiber & Materials Market Report 2017," 2017.

[19] Textile Exchange, "What is Recycled Synthetics," 2016. [Online]. Available: http://textileexchange.org/learning-center/preferred-recycled-synthetics/. [Accessed July 2016].

[20] Safer Made, "Safer Chemistry Innovation in the Textile and Apparel Industry," Fashion for Good, 2018.

[21] Y. Wang, "Fiber and Textile Waste Utilization," *Waste Biomass Valor* , vol. 1, p. 135–143 , 2010.

[22] Interreg Europe, "Recycling in textile and waste disposal," in *Agora*, Alcoi, 2016.

[23] P. Thompson, P. Willis and N. Morley, "A review of commercial textile fibre recycling technologies," WRAP, 2012.

[24] S. S. Muthu, Y. Li, J.-Y. Hu and P.-Y. Mok, "Recyclability Potential Index (RPI): The concept and quantification of RPI for textile fibres," *Ecological Indicators,* vol. 18, pp. 58-62, 2012.

[25] Ellen MacArthur Foundation, "Growth Within: a circular economy vision for a competitive Europe," Ellen MacArthur Foundation, https://www.ellenmacarthurfoundation.org/assets/downloads/publications/EllenMacArthurFoundation_Growth-Within_July15.pdf, 2015 .

[26] Grand View Research, "Global Textile Chemicals Market Size To Reach $30.70 Billion By 2025," December 2016. [Online]. Available: https://www.grandviewresearch.com/press-release/global-textile-chemicals-market. [Accessed July 2018].

[27] For every kilogram of fabric, an estimated 0.58kg of various chemicals are used. Between 0.35 and 1.5kg of chemicals go into the production of 1kg of cotton textile. , (see Bluesign, Environmental Health & Safety (EHS) guidelines for brands and retailers), 2011.

[28] A. Schmidt, D. Watson, S. Roos, C. Askham and P. B. Poulsen, "Gaining benefits from discarded textiles - LCA of different treatment pathways," Nordic Council of Ministers, 2016.

[29] R. Kirchain, E. Olivetti, T. R. Miller and S. Greene, "Sustainable Apparel Materials," Materials Systems Laboratory, Massachusetts Institue of Technology, Cambridge, 2015.

[30] Alpek, "Polyester Production Process," 2015. [Online]. Available: http://www.alpek.com/polyester.html. [Accessed July 2018].

[31] Wood MacKenzie, "Making the case for sustainale polyester," 2015. [Online]. Available: https://isoi02addon0o9kfprod.blob.core.windows.net/cache/6/3/9/2/b/b/6392bb88df53e77ab79fee7a607b7c4e12dc4f61.jpg. [Accessed July 2018].

[32] Ametek, "The Importance of Intrinsic Viscosity Measurement," [Online]. Available: https://www.ametektest.com/learningzone/library/articles/the-importance-of-intrinsic-viscosity-measurement. [Accessed June 2018].

[33] J. Aguado and D. Serrano, Feedstock Recycling of Plastic Wastes, Cambridge: Royal Society of Chemistry, 2007.

[34] G. Arthur, "Facts you should know about recycled polyester," Suston Magazine, Norr Agency, 5 June 2017. [Online]. Available: http://sustonmagazine.com/2017/06/05/facts-you-should-know-about-recycled-polyester/. [Accessed July 2018].

[35] Image source: https://3.bp.blogspot.com/-wJWyt7IunXs/UkrbAbxkOGI/AAAAAAAAKZM/cJYgGVn-gkg/s1600/Melt+spinning.jpg, [Online].

[36] M. C. Thiry, "Everything Old is New Again - Recycling, Recycled, and Recyclable Fibers," *AATCC Review,* pp. 20-25, March 2009.

[37] Hyosung, "Nylon Polyester Fiber PU," 2011. [Online]. Available: http://www.hyosung.com/en/biz/textile/nylon_polyester_fiber.do. [Accessed August 2018].

[38] Polylana, "Polylana Functionality," 2018. [Online]. Available: http://www.polylana-yarn.com/functionality/. [Accessed August 2018].

[39] RadiciGroup, "To Be Glocal 2018 - RadiciGroup: Specialty Chemicals, Performance Plastics, Synthetic Fibres and Nonwovens," 2018. [Online]. Available: https://www.radicigroup.com/documents/73bc2290-1d8a-4dcd-81c7-7dc1919d247d. [Accessed August 2018].

