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Review

White Paper on Textile Fibre Recycling Technologies

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Abstract: As both governments and customers push for sustainable and recyclable textile products, textile companies will have to change their linear business model to a circular one. The aim of the present work is to help these companies take action by providing an update of the state-of-the-art of textile recycling technologies. Extensive desktop research was performed in order to prepare an overview of existing textile recycling technologies, their current state, and projected developments, also including facilitating technologies for sorting and disintegration of textile products, as well as virtual platforms that connect stakeholders and inform consumers.

Keywords: textile recycling; fibre-to-fibre recycling; textile sorting; textile disassembly; digital textile platforms

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Citation: Stubbe, B.; Van Vrekhem, S.; Huysman, S.; Tilkin, R.G.; De Schrijver, I.; Vanneste, M. White Paper on Textile Fibre Recycling Technologies. *Sustainability* **2024**, *16*, 618. https://doi.org/10.3390/su16020618

Academic Editors: Andrzej Pacana and Dominika Siwiec

Received: 15 November 2023
Revised: 21 December 2023
Accepted: 26 December 2023
Published: 10 January 2024

1. Introduction

In the European Union (EU), about 5.8 million tonnes of textiles are discarded every year, approximately 11–12 kg per person [1]. The consumption of textiles, which continues to grow, accounts, on average, for the fourth highest negative impact on the environment and climate change, and third highest for water and land use from a global life cycle perspective [2]. The origins of these negative impacts can be traced back to a linear model that is prevalent in the textile industry and is marked by low rates of (re)use, repair, and fibre-to-fibre recycling. Often, quality, durability, and recyclability in the design and manufacturing of textile products are neglected as priorities.

To help overcome these shortcomings, reduce the environmental footprint of textiles throughout their life cycle, increase the sector's resilience and competitiveness, and ensure the retention of the value of textiles in the economy for as long as possible, the European Commission approved the 'EU Strategy for Sustainable and Circular Textiles' in March 2022. The Commission's 2030 Vision for Textiles is that: (i) All textile products placed on the EU market are durable, repairable, and recyclable, to a great extent made of recycled fibres, free of hazardous substances, produced with respect to social rights and the environment. (ii) "Fast fashion is out of fashion," and consumers benefit longer from high-quality, affordable textiles, and (iii) profitable re-use and repair services are widely available. (iv) The textile sector is competitive, resilient, and innovative, with producers taking responsibility for their products along the value chain and with sufficient capacities for innovative fibre-to-fibre recycling and minimal incineration and landfilling.

Textile companies will have to adapt their linear business model to a circular model, not only to fulfil the requirements set forth in the EU strategy, but also due to the growing demand of customers for sustainable and recyclable textile products. Today, less than 1% of textile waste is fibre-to-fibre recycled. Nevertheless, the past years' fibre-to-fibre recycling technologies have been developed and scaled and, many of them are expected to reach industrial/commercial scale within 5 years/by 2030 [3]. This is also illustrated by the many initiatives listed in the current report. It has even been estimated that, once the new infrastructure is established, the different recycling technologies combined have the potential to recycle 70% of Europe's textile waste in a closed-loop manner [4]. Despite these technical innovations, there are still significant challenges to overcome, especially for post-consumer textile recycling.

The growing interest and importance in the field of textile recycling is also evident from the increasing number of publications on the subject. The existing literature on textile recycling covers various aspects, including classification, recycling technologies, environmental impacts and challenges, implementation of circular business models, supply and demand of recyclable textiles, etc. [5–9]. However, the variety of materials and structural complexity of textiles, coupled with rapid technological evolution, adds to the challenge of comprehending recycling processes and their environmental impact [10,11]. Therefore, the current paper intends to provide an update of previous reports and deliver a comprehensive yet accessible overview of the current state of textile recycling [9,12–14]. An effort was made to offer a holistic perspective by presenting a brief exploration of the different types of recycling technologies, highlighting key advantages and limitations. It includes a compilation of companies involved in technology development and actual recycling operations, their current production capacities, and anticipated future capacities, providing a practical understanding of the industry landscape. Additionally, the inclusion of key facilitating technologies and virtual platforms offers insights into the broader ecosystem that supports textile recycling. The final aim of this paper is to equip textile companies with a comprehensive understanding of the current state-of-the-art in textile recycling and supporting processes.

Information, comprising details about relevant companies and their present and expected production capacities, was sourced through desktop research (scientific articles, reports, press releases, etc.), direct interactions with companies, and participation in webinars, conferences, and events. While fibre-to-fibre recycling is, of course, preferable, the paper also includes companies/initiatives that have not fully adopted a 100% closed-loop approach but are actively working towards it or express the intention to do so. The geographical focus primarily centres on Europe, although noteworthy initiatives from North America, Asia, and Australia are incorporated as well. In addition to textile recycling processes, the paper also provides insights into key facilitating technologies. Furthermore, it lists virtual platforms that aid companies in connecting with stakeholders and that inform consumers. The eventual goal of this work is to provide relevant information that empowers textile companies to take action and transform to a circular model.

2. Mapping of the Textile Recycling Technologies

Recently, the EN ISO standard "5157 Textiles—Environmental Aspects—Vocabulary" [15] was published to provide a clear and concise vocabulary ensuring more effective communication and understanding. It provides general terms and definitions used in the textile value chain related to environmental and circular economy aspects, including design, production, retail, use and reuse, recycling processes, repair, and disposal. The standard defines recycling as follows: activities to obtain recovered resources for use in a product, excluding energy recovery (3.2.7.7). "Activities to obtain resources" can include activities such as collection (3.2.6.7), transport, sorting, cleaning, reprocessing, etc. Recycling occurs only through activities controlled by one or several organisations. The process can be mechanical, thermo-mechanical, and/or chemical. It does not include the reprocessing into materials intended to be used as fuels or for backfilling operations (Source: ISO/DIS 59004 [16]: —3.5.16, modified—Notes 2, 3, and 4 to entry have been added).

An overview of the categorisation of textile recycling technologies, as defined in the "Study on the technical, regulatory, economic, and environmental effectiveness of textile fibres" by Duhoux et al., is presented in Figure 1. Textile recycling stands out as a primary solution recognised for tackling the issue of textile waste. This approach is complemented by efforts to minimise waste generation, prolong the lifespan of textiles, and foster the growth of the second-hand economy [4,12]. The latter were, however, out of the scope of the current study.

