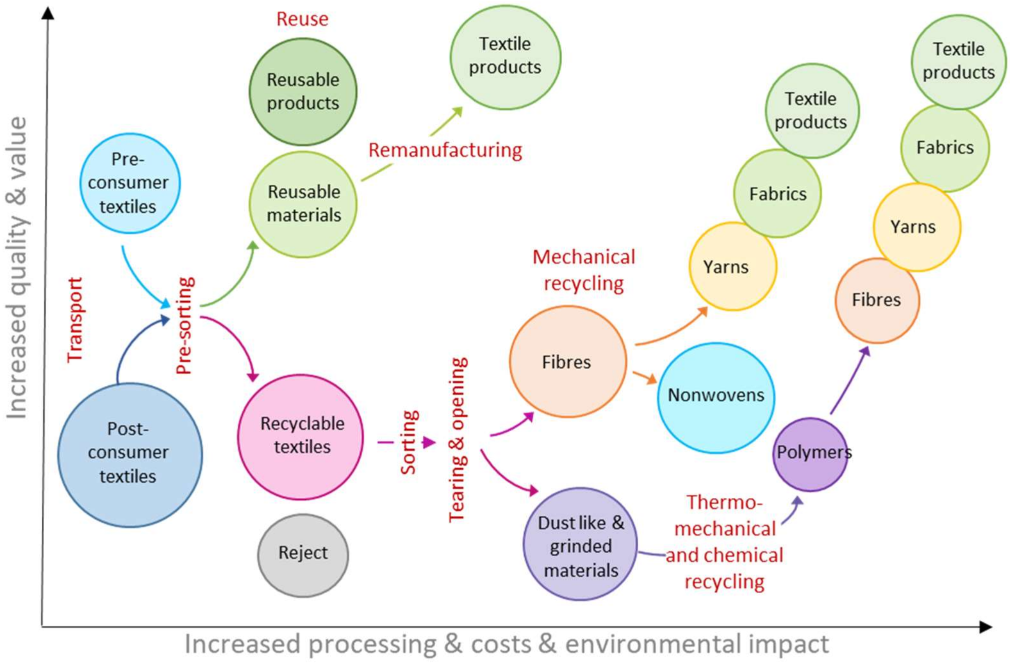
RESEARCH REPORT

VTT-R-00941-22



Technologies and Model for Sustainable Textile Recycling

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Editor:	Pirjo Heikkilä
Confidentiality:	PUBLIC
Version:	FINAL

beyond the obvious

Report's title

Technologies and Model for Sustainable Textile Recycling

Customer Telavalue consortium, Business Finland	**Order reference** 6478/31/2021
Project name Value chains for sustainable production, use and cycles of textiles	**Project number/Short name** 132060 / Telavalue
Author(s) Pirjo Heikkilä, Jouko Heikkilä, Taina Kamppuri, Anna Keskisaari, Marjo Määttänen, Eetta Saarimäki, Lea Heikinheimo, Anu Koivula, Niko Rintala, Ali Harlin	**Pages** 62
Keywords Circular economy, textile recycling, fibre mechanical recycling, thermo-mechanical recycling, chemical recycling	**Report identification code** VTT-R-00941-22

Summary

This report consists of technology review on textile recycling technologies and our visions for a model enabling sustainable textile cycles. This work was carried out as part of Value chains for sustainable production, use and cycles of textiles (Telavalue) project funded by Business Finland and project partners.

The technology review focus on the status and prospects of fibre-to-fibre recycling technologies complemented with shorter overview on the other recycling technologies aiming for example for non-textile applications and/or to raw material production for other industries. We explain fibre, polymer, and monomer level recycling methods, review scientific research and market examples. We made general level overview into environmental and economic issues related to textile recycling, and especially economics section is mostly based on Finnish case study. Furthermore, we made SWOT analyses and comparison of different recycling process categories, not individual processes.

In sustainable textile cycles model section, we discuss the trade-offs between different utilization routes and, thus, tried to illustrate how different process options 1) effect on quality and value, and 2) also increase resource use, costs, and cause environmental impacts. The main principle of sustainable textile circulation can be stated in way that discarded textiles should be utilized in highest value application its condition permits with least amount of processing; and more processing could be used when quality and/or value needs to be restored.

Confidentiality	VTT Public

Tampere

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Distribution (customer and VTT)

Telavalue consortium, Business Finland, VTT

Approval

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Preface

This report contains review of textile recycling technologies and model for retaining textile value in textile circularity if sustainable manner. Work was carried out as part of Telavalue – Value chains for sustainable production, use and cycles of textiles -project. Telavalue is Business Finland Co-Innovation project co-funded by project consortium: VTT Technical Research Centre of Finland Ltd., Kemira Oyj, Pure Waste Textiles Oy, Touchpoint Oy, Rester Oy, Image Wear Oy, Fiare Solutions Oy, Reima Oy, Fortum Power and Heat, Metsä Spring Oy, Valmet Technologies Oy, Mirka Oy, Freudenberg Home and Cleaning Solutions Oy, Lounais-Suomen Jätehuolto Oy, Helsingin seudun ympäristöpalvelut -kuntayhtymä, Saimas Spinnery Oy, Coveross Oy, and Suomen Tekstiili ja Muoti ry.

Basis for the work has been laid within the earlier Telaketju projects. Within Telavalue project we have updated our knowledge of recycling technologies with literature review and discussions, made SWOT analyses and comparison of different technologies, and visualised sustainable and value retaining model textile recycling. All this work was done in close collaboration with Telavalue partners and stakeholders.

The authors would like to acknowledge Business Finland and consortia of Telaketju projects for funding and support. Special thanks to those individuals and companies from the Telavalue project group and Science & Technology Board (STB) who provided their insights to technology review, analyses and modelling work.

Tampere 4.7.2024

Authors

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Terminology and Abbreviations Used in This Report

Terminology regarding textile (waste) materials and recycling is not fixed, and enable different interpretations leading to confusion and misunderstanding. Standard ISO 5157:2023[1] *Textiles — Environmental aspects — Vocabulary* has provided some guidance to this terminology, however, some determinations in there are not fully clear and some useful terms are missing from that. Therefore, we have listed and determined terminology used in this report. In some cases, we have included an alternative term also used about the same process.

It should also be noted that there is a significant difference in terminology used for textile and plastics recycling even though used polymers are the same. In case of plastics, *mechanical recycling* refers to melt process using heat and physical processing, while in case of textiles *fibre mechanical recycling* is used for process aiming unravelling the textile structure into fibre level using physical work only, *thermo-mechanical* recycling refers to melt processing.

Textile Materials Terminology

Discarded textiles – Textile materials and products that have become redundant for their owner/user (consumer or organization), which owner/user is willing to give up. May include reusables, recyclables and non-recyclables.

Reusables – Discarded textile products, that are clean, un-broken, and sufficiently attractive to have value in second hand market - not waste. In case of clothing, term rewearable could be used.

Recyclables – Discarded textile products and materials that are no more reusable in their original purpose, i.e., waste, but can be utilized via recycling.

Non-recyclables – Textile waste that cannot be reused nor recycled sustainably in current textile recycling methods, raw materials can be extracted for other purposes, or these can be used for recovery of energy.

Pre-consumer textile (waste) – Discarded textiles that have not been used. Within this report it includes post-industrial textile waste (see below), as well as unused textile products, for example unsold clothing from retailers.

Post-industrial textile (waste) - Production wastes/by-products/side-streams from textile industry.

Post-consumer textile (waste) – Discarded textiles that have been used by consumers/households and by different organizations.

Input material – Material to be fed to recycling process.

Output material – Material obtained from recycling process.

Recyclate – Recovered and pre-processed (waste) material i.e., input material, that is pre-treated and ready to be processed by a waste recycling facility.

Primary raw material – New, virgin raw material.

Secondary raw material – Recycled raw material, a raw material that has gone through recycling process and is ready to be used in production of new products. Also referred to as output material.

Polycotton – Blend of cotton and polyester fibres, most used fibre blend in clothing and textile products.

Recycling Terminology

Fibre-to-fibre recycling, i.e., Closed loop recycling of textiles – Recycling textile fibres into secondary raw materials for textile production, also called textile-to-textile recycling.

Fibre mechanical textile recycling – Mechanical process including cutting, tearing, and opening textile structures into fibres to be used as secondary raw materials, sometimes also referred to as fiberisation, garneting and fibre pulling.

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[1] Textiles – Environmental aspects – Vocabulary https://www.iso.org/obp/ui/en/#iso:std:iso:5157:ed-1:v1:en

Thermo-mechanical textile recycling – Processing of synthetic raw materials via melting for recycling of polymer. In plastics sector this method is usually referred to as mechanical recycling.

Chemical textile recycling – Recycling technologies based on chemical (including biochemical) processes. Include recycling polymers, such as cellulose, via dissolution, and processes breaking down polymers into monomers or other types of chemicals suitable for making secondary textile raw materials.

Biochemical recycling – Methods utilizing mainly biological processes, such as enzymes and microbial fermentations. These can be used in both closed loop as well as open loop recycling.

Solvolysis – Degradation of polymers using solvent, optional initial step for chemical recycling, sometimes also referred to as chemolysis.

Pyrolysis – Degradation of polymers using heat in absence of oxygen, optional initial step for chemical recycling.

Waste valorisation – Improving waste material properties for recycling. May be done simultaneously with recycling process.

Closed loop recycling – Using secondary raw materials for making same/similar products, and/or by same industries.

Open loop recycling – Using secondary raw materials for making other type of products, and/or by other industry.

Energy recovery – Incineration

Recovery of discarded textiles – System and value chain aiming for collecting, pre-sorting and pre-processing of discarded textiles to be either reused or recycled.

Abbreviations

AMIMCl	1-allyl-3-methylimidazolium chloride
BHET	bis (2-hydroxy ethyl) terephthalate
BMIMAc	1-butyl-3-methylimidazolium acetate
BTBAC	benzyltributylammonium chloride
CI	crystallization index
CO	cotton
DBNHAc	1,5-diazabicyclo[4.3.0]non-5-enium acetate
DMT	dimethyl terephthalate
DMSO	dimethyl sulfoxide
DOPO-PEPA	6H-dibenz[c,e][1,2]oxaphosphorin,6-[(1-oxido-2,6,7-trioxa-1-phosphabicyclo[2.2.2]oct-4-yl)methoxy]-, 6-oxide
DP	degree of polymerization
EF	environmental footprint
EG	ethylene glycol
EPR	extended producer responsibility
FR	flame retardant
GHG	greenhouse gas
GWP	global warming potential
HDPE	high density polyethylene
IL	ionic liquid

ILCD	international reference life cycle data system
LCA	life cycle analysis
MMCF	man-made cellulosic fibre
NMMO	N-methyl morpholine oxide
OE	open-end, i.e., rotor spinning
PA	polyamide
PE	polyethylene
PEF	product environmental footprint
PES	polyester
PET	polyethylene terephthalate, most common PES in textiles
PHA	polyhydroxyalkanoates, a large family of polyesters
PLA	polylactic acid (polyester)
PP	polypropylene
PU	polyurethane
rPET	recycled polyethylene terephthalate
RPI	recyclability potential index
STB	Science & Technology Board
SWOT	Strengths, weaknesses, opportunities, threads -analysis
TPA	terephthalic acid
TPU	thermoplastic polyurethane
TRL	technology readiness level. Scale showing readiness of technology ranging from one (basic principles observed) to nine (actual system proven in operational environment)[2]
WRV	water retention value

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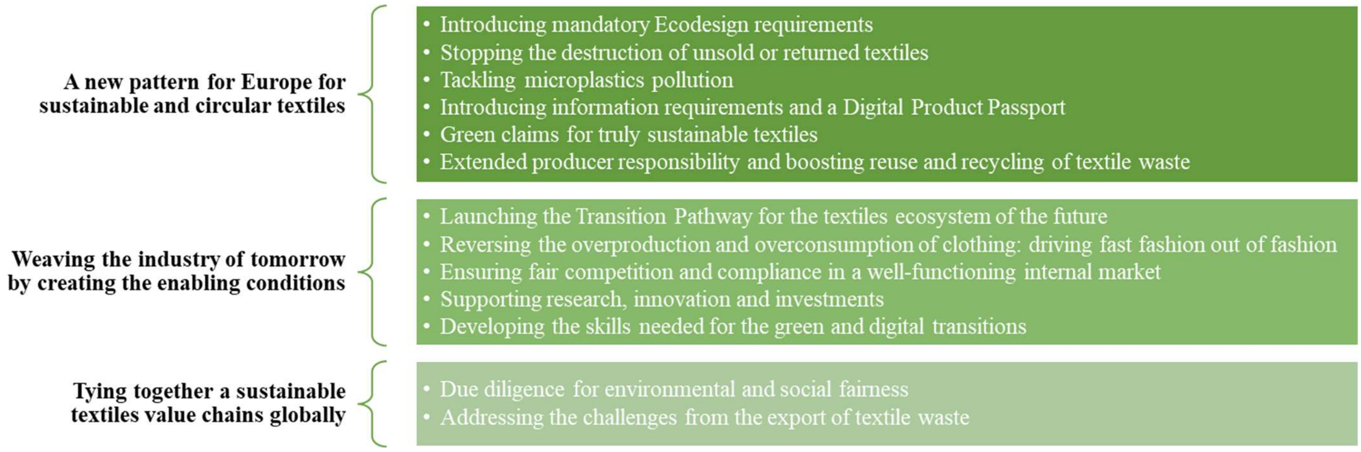
[2] https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf

1 Sustainable and Circular Textile System

Textile sector is often mentioned as one of the most polluting and unsustainable sectors globally. Sustainability issues are summary of environmentally and socially unsustainable production, and unsustainable textile consumption habits, which are enabled, for example, by very low prices of fast fashion textile products. Amount of textile waste generated annually is high in high income countries, and recycling of textile waste is quite minimal. In 2017 Ellen MacArthur foundation (2017) evaluated that around 13% of textile/clothing waste is recycled: 12% in cascaded systems, mainly downcycled, and less than 1% of textiles are recycled in fibre-to-fibre recycling processes back to clothes. There is urgent need to make corrective actions by moving towards sustainable and circular textile system, and Europe has decided to be a forerunner in this.

EU strategy for sustainable and circular textiles states that the future sustainable textile system will rely on long-lived textile products, which contain recycled fibres, and which are recyclable (European Commission, 2022). This strategy lists multiple activities rising also from other EU legislation, which are implemented in near future to achieve this future vision (see Figure 1).



A new pattern for Europe for sustainable and circular textiles

- Introducing mandatory Ecodesign requirements
- Stopping the destruction of unsold or returned textiles
- Tackling microplastics pollution
- Introducing information requirements and a Digital Product Passport
- Green claims for truly sustainable textiles
- Extended producer responsibility and boosting reuse and recycling of textile waste

Weaving the industry of tomorrow by creating the enabling conditions

- Launching the Transition Pathway for the textiles ecosystem of the future
- Reversing the overproduction and overconsumption of clothing: driving fast fashion out of fashion
- Ensuring fair competition and compliance in a well-functioning internal market
- Supporting research, innovation and investments
- Developing the skills needed for the green and digital transitions

Tying together a sustainable textiles value chains globally

- Due diligence for environmental and social fairness
- Addressing the challenges from the export of textile waste

Figure 1 Main themes and actions listed in EU strategy for sustainable and circular textiles (European Commission, 2022).

Textile recycling has been a hot topic in Europe for several years, since separate collection of textile (waste) should be started in all EU member states by 2025 (Directive (EU) 2018/851[3], article 10). Furthermore, *EU strategy for sustainable and circular textiles* will also lead to implementation of wide range of actions: firstly, to creation new models for European textile sector to implement sustainability and circularity in general, secondly, support transition by creation enabling conditions, and, thirdly, addressing also global value chains. Circularity of textiles, i.e., re-use cycles of products and recycling of materials, is only one of the activities with which EU wants to change textile sector to be more sustainable.

Future circular textile system is illustrated in Figure 2. It shows product loops in the centre (green), closest to textile users, and recycling is shown as the outer loop (blue). Extension of products' lifetimes and prevention of waste by different means – by repairing, and reuse of products and materials should be emphasized over recycling. Various circular strategies aiming for this are also introduced as nine R's by Potting *et al.* (2017). In addition to repair and reuse, these nine R's also list, for example, rethinking and reducing in textile use, and remanufacturing and repurposing for extension of lifetimes. In addition, EU waste hierarchy determines prevention of waste and preparing for reuse to be prioritized over recycling (Directive (EU) 2008/98/EC)[4].

Circular economy is thus not just recycling, but extended product use and reuse cycles are important part of textile circularity. And only when textile products are no longer suitable for re-use, their materials should be recycled. Furthermore, to reduce environmental impacts of textile sector, recycled textile materials should be used to replace primary raw materials in textile production. This means using fibre-to-fibre or closed loop recycling methods.

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[3] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32018L0851

[4] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32008L0098

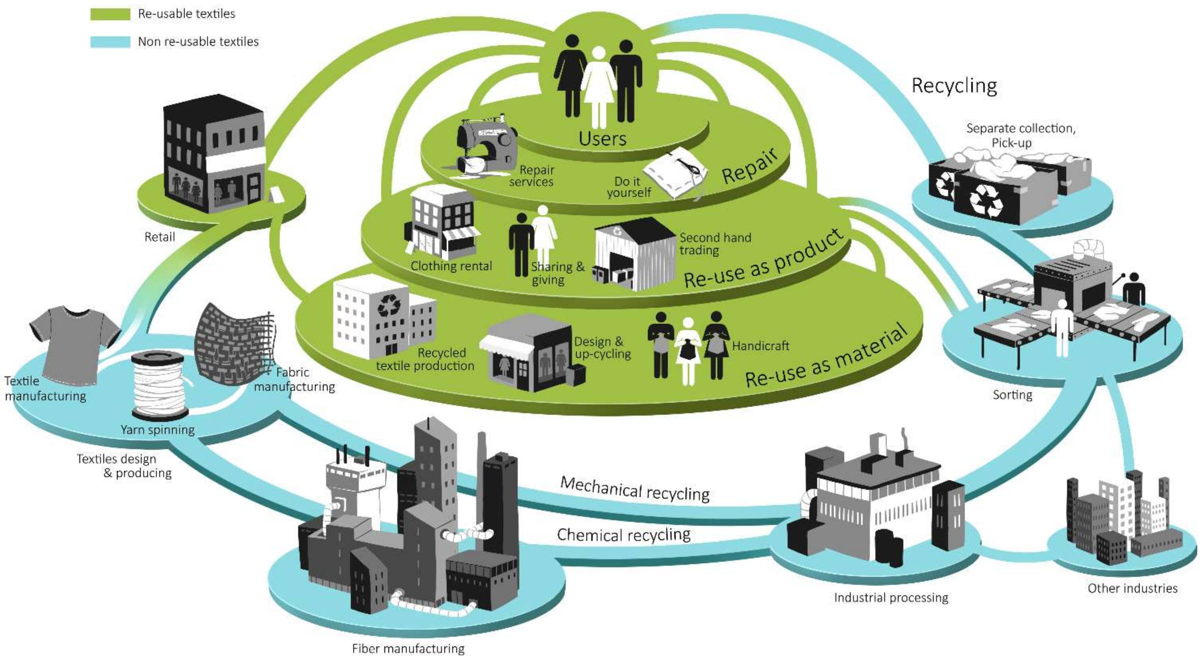

Figure 2 Illustration of circular textile system (Fontell & Heikkilä, 2017).

As part of Telavalue project we promised to make a review of recycling technologies to show current status and future prospects of textile recycling technologies and develop a simple model for determination of optimal utilization route for discarded textiles based on their quality and value and taking the waste hierarchy and environmental aspects into account. There were at least two other publicly available technology reviews published when we made plans to our Telavalue project: 'Study on the technical, regulatory, economic and environmental effectiveness of textile fibres recycling' published by European Commission in November 2021 (Duhoux *et al.*, 2021) and 'Scaling textile recycling in Europe-turning waste into value' published in McKinsey & Company (McKinsey, 2022). First of these was made to support EU level activities advancing green and digital transformation of textile sector, having a target to support legislation. McKinsey (2022) report has more industry-driven focus and has been done in collaboration with Euratex and its ReHubs Initiative[5]. Both reports are included as referenced literature in our work. We also reviewed scientific literature and web search about recycling technologies including their capabilities and made short reviews on literature and factors affecting their economic and environmental impacts as well. Telavalue project partners gave their valuable inputs in evaluation and comparison of different methods.

Main focus of this report is on closed loop, i.e., fibre-to-fibre recycling. Overview into recovery and recycling of textiles is included as Chapter 2. Material sorting, waste valorisation and open loop recycling methods are shortly discussed in that chapter giving examples. Fibre-to-fibre recycling technologies are reviewed in more details in the following chapters which are divided based on the level through which materials are taken apart. Chapter 3 focuses on fibre level recycling, i.e., fibre mechanical process, Chapter 4 on polymer level and Chapter 5 on monomer level recycling. Scientific and technical literature references can be found in the reference list, while, for example, company web pages and other updatable contents are indicated as footnotes. Web links were operational at the time of writing of the report, but contents may have changed, and web pages removed since then. Chapter 6 looks shortly on sustainability of recycling focusing on environmental aspects and looking on economics as well. In recycling costs review, focus is on Finnish cases studied within earlier Telaketju projects.

Based on literature review we evaluated possibilities for maintaining the value of discarded textile as high as possible while minimizing environmental impact in collaboration with Telavalue partner companies. Chapter 7 contains evaluation and comparison of recycling processes and description of simple model sustainable value retention model for textile cycles taking account of economics and environment aspects. And finally, summary and conclusion are given in Chapter 8.

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[5] European Apparel and Textile Confederation (Euratex) https://euratex.eu/; ReHubs https://euratex.eu/rehubs/

2 Recovery and Recycling of Textiles

Simplified illustration of different discarded textile (waste) streams, and possible processing options for them, with main focus on fibre-to-fibre recycling options, is shown in Figure 3. *Fibre-to-fibre recycling*, also sometimes referred to as *closed loop recycling* can be used to replace virgin fibres in clothing and textile production. Processes include, for example, *fibre mechanical*, *thermo-mechanical* and *chemical* processes. Other processes may be leading back to textile cycles via longer route. Principally, the existing processes and machinery of the textile industry, such as spinning, weaving, knitting, and sewing, can be used for all types of recycled fibres. However, possible lowered fibre quality needs to be considered and challenges related to that may be overcome, for example, by adjusting the processes and production speeds and/or mixing recycled fibres with virgin ones.