[40] L. Smith, "Recycled Fiber: From the Ocean to the Consumer," 27 September 2017. [Online]. Available: https://www.ispo.com/en/trends/id_79712512/recycled-polyester-fiber-from-the-ocean-to-the-consumer.html. [Accessed August 2018].

[41] Sinterama Corporate, "NEWLIFE EASY," [Online]. Available: http://www.sinterama.com/site/app01/lng/eng/public.nsf/content?openagent&grp=3&act=prd&sec=3&psp=WCNBRAC__000012&imp=. [Accessed August 2018].

[42] Stein Fibers Ltd., "Environment," [Online]. Available: https://www.steinfibers.com/environment/. [Accessed August 2018].

[43] Teijin Frontier Co., "ECOPET," [Online]. Available: https://www2.teijin-frontier.com/english/sozai/specifics/ecopet.html. [Accessed July 2018].

[44] Toray Industries, Inc., "ECOUSE," 2018. [Online]. Available: https://www.toray.us/products/fibers/fib_0132.html. [Accessed July 2018].

[45] Unifi, Inc., "Discover REPREVE," 2018. [Online]. Available: https://repreve.com/discover. [Accessed July 2018].

[46] Far Eastern New Century Corporation , "TOPGREEN Recyle Yarn," [Online]. Available: http://industry.fenc.com/fiber_product.aspx?lang=en&id=54. [Accessed August 2018].

[47] L. Shen, E. Worrell and M. K. Patel, "Open-loop recycling: A LCA case study of PET bottle-to-fibre recyling," *Resources, Conservation and Recycling,* vol. 55, pp. 34-52, 2010.

[48] S. Honcoop, "Ioniqa Technology Enables Limitless PET Recycling," 14 August 2017. [Online]. Available: https://www.plasticsoupfoundation.org/en/2017/08/ioniqa-imitless-pet-recycling/. [Accessed August 2018].

[49] JEPLAN, Inc., "Closed loop "Technology to make clothes from clothes."," [Online]. Available: https://www.jeplan.co.jp/en/technology/polyester_recycle/. [Accessed July 2018].

[50] Loop (TM), "Our innovative technology decouples plastic from fossil fuels," 2017. [Online]. Available: https://www.loopindustries.com/en/tech. [Accessed July 2018].

[51] Ashoka Changemakers, "Ambercycle: Using microbes to eat plastic and produce chemicals," 2018. [Online]. Available: https://www.changemakers.com/fabricofchange/entries/ambercycle. [Accessed August 2018].

[52] Polygenta Technologies Ltd., "The ReNew Unit: a patented technology," 2013. [Online]. Available: http://www.polygenta.com/Our_Breakthrough_process.html. [Accessed August 2018].

[53] Teijin Ltd., "The Outstanding Potential of Teijin's ECO CIRCLE," https://www.teijin.com/ir/library/annual_report/pdf/ar_08_07.pdf, 2007.

[54] Grand View Research, "Nylon 6 & 66 Market Analysis By Product (Nylon 6, Nylon 66) By Application (Automotive, Electrical & Electronic, Engineering Plastic, Textiles, Others), By Region, And Segment Forecasts, 2018 - 2025," July 2017. [Online]. Available: https://www.grandviewresearch.com/industry-analysis/nylon-6-6-market. [Accessed July 2018].

[55] T. Karthik and R. Rathinamoorthy, "8 - Sustainable synthetic fibre production," in *Sustainable Fibres and Textiles*, The Textile Institute, Woodhead Publishing, Elsevier, 2017, pp. 191-240.

[56] R. Ed. Francis, Recycling of Polymers: Methods, Characterization and Applications, Wiley-VCH Verlag GmbH & Co. KGaA, 2017, pp. 55-114.

[57] Image Source: https://d2vlcm61l7u1fs.cloudfront.net/media%2Fd84%2Fd843a285-701e-4c9e-92a9-6bd08da30081%2FphpZ6JSyZ.png, [Online].

[58] R. Nuretdinov, "Lifecycle of nylon," Bachelor's thesis: Tampere University of Applied Sciences, 2017.

[59] Image source: http://www.sentinellemedical.com/10433wteuct/10450VctxXb/, [Online].

[60] SpecialChem, "Polyamide (PA) or Nylon: Complete Guide," 2018. [Online]. Available: https://omnexus.specialchem.com/selection-guide/polyamide-pa-nylon. [Accessed July 2018].