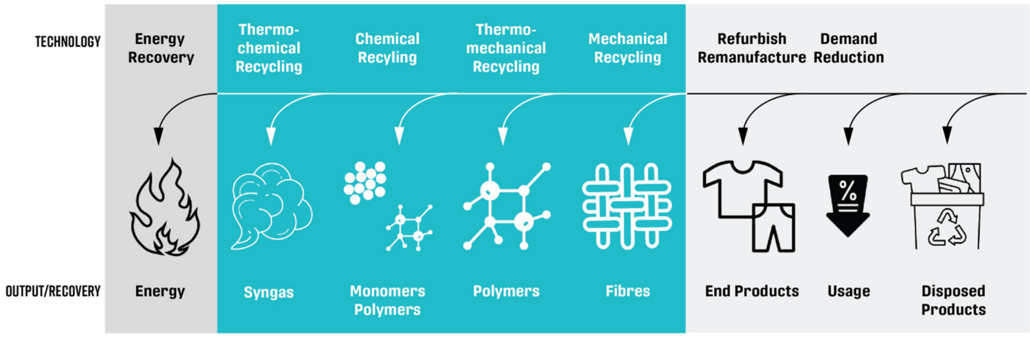

Figure 1. Categorisation of textile recycling technologies alongside other possible solutions to the textile waste problem [4,12].

An overview of the definitions of the textile recycling categories discussed in the current paper is provided in Table 1. For a detailed description of the recycling processes, including input/output, process steps, and (dis)advantages, the reader is referred to the above-mentioned study [12].

Table 1. Overview of the definitions of the different textile recycling categories according to EN ISO 5157:2023 "Textiles, Environmental Aspects, and Vocabulary", and Duhoux et al. [12].

Mechanical recycling	A process, used in a recycling system, based on physical forces, which may be used in isolation for textile or fibre recycling or as pre-processing for thermal or chemical recycling processes.
Thermal recycling	A recycling process based on heating, with the aim to recover either polymers or low-molecular-weight building blocks. Not to be mistaken for thermal recovery, an altogether different process that is not considered a recycling technology by the waste regulation.
Thermo-mechanical recycling	*Process used in a recycling system that melts a polymer, typically employed to permit polymer recycling.*
Thermo-chemical recycling	*Recycling process using partial oxidation reaction of polymers to produce low-molar-mass components or heat to degrade polymers to monomers that can be used as feedstock for the chemical industry, with the exclusion of fuels used for energy production or other combustion or energy recovery processes.*
Chemical recycling	A process using chemical dissolution or chemical reactions, which is employed in polymer or monomer recycling.
Monomer recycling	*System for breaking down polymeric textile materials into their constituent monomers and rebuilding polymeric fibres for new uses.*
Polymer recycling	*System for disassembling used fibres, extracting polymers, and re-spinning them for new uses.*

The different recycling technologies vary in their environmental impact, their ability to maintain or return to virgin quality, their capability to handle contaminations or impurities, etc. Quantitative environmental and economic analyses of the recycling technologies are complicated by a lack of data. Data-sharing challenges arise due to various reasons. Processes at low Technology Readiness Levels (TRL) may render Life Cycle Inventory (LCI) data less relevant, as they can undergo significant changes during further technological development. Additionally, companies may opt to keep certain information confidential to secure ownership of a developing technology. Time constraints further impede the collection of requested data, which may not always be readily available. While values for some recycling technologies are found in the literature, many lack detailed information essential for a comprehensive Life Cycle Assessment (LCA). Duhoux et al. performed qualitative evaluations on key criteria, such as energy, water, and chemical use, as well as process costs. A brief summary of this evaluation is provided in Table 2. For more information, as well as an evaluation of the impact on climate change using either published LCA studies or assessments performed with available LCI data, the reader is referred to the formerly mentioned study [12].

Table 2. Evaluation of the different textile recycling categories with respect to environmental factors, including energy use, water use, chemicals, process costs, ability to return to virgin quality, and ability to handle impurities/contaminations [4,12].

	Mechanical Recycling	**Thermo-Mechanical Recycling**	**Chemical Polymer Recycling**	**Chemical Monomer Recycling [1]**	**Thermo-Chemical Recycling**
Energy use	⚡	⚡⚡	⚡⚡	⚡⚡⚡	⚡⚡⚡⚡
Water use	💧	💧💧	💧💧(💧)	💧💧💧	💧
Chemicals	⚗	⚗⚗	⚗⚗	⚗⚗⚗	⚗
Process costs	🏷	🏷🏷	🏷🏷	🏷🏷🏷	🏷🏷 [2]
Ability to return to virgin quality	Low	Medium	Medium/high	High	High
Ability to handle impurities/contaminations	Low	Low	Medium	High	High

[1] Reduced impact and process costs for monomer recycling of PA6 compared to PET. [2] Limited information available.

Unfortunately, technologies that can achieve virgin quality typically have a higher impact on the environment. A long-term solution is, therefore, likely to require a variety of recycling technologies, which may even work together to achieve synergies. For instance, the non-spinnable fluff and dust from mechanical recycling might be recycled via a chemical process. An update on the status and projected developments of the different recycling technologies is provided in the next section.

3. Current Status and Projected Developments of Recycling Technology Processes

Although currently less than 1% of textile waste is fibre-to-fibre recycled, the forecast for the coming years is quite positive, according to the latest publications. As also confirmed by the current report, recycling technologies have evolved significantly and many of them are expected to reach industrial/commercial scale soon [3,4]. This, incidentally, is also promoted by the many partnerships forged between different companies within the value chain. Nevertheless, there are still significant challenges to overcome, especially for post-consumer textile recycling. A recent study on the supply and demand of recyclable textiles in the Nordic countries has concluded that although the anticipated sorting capacity in the Nordics is expected to handle a significant portion of total recyclable textile volumes, there exists surplus recycling capacity for certain fibres and insufficient capacity for others. The need for collaboration among stakeholders was suggested to overcome the notable imbalances between supply and demand at the country level [8].

In the subsections below, an update of the status and projected developments of each of the above-mentioned textile recycling technologies is provided. The main (technical) barriers are addressed as well, while some solutions and their current state of progress are discussed in the section "Facilitating Technologies". To date, the most advanced recycling facilities are for cotton pulping for man-made cellulosic fibre (MMCF) production.

3.1. Mechanical Recycling

Mechanical recycling via unravelling/garneting/tearing or cutting/grinding is a process based on physical forces, and the general process is illustrated in Figure 2 [12]. It is already a well-established technology (TRL, 9) in the market with a wide range of production capacities, ranging from 5000 to 36,000 tonnes per year. Basically, all kinds of textile waste, material types (natural, synthetic, or blends), types of textile products (yarns, fabrics, used garments, or carpets), and structures (knitted, woven, or non-woven) can be processed via mechanical recycling. Some technology holders focus on a selection of fibre types, for example, only wool, only cellulose-based fibres (cotton, jute, sisal, flax, kenaf, etc.), or only synthetics (polyester, polyamide, polypropylene, acrylic, etc.), while others process a broad range of materials. In addition, some companies prefer to work with knitwear, others only process production waste, and so on. Additionally, technical fibres, such as aramid and polyimide fibres, can be mechanically recycled. Different kinds of textile waste (in terms of material and product type) typically require adjusted machinery or set-up [12].