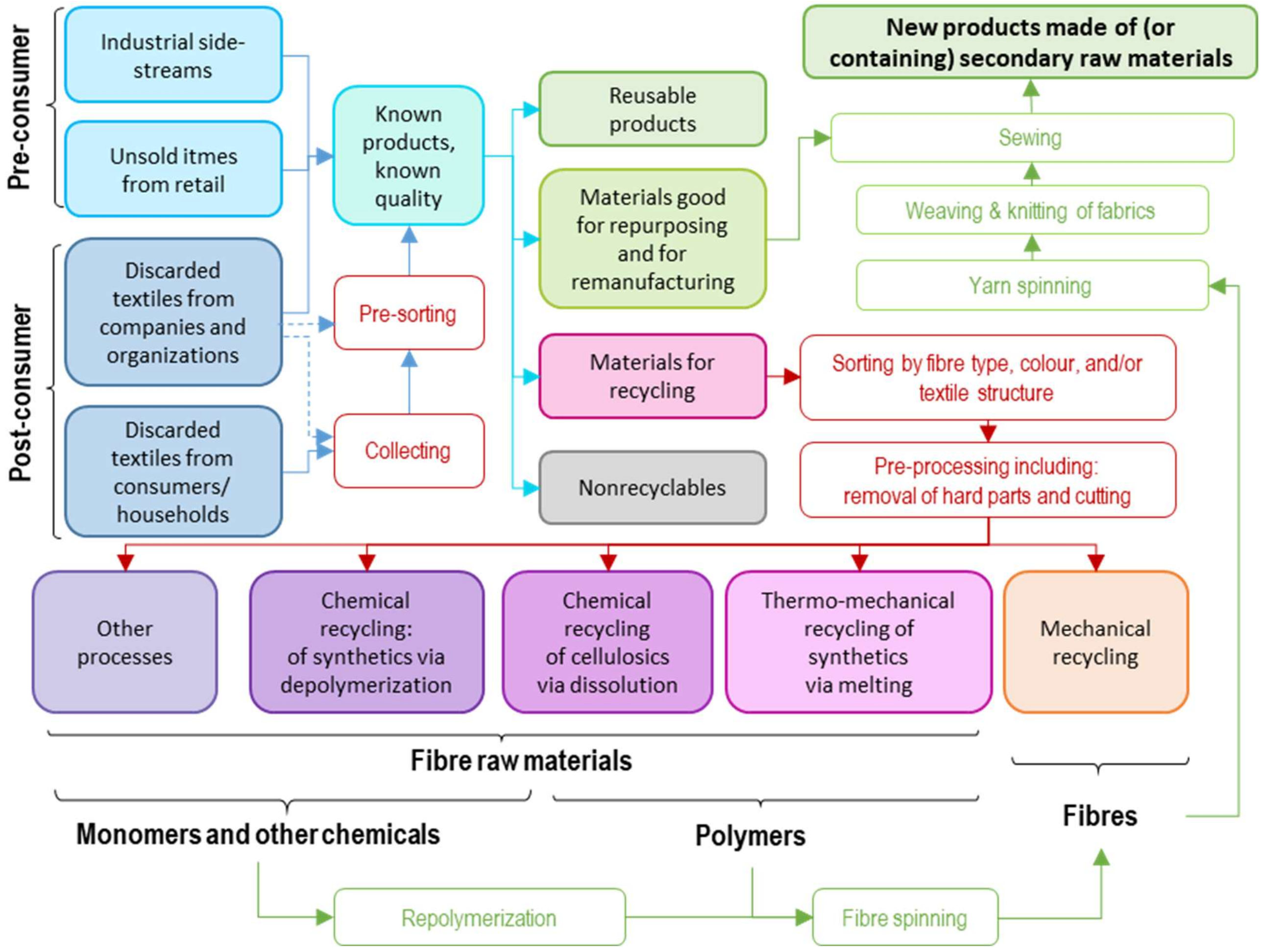

Figure 3 A simplified illustration of the recovery of discarded textiles, pre-processing for textile recycling, and optional routes in fibre-to-fibre recycling.

Textile products themselves are usually not made of a single fibre type, but blends, and they also contain other types of materials such as coatings, prints, buttons, zippers and other fasteners. Fibre mechanical recycling is, in principle, suitable for fibre blends, while fibre raw materials level recycling with chemical and thermo-mechanical methods are typically polymer specific. How much and what kinds of contaminants and other materials each recycling process can handle, varies.

Post-consumer textile materials can be worn out and contaminated, for example, dirty, wet, soiled, while quality of pre-consumer materials is practically as good as new. Wear of used textiles can be seen as reduced fibre length and strength. In *fibre mechanical recycling* fibre length is reduced and fibre strength remains unchanged, i.e., worn fibres remain worn, while fibre *raw materials recycling* enables restoration of properties in fibre spinning, which will follow the recycling process. Inhomogeneity in wear and in fibre composition both make optimization of recycling processes and end-product quality more difficult. *Pre-consumer* textiles flows are therefore easier to process, as the material composition is better known, and fibre quality is intact. Sorting and quality assessment are essential for mixed post-consumer textiles, especially when aiming for high quality applications.

According to McKinsey report (2022) amount of textile waste in Europe is more than 15 kg per capita, 85% of which are clothes and home textile discarded by consumers/household. Reports suggest fibre-to-fibre recycling as one of the most sustainable and scalable levers for addressing this waste problem. They estimated that once recycling technologies have reached maturity, around 70% of textile waste could be recycled fibre-to-fibre, and most of the remaining 30% could be utilized by open loop recycling and other solution. In addition to further development of recycling technologies and especially their ability to handle fibre blends, also collecting, sorting, and pre-processing need to be developed, and other barriers overcome. (McKinsey, 2022)

Main ingredients for success identified in McKinsey report (2022) are 1) critical scale across the value chain; 2) real collaboration; 3) transition funding; 4) investments; and 5) public sector push. They assumed that if barriers will be overcome, and sufficient investment made (estimated at €6-7 billion), fibre-to-fibre recycling rate could reach 18-26% of gross textile waste in Europe by 2030. In this vision textile recycling business could be self-standing, profitable industry with annual profit estimated at €1.5-2.2 billion, and holistic impact at €3.5-4.5 billion. In addition to economic benefit, such scenario would also enable creation of 15 000 new jobs and four million tons reduction of CO_2 emissions. (McKinsey, 2022)

This chapter reviews different flows and properties of discarded textiles (Chapter 2.1), textile waste valorisation processes (Chapter 2.2), fibre-to-fibre recycling processes (Chapter 2.3), and other recycling processes (Chapter 2.4).

2.1 Discarded Textiles and Pre-Sorting

Discarded textiles can be determined as textiles that are no longer needed for its owner. The main types for discarded textile flows are pre-consumer textiles which include industrial side-streams (sometimes referred to as post-industrial) and unsold items from retail; and post-consumer textiles i.e., textiles discarded by companies and other textile using organizations, and consumers/households. Textile (waste) flows from these different sources vary in their qualities and quantities. Planning separate collecting for different flows may be challenging, even if new textile strategy proposes harmonized extended producer responsibility (EPR) rules for textiles in Europe (European Commission, 2022). More clarification for the separate collection should be available within updated EU waste directive, which is expected in 2023.

Discarded textile flows often contain reusable products and materials in addition to end-of-life materials i.e., waste. In many European countries textile collection is focused on reusable products, and only recently also non-reusable items have been included into items to be collected. Sorting for reuse and recycling have been studied in recent years and more information about material flows and their prospected use, technologies, and processes can be found in literature and reports such as ‘Sorting for Circularity Europe’ (van Duijn *et al.*, 2022).

Preferably, reusable products should be cycled from one user to the next user as separate flows, for example, via second-hand store, on-line platform, charity re-use stores and flea markets. Furthermore, in addition to products, also material may be suitable for re-use even if products as whole are not, for example, due to broken and/or stained parts. Especially, jeans and specific fabrics/patterns from known brands are interesting materials remanufacturing and refurbishing into new textile products. This is typically done by relatively small-scale remanufacturing companies and artisans, for making new clothes, bags, accessories etc. Finnish examples of such activities include, for example, Globe Hope, Piece of Jeans, and Jouten[6]. In addition to remanufacturing, fabrics may be also utilized in more technical products. Palakurthi (2016), for example, made moulded composites from polyethylene terephthalate (PET) and cotton fabrics by applying heat to melt PET to act as matrix while cotton remained as reinforcement.

It may be difficult for textile users to determine if product is reusable or not. Furthermore, users and private citizens especially, may not be motivated to do pre-sorting and returning reusables and non-reusables into different collecting locations. Therefore, most discarded textile flows need pre-sorting for separating fractions suitable to be re-used.

Textiles that are not suited for re-use as a product (nor as a material) can be recyclables. Textile materials can be recycled in fibre level, by returning textile fabric and yarns structures within mechanical processes back into fibres,

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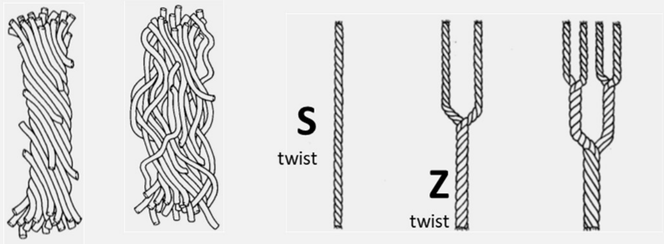
[6] Finnish companies involved in remanufacturing Globe Hope https://globehope.com/; Piece of Jeans https://pieceofjeans.com/en; Jouten https://jouten.fi/

which are used for making new products. In these processes fibre quality and length cannot be restores, and properties are, in fact, deteriorating. When fibre properties need to be restored recycling can be done in *fibre raw materials level*, i.e., by breaking down fibres either into polymer or monomer level. Infobox 1 included short introduction to textile and fibre construction to help understanding of different processes.

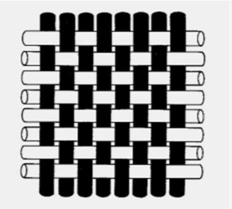
Infobox 1 Construction of textiles and fibres

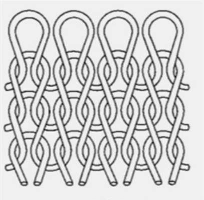
Textile products are composed of fibres, which are spun into yarns that are either knitted or woven into fabrics constructed typically by sewing. Main yarn type used in clothing and home textile applications is spun yarns composing of staple fibres. Yarn production starts with opening of fibres, carding and combing to separate and align them. Alignment rate and length of fibres affects the properties and structure of spun yarn. Main processes for spun yarn production are ring spinning leading to well aligned fibres of long fibres, as shorter fibres are removed during combing stages; and open-end (OE) spinning leading to less aligned fibres and containing wider range of fibre lengths. Typically, almost all textile yarns are twisted which gives them strength due to increased frictional forces, and they can be also plied or cabled, forming more complex structures.

The woven fabrics compose of (at least) two sets of yarn: warp and weft. They are interlaced over and under each other to create surfaces, most simple structure being plain weave (one over, one under). There are a lot of different weave types, and they can contain more than two yarn sets. In simplest case knitted fabric can be formed of single yarn that traverses the fabric crosswise forming stitches composing intermeshing loop structure (such as jersey), but in industrial knitting, structures are more complex: there are multitude of fibres and different stiches, also interlocked double knits where yarns system moves back and front.



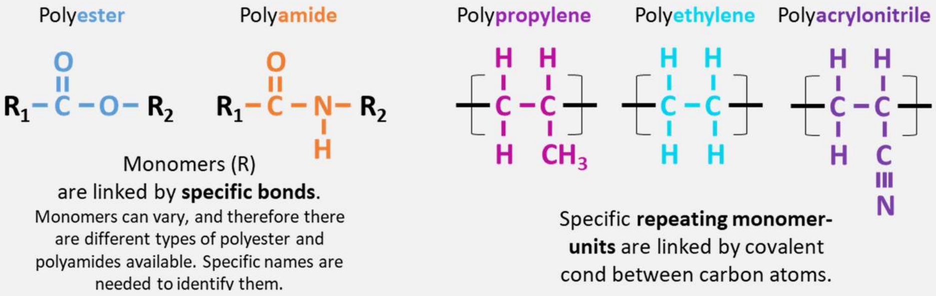
Ring spun, OE yarn, single, plied, and cabled yarn.


Woven fabric
- plain weave.


Knitted fabric
- jersey.

Fibres compose of chain like molecules called polymers, which are built up from one or more repeated simpler molecule units called monomers. Fibre raw materials can be recycled by extracting either polymers or monomers. Cotton composes of natural cellulose polymer, while man-made polymers are synthesized from biobased or oil-based monomers. Typical polymers used in textile fibres compose of one or two types of monomers as illustrated below, but, for example, elastanes are usually more complex structures. These fibres compose of repeating monomers combined into chain with specific bonds.

Some of the synthetic polymers are named based on the on the bond, like polyester (PES) and polyamide (PA), and some of them based on the monomer, like polypropylene (PP), polyethylene (PE) and acrylic. R1 and R2 refer to monomers.



Monomers (R)
are linked by **specific bonds.**
Monomers can vary, and therefore there are different types of polyester and polyamides available. Specific names are needed to identify them.

Specific **repeating monomer-units** are linked by covalent cond between carbon atoms.

Natural fibres have intrinsic properties (e.g., thickness, length, strength), but in case of man-made fibres also spinning method affects the properties. Main spinning methods are melt-spinning for thermoplastic polymers, and dry- and wet-spinning for soluble polymers. They are all based on extrusion of polymer melt or solution through spinneret containing tiny holes, and solidification of extruded fibres. After spinning, textile fibres are drawn, chemically treated/finished, and in many cases crimped/textured as well as cut into staple fibres suitable to be mixed with natural fibres for yarn spinning.

2.2 Material Sorting and Waste Valorisation

Recyclability of textile waste is improved by sorting and waste valorisation processes. Sorting in necessary since many of the recycling methods are fibre specific, but also because there are expectations for secondary raw materials coming from the needs of manufacturers using recycled materials in their products. Therefore, recyclables need to be sorted when aiming for any higher value application.

Main factor for sorting is fibre content of the products, however, for example, for fibre level and in some polymer level recycling methods colour based sorting can be used, since colours can be preserved in recycling and thus colour sorting increased the value of the textile waste. Furthermore, for fibre level recycling sorting based on the textile structure and type of product is beneficial, as mechanical process can be adjusted based on the structure for optimising properties of output materials.

Manual sorting based in the expertise of sorters is still the dominating procedure for textile sorting especially when input material has reusables to be sorted out from recyclables. However, machine-aided, and fully automated lines are currently emerging for material-based sorting[7]. In sorting centre of The Regional Textile Sorting Centre Twente (RTT) sorting discarded textile for both reuse and recycling have NIR sensors integrated into sorting tables for checking composition of recyclable items. Fibersort is commercial sorting line commercially available from Valvan Baling systems. Sysav sorting facility is stated to be world's first fully automated industrial scale sorting facility for textiles.

Textile waste materials may be challenging to be recycled especially due to use of fibre blends, colorants, thick prints, embroidery, finishes, and coatings, and possible contaminants also causing hygiene risks. There is a wide range of waste valorisation methods available for textile fibre raw materials which improve the quality and value of material or improve its recyclability. We have collected some examples here, but review of these methods is not, by any means, complete, but rather showing some examples studied and/or available in markets.

Separation or removal of different components of fibre blends is possible in chemical processes, examples included in Chapters 4.1.2, 4.2.2 and 5. There are, for example, many patented procedures for textile waste containing mixed polyester and cotton items (Sherwood, 2020). A solvent can be applied to selectively dissolve either cellulose or PET. The remaining, undissolved polymer can also be recycled after filtration and drying or alternatively converted into a derivative compound.

Cellulose may be dissolved in multiple solvents (see Chapter 4.2) leaving PET residue. Also, PET component can be dissolved, for example, in sulfolane, but that reduces the quality of the cellulose fibres. Nevertheless, the difficulty in dissolving cellulose has meant research efforts have focused on the solvent-based recovery of PET from textiles rather than the cotton. Similar approach can be used to purify polymers: the actual polymer is dissolved in proper solvent and recrystallize the polymer without impurities and additives for further uses. (Sherwood, 2020)

Dark-coloured textiles or different kinds of prints or patterns can cause challenges in reuse or recycling of textiles. New decolorization technologies of textiles and textile waste have been studied (e.g., Määttänen *et al.*, 2019; Li *et al.*, 2022) and commercialized recently. Cleaning and hygiene treatments of biological and other contaminants may also be needed (Heikkilä *et al.*, 2020). A laundry-type process may be done for whole products, but cleaning may be done also in later stages.

Worn Again (UK) has developed technology for the recycling of PET from bottles and textiles polycotton textiles. In the process PET is dissolved from textiles at elevated temperature with solvents such as aromatic esters and aldehydes. In case of polycotton undissolved cellulose is removed from the solution of PET using filtration and polyester is obtained with the use antisolvent such as isopropanol. Method enables removal of dyes that can deteriorate the quality of recyclate. (Sherwood, 2020)

Vividye[8] (SE) has developed a new production technology for circular textile printing and a new collection of cotton T-shirts, which are printed using the new method, has been released. The new method makes it possible to remove

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[7] RTT https://telaketju.turkuamk.fi/en/in-english-en/tutkijavierailu-saxionin-ammattikorkeakouluun/; Fibersort https://www.fibersort.com/ and https://www.valvan.com/en/solutions/textile-sorting-recycling; Sysav https://www.sysav.se/en/siptex/ and https://knowledge-hub.circle-lab.com/article/9121?n=Siptex-%7C-Sysav---The-world%27s-first-fully-automated-facility-in-industrial-scale-for-sorting-textiles

[8] Vividye https://www.vividye.com/, https://www.ginatricot.com/eu/gina-lab/vividye

old designs and print new ones on fabric. Elephantech Inc.[9] (JP) has developed *Neochromato Process*, a dye discharging method from PES. In this process the dispersed dye will be dissolved with two organic solvents and transferred from the fabric to the clean surface of paper using pressure and temperature. The environmental impacts are reduced by decolorizing of clothes or banners instead of recycling.

PureCycle technologies have solvent-based purification process for PP. Fluidic solvent does not affect PP, but dissolves dyes, pigments etc. impurities from PP waste (Thiounn & Smith, 2020).

2.3 Closed Loop Recycling

Closed loop, i.e., *fibre-to-fibre* recycling technologies include mechanical fibre level recycling, and thermo-mechanical and chemical methods that recycle fibre raw materials either in polymer or monomer level. When textiles are recycled in raw materials level, returning them into textile applications require more processing than in fibre level recycling. Textile waste can also be recycled to be used in other types of products within so called open loop recycling. Such alternative processes are also available for materials that cannot be easily recycled back to textiles. These include, for example, many laminated and coated textiles, and some blended textiles. Illustration of various possibilities for textile recycling is shown in Figure 4.

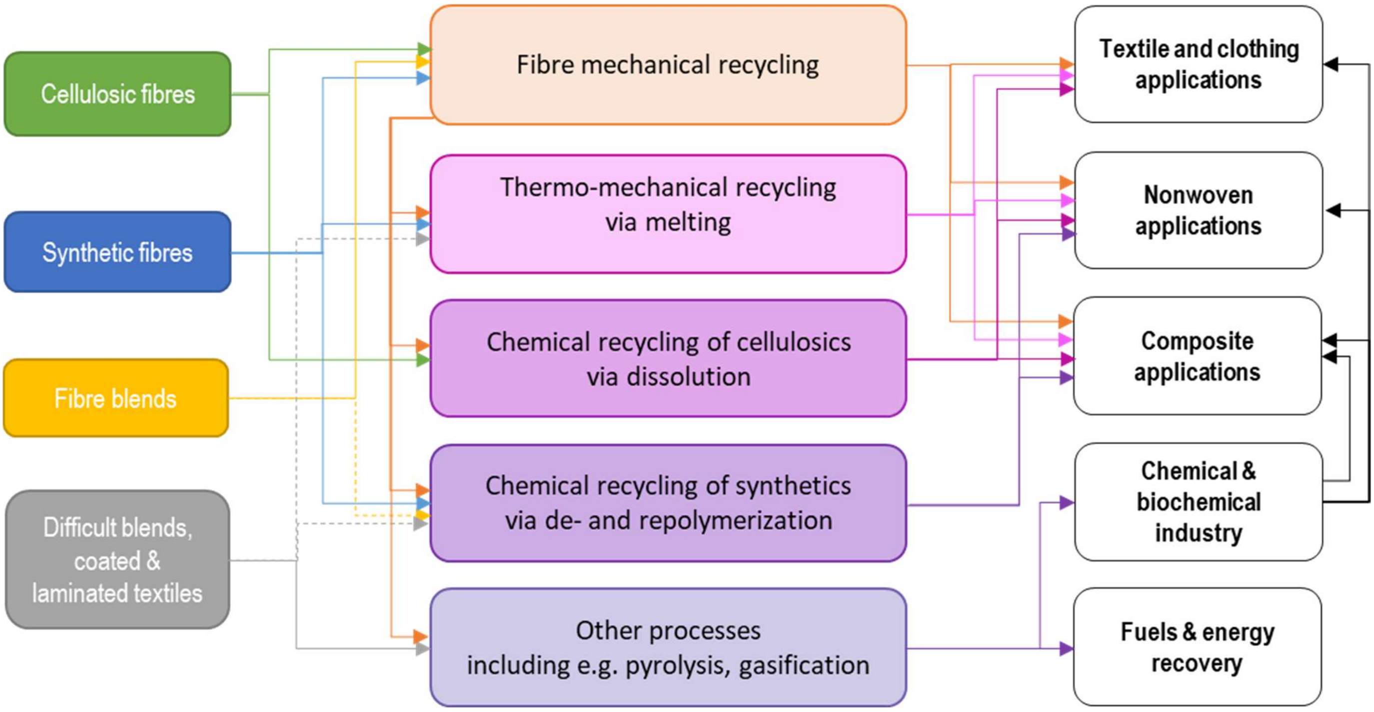

Figure 4 Simplified illustration of possible recycling routes and end-use applications for different types of textile materials and qualities: Continuous lines express typical routes, while dashed line shows exceptional options enabled in some variations of technologies. Side-streams of one recycling process could be fed to another process.

Fibre mechanical recycling is relatively simple process, but fibre raw materials recycling enables restoration of fibre properties. Many of the recycling technologies in their basic form are specific to fibre type, and thus quality of secondary raw materials is strongly dependent on the accuracy of the sorting. Large share of textile products composes of fibre blends. Some of the technologies (or variations of them) may be suitable for blends as well, and/or separation and extraction processes may be used to salvage one or more components from the mixture. In many cases, recycling of fibre blends will be a combination of multiple technologies and going into different levels with different fibres.

While most of the main fibre types can be recycled using fibre-to-fibre recycling methods, at least in lab scale, up-scaling of these methods in an economically and environmentally sustainable way is not an easy task. Challenges are

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[9] Elephantech Inc. https://www.nicca.co.jp/en/topics/product/720.html, https://info.elephantech.co.jp/en/neochromato

raised especially from difficult sourcing and inhomogeneity of textile waste, as well as inherent limitations of recycling methods.

When we process more, more costs, as well as use of energy, chemicals and water can be expected. The challenge is to find a suitable, economically feasible processing method for different types of materials taking also into account the environmental impact of recycling process, and to find the optimal high value application into which material quality allows it to be used. Furthermore, it should be noted that side-streams of one recycling method could be fed to another. Especially in fibre mechanical recycling there are fine fibres and other side streams that could be suitable for other fibre-to-fibre or open loop methods depending on their composition.

2.4 Open Loop Recycling

Open loop recycling refers here to methods, where secondary raw material is used by different industrial sectors into different products than from which it is originated. The most used recycled fibre currently in textile products is, for example, recycled polyethylene terephthalate (rPET) obtained from PET bottles. EU strategy for sustainable textiles, however, has indicated that closed loop recycling should be preferred over open loops. In this case meaning that food grade PET should be recycled in food packaging applications, and recycled PET fibres used in textiles should be made of other PET sources, such as textiles.

More often this also applies another way around. As shown in Figure 4 and described in previous Chapter, the secondary fibre materials obtained from textile recycling can also be used for production of other fibrous products like nonwovens and composites. Furthermore, materials that cannot be sustainably recycled by the means described in the fibre-to-fibre methods (e.g., various alloy materials and dirty fractions), chemical & biotechnical, thermal conversion hydrothermal, and processes may provide additional options. These methods may also be used for side-streams of other recycling methods. For example, from the fibre mechanical recycling we can obtain short, dust-like fibres, which could be used as a raw material for biotechnical solutions, such as microbial fermentations to produce ethanol and other chemicals, including monomers for biopolymers (polylactic acid (PLA), polyhydroxyalkanoates (PHA) etc).