[61] Y. Ed. Wang, Recycling in Textiles, Cambridge: Woodhead Publishing, 2006.

[62] A. Weiser, B. Streltses, U. Afek and A. Yermolaev, "Process of making recycled polyamide yarn". United States of America Patent US8366977B2, 12 November 2009.

[63] B. Sethi, 3.1 Methods of Recycling of Polymers: Addition Polymers, Weinheim: Wiley-VCH Verlag GmbH & Co. KGaA, 2017.

[64] INVISTA, "The Recyclability of Type 6,6 Nylon," 2017. [Online]. Available: http://antron.net/na/pdfs/literature/tb/K02959_Technical_Bulletin_Recyclability_of_Type_66_Nylon.pdf. [Accessed July 2018].

[65] Image source: https://www.floortrendsmag.com/ext/resources/Issues/2016/03-March/0316_ft_TalkFloor_img2.jpg, [Online].

[66] Image source: https://encrypted-tbn0.gstatic.com/images?q=tbn:ANd9GcSIfeV-sHgzYd-jaNNZBcrWITT_hBsn9kG7VI7qdD6kn_BWMbno, [Online].

[67] Image source: https://encrypted-tbn0.gstatic.com/images?q=tbn:ANd9GcSIfeV-sHgzYd-jaNNZBcrWITT_hBsn9kG7VI7qdD6kn_BWMbno, [Online].

[68] Y. Wang, Y. Zhang, M. Polk, S. Kumar and J. Muzzy, "Chapter 16: Recycling of Carpet and Textile Fibers," in *Plastics in the Environment: A Handbook*, New York, John Wiley & Sons, 2003, pp. 697-725.

[69] Greener Industry UK, "Nylon recycling process used by DuPont," [Online]. Available: http://www.greener-industry.org.uk/pages/nylon/images/NylonDiag04.gif. [Accessed July 2018].

[70] Chainlon, "Greenlon® Eco-friendly yarn," [Online]. Available: http://www.chainlon.com.tw/english/product/brand.php?dpid=10. [Accessed August 2018].

[71] ECOALF, "Recycled Fabrics," 2017. [Online]. Available: https://ecoalf.com/gb/recycled-fabrics/fishing-nets/. [Accessed July 2018].

[72] Fulgar SpA, "Recycled Nylon - Q-NOVA® by Fulgar," 2018. [Online]. Available: http://www.fulgar.com/eng/insights/recycled-nylon-q-nova-by-fulgar. [Accessed August 2018].

[73] NILIT Ltd., "Fashioning the Future with Quality Nylon 6.6," [Online]. Available: http://www.nilit.com/fibers/. [Accessed August 2018].

[74] SGB Media, "Toray Industries Develops Recycled Nylon," 9 January 2007. [Online]. Available: https://sgbonline.com/toray-industries-develops-recycled-nylon/. [Accessed July 2018].

[75] Unifi Manufacturing Inc., "REPREVE Nylon Yarn," [Online]. Available: https://repreve.com/assets/pvas/REPREVE_Nylon_Sales_Collateral.pdf. [Accessed August 2018].

[76] Aquafil Group, "The ECONYL Regeneration System," 2015. [Online]. Available: https://www.econyl.com/assets/uploads/ECONYL_brochure_150318_EN.pdf. [Accessed July 2018].

[77] Hyosung, "Nylon Yarn Business Division," 2018. [Online]. Available: http://www.hyosungtnc.com/en/fiber/nylon.do. [Accessed August 2018].

[78] Toray Industries, Inc., "Promoting Recycling Initiatives," March 2004. [Online]. Available: https://www.toray.com/csr/activity/social/recycling.html. [Accessed July 2018].

[79] R. Murata and 良. 村田, "Recycling method for nylon 6 product". Japan Patent JP2011088943A, 20 October 2009.

[80] A. Palme, "Recycling of cotton textiles: Characterization, pretreatment, and purification," PhD Thesis, Chalmers University of Technology, 2017, 2017.

[81] World Willdlife Fund (WWF), "Cotton Overview," [Online]. Available: https://www.worldwildlife.org/industries/cotton. [Accessed July 2018].

[82] J. Shen, *Lecture Notes: "Conventional textile preparation and chemical finishing",* Shanghai: International Textiles Graduate Summer School. Donghua University, July 7, 2018.