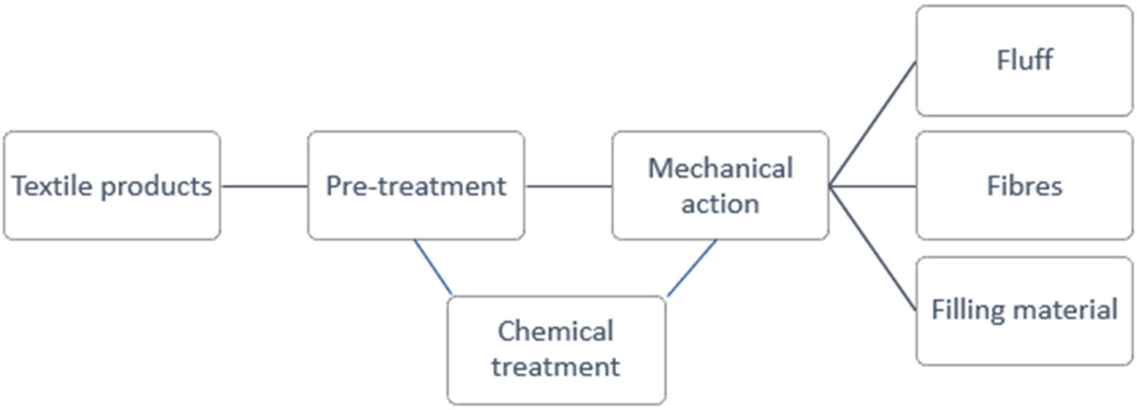

Figure 2. General process scheme for the mechanical recycling of textiles.

Mechanical recycling has many advantages, including the limited investment and space requirements, the low resource consumption, the high variety of materials that can be processed, etc. Nevertheless, reduction of the fibre length of recycled fibres up to 40% compared to virgin fibres is a well-known issue. This complicates closed-loop recycling, as a large portion of the output is un-spinnable fluff, utilised in the non-woven industry for the production of insulation or non-woven materials for the automotive industry, for example. In order to allow fibre-to-fibre recycling, higher-quality fibres can be achieved by blending with virgin fibres (products already on the market), but also via technological innovations.

The recently developed "soft" mechanical recycling technology presented by **Purfi** is "a process that uses a longer production line (upward ten times longer than a traditional shredding line)", combined with a treatment that can better maintain the original fibre length, thereby minimising losses from the subsequent carding and spinning processes [4,17]. Purfi is already operating at full capacity for elastane-free waste and is currently incorporating an elastane removal technology as well [18]. Likewise, **Recover™**'s proprietary technology and cutting-edge machinery for mechanical recycling of cotton results in longer fibres. Recover™ is currently producing recycled cotton fibres from post-industrial, pre-consumer, as well as post-consumer textile waste at the commercial scale. Moreover, they are investing to increase the global recycling capacities, aiming at a capacity of 350,000 tonnes of recycled cotton fibre per year in 2026 [19]. At ITMA 2023, Recover™ has announced their partnership with **Rieter** (supplier of staple fibre-spinning systems) and **Polopiqué** (vertically integrated textile manufacturing company) for the production of textiles with an increased mechanically recycled fibre content [20]. Another innovation for effectively lengthening and strengthening natural fibres is the Clarus® technology developed by **Natural Fibre Welding (NFW)**, which is based on increased intermolecular bonding in natural polymers, as illustrated in Figure 3. Although NFW is currently still operating as a start-up company, they recently acquired funding and are planning to open a larger manufacturing plant [21].

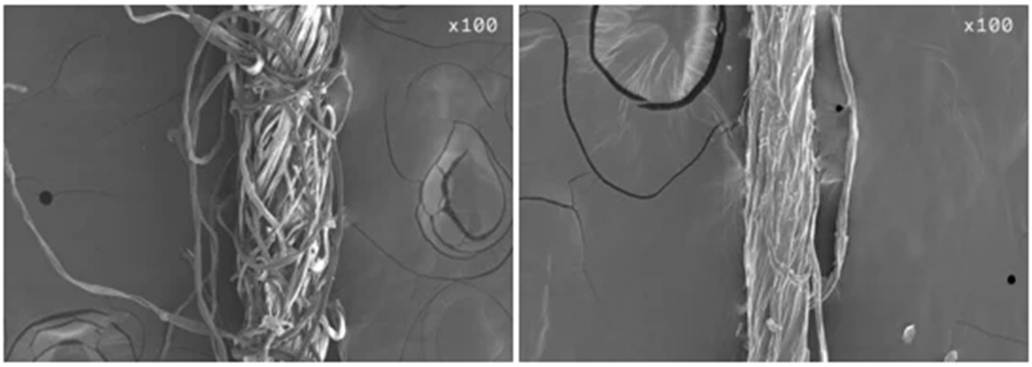

Figure 3. Microscopic image of cotton yarn, lengthwise, before (**left**) and after (**right**) one type of (tuneable) Clarus® fibre welding transformation by NFW [22]. Imparting these new tuneable morphologies gives CLARUS® yarns and fabrics new performance properties of increased durability, enhanced moisture wicking, and even new fabric construction options.

For most recycling processes, but for mechanical recycling in particular, the quality of the output is highly dependent on the quality of the input. This is especially challenging for post-consumer waste, which is a mixture of compositions and colours. In order to obtain high-value output from this type of waste, sorting will be an important pre-treatment step. The topic of textile sorting is discussed further in the section "Facilitating Technologies". The processing of contaminated and coated or laminated textiles via mechanical recycling is another issue being tackled by research initiatives at the moment. A brief overview of developments of treatments for removal of finishings and coatings as well as separation of layers is also presented in the section "Facilitating Technologies".

A (non-exhaustive) list of companies involved in mechanical recycling, as recyclers or technology developers/machine builders, is presented in Table 3 below.

Table 3. Non-exhaustive list of different companies involved in mechanical recycling.