2.4.1 Thermal Conversion, Hydrothermal and Chemical Processes

In thermal conversion processes, the polymer structure is re-assembled in thermal conversion into short-chain hydrocarbons or other molecular structures. The processes of thermal conversion are called pyrolysis and gasification. They are very similar processes to each other but produce different types of finished products. Pyrolysis produces mostly liquid products containing solid carbon of 15-25% and gaseous compounds of 10-20%, while gasification typically produces approximately 85% of the gaseous final product, 10% of solid carbon and 5% of fluid (Kamppuri *et al.*, 2019). Other types of processes which can be used for conversion of polymers into different kinds of smaller molecular structures include, for example, microwave technology, plasma, supercritical. The characteristics of the raw materials entered these conversion processes affect the characteristics of the finished product obtained. Such products may also be used by chemical industry: they could be suitable, for example, to make polymers for textile fibre production.

Since PE is inert polymer, its chemical recycling research focus has been via variations on pyrolysis. Pyrolysis is often used for production of hydrocarbons for fuel/energy applications, however, with specific processes it is also possible to produce more complex mixture containing also heavier hydrocarbon. Mixture composing of similar molecules to those found in petroleum, could hypothetically be processed by established petroleum refining and cracking techniques. (Thiounn & Smith, 2020) PP has similar structure as PE, but PP has a methyl group as a sidechain and thus different properties and behaviour than PE, and also PP can be recycled into value-added feedstock for chemical industry. Treatments with plasma and supercritical water as well as catalytic pyrolysis have been used to decompose PP into gaseous and oily, and sometimes even solid substances (Thiounn & Smith, 2020). Du *et al.* (2016) used PET from carpet waste as a source and studied the thermal and catalytic decomposition of this waste into oils.

Hydrothermal methods are a group of processes carried out in water-based system at elevated temperatures. They degrade and decompose organic materials into products which can be gaseous, liquids, and solids. Processes can be divided into following sub-categories: hot water extraction, pressurized hot water extraction, hot liquid treatment, hydrothermal carbonization, and hydrothermal liquefaction. Products and conditions of textile recycling using hydrothermal methods have been reviewed by Damayanti *et al.* (2021). Cotton containing waste have been, for example, turned into cellulose powder, microcrystalline cellulose, nano powder, glucose and activated carbon. Mixture materials have also been turned into chemical and volatile compounds. (Damayanti *et al.*, 2021)

Similar chemical processes used in polymerization in fibre-to-fibre recycling (see Chapter 5) can be used in production of chemicals and molecules for other processes. Acid hydrolysis, for example, can be used to directly depolymerize the cotton fibres in waste textiles to produce a glucose solution. Process described by Sanchis-Sebastiá *et al.* (2021) enabled a glucose yield of over 90% through a two-step procedure, and glucose concentrations around 40 g/L were achieved by increasing the solids loading in the two-step process, which might be sufficiently high for the microbial fermentation of the solution into high-value products in biotechnical methods.

BASF, for example, has commercialized ChemCyclingTM process[10] based on pyrolysis, and Fulgar[11] is providing PA fibres based on that technology.

Eastman's Advanced Circular Recycling technologies[12] include carbon renewal technology, which has been use for recycling of carpets. In this reforming technology synthesis gas in formed, and it is used to make variety of products such as plastic resins, fibres, and acetyl chemical products, including cellulose acetate plastics and Eastman Naia™ cellulosic fibre.

2.4.2 Biotechnical Methods

Biotechnical processes, based on usage of enzymes and microorganisms, can be used to convert textile-derived feedstock into value-added products, either back to textile fibres (closed loop recycling) or other non-textile products (open loop recycling). Enzymes offer specificity, which allows for example depolymerisation of only certain component(s) in textile blends to monomers, while retaining other textile fibre(s) intact[13]. Thus, enzymatic hydrolysis can provide monomers to (bio)chemical polymerisation but can also be used as a means of purification of specific fibres.

An example of this is provided by the work by To *et al.* (2019), who tested different CO/PET textile blends (at ratios of 80/20, 60/40, 40/60) in a biological recycling process, where the CO was enzymatically degraded by a cellulase enzyme mixture, and the PET fibre was recovered[14]. The recovered PET fibre was used to produce PET yarn by a re-spinning process. To improve the quality of the yarn, pellets from recovered PET fibres were mixed with pure PET bottles. The resultant yarn was found to have a tenacity of over 3 g/den and an elongation of 20-40%, which is suitable to be applied in textile and apparel industries (To *et al.*, 2019). The authors state that the proposed optimised process would be able to recycle more than 70% of the textiles including 100% CO, 100% PES, jeans and cotton/PET blend textiles.

There are also patent applications related to biochemical methods used to for hydrolysing and removing the cellulose-based fibres from polycotton blends[15]. Further examples of the possibilities provided by enzymatic depolymerisation in textile recycling, i.e., usage of PET depolymerising enzyme, is provided in following chapters describing fibre-to-fibre recycling.

As most, if not all, current textile recycling methods are not providing everlasting recycling possibilities, the textile waste that is not suitable for other applications could be used as a feedstock for microbial transformation, in a similar manner as in lignocellulose-based biorefineries. Microbial fermentation, especially based on usage of glucose as a

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[10] BASF ChemCyclingTM https://www.basf.com/fi/en/who-we-are/sustainability/we-drive-sustainable-solutions/circular-economy/mass-balance-approach/chemcycling.html

[11] Fulgar Q-Cycle https://www.fulgar.com/eng/products/Q-CYCLE

[12] Eastman https://www.eastman.com/Company/Circular-Economy/Solutions/Pages/Carbon-Renewal.aspx; https://www.eastman.com/Company/Circular-Economy/Resources/Documents/CRT-Technical-LCA-report.pdf

[13] JP8158265.A Method for recovering textile product. Ekorogu Recycling Japan; RO122919.B1 Ecological process for recovering polyester from polyester/cotton textile wastes. Institutul National ICCF, Universitatea Aurel Vlaicu din Arad; EP0646620.A1 Recycling materials comprising cellulosic and synthetic fibers. Hoechst AG

[14] For pre-treatment, prior the enzymatic depolymerisation, three different methods were tested including 1) autoclavation, 2) freezing in presence of NaOH and urea, and 3) milling of autoclaved material. Downstream processing of textile hydrolysate into purified glucose syrup was conducted via adsorption by activated carbon, ion exchange chromatography and evaporation, for removal of colour, ions and production of highly concentrated syrup. (To *et al.*, 2019)

[15] JP8158265.A Method for recovering textile product. Ekorogu Recycling Japan; RO122919.B1 Ecological process for recovering polyester from polyester/cotton textile wastes. Institutul National ICCF, Universitatea Aurel Vlaicu din Arad; EP0646620.A1 Recycling materials comprising cellulosic and synthetic fibers. Hoechst AG

feedstock, can be used to produce ethanol and other chemicals, including monomers for various biopolymers (PLA, PHA, silk, etc.) as reviewed by Ribul *et al.* (2021) and shown in Figure 5. Enzymes can be used to specifically depolymerize cellulosic, synthetics (PET, polyamide) or wool fibres. The illustration also depicts the possibilities of using microbial fermentation to produce from the cellulose-derived glucose new polymers (bacterial cellulose, PLA, PHA, silk) that could be used as polymers in textiles. What is not shown in the Figure 5, is the possibility to microbially produce ethanol, discussed in the next paragraph. Interestingly, the glucose derived from the textile waste could also be used to cultivate mycelium materials, which can be used, for example, as a vegan alternative to leather, construction, and insulation materials. These types of materials are currently being studied and commercialised by several companies.

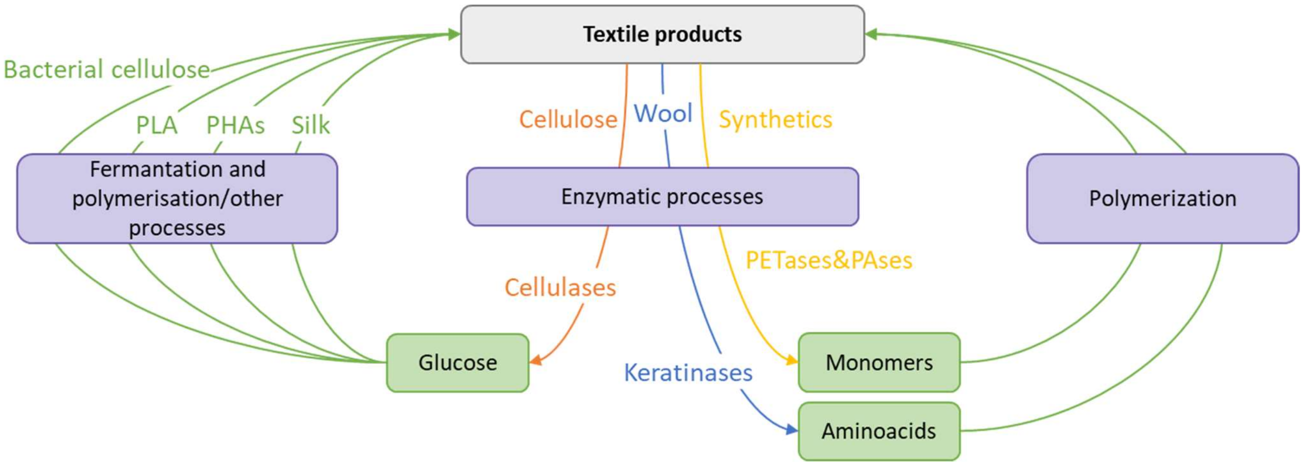

Figure 5 Some options for biochemical recycling of waste textiles, adopted/re-drawn from Ribul et al. *(2021).*

The most studied example of microbial fermentation is the usage of cotton textile waste derived glucose for production of ethanol. Damayanti *et al.* (2021) has listed several scientific publications on these studies in their review. Raw materials included 100% cotton, CO/PES mixtures (PES up to 50%) and viscose/PES mixture (40% PES). Pre-treatment methods utilised included acid, alkaline or solvent (NMMO) treatment prior to enzymatic depolymerization step. Enzymatic hydrolysis time ranged from 48 hours to 96 hours in temperatures around 50°C, and fermentation process time ranged from 24 to 72 hours in temperatures of 30-37°C. Reported cellulosic ethanol yields ranged from 70% up to 95% (Damayanti *et al.*, 2021). Similarly, to other cellulose-based raw materials, the ethanol yields obtained depend on the starting textile material, pre-treatment method as well as on the enzyme mixture and the fermenting micro-organism utilised.

It is worth noting that as enzymes have been developed and used both in textile industry as well as in biomass degradation and modification for decades, there are currently some commercially available enzymes suitable for textile recycling. However, it is anticipated that for optimal performance in various textile recycling applications, more work in finding and producing the optimal enzymes for the specific target applications would be required.

Furthermore, the same comment for requirement of optimization concerns also the utilization of textile wastes (after enzymatic depolymerization) as a feedstock for microbial fermentations to produce chemicals and polymers. As an example of enzymes and microbial recycling processes that would require more optimization, is biological recycling of elastane, the polyether-polyurea copolymer which is usually present in 5-10% in textiles. The recent advances in enzymatic depolymerization of elastane and microbial utilization of the elastane-derived mono- and oligomers have been reviewed by Liu *et al.* (2021).

Carbios, a French SME, has applied **enzymatic hydrolysis for PET bottles and textiles** (Thiounn & Smith, 2020; Tournier *et al.*, 2020). Carbios has recently signed an agreement with On, Patagonia, Puma and Salomon meant to accelerate the commercialization of its bio-recycling technology for textiles. The consortium aims to develop the industry's first large-scale fibre-to-fibre polyester recycling system[16].

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[16] https://www.greenbiz.com/article/bio-recycling-gets-fashionable-enzymes-will-eat-your-shoes

Caracara collective[17] is reporting in their web pages of cultivating fungi to **produce fungal mycelium materials** using e.g., sawdust and textile waste. It is said that in a couple of weeks' time period the mycelium will bind the matter (wastes) into a solid object. This type of mycelium materials is suggested to have good properties for insulation and fire-resistance. Mycological Innovations Challenge Grant has recently funded a project to study the usage of textile waste as a raw material for the growth of mycelium leathers.[18]

There are also several companies and research groups working on producing mycelium materials, such as VTT, Bolt Threads, Ecovative, MycoWorks, and Mogu[19]. The feedstock used for cultivating the mycelium materials can be all sorts of waste- and side-streams, however, textile waste is only mentioned in the web pages of Mogu.

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[17] https://www.caracaracollective.com/materials

[18] https://experiment.com/projects/can-we-produce-composite-leather-by-biodegrading-textile-waste-using-mycelium

[19] VTT https://www.vttresearch.com/en/news-and-ideas/alternative-leather-and-synthetic-leather-vtt-succeeded-demonstrating-continuous; Bolt Threads https://boltthreads.com/technology/mylo/; Ecovative https://www.ecovative.com/pages/mycocomposite; MycoWorks https://www.mycoworks.com/our-products; Mogu https://mogu.bio/

3 Mechanical, i.e., Fibre Level Recycling

Fibre mechanical recycling refers to a process using only on physical forces. Mechanical pre-processing includes cutting the textile products first into smaller pieces, typically by using guillotine cutting. First, the guillotine cuts textiles into strips after which the direction of the cutter changes 90 degrees, forming a textile shred. In this stage, the pieces containing non-textile and hard parts, such as buttons, sections of zippers etc., can be removed from shred. Further sorting is also possible at this stage, for example, if linings and outer fabrics may have been separated in shredding process. This shredded fabric material can be fed into fibre mechanical recycling. However, same or similar processing can also be used as pre-processing for fibre raw material recycling when instead of unravelling into fibres, fabric shred can be cut or grinded into smaller pieces. (Kamppuri *et al.*, 2019)

Fibre mechanical recycling means textile structures are mechanically torn, opened, and unravelled into separate fibres using physical forces (Duhoux *et al.*, 2021). Tearing and opening is done in machines composing of cylinders covered with saw wires or steel pins. Rotating motion unravels the structure. Number of cylinders can vary from three to six and up to nine, and process can be divided into pre-opening and fine-opening, with some blending boxes and cleaning steps included also in the process. Most of the unopened material pieces, also those containing non-textile parts, fibre bundles, thick prints, elastic and other trims, and debris are removed during the different steps of the opening process. However, it should be noted that not all opening lines are able to process textile waste containing non-textile parts, such as pieces of zippers, buttons etc., but separate process is needed for that. And it should also be noted that even if the line is designed for removal of these pieces, the efficiency of the removal of all non-textile pieces may be limited.

Quality of output depends on quality of input, especially uniformity, treatments, damages, and contaminants (Duhoux *et al.*, 2021). Output fibres may be classified based on the fibre length, for example spinnable fibres, fluff, filling materials and dust (Duhoux *et al.*, 2021). Recovered fibres can be used in either spinning of yarns to make fabrics and textile products for the textile industry, or for manufacturing nonwovens and composites (see Figure 4). Especially post-industrial wastes are applicable in recycling, and in-house recycling of production wastes may also have economic impact (e.g., Wanassi *et al.*, 2016). Post-industrial fibre waste may be usable as such for yarn spinning or making nonwovens.

3.1 Tearing and Opening

In opening textile structure is unravelled. Process is also sometimes referred to tearing or pulling. The opening process can be continued until the textile structure is sufficiently opened and suitable for the selected further process. Mechanically opened fibres often contain unopened materials (pieces of fabrics and yarns). The opening quality can be adjusted, for example opened fibres for nonwoven and yarn spinning qualities are available. In practise, for yarn spinning quality, the output of the mechanical opening process is clearly lower comparing to nonwoven quality.

Unnecessary processing should, however, be avoided, as mechanical processing shortens the length of fibres. Ütebay *et al.* (2019) studied effect of various raw material and processing parameters on quality of opened mechanically recycled pre-consumer cotton fibres. Fibre mechanically recycled pre-consumer cotton fibres were 25-35% shorter than virgin cotton. Yarn properties deteriorate when number of opening passage times exceeded three. (Ütebay *et al.*, 2019) However, in addition to minimize the loss of fibre length, care must be taken to make sure that also hard parts are efficiently removed, since those can cause damages to card and spinning lines.

Shred size affects the length of reclaimed fibres and easiness of opening. Better opening quality, and thus better spinnability, can be obtained with smaller shred size and number of shredding passages, but this leads to higher waste ratio compared to larger pieces and fewer passages (Ütebay *et al.*, 2019). Yarns obtained from larger shred have higher tenacity than those made of smaller shred (Ütebay *et al.*, 2019).

It has been noticed that both yarn and fabric properties affect how well the textile structure is opened and thus also what is the loss of fibre length during the process (Russell *et al.*, 2016; Aronsson & Persson, 2020). The yarn properties include yarn type, count and twist, and fabric properties include thread count and weave. For example, disintegration of short fibres and looser yarns seem to be less traumatic causing smaller length losses during opening (Aronsson & Persson, 2020). Post-consumer wool, especially those obtained from knitwear, are very useful raw material for woollen yarn manufacturing, while woven fabrics yield a shorter fibre after pulling making them more difficult to spin into new yarns (Russel *et al.,* 2016). Knitted materials are in general considered to have better processability in fibre mechanical recycling. However, knitting structure and tightness of fabric may also affect this. Ütebay *et al.* (2019), for example, who studied recycling of cotton, noticed that tearing of woven single jersey was gentler process than tearing of knitted interlock fabric. Effect of fabric tightness on short fibre content was insignificant (Ütebay *et al.*, 2019).

In comparison to virgin fibres, mechanically recycled fibres vary greatly in quality as the fibre length is often short (Albrecht *et al.*, 2003). Waste ratio (i.e., number of short fibres dropping out during processing) decreases with increasing passes (Ütebay *et al.*, 2019). Recyclate can be blends and mixed material, but process may be easier to optimize for processing of single fibre type, and one type of yarns and textile structure. Tearing process has not been changed much for over 250 years, however, for recycling new process developments are needed to preserve fibre length (Aronsson & Persson, 2020; Russell *et al.*, 2016). Additionally, common specification of fibre mechanically recycled fibres is lacking and often the measurement of properties recycled fibres is not straightforward with the methods developed for virgin fibres. The properties of mechanically opened fibres could include determination of colour, tensile properties, stiffness, titre, as well as fibre length and length distribution.

There is lot of fibre loss during the pulling process. In small scale trials yields may be as small as approximately 25%, however, it should be noted that steady state opening process should be obtained to evaluate the true yield of opening process (Aronsson & Persson, 2020). Ütebay *et al.* (2019) has suggested 50-60% fibre loss in pulling and spinning combined. They noticed thar short fibre content is higher in opening of dyed fabrics compared to opening of greige fabrics, since dyeing also reduces fibre strength. It should be noted that short fibres fraction losses during pulling, and spinning may be collected and used for other processes, such as nonwovens (Heikkilä *et al.*, 2021) or in chemical recycling (Aronsson & Persson, 2020), and is not waste *per se*.

Fibre mechanical textile recycling commercially used, i.e., in Technology Readiness Level 9 (TRL9). Newest developments are focusing on increasing the number of fibres suitable for yarns spinning and improving the quality by adjustment of machinery, adding chemical treatments and/or by better sorting. (Dohoux *et al.*, 2021)

Mechanical opening lines are commercially available, for example, from Andritz Laroche (FR), Ommi (IT), Margasa (ES), and Dell'Orco & Villani[20]. Companies offering opening process services and/or providing mechanically recycled fibres for further processing include, for example, Rester (FI), Frankenhuis (NL), and Altex Textile Recycling (DE)[21]. To tackle the problem of shortening of fibres, new, softer processes have also been emerging, such as Rejuvenation process by PurFi (BE)[22].

3.2 Production of Yarns and Fabrics

In yarn spinning, the length of fibre is a key determinant for the method used. The shortest fibres, less than 4-5 mm long, are lost during the processing; fibres that are 12-15 mm long provide bulk and thickness; and fibres longer that 15 mm give spinnability and provide strength and smoothness to the yarns (Klein, 2016). There are various yarn spinning methods available for recycled fibres (Kamppuri *et al.*, 2019). Ring spinning can be adjusted based on the fibre length; however, the range of 20-45 mm is considered slightly short for the method. For open-end (OE) spinning, the minimum required fibre length is 17 mm, preferably above 20 mm, and length of 25 mm is considered good. It is not surprising that OE spinning is favoured for recycled materials as the required fibre length can be shorter compared to ring-spinning.

In many cases recycled fibres are blended with longer fibres that have been recycled or with new virgin fibres to ensure high yarn quality. (Auranen, 2018; Kamppuri *et al.*, 2019) When blending waste, fibres should be compatible with same carding, spinning and fabric manufacturing processes than with virgin fibre (Russell *et al.*, 2016). Examples of yarns and woven fabrics from mechanically opened fibres produced within Telaketju 2 project[23] are collected in Figure 6.

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[20] Andritz Laroche https://www.laroche.fr/en/domaines-dactivites/recycling.html; Ommi https://www.ommi.it/2021/06/30/recycling/; Margasa https://www.margasa.com/products/textile-recycling/; Dell'Orco & Villani

[21] Rester https://rester.fi/en/; Frankenhuis https://www.frankenhuisbv.nl/; Altex https://www.altex.de/en/home-page/sustainability/

[22] Purfi https://purfiglobal.com/

[23] Telaketju 2 project https://cris.vtt.fi/en/projects/liiketoimintaa-tekstiilien-kiertotaloudesta-business-from-circula

Figure 6 Yarns and woven fabrics made from mechanically opened fibres (Heikkilä et al.*, 2021).*

In spinning mills production side-streams can be easily used in spinning, even though primary fibres have better fibre properties than production wastes. Russell *et al.* (2016) stated that wool processing is typically made up in a way that waste wool fibre from one processing step may be fed to another one during the process. In comparison of three pre-consumer cotton waste fractions collected from cotton yarn spinning mill by Yilmaz *et al.* (2017), carding waste (flat) had highest contents of contaminants compared to bale opening (blowroom) and yarn spinning (pneumafil) wastes, and shortest fibre length and smallest uniformity index. Blowroom waste led to highest yarn unevenness, thick and thin places, and lowest strength, but highest neps and hairiness values was obtained with flat waste (Yilmaz *et al.*, 2017). Halimi *et al.* (2008) have noticed that up to 50% of side-stream composed of good fibres, and up to 25% of side-stream cotton fibres may be added to OE spinning without noticeable effect on quality of the yarn. In later publications much higher blending mixtures as well as post-consumer fibres have been used without compromising the quality, for example, 100% cotton garments from pre-consumer cotton by Pure Waste Textiles[24], and 50% with denim waste by Luiken and Bouwhuis (2015).

In case of opened fibres resultant yarn properties are associated with waste fabric properties and shredding parameters (Ütebay *et al.*, 2019). In processing of pre-consumer textiles, the relation between certain variable and property (e.g., shred size and yarn tenacity) are sometimes significant and other times insignificant depending on the variables (Ütebay *et al.*, 2019).

Length of the fibre has a key role in creation of strong and durable textiles from mechanically recycled fibres (see e.g., Aronsson & Persson, 2020). There were differences between post-industrial wastes depending on from which processing stages they have been obtained in processability during ring spinning, but in OE spinning these differences were less apparent (Yilmaz *et al.*, 2017). In ring spinning openness of waste fibres was most crucial factor on yarns quality (but also contaminants affected it), while contaminants and fibre quality were most crucial factors on yarns quality (Yilmaz *et al.*, 2017). Hairiness depends on the short fibre content (Ütebay *et al.*, 2019). Yarns obtained from fibres from greige fabric were less hairy and had higher tenacity than those obtained from dyed fabrics (Ütebay *et al.*, 2019).

Proportion of recycled fibres also increases irregularities of ring spun yarns observed by mass variation, increases hairiness, and amounts of neps, and reduces yarn tenacity and elongation values. Changes get more significant as blending ratio increases (Yilmaz *et al.*, 2017). Including post-industrial into OE spinning also reduces the quality. However, the number of irregularities in OE yarns are typically smaller, but loss on tensile properties (tenacity and elongation) are more pronounced compared to ring-spun yarns (Yilmaz *et al.*, 2017).