[83] Image source: https://cdn4.iconfinder.com/data/icons/cotton/5/Cotton-17-512.png, [Online].

[84] Image source: https://media.istockphoto.com/vectors/set-of-sewing-machines-vector-id452221209?k=6&m=452221209&s=612x612&w=0&h=wXRZyLl24OIFJ-5gqnhRrYAloJqSLk81jr3KIzmEgbk=, [Online]

[85] Image source: https://media.istockphoto.com/vectors/set-of-sewing-machines-vector-id452221209?k=6&m=452221209&s=612x612&w=0&h=wXRZyLl24OIFJ-5gqnhRrYAloJqSLk81jr3KIzmEgbk=, [Online]

[86] Image source: https://thenounproject.com/term/needle-and-thread/91308/, [Online]

[87] A. Rengel, "Recycled Textile Fibres and Textile Recycling: An overview of the Market and its possibilities for Public Procurers in Switzerland," Be Sustainable, Federal Office for the Environment (FOEN) , Bern, 2017.

[88] C. Li-Carrillo, W. Porter Orr, P. Ford and B. Nadella, "Recycled Cotton for Gap Inc.," MIT Sloane School of Management, Boston, 2016.

[89] "Carbon disulfide in Air Quality Guidelines," WHO Regional Office for Europe, Copenhagen, 2000.

[90] N. Morley, "Closed loop fibre recycling - current status and future challenges," Oakdene Hollins, Cambridge, 2013.

[91] L. V. Haule, C. M. Carr and R. M, "Preparation and Physical Properties of Regenerated Cellulose Fibres from Cotton Waste Garments," *Journal of Cleaner Production,* vol. 112, pp. 4445-4451, 2016.

[92] L. V. Haule, C. M. Carr and R. M, "Investigation into the Removal of an Easy-care Crosslinking Agent from Cotton and the Subsequent Regeneration of Lyocell-type Fibres," *Cellulose* , vol. 21, no. 3, pp. 2147-2156, 2014.

[93] A. Schuch, "The Chemical Recycle of Cotton," *Revista Produção e Desenvolvimento,* vol. 2, no. 2, pp. 64-76, 2016.

[94] R. De Silva, X. Wang and N. Byrne, "The separation & utilization of polyester/cotton blends," in *17th Australian cotton conference proceedings, Australian Cotton Conference,.*, 2014.

[95] Hilaturas Ferre, "Hilaturas Ferre company website," 2012. [Online]. Available: http://www.hifesa.com/?lang=en. [Accessed August 2018].

[96] European Circular Economy Stakeholder Platform, "Recover® recycled yarns address the high environmental pressure of cotton textile production," European Union, 2015. [Online]. Available: https://circulareconomy.europa.eu/platform/en/good-practices/recoverr-recycled-yarns-adress-high-environmental-pressure-cotton-textile-production. [Accessed August 2018].

[97] Gebrueder Otto GmbH & Co. KG, "OTTO company website," 2018. [Online]. Available: https://www.otto-garne.com/. [Accessed August 2018].

[98] Gebrüder Otto Baumwollfeinzwirnerei GmbH, "Successful sustainable spinning - Gebrüder Otto GmbH & Co. KG is certified according to OEKO-TEX Standard 100plus," 01 May 2013. [Online]. Available: https://businessdocbox.com/Green_Solutions/73457405-Successful-sustainable-spinning.html. [Accessed August 2018].

[99] Gebrueder Otto GmbH & Co. KG, "Recot²® - an innovative and eco-friendly yarn made of 75% organic cotton and 25% pre-consumer recycled cotton," November 2013. [Online]. Available: https://www.otto-garne.de/2013/wp-content/uploads/2013/11/Infoblatt-Recot-englisch-November-2013.pdf. [Accessed August 2018].

[100] Gebrueder Otto GmbH & Co. KG, "Sustainable Concepts / recot²®," [Online]. Available: https://www.otto-garne.de/sustainable-concepts/recot%c2%b2/. [Accessed August 2018].

[101] Giotex™ LTD , "What is Giotex™?," 2012. [Online]. Available: http://www.giotexusa.com/trade/. [Accessed August 2018].

[102] Evrnu, "Evrnu company website," 2018. [Online]. Available: https://www.evrnu.com/. [Accessed August 2018].