Company	Type	Website
Andritz Laroche (Cours, France)	Technology development	https://www.andritz.com/products-en/nonwoven-textile/textile-recycling-overview-nonwoven-and-textile *(accessed on 5 October 2023)*
Cormatex (Montemurlo, Italy)	Technology development	www.cormatex.it/en *(accessed on 5 October 2023)*
Dell'Orco & Villani SRL (Capalle, Italy)	Technology development	www.dellorco-villani.it/en/ *(accessed on 5 October 2023)*
ALTEX Textil-Recycling GmbH & Co. KG (Gronau, Germany)	Recycling (all kinds of natural, synthetic, and technical fibres)	www.altex.de *(accessed on 5 October 2023)*
Cyclo® (Dhaka, Bangladesh)	Recycling (cotton) and yarn spinning	https://www.cyclofibers.com/ *(accessed on 5 October 2023)*
Derotex NV (Wielsbeke, Belgium)	Recycling (mainly natural fibres)	www.derotex.be *(accessed on 5 October 2023)*
Natural Fiber Welding Clarus (Peoria, IL, USA)	Recycling/material production (natural fibres)	https://clarus.naturalfiberwelding.com/ *(accessed on 5 October 2023)*
Nouvelles Fibres Textiles (Amplepuis, France)	Post-consumer textile sorting and recycling (all kinds of natural and synthetic fibres)	https://www.nouvellesfibrestextiles.com/ *(accessed on 5 October 2023)*
Nova Fides (Montemurlo, Italy)	Recycling (wool)	www.novafides.it *(accessed on 5 October 2023)*
Procotex SA Corporation NV (Dottigniesm, Belgium)	Recycling (all kinds of natural, synthetic, and technical fibres)	https://en.procotex.com/ *(accessed on 5 October 2023)*
Pure Waste® (Helsinki, Finland)	Recycling (cotton) and yarn spinning, garment production	https://purewaste.com/ *(accessed on 5 October 2023)*

Table 3. *Cont.*

Company	Type	Website
Purfi (Waregem, Belgium)	Recycling (all kinds of natural, synthetic, and technical fibres)	https://purfi.com/ (*accessed on 5 October 2023*)
Recover (Banyeres de Mariola, Spain)	Recycling (cotton fibres)	https://recoverfiber.com/ (*accessed on 5 October 2023*)
Rester (Paimio, Finland)	Recycling (cotton, polyester, wool, PP, and blends)	https://rester.fi/en/ (*accessed on 5 October 2023*)
Säntis Textiles (Singapore)	Recycling (cotton), yarn spinning and weaving	https://www.saentis-textiles.com/ (*accessed on 5 October 2023*)
Soex I:CO (Ahrensburg, Germany)	Recycling (all kinds of fibres)	https://www.soex.de/ (*accessed on 5 October 2023*)
TexloopTM RCotTM (Los Angeles, CA, USA)	Recycling (cotton) and yarn spinning	https://circularsystems.com/texloop#texloop-summary (*accessed on 5 October 2023*)
Usha Yarns Limited^{TM} (Chandigarh, India)	Recycling (cotton, wool, viscose, polyester, and blends) and yarn spinning	https://ushayarns.com/ (*accessed on 5 October 2023*)
Vanotex NV (Deinze, Belgium)	Recycling (all kinds of natural and synthetic fibres)	www.vanotex.be (*accessed on 5 October 2023*)
Wolkat (Tilburg, The Netherlands)	Recycling (all kinds of fibres), yarn spinning, and textile production	https://wolkat.com/ (*accessed on 5 October 2023*)

3.2. Thermo-Mechanical Recycling

Thermo-mechanical recycling is a process based on remelting thermoplastic waste materials (see Figure 4) [12]. It is a cost-effective, efficient, and well-known process that can be easily implemented. Although already established at the commercial scale for plastics, such as PET bottles, it is generally still at a demonstration scale for textiles consisting of thermoplastic materials, such as PET, PP, PE, and PLA [4,12]. Nevertheless, several textile companies recycle their production waste internally in a thermo-mechanical way and several yarn producers and plastic recycling companies are effectively recycling post-production and pre-consumer waste, including polyolefin carpets and artificial grass, polyester textiles, etc., using a thermo-mechanical process.

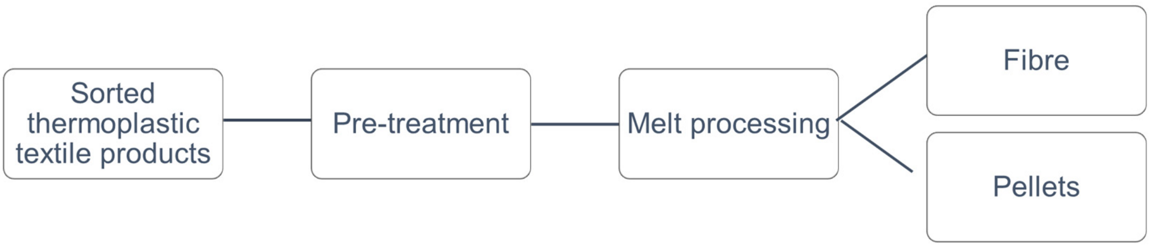

Figure 4. General process scheme for the thermo-mechanical recycling of textiles.

Limitations affecting the technology include viscosity issues for PET (owing to polymer degradation, which is inherent to the thermal process) and stringent feedstock requirements (more than 99% single or compatible polymers required). Therefore, the technology is mainly considered for the recycling of production waste and some specific consumer waste that has been collected in specialised centres [4,12]. Suppliers of thermo-mechanical recycling machinery offer solutions to improve the recyclate quality, such as:

- High-level (vacuum) degassing for removal of volatile contaminants and moisture, as well as viscosity stabilisation for PET.
- High-performance filtration for removal of non-melting particles.
- Solid-state or liquid-state polymerisation units (SSP or LSP) to increase PET's intrinsic viscosity (IV).

The intrinsic viscosity of PET can also be enhanced via the addition of chain extenders. The chemical chain-extending method is widely used for the modification of the IV of

PET because it has a low energy consumption and high efficiency compared to solid-state and melt polycondensation [23]. Several chain extenders are commercially available from companies such as BASF, Sukano, Nexam Chemicals, etc.

To understand how the chain-extending method works, and what the differences are between various chain extender types, some background on the degradation mechanism of rPET is required: during thermo-mechanical recycling, high processing temperatures and the presence of moisture cause polymer chain scission reactions, resulting in vinyl ester and hydroxyl ester end groups, and these degradation pathways produce carboxyl acid end groups [24]. As a result, there is a decrease in the molecular weight, which is associated with a decrease in the intrinsic viscosity. The addition of chain extenders can mitigate the challenges posed by chain scission. Chain extenders are small molecules with at least two functional groups, which are able to react with the end groups of the (broken) polymeric chains. This bonding leads to chain extension and, consequently, an increase in molecular weight and IV [24,25]. Different types of chain extenders exist, each having different functional groups. The classification of functional groups is presented below [24]. For each class, an example of a commercially available additive is provided:

- Epoxy, e.g., Joncryl ADR grades (BASF),
- Isocyanate, e.g., regular PMDI (Bayer Material Science AG),
- Oxazoline, e.g., Nexamite M992000 (Nexam Chemicals)—contains 1,3-phenylene-bis-oxazoline,
- Anhydride, e.g., Nexamite M021200 (Nexam Chemicals)—contains pyromellitic dianhydride,
- Others, e.g., Allnico CBC (DSM)—contains carbonylbiscaprolactam.

A number of different companies involved in thermo-mechanical recycling are listed in Table 4.

Table 4. Non-exhaustive list of different companies involved in thermo-mechanical recycling.