Also, wool fibre recyclate from post-consumer origin is considered as important and cost-effective raw materials to be used as mixed with virgin fibres and alone (Russell *et al.*, 2016). In wool recycling wool content of over 80% is preferred, and virgin fibre blending may vary between 5% and 50% in new yarns (Russell *et al.*, 2016).

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[24] Pure Waste Textiles https://www.purewaste.com/

It might be a challenge to compare post-industrial wastes to post-consumer waste. Industrial cotton waste includes contaminants such as seed coat fragments, dust and neps (Yilmaz *et al.*, 2017), while post-consumer waste may contain some residual yarn structures.

Some spinning mills offer yarns at least partly made of mechanically recycled pre-consumer fibres, for example Marchi & Fildi (IT)[25]. Textile company's business can also be based on 100% recycled fibres, like Pure Waste Textiles (FI)[24], whose *Post waste era* collection includes yarns containing 20% of post-consumer cotton fibres blended with other types of recycled fibres (Heikkilä *et al.*, 2019 & 2020).

3.3 Nonwovens and Composite Applications

Shorter fibres are suitable for nonwovens, which is a group of sheet materials manufactured directly from fibres and bonded into consolidated structure. The shortest fibres (< 5 mm) can be utilized in airlaid nonwovens (i.e., dry papers) and in wetlaid nonwovens. The air-lay and carding processes are also suitable for longer fibres (≥ 50 mm). Fibres need to be well opened for the wet-laying and carding processes, while in the air-lay process the opening quality is not that critical (Albrecht *et al.*, 2003). Nonwoven technologies also enable production of thicker products, such as insulation materials (Figure 7).

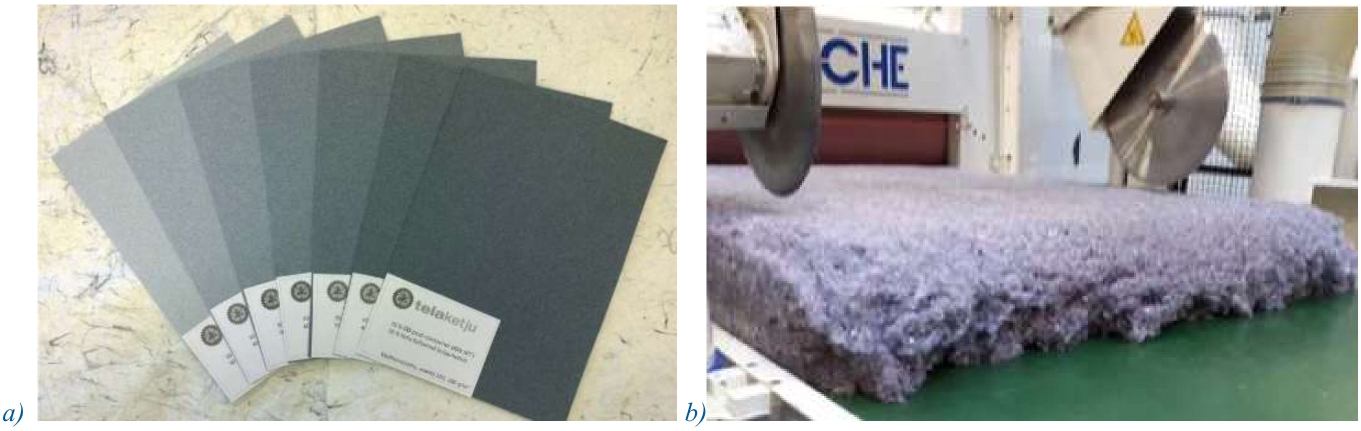

Figure 7 a) Thin foam formed sheets from very short cotton fibres (dust from the mechanical opening process of denim) mixed with pulp fibres. b) Thick air-laid felt from mechanically opened post-consumer fibres bonded with bi-component fibres. (Heikkilä et al.*, 2019b).*

The use of recycled polyester is common in nonwovens from staple fibres. For example, the European nonwoven industry used over 200 000 tonnes of rPET staple fibres in 2020. rPET fibres were used for example in roofing products, automotive sector and nonwoven geotextiles (Wiertz & Prigneaux, 2021). There are options for the processing of nonwovens that are very robust and can tolerate different fibre lengths and unopened fragments. For example, carding and air-laying together with needle-punching have been mainstream to use mechanically opened fibres for example for felts, mattress, and sound insulator felts. The carding and air-laying with needle-punching are very tolerate processes for different mechanically recycled fibre materials. The scientific research has focused on the use of recycled textile fibres in certain end-application and data from opening process and properties of recycled fibres is often missing. For example, post-consumer wool fibres have been used for nonwoven mattress insulator pads and sound insulation materials for automotive industry (Russell *et al.*, 2016) and nonwoven felts for wastewater treatments (Radetic *et al.*, 2009). Mechanically opened polyester and cotton from textile waste was used for needlepunched felts (Sharma & Goel, 2017) and pre-consumer textile waste after mechanical opening for needlepunched geotextiles (Leon *et al.*, 2016).

Opened recycled fibres can be used in composites either as reinforcement (length > 1 mm) or as filler (length < 1 mm). (Kamppuri *et al.*, 2019). The matrix materials have been thermosetting resins, thermoplastic polymers, and additionally other materials have been mixed with textile fibres, such as concrete. As an example, cotton waste, comber noil waste from spinning and knitting wastes, has been laminated with an unsaturated polyester

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[25] Marchi & Fildi https://www.marchifildi.com/en/ecotec-eng/ and https://www.marchifildi.com/en/home-page-eng/

to replace glass fibre alternatives (Umar *et al.*, 2017). Masood *et al.* (2018) concluded that recycled cotton fibres can be used in thermoset composites (unsaturated polyester) together with glass fibres and with virgin natural fibres, such as jute fibres, to gain more economical and environmentally sound composite materials (Masood *et al.*, 2018).

Serra *et al.* (2017) studied the use of recycled cotton fibres together with polypropylene matrix, and they concluded that dyed cotton fibres increased the affinity with the polypropylene resin (Serra *et al.*, 2017). Cao *et al.* (2022) used PET-cotton mixture fibres as reinforcement of high-density polyethylene (HDPE) composite. They studied use of modifiers to improve thermal stability, chemical bonding and mechanical interlocking between fibres and matrix. Cotton fibres were more resistant to carbonization, breaking force of fibres was improved, and bending strength, modulus and impact strength of composites increased with the use on synthesized modifier. Echeverria *et al.* (2019) have studied the production of composite material for insulation panels, where the reinforcement material as well as the matrix were from mechanically opened end-of-life textiles. The matrix was from polypropylene fleece textiles. Recycled textile fibres have been also used as reinforcement in recycled gypsum and cork composites for construction blocks for the use in walls (Vasconcelos *et al.*, 2015).

Nonwoven production is currently the state-of-the-art for textile recycling and commercialized for multiple types of nonwovens[26]. Recycled side streams and post-consumer materials are used for example in Freudenberg Nonwovens. In Finland, Dafecor has commercial products from recycled textile fibres. Rockline Industries sells biodegradable wipes made from 25% Lenzing Tencel and 75% fibre mechanically recycled post-industrial cotton (waste from T-shirt manufacturing).

Jasztex Fibres Inc. is recycling textiles and recycled fibres into added value products for example, from denim jeans into insulation padding, and from other recycled fibres into needle punched nonwoven humanitarian blankets. John Cotton Nonwovens Division’s high loft nonwovens are made by mechanically or thermally bonding natural, recycled, synthetic and blended fibres. Part of the recycled fibres are from post-consumer textiles.

Andritz Laroche is technology provider for recycling of textiles and nonwoven processing. Sikoplast Madchinebau produces machinery for processing polypropylene waste into nonwovens and films. Linyi Yuelong Nonwoven Equipment Co., Ltd. is supplier of nonwoven machinery suitable for recycled textile fibres.

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[26] Freudenberg https://buildingmaterials.freudenberg-pm.com/Sustainability/Recycling; Dafecor http://dafecor.fi/; Rockline industries https://www.nonwovens-industry.com/issues/2013-04/view_features/second-chance/; Jasztex https://www.jasztex.com/; John Cotton Nonwovens Division https://johncotton-nonwovens.co.uk/en/; Andritz Laroche https://www.andritz.com/nonwoven-textile-en/blog/nonwoven-newsletter/01-2021/introduction-laroche-2021; Sikoplast http://www.sikoplast.de/en/products/pp-non-woven-solutions/sikorex.html; Linyi Yuelong Nonwoven Equipment http://nonwovenlines.com/1-2-textiles-waste-recycling-line.html

4 Polymer Level Recycling

Textile fibres are formed from natural or synthetic polymers. Polymers are chain-like molecules composing of repeated simple units called monomers. Cellulose is a natural polymer composing of sugar units, and synthetic polymers are synthesized via polymerization of various monomers typically obtained from petrochemical industry. These chain structures make polymer materials tough and somewhat elastic. Polymers contain strong (covalent) bonds between monomer units and much weaker forces between the polymer chains. Therefore, it is easier to work on a polymer level rather than monomer level, if fibre properties are not sufficient for mechanical, fibre level recycling.

Many synthetic polymers used in textile products are thermoplastic, which means that they can be melted and formed into preferred shapes, for example melt-spun into textile fibres several times, by applying heat keeping the chain structure intact. Cellulose and some of the synthetic polymers are not thermoplastic but can be dissolved into solvents. Polymer solution can be used to make textile fibres via dry and wet-spinning processes. In this Chapter we review thermo-mechanical melt-processing for recycling of synthetic fibres (Sub-chapter 4.1) and chemical dissolution process for recycling of cellulose-based fibres (Sub-chapter 4.2).

4.1 Thermo-Mechanical Recycling of Synthetic Polymers

Thermo-mechanical recycling refers to a process where materials are processes as melt, and it is suitable for thermoplastic polymers. In plastic sector this method is referred to as mechanical recycling. Many of the synthetic textile fibres are thermoplastic, for example, polyester, polyamide, and polypropylene, and they can be melted several times. Acrylic fibre decomposes close to its melting point and cannot thus be processed this way.

In this process plastic is melted in extruder. Melting occurs due to heating elements and frictional heat caused by extruder screw. Volatile substances are removed via degassing system, and solid contaminant by filtration. Typically, polymer melt is pushed through a hole, to form a string, which can be cut into granulates similar to those produced from primary plastic raw materials. These granulates can then be re-spun into new fibres or reshaped into other forms. For most processes and applications monomaterials are preferred, however, there are exceptions in processes and applications, and some enable the use of blends and mixed materials in thermo-mechanical processes.

4.1.1 Processing Monomaterials

Thermo-mechanical processing can be used for thermoplastic PET. Most of the commercially available recycled polyester fibres are currently made with melt spinning polymer obtained from PET bottles that have been collected from consumers. Properties of fibres and fabrics made of rPET fibres have been studied for example, by Majumdar *et al.* (2020) and they observed lower level of crystallinity and tensile strength of rPET compared to its primary counterpart. Air and moisture vapour permeabilities of fabric did not change significantly, but shear and bending rigidities increased with inclusion of rPET, making fabrics thus stiffer and less pliable than virgin PET. (Majumdar *et al.*, 2020)

Challenges for using post-consumer textiles in these processes include physical and chemical changes in polymer occurred during the use. More changes, for example in crystallinity and in molecular weight, may occur during melt processing itself. Furthermore, contaminants may cause chemical reactions that lower the polyester molecular weight, and residues of other materials may weaken the fibres. Processes for thermo-mechanical recycling of textile fibres have been studied (e.g., Bascucci *et al.*, 2022) and are slowly emerging.

Contaminants, as well as heterogeneity of PET waste, makes thermo-mechanical recycling challenging (Park & Kim, 2014). Small amounts of other polymers in PET may significantly change properties of PET. Furthermore, PET is degraded during use due to UV, heat, oxygen, ozone and mechanical stresses, leading to reduction of molecular weight, viscosity and therefore quality of recycled fibres. Advantages of thermo-mechanical processing compared to chemical recycling include simplicity of the process, lower investment costs, utilization of existing equipment, flexibility in feedstock, and smaller negative environmental impact. (Park & Kim, 2014)

Bascucci *et al.* (2022) studied thermo-mechanical recycling of PET fibres, focusing on effect of flame retardants (FRs) which are often used, for example, in interior textiles, upholstery and carpets in transportation. They compared two FR treated PET to pristine PET. PET polymers undergo both thermo-oxidative chain degradation and chain coupling reactions (i.e., chain extension, branching, and/or crosslinking) during melt processing. Bascucci *et al.* (2022) noticed (in constant shear rate rotational tests) that presence of FR agents may change the balance of these reactions: one may have fortified degradation and/or hindered coupling reaction thus reducing viscosity, while another one fortified branching, thus increasing viscosity balancing the effect of chain degradation[27]. Kopf (2020) studied thermo-mechanical recycling of PET. Aim was to facilitate polymer coupling reactions in extruder to increase molecular weight in the molten state without supplementary substances. This approach was not successful, possibly due to complications during the process, but author sees that with further process development such rejuvenation may be possible in optimized conditions. (Kopf, 2020)

Lozano-González *et al.* (2000) investigated thermo-mechanical recyclability of PA6 to determine how many times it can be recycled in injection moulding process (up to ten cycles) without significant changes in its quality. They concluded that material properties remained almost constant until eight cycle (Lozano-González *et al.*, 2000). The first two cycles affected those tensile properties most sensible to polymer degradation - textile strength which increased and elongation which reduced - and then results levelled. (Lozano-González *et al.*, 2000). However, impact resistance and flexural modulus remained intact until seventh cycle, after which impact resistance reduced and flexural modulus increased (Lozano-González *et al.*, 2000). Molecular weight started to increase slowly with increasing cycles, molecular weight after five cycles and Mn after seven cycles, while melt flow index started to reduce and gel content increased in second cycle (Lozano-González *et al.*, 2000).

Molecular weight is a limiting factor for the number of recycling cycles. However, it is possible to valorise polymer melts with additives such as by chain extenders. Ozmen *et al.* (2019) studied use of various commercial chain extenders for improvement of recycled PA6 during reactive extrusion. All chain extenders increased molecular weight and melt-viscosity, but extenders had different reaction mechanisms with PA: some of them led to grafted, brush like polymer structure, while others led to liner resultant structure[28] (Ozmen *et al.*, 2019). Therefore, also effect on polymer properties, such as tensile strength, elongation, impact, ductility, and toughness, varied.

Buccella *et al.* (2013) have studied effectiveness of chain lengtheners[29] on thermo-mechanical behaviour of PA6. They observed increase of the melt viscosity with the amount of chain extender and decrease with increased residence times at high temperature. Number of functional groups on molecule chain and crystallinity of polymer was lower, strain at break increased, and stiffness similar to that of reference PA6 with corresponding molecular weight. (Buccella *et al.*, 2013)

Mondragon *et al.* (2019) have studied thermo-mechanical recycling of PA6 fibres from fishing net waste. They noticed that mechanical properties of recovered samples were similar to commercial PA6 implicating that not marine environment nor processing caused noticeable degradation of polymers.

Polypropylene (PP) and polyethylene (PE) are also thermoplastic polymers used in textile fibres. Their overall share of all global textile fibre production is quite small, and their application areas are mainly limited to sports and technical clothing, and to technical textiles. Therefore, finding references about recycling PP or PE textile fibres cannot be easily found, but information about thermo-mechanical recycling of these polymers can be found from more general plastic and their recycling literature, for example, by Jubinville *et al.* (2020).

4.1.2 Processes for Fibre Blends and Other Mixed Products

There are two optional approaches for fibre blends and other mixed materials products for thermo-mechanical processing; thermoplastic component may be separated from the blend/mixture and used like monomaterials, or mixtures may be used as mixtures leading to composite materials of different kinds.

As also explained in Chapter 2.4.2, biochemical approaches can be utilised to separate textile blends. Gholamzad *et al.* (2014) have described a method for polycotton blends that used enzymatic hydrolysis, saccharification and fermentation of cotton into ethanol, leaving out PES. Analyses of PES showed only minor changes in melt temperature, viscosity and molecular weight (Gholamzad *et al.*, 2014), i.e., properties affecting in thermoplastic processability. Similar approach for separation of PET from polycotton was presented by Hu *et al.* (2018) using fungal enzymes and Li *et al.* (2019) using commercial cellulase and β-glucosidase for recovery of glucose from

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[27] 6H-dibenz[c,e][1,2]oxaphosphorin,6-[(1-oxido-2,6,7-trioxa-1-phosphabicyclo[2.2.2]oct-4-yl)methoxy]-,6-oxide (DOPO-PEPA) fortified degradation, while Aflammit PCO 900 fortified branching

[28] Zemac E-60 from Vertellus e.g. led to grafted structure, while Addolink TT from Lanxess Chemicals led to liner structure

[29] 1,1′-Carbonyl-Bis-Caprolactam (CBC) and 1,3-Phenylene-Bis-2-Oxazoline (PBO)

cotton component. In addition to used enzymes, also other variables, such as pre-treatments of fabric and CO-PES blending ratio, affected the glucose yield. However, even though PET was suggested to be used in high value applications, the properties of PET was not studied in these two articles (Hu *et al.*, 2018; Li *et al.*, 2019).

Kunchimon *et al.* (2019) studied thermo-mechanical recycling of blends of PA and thermoplastic polyurethane (TPU) to produce hybrid fibres by melt extrusion process. Fibre structure was porous, but analyses indicated interactions between PA6 and TPU. Obtained hybrid fibres had strength properties between pure PA and elastane, having lower strength compared to PA, but higher compared to elastane. Study was carried out using primary plastics, but results could be applicable to mixed waste including TPU coated polyamide fabrics used, for example, in marine products such as inflatable raft, life vest and buoyancy control products. (Kunchimon *et al.,* 2019)

Thermoplastic materials can also be used for making composites, where they can be either as fibres or as matrix. Composite can also be made of a cellulosic-synthetic fibre mixtures, where the synthetic man-made fibre(s) are melted around cellulose based staple fibres (e.g., CO or MMCF). (Kamppuri *et al.*, 2019) Thermo-mechanical methods have shown to be very promising also for recycling of technical textile materials into high quality plastic and composite materials (Saarimäki & Sarsama, 2021; Heikkilä *et al.*, 2021). It is possible to keep colour intact during the process, see Figure 8.

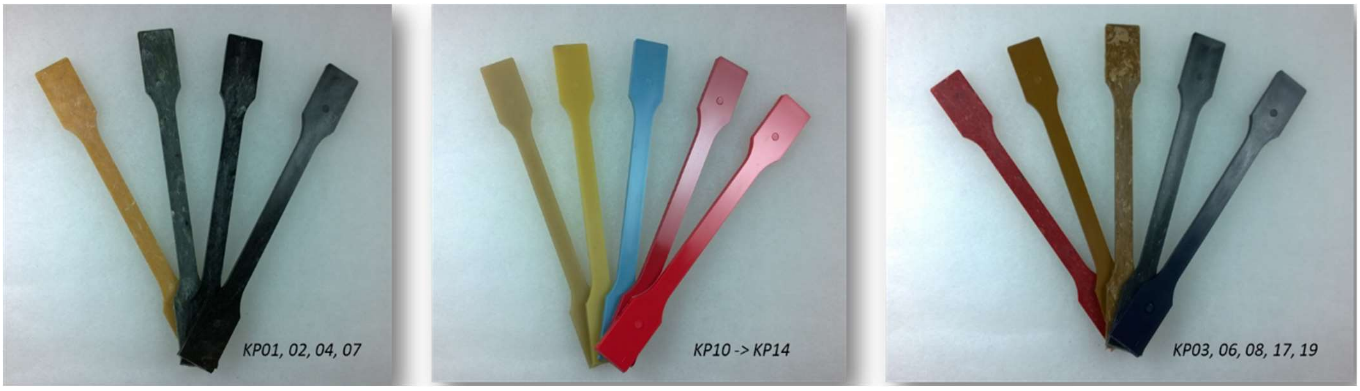

Figure 8 Plastic and composite rods made of various textile wastes (Heikkilä et al.*, 2021)*

The thermo-mechanical recycling process is excellent for industrial textile side-streams and established commercially for specific streams at TRL 9. In most cases, textile recycling, especially for post-consumer textile waste, is still in lower TRL levels. (Duhoux *et al.*, 2021)

Companies such as Nurel (ES), Racidi (IT) and Fulgar (IT)[30] offer fibres made of remelted PA from production. There are also some examples for thermo-mechanical recycling and upgrading of post-consumer synthetic polymers. Development work for these processes is on-going, and fishing nets, for example, have been successfully thermo-mechanically recycled (Mondragon *et al.*, 2019), but those are also suitable for other plastic processes.

There are also machinery provides for thermo-mechanical recycling of plastics such as Erema Group and Starlinger Company[31].

4.2 Chemical Recycling of Fibres Composing of Cellulose Polymer

Cellulose is a natural polymer available in plants, including wood. Wood-based cellulose has been used for over a century to manufacturing of man-made cellulosic fibres (MMCF) for textile production. Viscose is the main type of MMFC dominating markets. Lyocell type fibres, like Tencel, have been available for a few decades. Natural fibres such as cotton, flax, viscose and lyocell, are composed of cellulose as well. Both MMCFs and cellulosic natural fibres can be recycled by dissolving and spinning them into MMCFs. This is considered as chemical recycling method.

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[30] Nurel https://fibers.nurel.com/en/products/eco/reco-nylon-fibers; Radici https://www.radicigroup.com/en/products/plastics/sustainable-engineering-polymers-renycle; Fulgar https://www.fulgar.com/eng/products/q-nova

[31] Erema https://www.erema-group.com/en; Starlinger https://www.starlinger.com/en/company/

The dissolution and spinning processes vary slightly, but in principle they are the same methods used for making primary MMCFs from wood pulp. Cellulosic fibres are dissolved, and the cellulose solution is pressed through holes in a nozzle into a spinning bath where fibres are formed by precipitation by traditional wet-spinning or via dry-jet-wet-spinning with airgap between the nozzle and the bath.

Recycling of cotton has been demonstrated with the main commercial MMCF processes i.e., viscose (e.g., Wedin *et al.*, 2018) and lyocell processes (e.g. Haule *et al.*, 2016; Björquist *et al.*, 2018), and emerging processes including cellulose carbamate (Paunonen *et al.*, 2019; Heikkilä *et al.*, 2018), Biocelsol (Vehviläinen *et al.*, 2018, as cited in Vehviläinen *et al.*, 2020), Ioncell processes (Asaadi *et al.*, 2016; Haslinger *et al.*, 2019a), and Cold NaOH(aq) (Määttänen *et al.*, 2021). Ma *et al.* (2019), on the other hand, used mixed solvent process[32] enabling fast dissolution and reduction of process costs. Processing principles and main differences of the processes are illustrated in Figure 9.

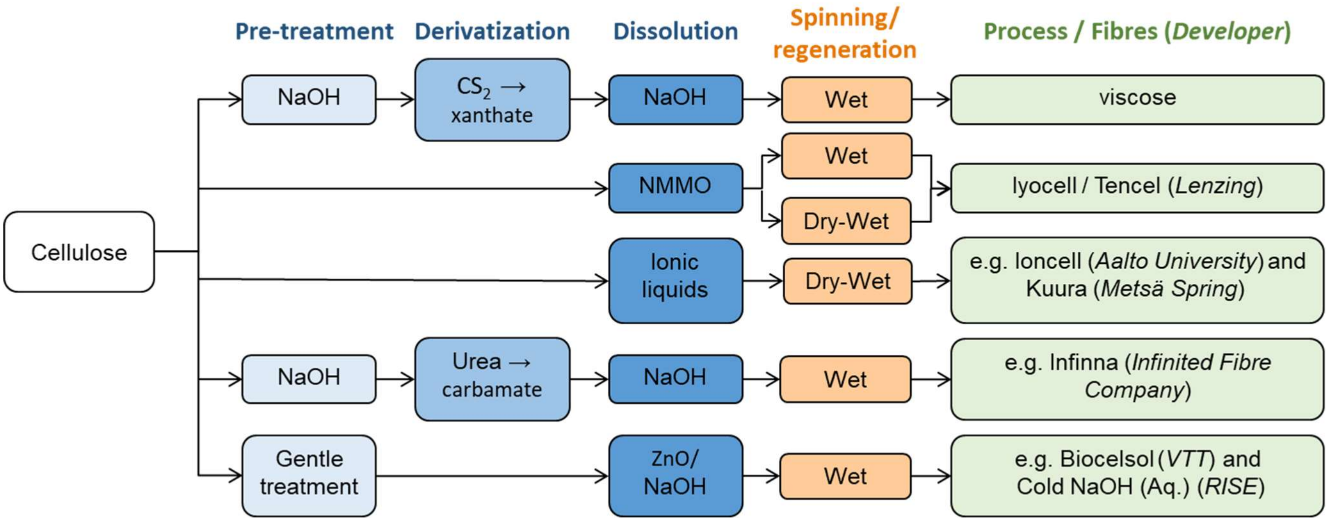

Figure 9 Cellulose fibre regeneration processes with main steps showing the main differences between them. NMMO = N-methyl morpholine oxide. Gentle treatment refers to biochemical methods and/or temperature adjustment.