[103] J. McCurry, "Evrnu Regenerated Cotton: Sustainable the Second Time Around," TLM Publishing Corp., 08 December 2016. [Online]. Available: https://www.apparelnews.net/news/2016/dec/08/evrnu-regenerated-cotton-sustainable-second-time-a/. [Accessed August 2018].

[104] Ellen MacArthur Foundation, "CE100 Member - Evrnu," 2017. [Online]. Available: https://www.ellenmacarthurfoundation.org/ce100/directory/evrnu. [Accessed August 2018].

[105] Aalto University, "Ioncell-F," 18 12 2017. [Online]. Available: http://bio2.aalto.fi/en/research_groups/biorefineries/ioncell/. [Accessed August 2018].

[106] re:newcell AB, "re:newcell company website," 2018. [Online]. Available: https://renewcell.com/. [Accessed August 2018].

[107] SaXcell BV, "SaXcell - a revolutionary new fibre," 2018. [Online]. Available: http://saxcell.nl/?page_id=18. [Accessed August 2018].

[108] Patagonia, "Recycled Wool," [Online]. Available: https://www.patagonia.com/recycled-wool.html. [Accessed August 2018].

[109] S. Russell, P. Swan, M. Trebowicz and A. Ireland, "Review of Wool Recycling and Reuse," in *Natural Fibres: Advances in Science and Technology Towards Industrial Applications*, RILEM, 2016, pp. 415-427.

[110] International Wool Textile Organization, "The Wool Industry Supply Chain," [Online]. Available: https://www.iwto.org/wool-supply-chain. [Accessed July 2018].

[111] International Wool Textile Organization, "Wool," [Online]. Available: https://www.iwto.org/wool. [Accessed August 2018].

[112] E. Smith and J. Shen, "Surface modification of wool with protease extracted polypeptides," *Journal of Biotechnology,* vol. 156, no. 2, pp. 134-140, 2011.

[113] Z. Du, B. Ji and K. Yan, "Recycling keratin polypeptides for anti-felting treatment of wool based on L-cysteine pretreatment," *Journal of Cleaner Production,* vol. 183, no. 10, pp. 810-817, 2018.

[114] A. Shavandi, A. E.-D. A. Bekhit, A. Carne and A. Bekhit, "Evaluation of keratin extraction from wool by chemical methods for bio-polymer application," *Journal of Bioactive and Compatible Polymers,* vol. 32, no. 2, pp. 163-177, 2016.

[115] S. Harbi, "Recycling textile waste into secondary material: Experience from the innovative RESYNTEX project using circular economy concepts," in *7th International Conference on Life Cycle Management*, Bordeaux, 2017.

[116] ""CARDATO" BRAND," Cardato, 2018. [Online]. Available: http://www.cardato.it/en/brand-cardato/. [Accessed August 2018].

[117] ""CARDATO RECYCLED" BRAND," Cardato, 2018. [Online]. Available: http://www.cardato.it/en/brand-cardato-recycled/. [Accessed August 2018].

[118] ECOALF, "Recycled wool," 2017. [Online]. Available: https://ecoalf.com/gb/recycled-fabrics/wool/. [Accessed August 2018].

[119] Woolagain, "100% recycled post consumer wool," 2009. [Online]. Available: http://www.woolagain.com/woolyarnknittingproducts.html. [Accessed August 2018].

[120] "Fabrics - Christian Fischbacher," [Online]. Available: http://www.fischbacher.com/collections/en/fabrics/. [Accessed August 2018].

[121] Leigh Fibers Inc., "Leigh Fibers company website," 2018. [Online]. Available: https://leighfibers.com/. [Accessed August 2018].

[122] D. Bockoven, Interviewee, *President & CEO.* [Interview]. 02 July 2018.

[123] Leigh Fibers Inc., "Leigh-Branded Fibers," 2018. [Online]. Available: https://leighfibers.com/solutions/branded-fibers/. [Accessed August 2018].

[124] Martex Fiber, "Martex Fiber company website," 2014. [Online]. Available: http://www.martexfiber.com. [Accessed August 2018].

[125] Martex Fiber, "Waste Services," 2014. [Online]. Available: www.martexfiber.com/waste-services/. [Accessed August 2018].

[126] Martex Fiber, "Products," 2014. [Online]. Available: http://www.martexfiber.com/products/ . [Accessed August 2018].

[127] Phoenix Fibers, "Fiber Conversion," 2015. [Online]. Available: https://www.phxfibers.com/fiber-conversion/. [Accessed August 2018].