Company	Type	Website
BB Engineering (Remscheid, Germany)	Technology development	https://bbeng.de/en/recycling-2/ *(accessed on 10 October 2023)*
Erema (Ansfelden, Austria)	Technology development	https://www.erema.com/en/pet-fibre-recycling/ *(accessed on 10 October 2023)*
Gneuss (Bad Oeynhausen, Germany)	Technology development	https://www.gneuss.com/en/ *(accessed on 10 October 2023)*
NGR (Feldkirchen an der Donau, Austria)	Technology development	https://www.ngr-world.com/ *(accessed on 10 October 2023)*
Starlinger (Vienna, Austria)	Technology development	https://www.starlinger.com/en/recycling/ *(accessed on 10 October 2023)*
Antex (Girona, Spain)	Fibre production and recycling (polyester)	www.antex.net *(accessed on 10 October 2023)*
DS Fibres (Dendermonde, Belgium)	Fibre production and recycling (polyester and PLA)	www.dstg.com/ds-fibres *(accessed on 10 October 2023)*
LoopLife Polymers—Despriet Gebroeders (Hulshout, Belgium)	Recycling (PLA and polyolefin textile products)	http://www.looplife-polymers.eu/drupal/ https://plasticrecyclingdespriet.be/ *(accessed on 10 October 2023)*
Vanheede Environment Group (Vanheede Polymers and Compounds) (Bruxelles, Belgium)	Waste management and recycling (polyolefin textile products)	https://www.vanheede.com/en/our-treatment/plastic-recycling/ *(accessed on 10 October 2023)*

3.3. Chemical Recycling

Chemical recycling technologies for textiles are rapidly emerging, and many companies are currently constructing pilot and commercial recycling plants for cellulosic as well as synthetic textiles [4]. Chemical technologies are better suited for the treatment of textile material blends compared to (thermo-)mechanical technologies, as the recycled material can be purified and separated to obtain a pure, colourless polymer or monomer of virgin-like quality. On the other hand, these technologies typically require higher energy and water inputs as well as larger scales to ensure economic viability. Generally, chemical recycling companies also request sorted and disassembled or separated input, albeit mostly for economic rather than technical reasons.

A distinction is made between monomer recycling (materials are broken down into their constituent monomers) or polymer recycling (polymers are extracted and kept largely intact). Three categories of technologies were identified [12]:

1. Polymer recycling of cellulosics via pulping,
2. Recycling of synthetic and blended textiles,
3. Monomer recycling of synthetic textiles.

These will be discussed below.

3.3.1. Polymer Recycling of Cellulosic Textiles via Pulping

Cellulosic fibres, such as cotton, can be chemically recycled via a pulping process in which the cellulose is suspended in a liquid that can then be spun into MMCF, as illustrated in Figure 5 [12]. Most of these technologies have already reached a high TRL, especially for pure cotton as feedstock. They are expected to achieve true commercial scale in the next two years. Several companies have established partnerships to accelerate the commercialisation, such as the supply agreements from Lenzing and Birla Cellulose with Renewcell and the strategic partnerships between Lenzing and Södra and between Renewcell and Spinnova. Since 2021, Lenzing and Södra have collaborated on textile recycling, sharing expertise and co-developing methods. The jointly created OnceMore® pulp will serve as a raw material for the production of Lenzing's REFIBRA™ fibres, among other uses [26]. Additionally, Renewcell and Spinnova have revealed plans to introduce a new fibre production concept, merging the patented technologies of both companies; specifically, the CIRCULOSE® pulp from Renewcell and the SPINNOVA® fibre-spinning technology [27].

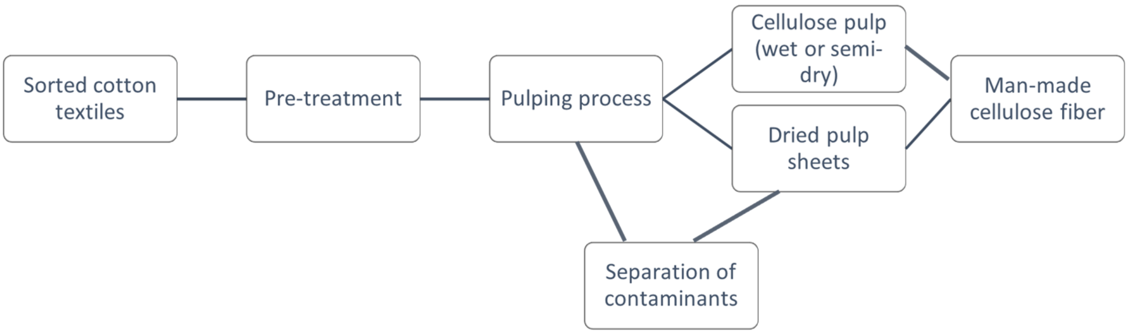

Figure 5. General process scheme for the recycling of cotton textiles via a pulping process.

There are also a number of start-ups developing new technologies that are expected to reach the commercial stage in 5 to 10 years. Despite these efforts, the proclaimed output capacities will not be able to cover the demand for MMCF, which has been estimated to be over 4.5 million tonnes by 2030 [4,28].

In principle, most of these technologies allow separation of polyester-cotton blends by selective dissolution of the cotton fraction. Although several technology holders have indicated that they are also exploring the recycling of polyester from polycotton blends, to the best of our knowledge, to date, only the cotton fraction is being recovered. Moreover, despite these technologies being specifically developed or adapted to cotton textiles, MMCFs, such as viscose, Lyocell, etc., should be able to be processed as well, with or without adaptations to the process.

A (non-exhaustive) overview of companies involved in polymer recycling of cellulosic textiles via pulping is presented in Table 5.

Table 5. Non-exhaustive list of different companies involved in polymer recycling of cellulosic textiles via pulping.