4.2.1 Processing of Cotton Waste

Spinnability of cellulose solution depends on solution viscosity and rheology influenced by molecular mass (chain length) and its distribution, but also various other factors including rate of crystallization, gelation, crosslinking, and temperature. Cellulose from cotton seems very feasible raw material for making such fibres, and cotton lint (side-stream of cotton processing) have increased mechanical properties of MMCF compared to fibres made of wood pulp (De Silva & Byrne, 2017). This is caused by the higher chain length (degree of polymerization – DP) of the cellulose molecules of cotton compared to that of the dissolving pulp. However, limitations of solvents to dissolve high DP cellulose limits the use of very high DP cellulose materials, and for each MMFC processes DP should be adjusted to preferred level. In case of ionic liquids (ILs), for example, no benefits were observed using cellulose with DP over 1150. (De Silva & Byrne, 2017)

Molecular structure of cotton fibres overcome changes during use and laundry cycles. Palme *et al.* (2014) observed, for example, damages like fibrillation on fibre surfaces, minor decrease in water retention value (WRV), decrease in molecular mass, and widening of molecular mass distribution. Since DP of cotton is higher than that of the dissolving pulp, wear of fibres is typically not a problem in cotton recycling. Palme *et al.* (2014) noticed that molecular mass of cotton sample laundered more than 50 times was in the range of what is preferred by viscose producers, so only light pre-treatment may suffice for heavy used cotton. Various processes including acid treatment and enzymatic hydrolysis (Asaadi *et al.*, 2016, Vehviläinen *et al.*, *2018*) as well as alkali treatment (De Silva & Byrne, 2017), ozone and hydrogen peroxide treatments (Määttänen *et al.,* 2021) can be used to decrease degree of polymerization and thus adjust the intrinsic viscosity of cotton material in preferred level. Selected DP reduction method may have

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[32] Ma *et al.* (2019) mixed solvent was ionic liquid (IL):dimethyl sulfoxide (DMSO)

significant impact on sustainability of the process (Russon & Byrne, 2020). Asaadi *et al.* (2016) studied preparation of Ioncell fibres from cotton waste for dry-jet wet spinning. They were able to make spinnable dope and produce fibres from cotton waste samples, and that spinnability could be improved by blending cotton waste with softwood pulp.

In addition to changes in molecular structure, post-consumer cotton waste contains other fibres and different contaminants from textile manufacturing and use, which may affect their recyclability. Typically, raw cellulosic materials entering the chemical recycling process should have high cellulose fibre contents (between 97% and 98%) to reach MMCF, however, methods for higher mixing ratio blends and separation of blends have been developed, see Chapter 4.2.2.

Pre-treatment steps include processes activating cellulose and making it more soluble, but also impurities such as silicates and metals can be chemically removed from grinded fibres, and a coloured fraction can be bleached (Paunonen *et al.*, 2019, Määttänen *et al.*, 2021). If needed, colour and fibre finish removal steps may also be included into recycling processes (Wedin *et al.*, 2018). Määttänen *et al.* (2019) studied how the type of used dyeing method, i.e., direct, reactive and vat dyeing, influenced on the bleaching of the cotton material. Direct dye was removed the most effectively to full brightness whereas vat dye was the most challenging (Figure 10). Ma *et al.* (2020) treated red denim with NaOH prior to dissolution and obtain neutral fibres. Treatment time needed to remove different colours varied. However, they also demonstrated that the red colour of fibres can be saved during chemical recycling (IL/DMSO solvent system). Also, Haslinger *et al.* (2019b) have demonstrated the recycling of vat and reactive dyed textile waste to Ioncell-F fibres and retaining the dye in fibres.

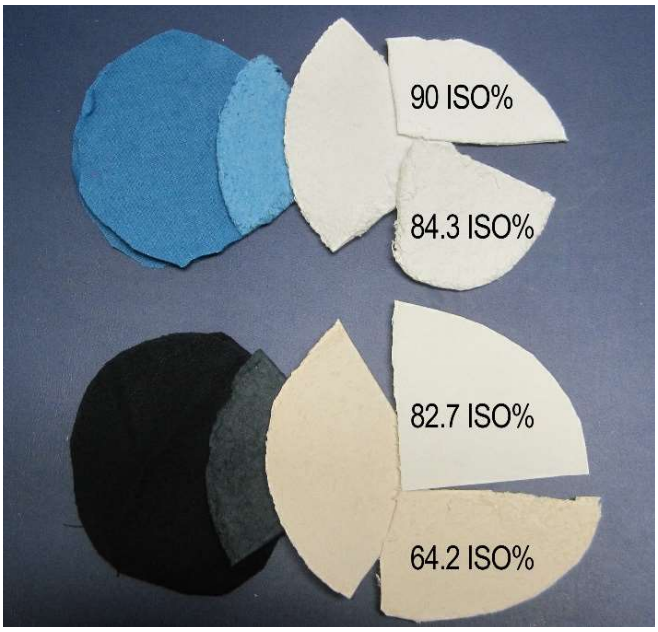

Figure 10 The removal of dye during pre-treatment sequences of direct blue (upper) and reactive black (lower). Order: dyed fabric, after wet milling, after alkaline treatment, the highest final brightness with sequence including ozone, hydrogen peroxide and acid treatment (upper) and the lowest final brightness with acid treatment after alkaline treatment (lower). Määttänen et al. *(2019).*

Haule *et al.* (2014) has successfully removed easy care finishing agent[33] from the waste cotton to improve its solubility and thus recyclability without lowering DP below values of wood pulp. Björquist *et al.* (2018), on the other hand, has suggested that residues of pigments and other chemicals in polymer chains could increase friction and therefore improve chemical properties of regenerated fibres made of cotton waste instead of wood pulp.

Chemical recycling of cotton produces man-made cellulosic fibres (MMCF)s, properties of which differ from those of cotton. Lyocell type fibres have typically higher tenacity than cotton, and therefore if cotton is recycled into MMFCs, resulted fibres can be stronger than original virgin cotton fibres. Asaadi *et al.* (2016) have reported Ioncell-F

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[33] Easy care finishing agent used by Haule *et al.* (2014) was dimethylol dihydroxyethylene urea

fibres from recycled cotton having tenacities of 680-880 MPA and elastic moduli of 20-29 GPA, exceeding values of cotton[34]. Furthermore, tenacities of MMFC composing of or containing recycled cotton could be higher than those of commercial MMFC fibres. For example, Björquist *et al.* (2018) and Haule *et al.* (2016) have reported higher tenacities of lyocell fibres with recycled cotton compared to reference lyocell fibres.

Chemically recycled fibres can be used as making textile products like any other MMCF. Single jersey knitted fabrics made 100% of and containing 10% of cotton waste pulp performed as good as the references besides of poorer colour fastness of 100% cotton waste pulp (testing included also, e.g., pilling, dyeability, abrasion resistance) (Björquist *et al.*, 2018).

Many technologies have already reached TRL 9 at least for pure cotton with capacities of up to thousands of tons per year, and most TRL 7-8 technologies will achieve TRL9 by 2025. New developments are focusing, for example, on recycling of or dealing with blended materials, especially polycotton. (Dohoux *et al.*, 2021)

Traditional MMFC companies like Lenzing (AU) and Kelheim (DE) have introduced products utilizing recycled pulp as raw material, but within last ten year also new companies have been founded for around this business including, for example, ReNewcell (SE) and ShareTex (SE) making dissolving pulp from cotton containing textiles, Infinited Fibre Company (FI) making Infinna fibres using cellulose carbamate technology, Evrnu (US) making Nucycl fibres, and SaXcell (NL)[35] making SaXcell fibres using lyocell type process.

4.2.2 Processing of Blends of Cellulosic Fibres

CO/PES is the most used fibre blends in clothing applications, and their separation can be done by dissolving cotton and filtering polyester out from the cellulose solution (De Silva *et al.*, 2014). Filtration may, however, increase the cost of the process. Similar approach can apply to other fibres as well, however, if blended fibres are soluble to the same solvent as cotton, they cannot be processed this way.

According to De Silva *et al.* (2014) ionic liquids are easy to use for separation of PES and CO. They used two ILs[36], and both were able to dissolve cotton. Analysis of recovered PES fibres showed no changes in melting behaviour of polymer indicating that PES properties remained intact, and regenerated cellulose (film) in water showed no changes in mechanical behaviour compared to reference made from 100% cotton. (De Silva *et al.*, 2014)

Haslinger *et al.* (2019b) also used IL[37] dissolution for separation of CO from 50-50 CO-PES blends. The IL allowed a selective dissolution of the cotton material, and a subsequent dry-jet wet spinning of cellulose to textile fibres. The spun fibres had properties similar to lyocell. Cellulose pre-treatment had a negligible impact on properties of PET, but it went through notable degradation (tensile properties dropped to around half), caused by IL solvent even if dissolution time was kept short (1 hour). (Haslinger *et al.*, 2019b) When degradation of PET is not excessive, such residue can possibly be returned to textile application via thermo-mechanical valorisation process. VTT demonstrated the separation and recycling of the same pre-treated CO/PES blend than Haslinger used via cellulose carbamate and Biocelsol technology (Vehviläinen *et al.*, 2018). Cotton fraction was spun for Biocelsol and carbamate stable fibres and PES fraction was characterized and tested in thermoplastic processing using injection moulding (Figure 11). After purification rPES samples indicated that they could be used as such in some applications that are not very sensitive regarding to colour.

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[34] According to Ahmad & Akhtar (2017) cotton tenacity and modulus are 290-600 MPA and 6-13 GPA, respectively

[35] Lenzing https://www.tencel.com/refibra; Kelheim https://kelheim-fibres.com/en/pressreleases/renewcell-and-kelheim-fibres-form-collaboration-to-establish-a-european-closed-loop-for-fashion/; Renewcell https://www.renewcell.com/en/; Sharetex https://www.sharetex.com/home#process; Infinited Fiber Company https://infinitedfiber.com/; SaXcell https://saxcell.com/; Evrnu https://www.evrnu.com/

[36] ILs used by DeSilva *et al.* (2014) were 1-allyl-3-methylimidazolium chloride (AMIMCl) and 1-butyl-3-methylimidazolium acetate (BMIMAc)

[37] IL used by Haslinger *et al.* (2019b) was 1,5-diazabicyclo[4.3.0]non-5-enium acetate (DBNHAc)

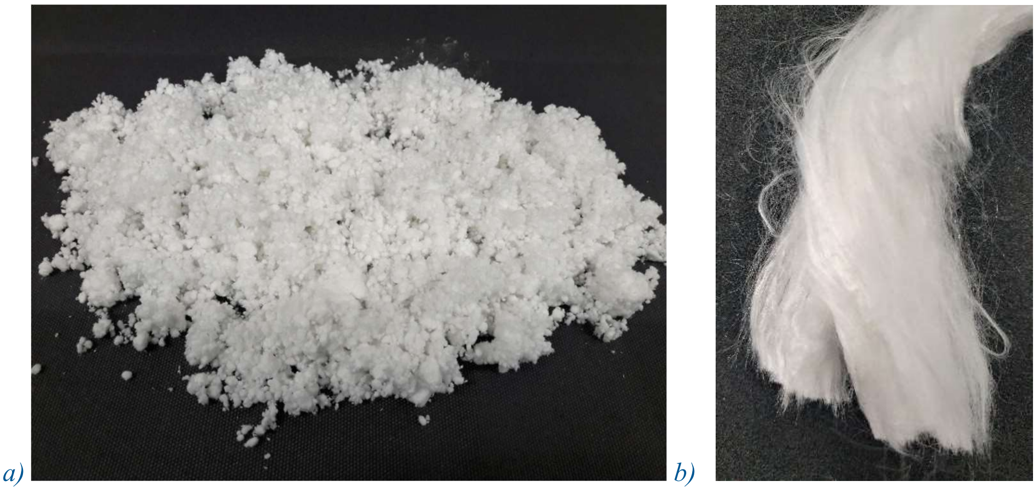

Figure 11 Separated PES fraction (a) and wet-spun Biocelsol fibres (b) from the dissolved cotton fraction (Vehviläinen et al.*, 2018).*

Palme *et al.* (2017) used approach where PES part was depolymerized via alkaline hydrolysis for re-polymerization (see Chapter 5.1), and residual cotton fibres were suggested to be used for spinning MMCFs. Similar approach was used by Peterson *et al.* (2022) to viscose-PES blends. However, since intrinsic viscosity of cellulose was decreased during PET hydrolysis up to 35%, authors suggested that it may not be sufficient for conventional fibre-to-fibre recycling, but interesting raw materials for emerging fibre processes or other purposes (Peterson *et al.*, 2022).

Ehime University and Shinshu University have developed process for the separation of three types of fibres from the blend fabrics (JP2019035022.A)[38]. The process utilizes organic acid, for example citric acid or oxalic acid at pH 2 or less, temperature 80-150°C and treatment time 1-6 hours. The fibres having carbon-carbon (C-C) bond, urethane bond or ester bond are maintained in fibrous form, for example PET, PP, acryl, PE, PU. The second types of fibres whose structural unit is bonded by a β-glycosidic bond (i.e. cotton and other cellulosic fibres) are decomposed into particles (powder like), and the third type of fibres bonded by an amide bond (nylon, protein fibres, aramid fibres) are dispersed in the acid solution.

Recycling of cellulose/PET textiles is of interest also for commercial actors such as Södra (SE), BlockTexx (AU), WornAgain (UK), Ambercycle (US) and Circ (formerly Tyton BioScience) (US)[39].

Södra has studied for example alkaline hydrolysis for separation of cotton from polycotton materials (WO2020013755.A), and Södra's OnceMore is commercial dissolving pulp grade made from cotton-rich textiles. Also, the method of Infinited Fiber Company includes an alkaline chemical step for the hydrolysis of PET fraction (WO2021181007.A1). Circ process, a hydrothermal process developed by Tyton BioScience, regenerates the cellulose portion and converts PET to TA and EG (Thiounn & Smith, 2020; WO2019140245.A). The hydrothermal process can be conducted also at alkaline environment (WO2019140245.A).

Process of WornAgain is based on extraction of both polymer components by dissolution (WO2020221932.A1). Ambercycle describes its process as molecular regeneration process separating components in complex textiles to create pure raw materials. They have developed engineered enzymes to degrade PET to monomers.

Blocktexx's technology (WO 2020/252523 Al) is based on treatment of polycotton with aqueous solution of sulphuric acid and collecting cellulose particles and PET fibres, which could be for further processing to be dried into powder and pelletized, respectively.

The Green Machine uses heat, water, pressure and biodegradable green chemicals (i.e., organic acids) to separate polyester fibres and form cellulose powder. Green Machine technology applies weak acid hydrolysis and recovers

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[38] JP2019035022.A Separation method of mixed fiber, production method of first fiber, production method of decomposed material of second fiber, and production method of decomposed material of third fiber. Shinshu University, Ehime University

[39] Södra (OnceMore) https://www.sodra.com/en/global/pulp/oncemore/ and https://www.sodra.com/en/global/pulp/old-oncemore-by-sodra/the-oncemore-pulp/; WornAgain https://wornagain.co.uk/; BlockTexx https://www.blocktexx.com/; AmberCycle https://www.ambercycle.com/; Tyton BioScience/Circ (US) http://www.tytonbio.com/our-services/recycling/ and https://circ.earth/; The Green Machine to transform textile recycling in Cambodia | H&M Foundation (hmfoundation.com)

PET fibre for re-spinning, re-producing of cellulose composite fibre, cellulosic superabsorbent polymer for cotton farming (Absorboost), and PFC-free function durable water-repellent (DWR) surface finish. The whole process uses only heat, water and less than 15% of green chemical with a recovery rate of over 97% and uses only 19 GJ to produce the same amount of separated polyester fibres, saving 70% of total production energy used. HK Rita has informed in cooperation with H&M in Indonesia a 1 kt facility. Technology is based on weak acid hydrolysis.[40]

Many of the cotton recycling processes, such as one used by Infinited Fiber Company, are able to handle cotton-rich polycotton materials within their process.[41] Nordic Bioproducts Group is Finnish start-up with novel process for regenerating wood-based feedstock into Norratex fibres. In addition to the wood-based raw material, the company has found that by modifying the technology, it can be used to recycle cotton-containing textiles, especially cotton-polyester blends. The advantage of the process is that it allows cotton and polyester to be separated into their own fractions and both materials can be reused for subsequent processing. Prospects of removal of elastane fibres with this process look promising.

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[40] Green machine https://www.hkrita.com/en/our-innovation-tech/projects/green-machine-phase-2

[41] WO2020013755.A A process for separation of the cellulosic part from a polyester and cellulose composition. Södra Skogsägarna ekonomisk förening; WO2021181007.A1 Separation of polycotton blends. Infinited Fiber Company Oy; WO2019140245.A Methods for recycling cotton and polyester fibers from waste textiles. Circ, Tyton Biosciences LLC; WO2020221932.A1 Recycling process. Worn Again Technologies Ltd; WO 2020/252523 Al A system and process for the separation and recycling of blended polyester and cotton textiles for re-use. BlockTexx Labs Pty Ltd

5 Monomer Level Recycling

Various chemical recycling methods have been developed to recycle synthetic fibres such as polyester, polyamide polyolefines and acrylic. These fibres compose of repeating monomers combined into chain with specific bonds. In the chemical recycling process, the polymer chain is depolymerized into monomers, oligomers or derives of them, then recovered and re-polymerized into a polymer of a completely new shape. Alternatively, the intermediates are used for other chemicals. Such re-polymerization methods are commercially available, for example, for polyamide, and polyester.

When polymer is broken down to monomer level, the process enables the production of new fibres with properties similar to new ones, i.e., both, the polymer and fibre properties, are restored. Processes enabling restoration of fibre properties use more energy and/or chemicals, and therefore they are expected to have higher environmental impact compared to mechanical processing. Actual yield may, however, effect on this picture.

Monomer level recycling processes typically involve cleaning, colour removal and separation of different molecules obtained in a depolymerization process. Therefore, purity and quality of the polymers can be restored. Many of the processes are not economically viable yet for post-consumer textiles, especially if extensive cleaning steps are needed. Also, the environmental impacts of such processes may not be known.

Chemical recycling methods open new possibilities for upcycling and making products similar to those made of new polymers. Processes are principally the same that are used for plastics recycling, however, additive chemistry and contaminants of textile waste are somewhat different compared to typical plastics products, such as packaging materials or bottles. Therefore, cleaning and pre-processing might be different. (Kamppuri *et al.*, 2019).

Biotechnology could also provide solutions for chemical recycling by enabling selective enzymatic depolymerization of recyclable fibres of natural and/or synthetic origin, to isolate constituents or even recover monomers (Jönsson *et al.*, 2021). For example, wool-polyester blended fabrics have been studied and complete degradation of wool fibres was achieved by application of a keratinase enzyme in a two-step process with addition of reducing agent, after which undigested polyester fibres were recovered (Navone *et al.*, 2020). The authors comment that the nutrient rich keratin hydrolysate could be used in microbial growth media or incorporated into bio-fertilisers or animal feed, thus contributing to the development of circular economy solutions. Enzymes and microorganisms have been used for hydrolysing and removing the cellulose-based fibres without damaging the polyester fibres[42] (see also Chapters 2.4.2 and 4.1.2)

Chemical recycling of plastics covers both de- and repolymerization route and other chemical methods based on for example thermal conversion processes. Monomer level recycling is used and has been studied for polyester and polyamide plastics in general, but studies focusing on textiles can also be found.

Other synthetic fibre raw materials include, for example, polyethylene (PE) and polypropylene (PP). Their share of textile fibres used in clothing and home textile applications is quite small, and literature references are mainly found on plastics recycling, not textile. These are quite inert polymers. Most studies on PE plastics recycling are based on different variations of pyrolysis, while the thermo-mechanical processes are the main approach used so far for recycling of PP (Thiounn & Smith, 2020). However, Guddeti *et al.* (2000), for example, have demonstrated use thermal plasma treatment for recycling of PP by converting it back into monomers or into other useful compounds.

In this Chapter we review monomer level, i.e., de- and repolymerization route for PES and PA, which provide kind of direct route back to polymers and fibres. Thermo-mechanical methods are reviewed in Chapter 4.1, and pyrolysis and other molecule level recycling methods are shortly reviewed in Chapter 2.4.

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[42] JP8158265.A Method for recovering textile product. Ekorogu Recycling Japan; RO122919.B1 Ecological process for recovering polyester from polyester/cotton textile wastes. Institutul National ICCF, Universitatea Aurel Vlaicu din Arad; EP0646620.A1 Recycling materials comprising cellulosic and synthetic fibers. Hoechst AG

5.1 De- and Repolymerization of PES

While there are several polyesters (PES) used in a wide range of applications, polyethylene terephthalate (PET) is most important of them for plastics and textile sectors alike. PET is composed of repeating ethylene terephthalate ($C_{10}H_8O_4$) units combined with ester bond, and it can be derived from terephthalic acid (TPA), or alternative from dimethyl terephthalate (DMT), and mono ethylene glycol (EG) via step-growth polymerization method. PET is commonly used in wide range of applications, including food, drink and other consumer goods packaging, and textiles. PET recycling has been evolved over the last decades (Park & Kim, 2014) focusing on recycling of plastic bottles.

In principle, same chemical reactions and processes apply to textile PET as to other types of PET, however, dyes, finishes etc. contaminants are somewhat different in different applications. Therefore, optimization of processes for specific waste streams are usually needed. Also, chemical recycling method for polyester fibres have been known since 1980’s. Due to low prices of primary raw materials and PET manufacturing, it has been a challenge to develop a cost-effective recycling process, but environmental benefits can be expected from recycling (Park & Kim, 2014). Dealing with contaminants, such as acidic compounds, moisture, colourants, and metallic compounds, is key factor for chemical recycling process as well as for quality of new products (Park & Kim, 2014). Beyond chemical contamination of polymer, in melt extrusion they cause decay of the molar mass, forcing to rehabilitate it.

In chemical recycling, polymer chain of PET is transformed and degenerated into monomers, oligomers, and other structural components. There are also several reaction types enabling chemical recycling of PET leading to different monomers/components. In case of PET these could be, for example, bis (2-hydroxy ethyl) terephthalate (BHET), TPA, glycols like EG, and DMT.

Raheem *et al.* (2019) highlight the superiority of glycolysis, but also have reviewed process alternatives including alcoholysis, hydrolysis, aminolysis and ammonolysis (Raheem *et al.*, 2019). These are shortly described in Table 1. Processes may include pre-treatment steps such as solvent degradation i.e., solvolysis, or by heat degradation in absence of oxygen i.e., pyrolysis. Furthermore, reactions may be biochemical such as enzymatic hydrolysis).