[128] Le Relais, "Metisse - Une innovation durable," [Online]. Available: http://www.isolantmetisse.com/rubriques/une-innovation-durable. [Accessed August 2018].

[129] Le Relais, "Notre engagement qualité - La qualité coton," [Online]. Available: http://www.isolantmetisse.com/rubriques/notre-engagement-qualite. [Accessed August 2018].

[130] Chroma, "CHROMA company website," 2018. [Online]. Available: https://chrrroma.ca/. [Accessed August 2018].

[131] R. Robello, F. Calenti, J. Denis and M. Mikuz, "Patent Application: Method of polyamide fiber recycling from elastomeric fabrics". WIPO Patent WO2013032408A1, 02 September 2011.

[132] Biocellection Inc., "Biocellection company website," [Online]. Available: https://www.biocellection.com/. [Accessed August 2018].

[133] D. Crouch, "BioCellection Breaks Down Sustainable Manufacturing," TLM Publishing Corp. , 28 June 2018. [Online]. Available: https://www.apparelnews.net/news/2018/jun/28/biocellection-breaks-down-sustainable-manufacturin/. [Accessed August 2018].

[134] CARBIOS, "Biorecycling - Principle of CARBIOS Enzymatic Biorecycling Process," [Online]. Available: https://patents.google.com/patent/US7947750B2/en. [Accessed August 2018].

[135] Y. Hu, C. Du, N. Pensupa and C. S. K. Lin, "Optimisation of fungal cellulase production from textile waste using experimental design," *Process Safety and Environmental Protection,* vol. 118, pp. 133-142, 2018.

[136] C. S. K. Lin, Interviewee, *Associate Professor, School of Energy and Environment at City University of Hong Kong.* [Interview]. 18 July 2018.

[137] HKRITA, "Post-consumer Blended Textile Separation and Recycling by Hydrothermal Treatment," 19 April 2018. [Online]. Available: https://www.youtube.com/watch?v=TL6zyMXQNSQ. [Accessed July 2018].

[138] G. Yao, Interviewee, *Director, Project Development, HKRITA.* [Email Interview]. 30 July 2018.

[139] HKRITA, "Upcycling Post-Consumer Blends Products," 6 June 2018. [Online]. Available: https://www.youtube.com/watch?v=jiHCAVHUci8. [Accessed August 2018].

[140] P. Majeranowski, *President & Co-Founder,* and team at *Tyton BioSciences LLC.* [Email Interview]. 03 July 2018.

[141] Worn Again Technologies , "Worn Again Technologies company website," [Online]. Available: http://wornagain.co.uk/. [Accessed August 2018].

[142] Invista, "BIO-BASED (Specialty Fiber)," 2018. [Online]. Available: https://connect.lycra.com/en/Textile-Processes/Circular-Knitting/Specialty-Fiber/BIO-BASED. [Accessed August 2018].

[143] K. Laird, "Invista says market is slowly warming up to biobased Lycra fiber," UBM Americas, 16 April 2015. [Online]. Available: https://www.plasticstoday.com/content/invista-says-market-slowly-warming-biobased-lycra-fiber/7005086022104. [Accessed August 2018].

[144] Virent, Inc., "Virent BioFormPX® Paraxylene Used to Produce World's First 100% Plant Based Polyester Shirts," 21 April 2016. [Online]. Available: http://www.virent.com/news/virent-bioformpx-paraxylene-used-to-produce-worlds-first-100-plant-based-polyester-shirts/. [Accessed August 2018].

[145] L. Ammayappan, J. Seiko and A. A. Raj, "Sustainable Production Processes in Textile Dyeing," in *Environmental Footprints and Eco-design of Products and Processes*, Singapore, Springer, 2016, pp. 185-216.

[146] J. Mowbray, "European textile groups slam REACH review," MCL News & Media , 14 August 2018. [Online]. Available: https://www.ecotextile.com/2018081423663/dyes-chemicals-news/european-textile-groups-slam-reach-review.html. [Accessed 14 August 2018].

[147] P. S. Kumar and E. Gunasundari, "Sustainable Wet Processing—An Alternative Source for Detoxifying Supply Chain in Textiles," in *Textile Science and Clothing Technology*, Singapore, Springer, 2018, pp. 37-60.

[148] The Swedish Chemicals Agency and Swerea IVF, "Chemicals in textiles – Risks to human health and the environment," Swedish Chemicals Agency, Stockholm, 2014.