Company + Technology	Type	Status	Website
Evrnu Nucycl (Seattle, USA)	Technology development/Recycling/Fibre production	First commercial production facility with capacity of 17 kt/y is due to be completed in 2024.	https://www.evrnu.com/ (accessed on 12 October 2023)
Ioncell (Espoo, Finland)	Technology development	Pilot line (kg scale) operational. Ambition to commercialise the technology in 5–10 years.	https://ioncell.fi/ (accessed on 12 October 2023)
Saxcell (Enschede, The Netherlands)	Technology development and/or recycling	Pilot facility with output of 100 kg pulp/day, target 25 t/y. Cooperation contract with Birla for industrial production of Saxcell fibre	https://saxcell.com/ (accessed on 12 October 2023)
Birla Cellulose Liva Reviva (Mumbai, India)	Recycling and fibre production	Ambition to scale up the Liva Reviva production to 100 kt/y by 2024/2025.	https://www.birlacellulose.com/ (accessed on 12 October 2023)
Infinited Fiber Company Infinna® (Espoo, Finland)	Recycling and fibre production	Two pilot plants operational since 2018, building a commercial plant of 30 kt/y, which is expected to reach full capacity in 2025.	https://infinitedfiber.com/ (accessed on 12 October 2023)
Lenzing Refibra® (Lenzing, Austria)	Recycling and fibre production	Lenzing and Södra have set a target of processing 25 kt of textile waste per year by 2025 and 50 kt by 2027.	https://www.lenzing.com/ (accessed on 12 October 2023)
Renewcell Circulose® (Sundsvall Sweden)	Recycling	Commercial plant of 60 kt/y has been running since 2022, expanding to 120 kt/y by 2024.	https://www.renewcell.com/en/ (accessed on 12 October 2023)
Södra OnceMore® (Mörrum, Sweden)	Recycling and fibre production	Production capacity of 6 kt/y. Lenzing and Södra have set a target of processing 25 kt of textile waste per year by 2025 and 50 kt by 2027.	https://www.sodra.com/ (accessed on 12 October 2023)

3.3.2. Recycling of Synthetic and Blended Textiles

Polymer recycling of synthetic and blended textiles features three different types of technologies:

1. **Solvent-based dissolution** followed by filtration to separate materials and extract the desired polymers, which can be re-spun via melt spinning (in case of thermoplastic materials) or into MMCF via a pulping process.
2. **Hydrothermal processes** using a certain combination of water, pressure, temperature, and green chemistry to (partially) degrade either cotton or polyester, or both. The resulting polyester monomers can be repolymerised into virgin resin and resin or fibres can be re-spun, while cellulose powder or pulp can be converted to MMCF.
3. **Enzymatic process** (i.e., biochemical recycling) for degradation of cotton to glucose and/or cellulose powder and recovering polyester fibres that can be re-spun. Glucose syrup can be converted into plastics, surfactants, and chemicals (via industrial biotechnologies).

None of these processes have reached the commercial stage yet, although some companies are now moving past the pilot stage with the construction or launch of an (pre-)industrial unit, as illustrated in Table 6.

Table 6. Non-exhaustive list of different companies involved in polymer recycling of synthetic and blended textiles via solvent-based dissolution, hydrothermal, or enzymatic processes.

Company + Technology	Type	Status	Website
Polycotton blends—solvent-based dissolution			
Worn Again Technologies (Nottingham, UK)	Technology development	Pilot line processing 80 kg batches, demonstration plant of 1 kt/y will be online from 2024, commercial plant (50 kt/y) expected by 2027	https://wornagain.co.uk/ *(accessed on 13 October 2023)*
Textile Change (Vejle, Denemarken)	Technology development	Pilot plant (capacity unknown) with plans to scale up to 15 kt/y in 2024/2025	https://textilechange.com/ *(accessed on 12 December 2023)*
Polycotton blends—hydrothermal processes			
BlockTexx Separation of Fibre Technology (Logan, Australia)	Technology development/Recycling	Recently commissioned commercial facility operating at 4 kt/y, to be further scaled to 10 kt/y	https://www.blocktexx.com/ *(accessed on 13 October 2023)*
Circ (Danville, USA)	Recycling	Operating a pilot plant with a capacity of several tons per day, plans to open its first factory of 65 kt/y capacity in 2025.	https://circ.earth/ *(accessed on 13 October 2023)*
HKRITA The Green Machine (Hung Hom Kowloon, Hong Kong)	Technology development	First industrial-scale system operational, with a capacity of 1.5 t/day	https://www.hkrita.com/en/our-innovation-tech/projects/green-machine-phase-2 *(accessed on 13 October 2023)*
Polycotton blends—Enzymatic processes			
HKRITA Textile Waste Recycling by Biological Method *(formerly called "the brewery")* (Hung Hom Kowloon, Hong Kong)	Technology development	Designing and building a pre-industrial scale system	https://www.innovationhub.hk/article/textile-waste-recycling-by-biological-method https://www.hkrita.com/en/our-innovation-tech/projects/textile-waste-recycling-biological *(accessed on 13 October 2023)*
Other materials			
Obbotec-SPEX *(solvent-based PP and PE plastics and textile recycling)* (Rotterdam, the Netherlands)	Technology development/Recycling	Pilot unit commissioned in November 2022, commercial demo plant (approximately 10 kt/y) foreseen end of 2024.	https://obbotec.com/en/spex-technologie/ *(accessed on 13 October 2023)*
PureCycle Technologies *(solvent-based PP textiles and plastics' recycling)* (Ironton, USA)	Recycling	First commercial plant has just produced the first run of Ultra-Pure Recycled (UPR) resin from post-industrial recycled material at commercial scale, estimated capacity +/- 50 kt/y.	https://www.purecycle.com/ *(accessed on 13 October 2023)*
Teijin Aramid *(solvent-based aramid recycling)* (plants in the Netherlands)	Recycling and fibre production	Aim for circular Twaron to be commercially available in 2024, recently performed first industrial-scale production run.	https://www.teijinaramid.com/en/sustainability/recycling-and-circularity/index.html *(accessed on 13 October 2023)*
Thai Acrylic Fibre Co. Regel^{TM} *(solvent-based acryl recycling)* (Saraburi, Thailand)	Recycling and fibre production	Commercial for larger deniers, now working on achieving finer deniers.	https://regel.world/ *(accessed on 13 October 2023)*

3.3.3. Monomer Recycling of Synthetic Textiles

Recycling of synthetics via depolymerisation implies that the polymer chains are completely broken down into monomers, which are then separated and purified before entering the polymerisation process again (see Figure 6) [12]. This yields virgin polymers that can be melt-spun into fibres again. Monomer recycling has been the subject of many R&D initiatives, which have been mainly focused on PET waste (plastics, mostly bottles, but also textiles). In principle, many polymers can be depolymerised, but efficient, practical processes are lacking, e.g., for PA6,6, a polymer with similar applications as PA6.

Figure 6. General process scheme for the recycling of synthetic fibres, such as polyamide and polyester, into the same synthetic fibres via monomer recycling.

Monomer recycling of PA6 has been commercial for over a decade, with **Aquafil** recovering the fibre from monofilament fishing lines and nets and textile waste, including apparel, fabric, and carpet waste. As mentioned, most developments have been focused on PET waste, plastics (mainly bottles), but often also considering textiles as input. In general, three different reaction pathways can be identified: glycolysis, methanolysis, and hydrolysis. The glycolysis pathway is the most developed, as several technologies are reaching, or have reached, commercial demonstration, while hydrolysis is currently the least developed [13]:

- Glycolysis: several demonstration plants constructed and even running.
- Methanolysis: first plant in operation, more underway.
- Hydrolysis: pilot stage, moving onto the industrial/demo stage.