Table 1 PET chemical recycling methods (Raheem et al.*, 2019).*

Process	Short description	Primary products	Processing notes
Glycolysis	Trans-esterification process in presence of glycols e.g., EG	BHET monomers, dimers, and oligomers	HT & HP, C, commercially most widely used method.
Alcoholysis	Trans-esterification process in presence of alcohols e.g., methanol, ethanol	DMT, glycols such as EG, alcohols and phthalate derivatives	HT & HP. C. high corrosiveness, complex products require separation and purification, high costs.
Hydrolysis	Acid hydrolysis with strong acids (sulphuric, phosphoric, and nitric)	TPA and EG	Corrosive process, large volume of liquid waste
	Alkaline hydrolysis with two steps: saponification process with NaOH and acidic process with H_2SO_4		HT & HP, long reaction time, pure TPA and EG
	Neutral hydrolysis – esterification process with water or steam		HT & HP, slow process, extensive purification required
Aminolysis	Wide range of amines can be used	EG and amines of TPA	Yield depends on used amine. No known industrials cases
Ammonolysis	Ammonia (NH_3)	TPA di-amide and EG	HT & HP beneficial
HT = high temperature (around or above 200°C), HP = high pressure, C = catalyst used e.g., organometallic, ILs			

Glycolysis reaction is typically done in high temperature and in presence of organometallic catalyst to break ester linkages by glycol to produce BHET and its dimers and oligomers. In hydrolysis functional ester group is hydrolysed to produce TPA and EG monomers. Reaction can be carried out in acid, alkaline or neutral conditions. Both processes are used for PET bottles and other types of PET waste also in commercial scale. (Raheem *et al.*, 2019) Park & Kim (2014) reviewed potential to use recycled PET for high value-added textiles, and Upasani *et al.* (2011)

for example, have studied using rPET in production of yarns. Chemical recycling of PET textiles in closed loop system, however, has been less studied until recently.

Alkaline hydrolysis consists of two steps. First, saponification process with NaOH produces alkaline metal salt of TPA and EG, and via acidification process with sulphuric acid (H_2SO_4), TPA and salt of used acid will be obtained. Palme *et al.* (2017) developed a method for depolymerization of PET from polycotton blend fabrics. PET was degraded by alkaline hydrolysis using aqueous NaOH system with catalyst[43] at temperature range between 70 and 90°C. After removal of cotton fibres, TPA was precipitated from liquid phase using H_2SO_4 to separate it from EG. Catalyst enabled complete hydrolysis of PET and recovery of TPA with 40 min treatment, and thus preserving cotton. Cotton was swollen, with small parts of it changed to from cellulose I to cellulose II form, however, intrinsic viscosity did show that cellulose was not severely degraded and could, thus be used for preparation of MMFCs as described in Chapter 4.2.1. Ling *et al.* (2019) used phosphotunstic acid for separation of cotton in form of microcrystalline cellulose from polycotton blends. Remaining PES was degraded into TPA by **neutral hydrolysis**. They obtained almost full (99.77%) yield of PES in separation, and hydrolysis followed by crystallization (used for removal of insoluble impurities) resulted in TPA with very high purity (99.92%), high crystallization index (CI), favourable thermal stability and small particles size, i.e., properties suitable for industrial grade TPA (Ling *et al.*, 2019).

Enzymatic hydrolysis can be also done with PET degrading enzymes, i.e., various esterases, found either in nature or engineered, have been studied for a couple of decades. One of the most efficient PET hydrolysing enzyme is cutinase, which was originally derived from a compost sample (Tournier *et al*, 2020; Charlier *et al.*, 2022). It has been then engineered to work at elevated temperatures to depolymerise PET to ethylene glycol and terephthalic acid. Enzyme is said to be capable of selectively decompose the polyester material, thus making it possible to recover basically all the polyester found in textile waste, even blended fabrics. Charlier *et al.* (2022) used process occurring at a temperature of 72°C, which is close to the PET glass transition temperature, while VTT has studied a few enzyme strains operating effectively at 30°C for PET (and PEF). However, there are still innovations that are needed to reduce the energy intensity of enzymatic PET recycling process.

Commercial PET recycling actors with processes interested from textile recycling include, for example, Teijin (JP), Cure Technology (NL), Carbios (FR), Gr3n (CH), Ioniqa (NL), Eastman (US) and Jeplan (JP)[44,45].

Teijin has published textile PET recycling based on **glycolysis** already in 1980's (JP58059214 A2), and have continued development, e.g., by introducing a new catalyst to the process in order to lower energy consumption. Commercial processes via glycolysis have been developed by Ioniqa Technologies and Jeplan, both including approach to remove colours and pigments. Metallic catalyst particles by Ioniqa act also as pigment adsorbent, while Jeplans BHEM solution is cleaned from dyes and impurities with activated carbon (Thiounn & Smith, 2020).

Depolymerization of PET and polyesters from PET bottles and polyester textiles by Gr3n with patented DEMETO technology is based on depolymerization via **alkaline hydrolysis** by microwave technology (Thiounn & Smith, 2020). DEMETO (Depolymerization by MicrowavE TechnolOgy) technology

Carbios, a French SME, has applied **enzymatic hydrolysis** for PET bottles and textiles (Thiounn & Smith, 2020; Tournier *et al.*, 2020). Carbios has recently signed an agreement with On, Patagonia, Puma and Salomon meant to accelerate the commercialization of its bio-recycling technology for textiles. The consortium aims to develop the industry's first large-scale fibre-to-fibre polyester recycling system. Carbios has also partnered with PET manufacturer Indorama Ventures to build and operate the world's first commercial-scale bio-recycling plant for PET-based plastic in France. The company expects the facility, which will recycle local plastic waste, to begin operations in 2025.

Cure Technology's Polyester Rejuvenation process is based on **alcoholysis** (WO 2022/003084 A1).

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[43] Palme *et al.* (2017) used benzyltributylammonium chloride (BTBAC) as catalyst

[44] Teijin https://www.chemengonline.com/teijin-develops-new-chemical-recycling-process-for-polyester/; Cure https://curetechnology.com/; Carbios https://www.carbios.com/en/enzymatic-recycling/ and https://www.greenbiz.com/article/bio-recycling-gets-fashionable-enzymes-will-eat-your-shoes; Gr3n https://gr3n-recycling.com/; Ioniqa https://ioniqa.com/; Eastman https://www.eastman.com/Company/Circular-Economy/Solutions/Pages/Mechanical-Molecular.aspx; Jeplan https://www.jeplan.co.jp/en/technology/

[45] Patents: JP58059214 A2 Recovery of terephthalic acid component. Teijin Ltd; WO 2022/003084 A1 A Method to enable recycling of polyester waste material and a system for applying the method. Cure technology B. V.

5.2 De- and Repolymerization of PA

Polyamides are polymers where one or more monomer types are linked together with amide bond (see Infobox 1, on page 13). Amide bond is formed between carboxylic acid group (-COOH) and amine group ($-NH_2$) releasing water (H_2O), and amount of carbon atoms in monomer units is stated as number. Polyamides can be formed from two monomers alternating in polymer chain: one having amine groups in both ends and another one having acid groups in both ends. Most used of this kind of polymers in textile fibres is PA6.6 which is made of hexamethylenediamine and adipic acid, both of which have six carbons in their structure.

In some polyamides are formed of one type of monomer having acid group in one and amine group in the other. Circular ε-caprolactam, monomer of PA6 is example of this type. Its ring contains six carbons and one amide group. If these rings are opened, ε-caprolactam can be rearranged into continuous polymer chain. Polymerization processes, and therefore also reactions that can be used for recycling, are different for different types of polyamides.

Alberti *et al.* (2019) studied recycling of PA6 via ring closing repolymerization. They used acetic anhydride as depolymerization reagent to convert PA6 to N-acetylcaprolactam, which can be turned into ε-caprolactam. They used the process for various household items including textile materials, namely thread and hammock. Yield and purity of N-acetylcaprolactam varied depending on the item used, which may be caused by different impurities such as plastic additives. (Alberti *et al.*, 2019)

PA6 can be hydrolysed in a process similar that is used for PET (Thiounn & Smith, 2020). Polyamides can also be hydrolysed through enzymatic means (Jönsson *et al.*, 2021), however, the reports have shown so far only very low amidase activities. Some protein engineering has also been applied to cutinase enzymes (esterases) to improve enzymatic hydrolysis of amide bonds, however, clearly more would still be needed (Biundo *et al.*, 2019).

Datta *et al.* (2018) studied decomposition of PA6.6 via glycolysis and amino-glycolysis processes. PA6.6 decomposed to glycolysates, and mixture hydroxyl and amine compounds of lower molecular weight. Obtained glycolysates were successfully used in synthesis of polyurethanes. (Datta *et al.*, 2018)

Chemical recycling process for PA6 have been used at TRL9 level over a decade, while maturity for PET processes vary between TRL4 and TRL7, but first technologies are expected to reach TRL9 in 2023. (Duhoux *et al.*, 2021)

Aquafil uses hydrolysis process for PA6 and recovered nylon textile to be re-spun into ECONYL yarn. Process can be used for polyurethane containing input materials, since PU can be removed by selective thermal decomposition (Thiounn & Smith, 2020).

6 Sustainability of Textile Recycling Processes

In this Chapter we will review sustainability of textile recycling. We acknowledge that there are also social issues related to textile value chains, but we have decided to focus on environmental impacts and economics of recycling. Study of environmental impacts discussed in Sub-chapter 6.1 is general level literature review aiming to give overview on possible environmental impacts involved in textile recycling, and showing challenges to determining those impacts for example, raised by geographical differences. Economic review in Sub-chapter 6.2 is mainly done from national point of view using Finnish case, economic of which was modelled in previous Telaketju projects as example.

6.1 Environmental Impact of Textile Recycling

6.1.1 Potential for Positive Environmental Impact of Recycling

Environmental impacts of textiles have been studied widely and reported in various publications. Munasinghe *et al.* (2021), for example, found 1600 scientific articles published between 2009 and 2019. However, they were able to use only 57 articles in systemic review of environmental impact of whole life cycle of clothing. The reason for this is that majority of these studies had very narrow scope, for example, one type of product, or one or just few stages of product life cycle. Also van der Velden *et al.* (2014) have discovered that life cycle analysis (LCA) studies from textile industry are not transparent, expired or clearly outside the range. Van der Velden *et al.* (2014) bring out that more detailed data in today's situation is urgently needed.

Textile industry is one of the largest industries globally being also one of the most polluting ones. Textile manufacturing is of one of the main contributors of greenhouse gas (GHG) emissions (Hole & Hole, 2019; Rana *et al.*, 2015) and textile as a material produces one of the highest GHG emissions per unit (Kissinger *et al.*, 2013; Rana *et al.*, 2015). One kilogram of textile production causes 15 kg carbon dioxide equivalents (Elander *et al.*, 2015). In year 2015, textile industry generated 1.7 billion tons of CO_2 emissions and used 79 billion cubic meters of water (Palacios-Mateo *et al.*, 2021).

EllenMcArthur Foundation (2017) reported that textile industry uses 98 million tonnes of non-renewable resources and 93 billion cubic metres of water annually causing GHG emissions of 1.2 billion tonnes of CO_2 equivalent. Environmental impacts of textiles are produced in differently depending on the material. Cotton is a problematic material in many ways. One kilogram of cotton requires 10 000 litres of water (Elander *et al.*, 2015). Over half of the cotton is produced in China, USA and India, and irrigation is used in 60% of their production. In most of other main cotton producer countries, 100% of production uses irrigation. (Chapagain *et al.*, 2005). Additionally, it has been estimated that 11% of world pesticides are utilized in cotton farming while the land use of arable land is only 2.4% (Bevilacqua *et al.*, 2014).

The most effective way to reduce negative environmental impacts from production is to reduce consumption (Munasinghe *et al.*, 2021). If use times of textiles can be doubled, the production and its environmental impact may be reduced by 44% (EllenMcArthur Foundation, 2017). Munasinghe *et al.* (2021) noticed that raw materials extraction phase cause most of the environmental impact of the textile life cycle phases[46]. Dahlbo *et al.* (2017) reviewed that production of cotton, polyester and viscose fibres cause GHG emissions 2.62, 3.1 and 3.43 kg CO_2eq/kg of textile fibres, respectively. Van der Velden *et al.* (2014) discovered that thickness of the yarn is proportional for energy use, thinner the yarn, more energy required for spinning. Knitting was also discovered more energy saving method than weaving (van der Velden *et al.*, 2014).

Thus, it is evident that textile sector has a substantial need – and potential - to reduce the negative environmental impacts. Textile recycling affects in the raw materials extraction phase, which has been noted to cause most of the environmental impacts of textile lifecycle. Therefore, recycling is a potential means to reduce the negative environmental impact of textile industry, although environmental aspect is not the only interest for recycling.

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[46] Other phases included in this study were: fabric manufacturing, clothing manufacturing, retailing, use and end of life, transportation

6.1.2 Overall Environmental Impact of Textile Recycling for Textile Industry

Only 13% of the total material input of textile industry is in some way recycled and less than 1% of material used to produce clothing is recycled into new clothing (EllenMcArthur Foundation, 2017). Over 70% of textile waste is ending as a landfill (Hole & Hole, 2019). This means vast amount lost material and a loss of potential to save the environmental impacts of materials production mentioned above.

The textile recycling is still only emerging, and therefore the number of available studies of environmental impact of recycling is limited. Life cycle analyses are typically case studies, so the data cannot be generalized as such. This is understandable since environmental impact consists of multiple different impacts categories, and several different factors affect the impacts. The affecting factors include, for example amount, content and quality of material, locations, distances, local climate, local energy production systems etc. The limitation of generalized estimates is that they probably do not represent any real case.

Life Cycle Assessment (LCA) evaluate inputs and outputs and potential environmental impact during the life cycle of the product system from raw material extraction to end-of-life. The standard includes the following impact categories: Climate change, Eutrophication, Land use, Resources depletion, Acidification, Ozone depletion, Ecotoxicity, Ionising radiation, Photochemical ozone formation, Water depletion, and Human toxicity. LCA evaluation can be made to any product or service.

Life cycle assessment has been guided by the ISO 14040 standard, that gives some boundaries to the evaluation process. The principles that ISO 14040 standard gives, are fundamental and they should be used as a guide when making decisions in planning as well as execution of the life cycle assessment. While the standard gives some guidance to conduct the assessment, there are several tools developed for this evaluation.

Ahonen *et al.* (2020) has evaluated different simplified LCA tools to be utilized in textile LCA evaluation. One of the most used tools is HIGG MSI (Laitala *et al.*, 2018) that is designed for clothing, footwear and home textile evaluation. Other used program is GaBi, that is not industry specific. GaBi utilized data from its own database. OpenLCA utilize data from its own database as well external databases. (Ahonen *et al.*, 2020) SimaPRO is also one used modelling system (Braun *et al.*, 2021) Whenever simplified models are used, there can be questions and doubts about the accuracy of the results.

There is a strong consensus in the studies that textile recycling in general reduce environmental impact compared to incineration and landfilling, and that reuse is mostly more environmentally friendly than recycling. While Sandin & Peters (2018) raised question of required transportations which may change the preference, EuRIC[47] has made a study showing that 'producing new textiles results in 70 times more environmental damage compared to global reuse' and that 'each garment reused saves 3 kg of CO_2'. EuRIC sees that global and local reuse is the best option for the environment instead of processing collected textile waste.

The LCA studies also mostly report positive environmental impacts compared to virgin material production, but this impact is based on assumption that recycling will replace production of virgin materials. However, some studies indicate that 50%, or even 10% replacement rate will give a positive environmental impact. Studies typically include only one cycle of recycling, and therefore it may seem that 1:1 replacement in recycling may be nearly possible. However, this may not necessarily be true in the long run because of the losses and decrease of the quality of material, especially in fibre mechanical recycling. If consumption and production increase because of lower prices or lower quality of material the positive environmental effect will be lost. Further, if the virgin material production is environmentally clean and replacing recycling is not, the situation is the same. Replacing the production of virgin materials in current countries with recycling in another countries means also transfer of environmental impacts, if not treated appropriately. (Sandin & Peters, 2018)

Climate impact is clearly the most studied environmental impact of textile circulation – most often *Global Warming Potential* (GWP). To include the other impact categories is quite uncommon and typically only few others are included. This is problematic since this may bypass those environmental impacts which are important in the case in question leading to decisions, which decrease some environmental impacts and increase others. All relevant impact categories should be included in each case. For example, in the case of cotton and other biobased

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[47] Press release by EuRIC in 28th Feb 2023, https://euric.org/images/Press-releases/EURIC_1.PDF

materials, the water depletion, toxicity, land use, land transformation and biodiversity are relevant impact categories in addition to the climate impact (Sandin & Peters, 2018).

Comparing the GHG emissions of virgin raw material production and recycling is problematic since the transportations as well as energy production have a significant effect and local variations. In many studies transportations have been omitted, because of difficulty to generalize those results (Sandin & Peters, 2018). For example, Esteve-Turrillas and de la Guardia (2017) have compared the environmental impacts of cultivation, ginning and dyeing of virgin cotton with cutting and shredding of recycled cotton ending up to 13.98 kg CO_2eq/kg for GWP savings. They noted that the global transportation of materials does not make a significant difference between the cases, since both cases include those, but they did not take into a count the collection and sorting of the textile waste.

Dismissal of collection and sorting is quite common in LCA studies (Sandin & Peters, 2018). However, for example, Abayneh (2014) estimated in his calculation cases that collection would cause about 0.22 kg CO_2 emissions per kilogram of collected waste. Dahlbo *et al.* (2017) noted that transportation plays a small role in overall impact, and that the impacts of domestic transportation are dominant. Regarding transportation local transfer of materials from collecting points to sorting is one thing, and further transport of collected materials another to recycling site another. While excessive transportation of mixed low value materials should be avoided, transportation of sorted ready-to-use recycling input material has lower impact per kg of output material and thus be better justified. Also geographics and population density play a role LCA related to recycling if transportation is included in calculations.

Additionally, the GWP of automatic sorting was 0.016 kg CO_2eq/kg of textile in the Finnish case (Dahlbo *et al.*, 2017). Esteve-Turrillas & de la Guardia (2017) also reviewed that GWP data for dyeing ranges from 7.0 to 17.3 kg CO_2eq/kg which are almost one order of magnitude higher than those obtained in cultivation step. This would suggest that if dyeing is used for recycled fibres too, the GHG emission impact change can be even negative. Comparing the water usage and chemical usage is simpler: in the case of fibre mechanical recycling, they are about zero, thus meaning substantial positive environmental impact.

Morley *et al.* (2006) stated that re-use of clothing compared to recycling saves up to 29 kg CO_2eq/kg of clothing (cotton or polyester) and up to 33 kg CO_2eq/kg compared to disposal. Fidan *et al.* (2021) has studied recycled cotton in the production of denim fabric and their environmental impacts. Energy issues were also taken into account, comparing different energy production methods as well as economical aspects. It was noticed that environmental impact decreased clearly utilizing recycled cotton. Woolridge *et al.* (2006) estimated that for every kilogram of virgin cotton displaced by second hand clothing approximately 65 kWh is saved, and for every kilogram of polyester around 90 kWh is saved taking into account extraction of resources, manufacture of materials, electricity generation, clothing collection, processing and distribution and final disposal of wastes. Substituting polyester with its recyclable counterpart, rPET, would reduce CO_2eq emissions by up to 40% (TextileExchange, 2018).

Dahlbo *et al.* (2017) compared environmental impacts of increasing reuse and recycling of textiles in Finland. They created two scenarios: one with twofold increase of collection and reuse, and another with a twofold increase in separate collection and increased material recovery. In their second scenario, most of the additional recycling would be done as chemical recycling, and the increased amount of recycled textile would be tenfold compared to the current situation. According to their LCA calculations, increased reuse scenario showed greater potential to improve the environmental performance than increased recycling scenario. However, the differences between scenarios were very small. The overall impacts were dominated by the avoided impacts of virgin textile production and incineration of textile waste. Compensating virgin textile production is crucial for obtaining benefits. (Dahlbo *et al.*, 2017). The environmental impact of chemical recycling seems to be the main factor making the reuse more favourable concerning environmental impacts. However, chemical recycling is needed since fibre mechanical recycling is not capable to produce all fibres to replace virgin fibres.

Similar case study was carried out in Sweden including three different recycling techniques for a model waste consisting of 50% cotton and 50% polyester and a life cycle assessment. The material reuse process exhibits the best performance of the studied systems, with savings of 8 kg of carbon dioxide equivalents (CO_2eq) and 164 MJ of primary energy per kilogram of textile waste. The polyester recycling process would save approximately 0.9 kg CO_2eq and 26 MJ of primary energy per kg of textile waste. Use of cellulose/polyester separation system for production of cellulose and polyester yarns would save primary energy and GWP, 46.5 MJ and 5.5 kg CO_2eq/kg, respectively, per kilogram of treated textile waste. They noted that the results are particularly sensitive to the considered yields of the processes and to the choice of replaced products. (Zamani *et al.*, 2014).

6.1.3 Environmental Impacts of Different Textile Recycling Methods

Previous Chapters introduced several methods to recycle textile material. For each material or material stream, the feasible way to recycle needs to be selected based on the different factors. Factors include for example, the economic aspects, utilization rate of material value chain, and environmental aspects, as well as material properties like fibre content or purity of the material. In the following, the environmental impacts of different recycling methods are reviewed.

Johnson *et al.* (2020) reviewed studies about the environmental impacts of fibre mechanically and chemically recycled cotton. They referred to three studies in which fibre mechanical recycling showed environmental impact savings compared to production of virgin fibre. However, they reminded that product quality and economic competitiveness should also be considered, and these were not examined in the studies. They also reviewed several chemical recycling processes for cotton waste summarizing that studies of environmental impacts are mostly missing. (Johnson *et al.*, 2020)

Spathas (2017) evaluated the environmental impacts of yarn production in four different recycling cases compared to the use of corresponding virgin material. The yarn cases included: 30% recycled cotton, recycled blended polycotton, viscose yarn from recycled cotton, and blended recycled and virgin PET, and cotton. The environmental impacts of these cases compared to virgin alternative, with relative value of 100, are summarized in Figure 12. This study shows that even though there are many significant savings in environmental impacts, there are also many only minor changes, and replacing virgin material with recycled ones may also increase impact in some LCA categories.

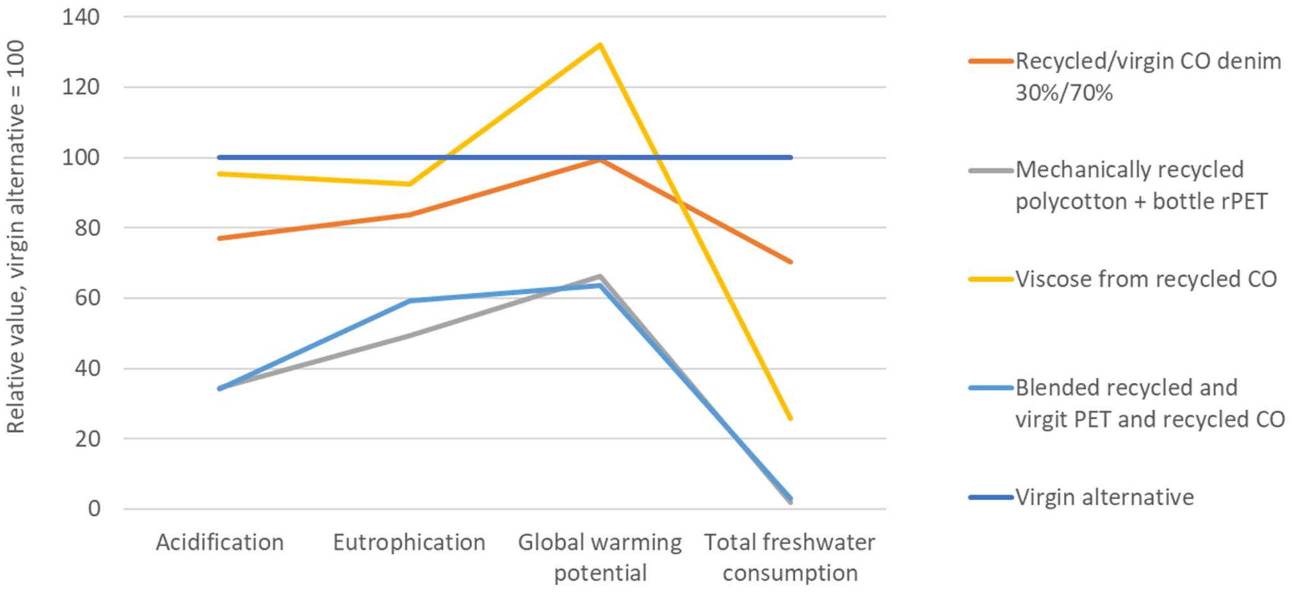

Figure 12 Environmental impacts of four different recycled yarn production cases. Drawn from data of Spathas (2017).