[149] Better Thinking Ltd., "Dyeing for a change: Current conventions and new futures in the textile colour industry," Better Thinking Ltd., 2006.

[150] ACS Webinars, "Sustainability Challenges of the Textiles, Dyeing and Finishing Industries: Opportunities for Innovation - Dr. Richard Blackburn," 2017. [Online]. Available: https://www.acs.org/content/dam/acsorg/events/popular-chemsitry/Slides/2017-03-30-textile-chem-slides.pdf. [Accessed July 2018].

[151] J. Liu, B. Wang, X. Xu, J. Chen, L. Chen and Y. Yang, "Green Finishing of Cotton Fabrics Using a Xylitol-Extended Citric Acid Cross-linking System on a Pilot Scale," *ACS Sustainable Chemistry & Engineering* , vol. 4, no. 3, pp. 1131-1138, 2016.

[152] "Environmentally Sustainable Flame Retardant Surface Treatments for Textiles: The Potential of a Novel Atmospheric Plasma/UV Laser Technology," *Fibers*, vol. 6, no. 2, p. 31, 2018.

[153] P. Mistry, "Treating materials with combined energy sources". United States of America Patent US9605376B2, 28 March 2017.

[154] M. Fiedot-Tobola, M. Ciesielska, I. Maliszewska, O. Rac-Rumijowska, P. Suchorska-Wozniak, Teterycz and M. Bryjak, "Deposition of Zinc Oxide on Different Polymer Textiles and Their Antibacterial Properties," *Materials (Basel),* vol. 11, no. 5, p. 707, 2018.

[155] K. Vellingiri, T. Ramachandran and M. Senthilkumar, "Eco-friendly Application of Nano Chitosan in Antimicrobial Coatings in the Textile Industry," *Nanoscience and Nanotechnology*, vol. 3, no. 4, pp. 75-89, 2013.

[156] S. Chen, S. Chen, S. Jiang, M. Xiong, J. Luo, J. Tang and Z. Ge, "Environmentally friendly antibacterial cotton textiles finished with siloxane sulfopropylbetaine.," *ACS Appl Mater Interfaces,* vol. 3, no. 4, pp. 1154-1162, 2011.

[157] J. Shen, E. Smith, M. Chizyuka, S. Walsh and L. and Martinková, "Sol-gel process of cotton fabric to achieve multifunctionality," in *13th AUTEX World Textile Conference*, Dresden, 2013.

[158] J. Mowbray, "Plasma fabric recovery from Taiwan," MCL News & Media , 20 February 2014. [Online]. Available: http://www.ecotextile.com/2014022012457/fashion-retail-news/plasma-fabric-recovery-from-taiwan.html. Ecotextile . [Accessed August 2018].

[159] Refinity, "Removing dye, finishing and coatings from textiles," 28 July 2015. [Online]. Available: http://www.refinity.eu/blog/removing-dye-finishing-and-coatings-from-textiles. [Accessed August 2018].

[160] SP Sveriges Tekniska Forskningsinstitut, Swerea IVF, "Textilåtervinning: Tekniska möjligheter och utmaningar," Naturvårdsverket , Stockholm, 2015.

[161] J. Mowbray, "The Textile Dyer, Concern over Recycled Polyester," Ecotextile News, 13 May 2008. [Online]. Available: http://www.ecotextile.com/20080513796/materials-production-news/concern-over-recycled-polyester.html . [Accessed July 2018].

[162] J. D. Shen, *Professor of Textile Chemistry and Biotechnology.* [Conversation]. 07 July 2018.

[163] K. Mukai and M. Nakashima, "Method for recovering useful components from dyed polyester fiber". United States of America Patent US7959807B2, 14 June 2011.

[164] H. Katsuragi, T. Ono and 孝. 大野, "Patent Application: Method for chemically recycling nylon fibers processed with polyurethane". Japan Patent JP2008031127A, 31 July 2006.

[165] R. Ozer and K. R. Gerzevske, "Method for removing color from polymeric material". United States of America Patent US7947750B2, 24 May 2011.

[166] Deakin University, "Denim goes green thanks to Deakin innovation," 06 April 2017. [Online]. Available: http://www.deakin.edu.au/about-deakin/media-releases/articles/denim-goes-green-thanks-to-deakin-innovation. [Accessed July 2018].