Axens, **Jeplan**, and **IFP Energies** partnered up in 2020 to accelerate the development and demonstration of the Rewind® PET recycling process, an optimised glycolysis process including specific purification steps to remove any (in)organic contaminants. Jeplan successfully operated the first industrial PET bottle chemical recycling plant and initiated a textile recycling demonstration plant in 2018. IFPEN and Axens have been collaborating to develop a process capable of recycling and upgrading coloured and opaque PET bottles into clear, food-grade PET. They are now in the final stage of starting up a 2 kt/y demonstration plant that can process all types of PET-based materials, including bottles, films, trays, and textiles [29].

In addition to PA6 and PET, monomer recycling of PLA textiles is being performed by the Belgian start-up **NOOSA** (capacity unknown) [30]. Another initiative worth mentioning is **Protein Evolution**, a technology in which enzymes are engineered to break down specific waste fractions. The company has announced they will apply their technology onto PET and PA6 fabric from Stella McCartney's collections (current scale unknown) [31]. Different companies involved in monomer recycling of PET-, PA-, and PLA-based textiles are listed in Table 7.

Table 7. Non-exhaustive list of different companies involved in monomer recycling of synthetic textiles.

Company + Technology	Type	Status	Website
PET—glycolysis			
Axens Rewind PET (Kitakyushu-city, Japan)	Technology development	Demonstration plant completed. New units coupled with Toray Films Europe's polymerisation plant, with annual production of 30 kt/y recycled PET expected by the end of 2025	https://www.axens.net/markets/plastic-recycling *(accessed on 16 October 2023)*
Garbo's CHEMPET (Cerano, Italy)	Technology development	Agreement with Saipem S.p.A. to develop a 45 kt/y industrial plant	https://garbo.it/en/chempet/ *(accessed on 16 October 2023)*
Ioniqa Technologies (Rotterdam and Geleen, The Netherlands)	Technology development	10 kt/y demonstration plant, announced a partnership to further scale up and commercialise the technology	https://ioniqa.com/ *(accessed on 16 October 2023)*
Poseidon Plastics (Teesside, UK)	Technology development/Recycling	10 kt/y recycling facility to be built, expected to be available in 2024	http://poseidonplastics.com/ *(accessed on 16 October 2023)*
CuRe Technology *(partial depolymerisation)* (Emmen, The Netherlands)	Recycling	Pilot plant with capacity of 20 kg/h in a continuous process, demonstration plant of 25 kt/y expected by 2025	https://curetechnology.com/ *(accessed on 16 October 2023)*
Eastman Polyester renewal technology (Kingsport, Tennessee, USA)	Recycling	Glycolysis plant (capacity unknown) is operational	https://www.eastman.com/Company/Circular-Economy/Solutions/Pages/Polyester-Renewal.aspx *(accessed on 16 October 2023)*
Jeplan BRING Technology (Kitakyushu City, Japan)	Recycling	2 kt/y demonstration plant (Kitakyushu Hibikinada Plant) aimed at textile-to-textile recycling since 2018	https://www.jeplan.co.jp/en/technology/ *(accessed on 16 October 2023)*
PERPETUAL Revalyu (Kleinostheim, Germany)	Recycling	Commercial for PET bottle waste (40 t/day), textile recycling still in the research phase	https://www.perpetual-global.com/ https://www.revalyu.com/ *(accessed on 16 October 2023)*
PET—methanolysis			
Loop Industries (Terrebonne, Canada)	Technology development	First commercial manufacturing facility with capacity of 70 kt/y is expected to be completed by the end of 2025	https://www.loopindustries.com/en *(accessed on 16 October 2023)*
RePEaT *(joint venture of Itochu, Teijin, and JGC)* (Tokyo, Japan)	Technology development	Unknown	https://repeat-inc.com/en/ *(accessed on 16 October 2023)*
Eastman Polyester Renewal Technology (Kingsport, Tennessee, USA)	Recycling	First methanolysis plant is under construction and due to be completed early next year (capacity 110 kt/y)	https://www.eastman.com/Company/Circular-Economy/Solutions/Pages/Polyester-Renewal.aspx *(accessed on 16 October 2023)*
Itochu's RENU technology (Japan)	Recycling	Commercial plant of 30 kt/y operational (Eunomia)	https://renu-project.com/en *(accessed on 16 October 2023)*
Jiaren New materials (Shaoxing, China)	Recycling and fibre production	Commercial plant of 25 kt/y and 2nd-phase project of 160 kt/y under construction	http://www.jiarenrecycle.com/en/ *(accessed on 16 October 2023)*

Table 7. *Cont.*

Company + Technology	Type	Status	Website
PET—hydrolysis			
Carbios *(enzymatic hydrolysis)*(Clermont-Ferrand, France)	Technology development	Partnership with Indorama Ventures to build a 40 kt/y PET bio-recycling plant, targeted commissioning in 2025	https://www.carbios.com/en/ *(accessed on 16 October 2023)*
DePoly(Valais, Switzerland)	Technology development/Recycling	Pilot plant (50 t/y) operational, about to build a 500 t/y showcase plant (expected to be operational by the end of 2024)	https://www.depoly.co/ *(accessed on 16 October 2023)*
Gr3n (Chiasso, Switzerland)	Technology development	Working on an industrial plant with a capacity of 40 kt/y, expected to be operational in 2025	https://gr3n-recycling.com/ *(accessed on 17 October 2023)*
Rittec RevolPET®/ RevolTEX® (Braunschweig, Germany)	Technology development	A mini-plant (1 kt/y) is being engineered, operation is planned to start by the end of 2023, pre-industrial plant (up to 20 kt/y) will be engineered in parallel	https://www.rittec.eu/solutions/revolpet-r.html *(accessed on 17 October 2023)*
Ambercycle Cycora® *(enzymatic hydrolysis)*(Los Angeles, USA)	Recycling	Scaled from 12 t/y in 2019 to 300 t/y in 2022, exploring the construction and operation of a commercial-scale manufacturing facility	https://www.ambercycle.com/ *(accessed on 17 October 2023)*
FENC® TopGreen™ ChemCycle (New Taipei City, Taiwan)	Recycling and Fibre production	Unknown	https://www.feg.com.tw/en/news/news_detail.aspx?id=10090 *(accessed on 17 October 2023)*
Ineos Infinia (Naperville, Illinois, USA)	Recycling	Pilot plant, capacity unknown	https://www.ineos.com/businesses/ineos-aromatics/ineos-infinia/ *(accessed on 17 October 2023)*
Plast Nordic AS *(Gr3n technology)* (Kristiansand, Norway)	Recycling	First 30 kt/y plant planned for 2025	www.plastnordic.no *(accessed on 17 October 2023)*
Other materials			
Aquafil's Econyl *(PA6)* (Trento, Italy)	Recycling/Fibre production	TRL 9, commercial	https://www.aquafil.com/ *(accessed on 17 October 2023)*
Noosa's NOOCYCLE *(PLA, hydrolysis)* (Brussels, Belgium)	Recycling/Fibre production	Unknown	http://www.noosafiber.com/ *(accessed on 17 October 2023)*

3.4. Thermo-Chemical Recycling ("Thermal Depolymerisation")

Thermo-chemical recycling is a process using heat to break down materials into monomers or low-molar-mass components (see Figure 7) that can be used as feedstock for the chemical industry. This technology can process more complex, heterogeneous waste streams, including blends of fibres and fibres that cannot be recycled by any other technology (e.g., thermosets, composites, coated and laminated textiles, etc.) and is more tolerant to contaminants. Different technologies can be identified, including pyrolysis, hydrothermal liquefaction, and gasification. For a more detailed description of these technologies, the reader is referred to specialised literature [32].