Global Warming Potential, energy consumption and loss of material when using different recycling methods are presented in Table 2. It would also be important to examine other environmental information. However, the studies providing such information in a comparable format were rare. For example, Schmidt *et al.* (2016) presented an extensive set of environmental impacts of different circulation cases, but only as a relative benefit figures in each case as Person Equivalents, and the results by Spathas (2017) were presented per one kilometre of uncoloured yarn.

Table 2 Global Warming Potential (GWP) (CO_2eq/kg of textile), energy consumption (MJ/kg of textile), and loss of material (as %) when using different recycling methods.

Recycling method	GWP	Energy consumption	Loss	Location	Ref
Washing and drying for reuse and recycling		5		Sweden	a
Mechanical, pre-processing		1.7	36%	Sweden	b
Mechanical; cutting and shredding	0.21	1.3	4%	Spain	c
Mechanical, cotton, shredding		0.4	20%	Sweden	a
Mechanical, cotton, shredding and carding		0.9	20%	Sweden	a
Mechanical; cutting and recycling		1.4	4%	Sweden	b
Chemical, separation of polyester and cellulosic fibres from mixed waste with BRW process	3.11	2.6 electricity 11.0 heat		Sweden	d
Chemical, cellulose/polyester separation using NMMO solvent		5.0 heat		Sweden	e
Chemical, polyester		17.3	10%	Sweden	a
Chemical, polyester, incl. Sorting and spinning	1.90	23.8		Finland	e,f
Chemical, Polyester DMT production		5.4 heat		Sweden	e
Chemical, Polyester polymerization		1.5 electricity 1.7 heat		Sweden	e
Chemical, Polyester yarn spinning		13.8 electricity 1.4 heat	2%	Sweden	e
Chemical recycling of cellulose-based textiles	2.14	26.9		Finland	f
Chemical, cotton, substituting virgin cellulose pulp		6.7 heat	10%	Sweden	a
Chemical, cotton, incl. pre-treatment, shredding, chemical treatments and drying		0.5 electricity 2.7 heat	5%	Sweden	b
Chemical, cotton, production of CCA fibres from cotton waste, including sorting, transportation, pre-treatment, carbamation and spinning	6.00 or 1.95*	1.5 electricity 16.7 heat	20%	Finland	g
Cotton yarn spinning		12.2 electricity 1.2 Heat	20%	Sweden	e
Yarn spinning		8.1 electricity	1%	Sweden	b

Reference: a) Schmidt *et al.*, 2016; b) Spathas, 2017; c) Esteve-Turrillas & de la Guardia, 2017; d) Peters *et al.*, 2019; e) Zamani *et al.*, 2014; f) Dahlbo *et al.*, 2017; g) Paunonen *et al.*, 2019

* 6.00 for stand alone factory, 1.95 if factory would in integrate to a pulp mill, the spinning process received cooling and process water, and heat energy from the pulp mill

EU has guided industry in last decades toward more sustainable production. For example, European Green Deal is one way toward more sustainable future. All products are guided to continuous environmental improvement in the EUs integrated Product policy (Damiani *et al.*, 2022). International Reference Life Cycle Data System (ILCD) has been created to support ISO standard 14040 to equalize data more comparable. The European Environmental Footprint (EF) is developed to guide policies and investments toward the environmentally sustainability goals like European Green Deal. The Product Environmental Footprint (PEF) is based on the LCA.

6.2 Economics

The overall reverse logistics of discarded textiles and the recycling path as a part of it is a complex multi-phased process as show in Figure 3. In this Chapter, the costs of different textile recycling phases and methods, as well as prices of recycled textiles are reviewed. It should be noted that costs and prices will continuously change. For example, at the time of writing this, the price of the fuels and energy has been dramatically increased, which affects more on the costs of those phases and methods which use more fuels and energy – generally transportations and chemical recycling. Primarily, the costs and prices represent the time of reference, even though in costs calculations some long-term values are used.

In general, when compared to the forward logistics (linear model), the extent of costs of reverse logistics are as follows (Tibben-Lembke & Rogers, 2002):

- Transportation costs are higher.
- Inventory holding costs are lower.
- Obsolescence costs may be higher.
- Collection costs are much higher and less standardized.
- Sorting and quality diagnosis costs are much higher.
- Handling costs are much higher.
- Refurbishment or repackaging costs are significant (and do not exist in forward logistics).
- Change from book value is significant (and do not exist in forward logistics).

The recycling related part of reverse logistics is presented in Figure 13. The Figure has been created as the framework for recycling cost modelling (Heikkilä *et al.*, 2021). The model included two options for sorting: fully locally organised sorting vs. two-phased sorting. The model also includes three alternative options sorting automation. Similarly, collection may be organised in different ways, which are not presented in this figure.

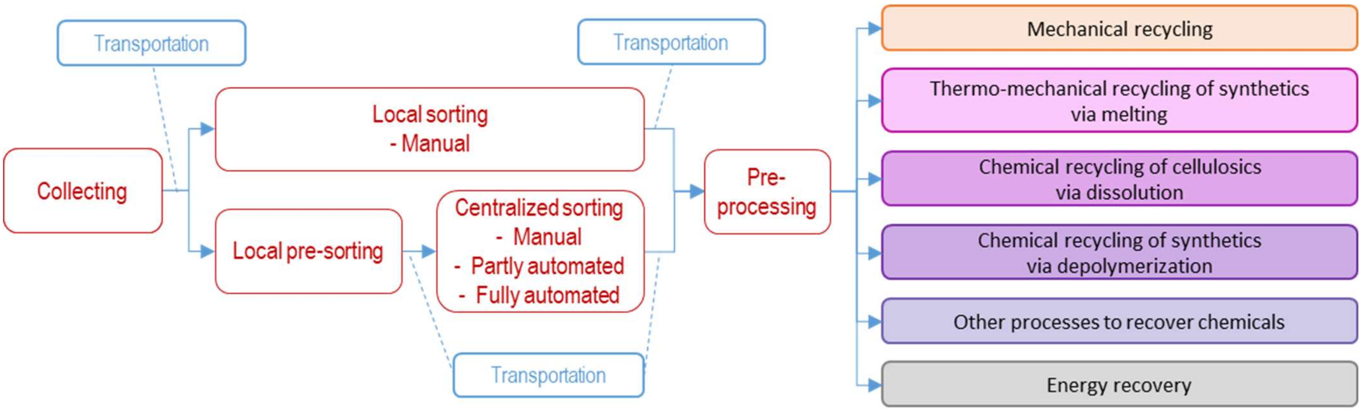

Figure 13 Steps of recycling value chain (adopted from Heikkilä et al.*, 2021).*

Every step and activity in recycling value chain causes costs to the actors. However, all costs do not necessarily sum up as the total costs of the recycling of the material: for example, the consumers typically are expected to do the first sorting and transportation of waste at their own cost. Heikkilä *et al.* (2019c) suggest that sufficiently functioning sorting by consumer would help to simplify recycling model and lower the costs. It should be also noted that 'competing' actions, like production of virgin materials as well as organised waste management, cause many similar costs than recycling. Basically, recycling is just another process to produce materials and take care of waste management. How costly recycling is in each case, is partly dependent on how effectively it has been organized. In principle, the smaller the loop (activity-wise and geographically) the more profitable and resource-efficient it is (Stahel, 2013).

It has been claimed that virgin materials have (in most cases) cost advantage over recycled materials, especially concerning the low value materials (Stahel, 2013). This is because the overall recycling chain includes more phases and transportation, and because recycling is more difficult to manage (Abayneh, 2014). The difficulty in management is mainly caused by variation and uncertainty in supply of discarded textiles (Abayneh, 2014). Many used materials today have a higher price than virgin materials because of the recycling of high-quality high-price material needs labour-intensive sorting into clean mono-materials. Alternatively, mass recycling can be done using machines but leads to downcycling and mixed secondary resources, which fetch a low market price (Stahel, 2013). However, the modelling and calculations by Heikkilä *et al.* (2019c) indicated that production of, for example, recycled cotton with competitive price could be possible. However, market forces and changes in business ecosystem and regulatory actions should be expected to play a role in economics of recycling.

The costs caused by possible unfavourable impacts on environment or society are not typically counted as the (indirect) costs of production or recycling unless they will be realized, for example, in the form of direct costs, like waste management fees or the costs of required decent working conditions. The environmental and social regulations vary in different countries and, thus, the related costs vary, which distort the price competition. Aims of recycling are to reduce negative environmental or social impact, but it should not be taken as granted since recycling, for example, normally include transportation, and working in recycling includes many hazards.

One of the key factors affecting recycling costs is the amount of the collected textiles, and, more precisely, the amount of the collected textiles on the certain area, as shown by cost models by Heikkilä *et al.* (2019c) and Abayneh (2014). For example, if the amount of the collected textile per person could be increased, the collection cost per kg of textile could be significantly decreased as well as the utilization rate of recycling lines could be increased (Heikkilä *et al.*, 2019c). The latter is highly important factor for the costs of actual recycling processes and especially for chemical recycling, where nearly 50% of the costs are originated from the investment (Heikkilä *et al.*, 2019c).

Another key issue is the share of collected textiles that finally will be recycled. The handling costs of different phases cumulate to the final recycled material, and the handling cost of the material lost in the process due to low material yield, will be counted as a part of the total costs of recycled material. Therefore, the lower the material yield, the more expensive the final recycled material is. For example, if 30% of the collected textile is lost in sorting, the costs of sorted textile are about 40% higher than if all the collected textiles could be utilised (Heikkilä *et al.*, 2019c).

The collected textiles may end up to reuse, remanufacturing, recycling, or incineration (or landfill) as shown in Figure 3. From the recycling point of view, collecting other than the recyclable textiles cause additional costs in collection, (pre-)sorting and waste management. On the other hand, the sales of reusable textiles could cover the costs of pre-sorting (Hinkka *et al.*, 2018). The unrecyclable textile includes, for example, contaminated, coated, and laminated textiles, and Heikkilä *et al.* (2021) estimated its amount as 20% of the collected textile. However, the amount of collected unrecyclable textile or textile contaminated during collection varies a lot depending on, for example, the collection system Heikkilä *et al.* (2019c). Additionally, recyclable or even recycled textile may end up to incineration because of lack of room for storage if they cannot be delivered to the following steps in the recycling value chain (Heikkilä *et al.,* 2019c). Such situation may be caused by occasional excessive supply of discarded textile, drop of recycled material demand, mismatch between the processing (and storage) capacity of different phases of recycling value chain or mismatch between the supply and demand of certain recycled materials (Heikkilä & Heikkilä, 2018). Storage capacity increases the resilience of production and supply but increases the costs at the same time, especially because dry and clean storage is required for recycled textiles. The balance of the capacity of the whole recycling value chain taking into account the variation in supply and demand is important factor of the costs.

Since the textile material for recycling is spread out all over the country (with the citizens and the companies), logistics is needed. The pre-consumer material is available as bigger lots in companies, but still mostly not very close to recycling centres. Logistics may be optimized, for example, by optimal locations of collection and recycling centres (Heikkilä *et al.*, 2019c), but significant amount of transportation is needed in any case. The collection costs may be diminished by applying the unused capacity of existing supply logistics for retailers and industry (Heikkilä *et al.*, 2019c). Transportation of different sorted fractions is more demanding and more costly (Heikkilä *et al.*, 2019c). Collection causes about 11% of total recycling costs and additionally there are about 2% of (other) transportation costs in the fairly optimized model (Heikkilä *et al.*, 2021). Abayneh (2014) did not find any significant differences between the costs of the door-to-door collection and the collection using the collection bins.

Sorting may be organized (more or less) locally, centralized of as a combination of these. The benefits of local handling include a reduced need for transportation, flexible local decision making and local availability of the sorted raw material (Abayneh, 2014; Hinkka *et al.*, 2018). Bigger volumes of centralized handling, for example, make investments in automation economically more feasible and may enable better expertise, but increase the transport costs (Abayneh, 2014; Hinkka *et al.*, 2018). The most local sorting would be done by the producers of the discarded textiles (companies or consumers).

Comprehensive and correct sorting in this first phase would diminish the cross-transportation between different actions (reuse, recycling, and energy recovery) and the related costs (Heikkilä *et al.*, 2019c). However, the efforts to influence on human behaviour cause some costs, too. The challenge is that even the division of reusable, recyclable and non-recyclable textile is not a simple and clear decision for layperson, not to mention the separation of different materials, and any additional effort needed would also weaken the motivation for recycling (Heikkilä *et al.*, 2019c). Removing the materials, which contaminate circulatable textile (and other non-circulatable materials), as early as possible would have several positive effects: cutting off the cross-transportation, diminishing the sorting effort and increasing the gain of circulatable textiles – all of them affecting the costs of recycling (Heikkilä *et al.*, 2019c).

Sorting requires professional sorting personnel, premises, in-house logistics, facilities, and, optionally, investment to automatic sorting line(s). In manual sorting, a seemingly simple work requires professional personnel in order to ensure good quality and efficient operation (Heikkilä *et al.*, 2019c). It is not necessarily realistic to rely on, for example, partly disabled employees or subsidised job even though the labour costs would be lower in such case (Heikkilä *et al.*, 2019c). Working in shifts increase labour costs but decrease the unit costs of premises, facilities and investments (Heikkilä *et al.*, 2019c). Automatic sorting requires investments causing additional costs. In the calculation cases in Heikkilä *et al.* (2021), automatic sorting appeared to cause lowest cost and manual sorting highest costs and the costs of partly automated sorting were in between. The estimated costs of collection and sorting vary depending on the model and assumptions, but for example Abayneh (2014) ended up to similar cost level in Swedish modelling case (0.47 €/kg) than Heikkilä *et al.* (2019b) in quite similar the Finnish case (0.43 €/kg). Costs for sorting and transportation (0.35 €/kg and 0.07 €/kg, respectively) in European study (van Duijn *et al.*, 2022) leads to similar sum. The costs in the modelling case of Ethiopia, for example, were somewhat higher (0.74 €/kg) because of much less amount of collected textile per capita (Abayneh, 2014).

Sorting of textiles is the most expensive phase, if fibre mechanical recycling is used (Hinkka *et al.,* 2018). Value of bales of clothing pre-sorted into different grades is a function of fibre composition, the homogeneity, colour/shade, and type of fabric influencing for example, the fibre shortening in mechanical recycling (Russell *et al.*, 2016). Price of discarded clothing pre-sorted for recycling can be smaller than costs of collecting and sorting but should be higher than costs of disposal (Russell *et al.*, 2016). It has been more profitable to donate the collected and sorted low-quality textile products abroad rather than pay for waste treatment (Heikkilä *et al.*, 2019c).

There are several different recycling methods: fibre mechanical, chemical, and thermo-mechanical, and the cost structures and the costs of these methods are different as well (Heikkilä *et al.*, 2021). Within Telaketju project we modelled costs of mechanical and chemical recycling (of cotton rich textiles) in Telaketju-Tekes project (Heikkilä *et al.*, 2019c), and updated those numbers and included thermo-mechanical recycling in Telaketju2 project (Heikkilä *et al.*, 2021)[48].

Fibre mechanical recycling requires investments in opening and carding machinery (Heikkilä *et al.*, 2019c). The textile should be cut as shred and hard parts should be removed before fibre mechanical recycling (Kamppuri *et al.*, 2019). Investment in machinery for cutting and removal of hard part increase costs, when required (Heikkilä *et al.*, 2019c). Adding cutting machine to the end of automated sorting lines would be a relatively small cost (Hinkka *et al.*, 2018). Additional costs of removing hard parts have been estimated as 0.10 €/kg (Heikkilä *et al.*, 2019c). Washing, if needed as pre-processing increase the costs significantly (Hinkka *et al.*, 2018). The estimated costs of fibre mechanical recycling was 0.52-0.64 €/kg (Heikkilä *et al.*, 2021). In case of fibre mechanical recycling, nearly half of the costs were labour costs, a quarter of investment costs, and one fifth of energy costs (Heikkilä *et al.*, 2019c).

Chemical recycling requires expensive investments because of required advanced technology and large size of feasible facilities (Heikkilä *et al.*, 2019c). The estimated costs of fibre mechanical recycling were 0.95-1.07 €/kg (Heikkilä *et al.*, 2021). In case of chemical recycling (of cotton) nearly half of the costs are investment costs, over 20% chemical costs, less than 20% energy costs, less than 10% labour costs and rest are the costs of premises and maintenance (Heikkilä *et al.*, 2019c). The utilization rate affects significantly to the costs and the previous estimation is based on the 80% utilization rate, as well as continuous three shift operation (Heikkilä *et al.*, 2021; Heikkilä *et al.*, 2019c).

Thermo-mechanical recycling may apply existing technology and facilities. Therefore, Heikkilä *et al.* (2021) have not included the investment costs in the estimation of the costs of thermo-mechanical recycling. The costs of thermo-mechanical recycling for composites have been estimated as 1.22-1.52 €/kg (depending on the required quality), half of which are compounding costs (Heikkilä *et al.*, 2021). The estimated costs of thermo-mechanical recycling for plastic products are 1.07 €/kg, including some virgin plastics to get sufficient quality.

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[48] Telaketju projects www.telaketju.fi; Telaketju-Tekes https://cris.vtt.fi/en/projects/the-chain-on-sorting-and-exploitation-of-textile-waste-tekstiilie ; Telaketju 2 https://cris.vtt.fi/en/projects/liiketoimintaa-tekstiilien-kiertotaloudesta-business-from-circula

Recycling costs calculations differ based on how they are done and what is included. The estimated costs of different recycling methods with technologies available and/or currently studied in Finland as described above are summarized in Table 3. Furthermore, estimation of the costs of developing technologies includes many uncertainties. McKinsey (2022) report contains summary of estimated costs at maturity for range of processes, summarised in Table 4.

Table 3 Calculated costs of recycling processes and incineration in Finland, estimated at 2020 (Heikkilä et al.*, 2019c & 2021).*

Process	**Cost €/kg**
Collecting and sorting – needed in most cases	0.43
Mechanical pre-processing – needed before all recycling processes	0.3 – 0.42
Fibre mechanical recycling	0.22
Chemical recycling of cotton rich textiles (cellulose carbamate process)	0.65
Thermo-mechanical recycling to composites	1.22
Thermo-mechanical recycling to plastic products	1.07
Energy recovery	0.09

Table 4 Estimated costs at maturity for range of recycling processes (McKinsey, 2022).

Method		**Total costs €/kg**	**Potential price**
Mechanical	Open-loop / downcycling	0.28-0.56	Low
	Traditional closed loop	0.5-0.9	Medium
	Soft closed loop	3-3.9	Very high
Thermo-mechanical		0.5-0.95	High
Chemical (polymer)	Pulping	1.57-2.6	High
	Solvent based	0.95-1.5	High
Chemical (monomer)	Methanolysis	1.2-2.3	High
	Glycolysis	1.15-2.2	High

Different recycling methods are not (totally) replaceable with each other, but they have their strengths and weaknesses, as shown in the results of SWOT analysis in this document (Chapter 7.1). Some of the methods are also applicable for only certain materials, so different methods are needed to cover the processing of all different discarded textiles. Therefore, the direct comparison of costs of different recycling methods is not meaningful as such. However, in cases when they are replaceable, the comparison is reasonable. For example, if the (lower) quality of mechanically recycled cotton is sufficient, it is more feasible than chemical recycling. Fibre mechanical recycling has lower costs, requires less investments, and has less environmental impact. On the other hand, chemical recycling can offer improved quality of fibre with higher, but possibly competitive costs.

7 Model for Sustainable Value Retention in Textile Circularity

In principle almost everything can be recycled using various chemical processes in lab scale, however, these processes are not necessarily sustainable either from environmental or economical point of view. Sometimes incineration may be better option from environmentally point of view than using any means necessary to recycle some challenging materials. Furthermore, scaling up and commercialization cannot be expected for economically non-feasible processes, regardless of how good they are from environment point of view.

7.1 Comparison of Textile Recycling Methods

Within SWOT analyses we have considered different recycling technologies from different points of view input and output materials, processability and technology points of view. We noticed that there are some things that are true for all recycling methods. Regarding opportunities, for example, quality processability and quality of output materials can improve in all cases by improving by using pre-consumer materials compared to post-consumer materials and by improving sorting quality via accurate identification. Furthermore, economics can be improved regardless of the technology by ensuring sufficient flow of high-quality input materials, for example, by efficient collection and automated sorting technologies. And threads in all cases include low prices of corresponding and competing virgin fibres,

SWOT analysis for fibre mechanical, thermo-mechanical and chemical recycling for cellulosics (via dissolution) and synthetics (via repolymerization) is shown in Table 5. It should be noted that all these recycling method categories include multiple processing options and also processing lines/facilities differ. SWOT is therefore done in general level and cannot be generalized to all processes under each category. Information is collected from technology review work reported in earlier Chapters, from Telavalue consortium and Tela3-STB[49], and using earlier technology reviews by Duhoux *et al.* (2021) and McKinsey (2022).

Table 5 Strengths, weaknesses, opportunities, and threats (SWOT) related to textile recycling methods.

Fibre mechanical textile recycling	
Strengths	**Weaknesses**
• Suitability for wide range of fibres, both monomaterials of different kinds and blends alike. • Only option for natural fibres such as cotton to preserve their macroscopic/ physical structure. • High quality output materials can be easily obtained from pre-consumer materials, and relatively easily obtained from known, clean, fixed material streams. • Possibility to easily blend fibres, e.g., recycled with virgin if needed with post-consumer materials. • Flexibility of the process - it can be adjusted for different products by changing amount of opening. • High TRL level: machine dealers, commercial actors and mechanically recycled textile materials commercially available. • Automation for removing hard parts may be included in process. • Low investment and processing costs compared to other methods, processing smaller batch sizes is possible.	• Fibre quality, length, and strength cannot be restored, this alone is not a circular solution in long term. • Further reduction of fibre length and strength as well as damages of fibre surfaces occur during mechanical processing. • Suitable for staple fibres production only • If used for mixed, unsorted material, properties and appearance of secondary raw material cannot be controlled, e.g., colour is greyish mixture. • Even if colour-sorted materials used, other colour fibres may easily remain in machinery and cause colour contamination. • Textiles containing elastane may be difficult to process, especially if content is high, acceptable level vary between lines/facilities. • Inhomogeneity of output fibre lengths since there is no separation of shorter and longer fibres, except fines.