[167] S. Kim, A. Zillie, A. Vasconcelos and A. Cavaco-Paulo, "New developments of enzymatic treatments on cellulosic fibers," in *Industrial Application of Enzymes on Carbohydrate-Based Material*, Washington, DC, American Chemical Society, 2007, pp. 186-194.

[168] E. Abadulla, T. Tzanov, S. Costa, K. H. Robra, A. Cavaco-Paulo and G. M. Gübitz, "Decolorization and detoxification of textile dyes with laccase from Trametes hirsute," *Appl. Environ. Microbiol.* , vol. 66, no. 8, pp. 3357-3362, 2000.

[169] R. Campos, A. Kandelbauer, K. H. Robra, A. Cavaco-Paulo and G. M. Gübitz, "Indigo degradation with purified laccases from Trametes hirsute and Sclerotium rolfsii," *J. Biotechnol.*, vol. 89, no. 2-3, pp. 131-139, 2001.

[170] H. F. Cheung, C. W. Kan, W. M. Yuen, J. Yip and M. C. Law, "Colour Fading of Textile Fabric by Plasma Treatment," *Journal of Textiles,* vol. Article ID 214706, p. 4, 2013.

[171] S. Minko, S. Sharma, I. Hardin, I. Luzinov, S. Wu Daubenmire, A. Zakharchenko, R. Saremi and Y. Sang Kim, "Textile dyeing using nanocellulosic fibers". United States of America Patent US14796195, 10 July 2015.

[172] Y. Kim, R. Saremi, E. Lee and L. Tolbert, "Novel, Sustainable and Cost-effective Textile Dyeing Techniques Using Nanocellulosic Fibers," May 2015. [Online]. Available: http://nsmlab.com/wp-content/uploads/2015/04/Walmart_Nanocellulosic-Fibers.pdf. [Accessed August 2018].

[173] L. Morgan, J. R. Tyrer, F. Kane and S. Jinsong, "Laser enhanced dyeing of wool for textile design," in *Transition: Re-Thinking Textiles and Surfaces, University of Huddersfield, UK, 26-27 November 2014.*, Huddersfield, 2014.

[174] L. Morgan, "Laser textile design: the development of laser dyeing and laser moulding processes to support sustainable design," PhD Thesis: Loughborough University, Loughborough, 2016.

[175] R. Bai, Y. Yu, Q. Wang, J. Yuan, X. Fan and J. Shen, "Laccase-catalyzed in-situ dyeing of wool fabric," *The Journal of The Textile Institute,* vol. 107, no. 8, pp. 995-1003, 2016.

[176] K. Akiwowo, F. Kane, J. Tyrer, G. Weaver and A. Filarowski, "Digital Laser-dyeing for Polyester Fabrics," *Journal of Textile Design Research and Practice,* vol. 2, no. 2, pp. 133-151, 2014.

[177] L. Chen, B. Wang, X. Ruan, J. Chen and Y. Yang, "Hydrolysis-free and fully recyclable reactive dyeing of cotton in green, non-nucleophilic solvents for a sustainable textile industry," *Journal of Cleaner Production,* vol. 107, pp. 550-556, 2015.

[178] J. Zitting, "Optical sorting technology for textile waste: Development of an identification method with NIR spectroscopy," Bachelor's Thesis, Lahti University of Applied Sciences, Lahti, 2017.

[179] Valvan Baling Systems, "FIBERSORT leaflet," October 2015. [Online]. Available: http://www.valvan.com/wp-content/uploads/2015/10/Valvan-leaflet-FIBERSORT_LR.pdf. [Accessed August 2018].

[180] "New technology may revolutionize textile recycling," IVL Svenska Miljöinstitutet AB , 28 March 2017. [Online]. Available: https://www.ivl.se/english/startpage/top-menu/pressroom/press-releases/press-releases---arkiv/2017-03-28-new-technology-may-revolutionize-textile-recycling.html. [Accessed August 2018].

[181] REISKA, "Tekstiilien tunnistus- ja lajittelulaitteisto – REISKAtex®," 2017. [Online]. Available: http://reiska.info/tekstiililajitin. [Accessed August 2018].

[182] "HKRITA's winning projects in the 46th International Exhibition of Inventions of Geneva," 19 April 2018. [Online]. Available: http://www.hkrita.com/marketing/PressRelease/20180419_HKRITA_46th_Invention_Award_Press_Brief/Award_projects_eng.pdf. [Accessed August 2018].