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[49] Telavalue consortium workshop 5.10.2022 and commenting rounds during project, Tela3-STB commenting round in Spring 2023

• Simple process principle, personnel skills not as crucial as, e.g., in chemical recycling. • Relatively simple process based on physical processing only, leading to lower LCA impact compared to other textile recycling processes.	• Quality of output fibres vary with inhomogeneity of material including, e.g., mixed fabric types (woven – knitted, loose – tight). • Process (and machinery) may need to be adjusted based on the type of fibre and textile structure in order to get best output quality. • Relatively high fibre loss, when aiming for spinning quality fibres and when processing small batches.
Opportunities	**Threats**
• Colours and finishes in fibres may be preserved, in secondary raw material, if raw material feeds known and kept separate. • Processes already existing for pre-consumer and even industrial post-consumer materials. • Multiple feasible uses for recycled fibres - options from paper to nonwovens and yarns depending on fibre quality. • Applying eco-design principles for better recyclability (e.g., easy removal of accessories) could increase the amount of textiles suitable for fibre mechanical recycling. • Side-stream, i.e., dust-like fibre residues, may be fed to other recycling processes as input. • Relatively small factory size can be economically feasible, i.e., investments are moderate.	• Hygiene issues related to post-consumer materials and finishing agents in fibres may restrict use in certain products and/or reduce consumer acceptance • Not suitable for layered textiles unless solutions for separation of layers solved • System itself is sensitive to hard parts, and especially yarn spinning process following the fibre mechanical recycling are also sensitive to residual hard parts and unopened pieces of yarns and fabrics. • Colour might be an issue in some applications. • Quality of input material and quality of sorting has significant effect on quality, and therefore reproducibility is challenging especially with post-consumer textiles. • No established local value chain yet for post-consumer textile waste, actors far apart. • Scarcity of homogeneous streams (not only composition, but also colour and fabric structure). • Chemical content of old textile products, and contaminated products may conflict with REACH.
Thermo-mechanical textile recycling for synthetics via melting	
Strengths	**Weaknesses**
• Possibility to restore fibre length, and possibly also strength. • Hygiene problems solved by high temperature. • Can be used to produce staple fibres and filaments. • Small amounts of impurities may be acceptable. • Same polymer from different products may be combined into the same process. • Known process - similar processes already available for other plastics, e.g., rPET from bottles. • Cost-efficient and efficient process - relatively small factory size can be economically feasible. • Lower investment costs than in chemical recycling and use of existing equipment is possible.	• In many cases processes are suitable for monomaterials only, mixed materials, like most textiles, are challenging. • Processing in high temperature causes degradation of polymers, this alone is not a circular solution in a long term. • Inhomogeneous fractions may lead to lowered quality, especially seen as wide polymer length distribution. • Impurities in textiles may affect thermal processes, e.g., by causing new reactions. • Additives may be needed to preserve quality. • Not much emissions - environmental impact of processes higher compared to fibre mechanical, but generally lower compared to chemical recycling.

Opportunities	**Threats**
• Colours in fibres may be preserved in secondary raw material • Processes same as in plastic recycling, it may be possible to combining some waste flows • Waste valorisation e.g., by chain lengtheners and compatibilizers is possible • Some solutions are in some extent suitable for blends and challenging textile fractions (e.g., coated and laminated textiles) and also some hard parts (e.g., plastic buttons) • Recycling of technical textile materials into high quality plastic and composite materials • Replacement of virgin materials possible	• Monomaterial streams difficult to find, textile labelling system, for example, does not differentiate polyester types from each other, but their thermal processability might have significant differences • Incompatible polymers cause quality problems especially in melt-spinning, i.e., fibre-to-fibre thermo-mechanical recycling • Release of harmful volatile chemicals possible during heat treatment, occupation health and safety needs to be considered • If used to make composite fibres/materials, recyclability of those secondary raw materials may be challenging • Even though process similar to those used by recycling of other plastics products, specialized equipment may be needed for textile waste
Chemical recycling of cellulose-based textiles via dissolution	
Strengths	**Weaknesses**
• Possibility to restore quality (length & strength) to be equal or higher compared to virgin materials depending on used process enabling multiple cycles. • Hygiene problems solved by chemical treatment, and also certain impurities can be removed. • Fabric structure (knitted, woven, nonwoven) does not affect the recyclability of material. • Both pre- and post-consumer materials can be used easily. • Processes similar as in man-made fibre manufacturing, possibility to mix waste flow with virgin cellulose and other cellulose containing waste flow. • Fully cellulosic and biodegradable output products.	• There are environmental impacts associated with these processes, e.g., due to use of solvents and water. • Removal of other fibres and insoluble matter may increase costs of process. • Polymer length of cellulose is reduced in the process and thus recyclability of output products repeatedly is reduced. • Existing MMCF processes require adjustments to accommodate cellulose from recycled textiles, e.g. cleaning and viscosity control, mixing of raw materials from other origins • Sensitive to the variations in supply of discarded textiles and the demand of the output product, because of large investments.
Opportunities	**Threats**
• Decolouration, bleaching and finish removal may be included into the process, possibility to dye in any colours afterwards. • Wide range of processes, viscose and lyocell like processes, leading to slightly different fibre properties suitable for different applications. • Residues of chemicals could improve chemical properties of regenerated cotton fibres. • Chemically recycled cotton better choice than virgin cotton.	• Impurities may affect chemical processes e.g. via catalytic reactions. • High processing costs: Economically feasible factory size is large requiring large investments, and large sites need transportation of waste from longer distances. • Profitability is highly dependent on utilization rate, and high continuous long-term utilization rate possibly cannot be guaranteed easily. • Relatively low price of new viscose fibres can weaken profitability.

Chemical recycling of synthetic via repolymerization	
Strengths	**Weaknesses**
• Possibility to restore purity and quality of polymer properties and fibre properties to be equal or higher to virgin materials. • Hygiene problems solved by chemical treatment. • Alloy materials and dirty fractions can be processed with some of these technologies. • Fully circular method enabling continuous circulation.	• Environmental impacts of processes expected to be high due to used energy, chemicals, solvents and water. • Separate purification steps may be needed in some processes when mixed materials are used. • This group includes processes that are not economically viable.
Opportunities	**Threats**
• Option for degraded and contaminated polymers as well as materials that cannot be recycled by fibre mechanical or thermo-mechanical means. • Due to the selectivity of depolymerisation reactions, it is possible to recover basically all synthetic polymers found in textile waste, including blended fabrics, laminated and coated material. • Processes are principally the same that are used for plastics recycling, which is advantage in knowledge and technology development. • Separation of fibre blends may be combined to recycling process since chemical reactions are molecule specific. • Biochemical processes, e.g., using enzymes, provide more sustainable alternatives for chemical processes.	• Great variety of synthetic material types and processes and mixes with other synthetics as well as with natural fibres. • Impurities may affect chemical processes. • Economically feasible factory size is large requiring large investments and continuous flows of materials to be recycled. • Low prices of primary raw materials and new PET manufacturing can weaken profitability. • Unknown environmental impacts.

Comparison of the four main fibre-to-fibre recycling technology types in included in Table 6. We have evaluated performance of fibre mechanical, thermo-mechanical, chemical recycling of cellulosics, and via dissolution and chemical recycling of synthetics via depolymerization within several factor using four tier scale: *** Very good / Positive effect, **Good / Somewhat positive effect, * Ok / None or slightly positive effect, † Negative score / effect. Evaluation is suggestive and based on literature review included in this report and views on Telavalue project group. Comparison is made between recycling methods and fibres obtained, not compared with primary fibres. Since there are multiple processes included into each category, this comparison is generalizing and cannot be considered exact truth applicable to all cases. Evaluation is subjective view of Telavalue partners, not based on specific calculations.

Table 6 Comparison of textile recycling methods. *** Very good / Positive effect, **Good / Somewhat positive effect, * Ok / None or slightly positive effect, † Negative score / effect.

Factor	**Fibre mechanical**	**Thermo-mechanical**	**Chemical cellulosics**	**Chemical synthetics**
Restoration of fibre quality – including fibre length and strength, and polymer quality	†	*	**	***
Suitability of technology on fibre blends	**	*	*	*
Tolerance of process to impurities such as finishing's, chemicals, dirt and other contaminants	***	*	*	**
Suitability of output materials to further textile processes	†	**	***	***
Possibility to use output materials to other than textile products	**	**	**	***
Value gain, i.e. comparison of value of input and output materials	*	*	**	*
Easiness to obtain economically feasible scale	***	**	*	*

7.2 Model for Sustainable Textile Circularity

There has been some attempt to quantification of different recycling options. Muthu *et al.* (2012), for example, have presented concept and quantification form *Recyclability Potential Index* (RPI) for textile fibres. Suggested RPI is considering both environmental and economic gains from the recycling process, thus it is a sum of *Environmental gain* and *Economic gain*. Environmental gain takes into account saving of potential resources, environmental impact caused by production of virgin fibres and those caused by landfilling, and environmental benefit gained out of recycling versus incineration. Economic gain is obtained by comparing price of recycled fibre to the price of virgin fibre. Highest RPIs were obtained by PES, PP and PE, which were followed by acrylic, CO, wool, viscose and PA6 and PA66 in this order.

RPI system by Muthu *et al.* (2012) is interesting view on recycling from technical and economical point of view, however, it have some shortcomings. Firstly, it focuses on pure fractions, while large portion of recyclable textiles are blends, and it does not take into account the origin of textile waste – is it unused/high quality or used/lowered quality. It, for example, calculates *environmental benefit gained out of recycling versus incineration* (X_4) based on energy conservation obtained by substituting primary raw materials by secondary raw materials, not including on energy used for recycling itself. And these energy conservation values were obtained from literature originated from 1990's. Furthermore, it calculates economic benefit based on fibre prices, not taking into account the costs of textile waste recovery, valorisation and recycling processed. Concept for calculation of recyclability potential considering environmental and economical aspects is interesting, however, true recyclability of specific material is more complex puzzle to be solved, and more factors needs to be considered. Furthermore, such model focus only on recycling, however, textile circularity is much more than just recycling, and discarded textiles should be kept in re-use cycles as long as possible before recycling.

Within Telaketju projects and network we have built common understanding of sustainable circular textile system. In this modelling work look how to obtain value but also looking where and how much processing is needed, since all processing increases costs and environmental impacts. Figure 14 illustrates relative quality and value of products and materials in different stages of textile recovery and recycling processing stages in fibre-to-fibre recycling. Directive changes and difference is quality and value are shown as y-axis, and amount of processing linked to increased costs and environmental impacts is shown in x-axis. In principle any kind of processing increases the costs and environmental impact at some extent but can be done if increased value will justify the cost and impacts.

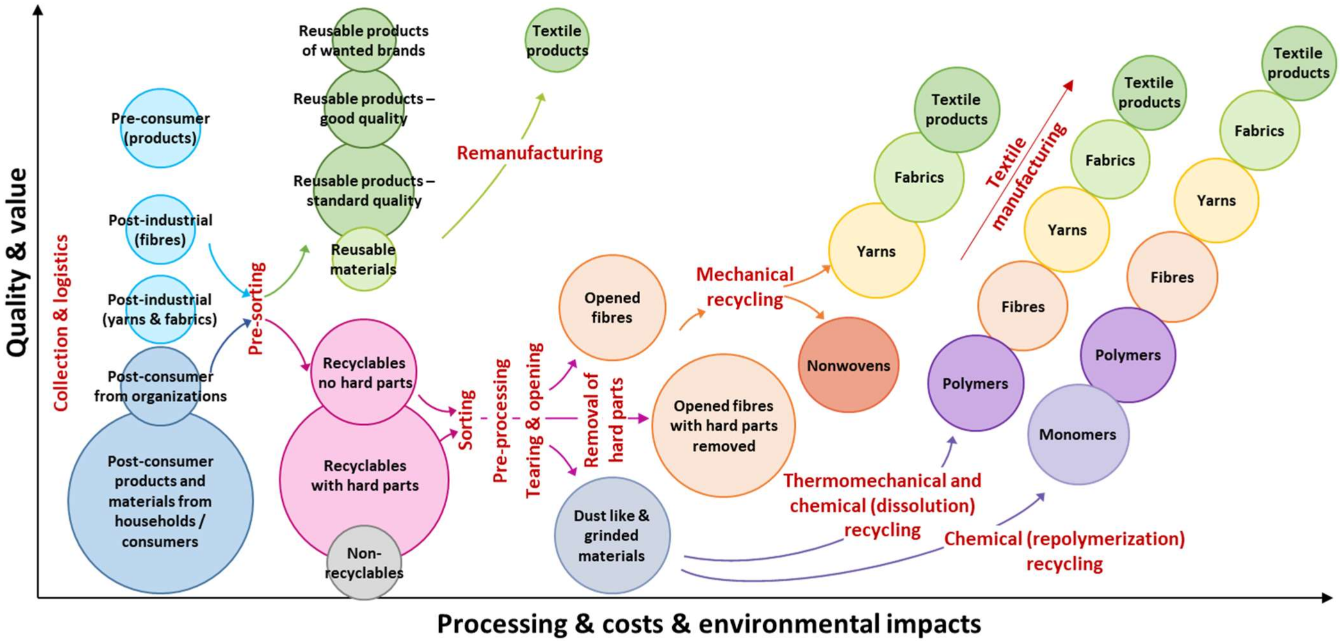

Figure 14 Directive effects of different processes of textile recovery, pre-processing and fibre-to-fibre recycling options on quality and value of fibres (y-axis) and costs and environmental impacts (x-axis).

Waste fractions. Different textile (waste) fractions are shown in left. Unsold products are valued highest in the illustration due to quality, which is not reduced. Of course, unsold items may also be a problem and cause expenses, if they cannot be sold or used as products (e.g., police or army uniforms), or they can be gems, if they just have been offered into wrong markets and are attractive to someone/somewhere else. Main question is, can these items still be used somehow.

Other pre-consumer waste fractions have slightly lower value, side-stream fibres can be considered slightly higher in value, since they do not require that much processing to be used in textile processing than for example yarn and fabric wastes. From pre-consumer waste fractions coming from organizations can be considered to be more valuable compared to household textile waste since even though those are worn, their composition and cleanliness are often known, and there are larger volumes of specific materials available. In this simplified illustration they are all located in same point in x-axis, but collecting and transfer processes may of course vary and in these costs vary case by case. Unnecessary transportation of mixed, low value textile waste fractions should be avoided.

Pre-sorting. First process included in this model is pre-sorting since as a results of this stage fractions with very different value can be obtained. Main categories are re-usables, recyclables, and non-recyclables. Reusables are utilized again as products or as raw materials for remanufacturing. Recyclables contain all materials which are suitable for recycling processes. Unfortunately, textile system will contain also nonrecyclables (or reject).

Textiles are materials sensitive to moisture, dirt, smells, microbiological contaminants etc. Contaminated products should be removed from textile flows as early as possible, so that contaminants do not spoil more materials. In addition, nonrecyclable here should be considered to contain those materials recycling of which is not possible and /or environmentally and economically feasible, at least not at the moment. Furthermore, if the is no capacity available for recycling i.e., no market demand for certain fraction, it can be considered as non-recyclable. Keeping non-recyclables in the process, transporting them into sorting phase for example, is futile.

Like discussed earlier in this report, there are some recycling options also for this nonrecyclables, but those are left out from this model focusing on fibre-to-fibre processes. In the future as designing for circularity increases and waste valorisation and recycling processes are developed further, this fraction should be reducing.

Reusables. The reusables contain highly valued products from wanted brands and other good quality clothes suitable for second hand markets. Relative amount of these is quite small, but demand for these is already high. In many cases these find their way from used to used also without going into collection and pre-sorting, directly from consumer to consumer or via second hand actors.

Standard quality reusable items are quite large fraction of products. This refers to products that may show signs of wear and laundry cycles, but are clean, unbroken, visually attractive, and usable in all means. These may be cycled via reuse centres and other non-profit actors like charities as well as commercial second-hand stores. It has been discussed in public that currently very low-quality products are 'dumped' from Europe to developing markets such as Africa. In this optimal system such low quality products will be sorted into recyclables, since first world countries should not transfer their waste problem to others but utilize those as valuable raw materials.

The fourth group of reusables are products containing reusable materials, especially fabrics. These can be raw materials for handicraft hobbyist, but also valuable and highly sought raw materials for small businesses as well. They are valued in these co-ordinates lower than products that are reusable as such, since they would need remanufacturing process until they can achieve the highest level of quality and value as a product.

Recyclables. Recyclables materials will go to material sorting. In Figure 14 we have taken out one small fractions from the rest with higher relative value. That is products that do not contain hard parts such as buttons and zippers, which include most home textiles like towels, bed sheets and tablecloths, but also clothing items such as tricot products and other knitwear. Division has been made since processing following the sorting is simpler for those materials not requiring hard parts removed, and furthermore since residues of such hard parts may cause harm in future processing include spinning or even safety risk, value of these materials is lower. Opening and tearing lines without separation of hard parts are simpler and those have been used for industrial wastes for a long time already. While newer commercial lines contain this removal steps, many recycling operator also has older machinery- without that option, and thus, manual or machine aided separate hard parts removal steps may be needed adding cost of process.

Sorting. Sorting is typically done based on fibre type, and sometimes also by colour and fabric structure especially in case of fibre mechanical recycling. Automated sorting is more cost efficient and can be more accurate in case of fibre blends, however, automated sorting has its drawbacks especially if its identification is based on surface NIR only. Also pre-sorting affect the efficacy of sorting and quality and value of materials coming out of it. In the future identification of quality of fibre raw materials should be added.

Mechanical opening and tearing. As explained in Chapter 3 textile recycling starts by mechanical process even if material would go to thermo-mechanical or chemical processing. Quality of fibres obtained from opening process without hard parts removal can be expected to be in general slightly higher than the rest of fibres, since processing lines are shorter and process gentler. In addition to fibres of different lengths also other types of materials can be obtained, which are suitable raw material for thermo-mechanical and chemical recycling processes. This category include, at least, grinded materials, pieces containing unopened textile structures and dust like fibres, side-stream of mechanical process. If target is fibre raw materials recycling, target of mechanical pre-processing may be from the beginning grinding instead of obtained fibres. In this case market value may be identical to mechanically recycled fibres, but in this illustration, it has located lower within y-axis related to fibre, since it requires more processing before returning into textile product.

Recycling. Textiles textile can end up back into textiles via fibre mechanical recycling or via raw materials recycling. Since fibre quality cannot be restored in fibre mechanical recycling textile product is valued slightly lower compared to those obtained via fibre raw materials recycling. Processing and cost of higher quality products obtained with other fibre-to-fibre recycling technologies are, however, higher. This is the difficult part of the optimization of the system – when to go to methods that can restore quality and when fibre mechanical route provides better option with sufficient quality. Acceptable costs are more easily determined by markets, but as long as sufficient LCA data is not available, acceptable environmental costs are more difficult to define.

Illustration shown in Figure 14 is missing some dimensions related to original quality (fibre type and fibre length) on possible utilization route of specific textile waste and value of obtained materials. Pure materials, such as 100% cotton or 100% PES, have higher value than blends as discussed in Chapter 6.2, while separation and identification of these fractions may increase costs. Especially in case fibre mechanical recycling the length of fibres obtained from tearing and opening determines the possible uses of them as described in Chapter 3. That dimension is illustrated separately in Figure 15.

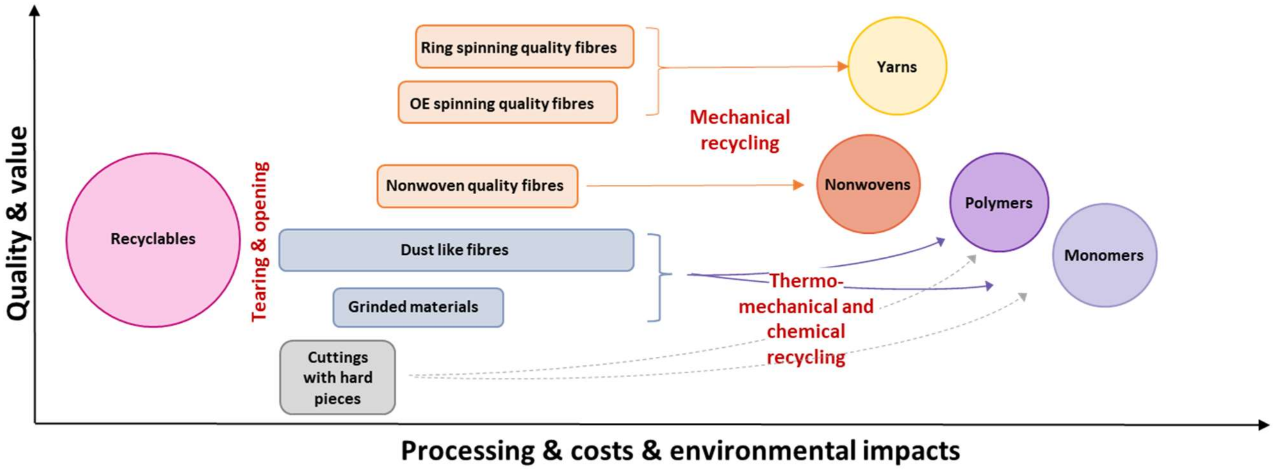

Figure 15 Effect of fibre length on processability and value.

Within Telaketju projects and network we have built common understanding of sustainable circular textile system. Principle of such of optimized textile cycling model is simple: based on the quality and value of product and its materials, most sustainable route should be selected to achieve valuable product or material. Circularity can be achieved when inputs and outputs of the system are minimized, and product and materials cycling is maximized. In practise this is not simple, since technical quality is not easy to determine, value depends on many factors, and sustainability also has several components, social, environmental, and economical, from which especially environmental impacts and processing costs and demand of different types of recycled fibres should be considered when thinking of textile cycles in Europe. So, in other words, best possible value should be aimed in economically and ecologically feasible way. System is also dynamic, as textile waste flows are not constant in quality and quantity. In near future processes are developed, new actors will be coming into ecosystem for all stages of the value chain. Processing and transporting materials, especially low materials, needs to be justifiable.

8 Summary and Conclusions

This report was written part of Telavalue project and contains outcome of activities related to technology review of textile technologies and model for sustainable textile cycles. In the beginning we give an overview of circular textile system (Chapters 1 and 2), but then technology review focuses on textile recycling only (Chapters 3-6). In model for sustainable textile circularity (Chapter 7) compare recycling routes in general level using SWOT analysis and then we again look textile system with wider scope, since extended life-spans and reuse of textile products should be prioritized in circular economy.

Different recycling routes have some principal differences. Fibre mechanical recycling is the simplest method but cannot restore the fibre quality. Restoration of quality in terms of fibre length and strength require going into fibre raw materials recycling in polymer or monomer level. Deeper we go into structure, more processing is needed, and thus more costs and environmental impacts are to be expected.

Recycling technologies have their inherent strengths and weaknesses. Fibre mechanical recycling is most suitable for fibre blends and tolerant for impurities from processing point of view, but of course these might have an effect on quality of output fibres and their suitability on textile and clothing applications. Blends and impurities may be more of a challenge in other recycling methods, while output fibres are more suitable for high value applications. At the moment, the best value gain seems to be on chemical recycling of cellulosic materials, but with technology developments and investments as well as extended availability of specific input materials in the future hopefully improves value gain of all recycling options. The main principle of sustainable textile circulation can be stated is way that discarded textiles should be utilized in highest value application its quality and condition permit with least amount of processing. Such approach enables cascading loops where re-use as product, or as material, could be cover one or more cycles, followed by recycling, which also may consist of several stages, first fibre mechanical and if/when fibre quality requires restoration, taken into fibre raw materials recycling.

In optimized system multiple factors needs to be taking into account for determining best route for each textile material batch. We need to be able to determine not just composition, but also quality of input materials. More detailed knowledge about environmental and social impacts is needed. Economics of recycling can be expected to be fluctuating system, since prices of primary raw materials vary, input material flows are not stabile especially in case of post-consumer materials, and new actors and infrastructure are expected to be built to Europe as EU member states are getting ready for utilization of textile waste collection of which needs to be started by 2025. We also need digital tools for gathering information needed for this multi-variable optimization challenge. Further research activities, especially EU project tExtended – Knowledge based Framework for Extended Textile Circularity (Horizon Europe Programme Grant Agreement 101091575) will be tackling this challenge.

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