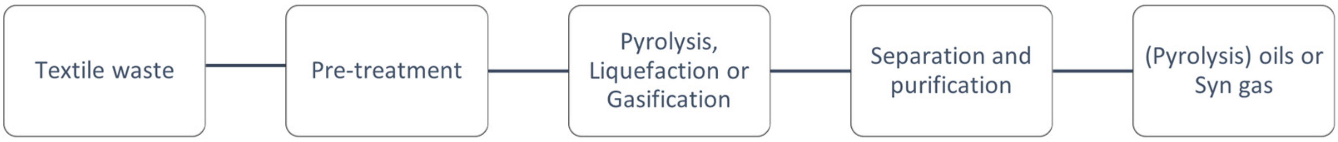

Figure 7. General process scheme for thermo-chemical recycling via pyrolysis, liquefaction, or gasification.

It should be noted that the core technology already exists at the commercial scale; however, it is optimised for energy recovery and fuel production from biomass or plastic waste. Adaptations and additional purification steps are required in order to be suitable for textiles as input and monomers or feedstock for the chemical industry as output [4,12]. Even though installations producing monomers or other chemical feedstock exist at the pilot or industrial scales, the process is generally still combined with fuel production to keep it economically viable. It has been estimated that over 100 pyrolysis processes for chemical recycling of plastic waste are on the market [13]. A list of thermo-chemical technologies is presented in Table 8. It should be noted that these mainly focus on plastic recycling. To the best of our knowledge, only Eastman's Carbon Renewal technology performs fibre-to-fibre textile recycling in the sense that it processes polyester textiles and carpets (among other materials) while converting the resulting syngas into acetic acid, which is then applied for the production of Naia™ Renew cellulose acetate fibres [33].

Table 8. Non-exhaustive list of different companies involved in thermo-chemical recycling.

Company + Technology	Type	Status	Website
Gasification			
Eastman Carbon Renewal (Kingsport, Tennessee, USA)	Recycling	Commercial	https://www.eastman.com/Company/Circular-Economy/Solutions/Pages/Carbon-Renewal.aspx *(accessed on 19 October 2023)*
Resonac (Kawasaki, Japan)	Recycling	195 t/day installation	https://www.resonac.com/ *(accessed on 19 October 2023)*
Pyrolysis			
Arcus Greencycling (Frankfurt, Germany)	Technology development	4 kt/y pilot installation	https://www.arcus-greencycling.com/ *(accessed on 19 October 2023)*
Axens Rewind Mix *(Purification of pyrolysis oils)* (Rueil-Malmaison, France)	Technology development	Unit of 50 kt/y expected to be operational in 2025 (licensed for Borealis)	https://www.axens.net/markets/plastic-recycling *(accessed on 19 October 2023)*
Fuenix (Weert, Nederland)	Technology development	Unknown	https://fuenix.com/ *(accessed on 19 October 2023)*
Plastic Energy (Spain)	Technology development/Recycling	Commercial	https://plasticenergy.com/ *(accessed on 19 October 2023)*
Recycling Technologies Plaxx® (Swindon, UK)	Technology development/Recycling	Pilot	https://recyclingtechnologies.co.uk/ *(accessed on 19 October 2023)*
CLS-Tex HTEX *(hydropyrolysis)* (Bemmel, the Netherlands)	Recycling	Construction of 8 t/day production line started	https://www.cls-tex.nl/cls-inside-workwear-htex *(accessed on 19 October 2023)*
GreenMantra Technologies (Brantford, Canada)	Recycling	Commercial	https://greenmantra.com/ *(accessed on 19 October 2023)*
Hydrothermal liquefaction			
Mura Technology ReNew ELP HydroPRS™ (Wilton, UK)	Technology development	Pilot scale, recycling facility of 20 kt/y under construction, due to launch in 2023	https://muratechnology.com/renewelp/ *(accessed on 19 October 2023)*
Carboliq (Remscheid, Germany)	Recycling	Semi-industrial pilot plant (200 kg/h), recycling facility of 10 kt/y expected to be operational by 2025	https://www.carboliq.com/en/ *(accessed on 19 October 2023)*
OMV ReOil 100® (Schwechat, Austria)	Recycling	Semi-industrial pilot plant (100 kg/h), start-up of demo plant of 16 kt/y planned for 2023	https://www.omv.com/en/recycling-technologies *(accessed on 20 december 2023)*

4. Facilitating Technologies

As illustrated above, textile fibre-to-fibre recycling is truly at its tipping point. However, there are still some barriers to overcome. The quality of the output of recycling heavily depends on the quality of the input, and virtually all technologies require textiles with a certain composition and sometimes also colour. Hence, textile sorting is a fundamental part of the pre-treatment process. However, as textiles are rarely mono-materials, disassembly is another vital step. The latter includes the removal of hard parts, such as buttons and zippers, prints and coatings, etc. [12,34].

The current section provides an overview of facilitating technologies to tackle the above-mentioned obstacles.

4.1. Automated Sorting

Post-consumer textiles are initially manually sorted for reuse, a labour-intensive process involving categorising clothing, shoes, and accessories based on product and quality [34,35]. This pre-sorting step, with potentially over 300 categories depending on factors such as quality, condition, and product type, is in need of automation to increase the efficiency and accuracy. In the Transform Textile into Feedstock (TTWiF) project led by TEXAID, a technology assessment was conducted to identify the best techniques and processes for sorting for both reuse and recycling. Automated sorting for reuse would require a system capable of recognising the product type, condition, size, brand, style, main material, colour, textile construction, and trims, as well as technologies for handling and transportation. Automated folding systems and garment-on-hanger sortation systems already implemented in textile manufacturing could be applied for sorting, but they face limitations due to the major product variations. Additional solutions include tray sorters and separation robots. Unfortunately, the feasibility of the current solutions remains unproven [35].

The non-reusable fraction requires additional sorting for recycling, a process that is currently also predominantly carried out manually. Manual textile sorting can be carried out based on clothing type and product labels or handheld material identification equipment. However, to develop the scale required to achieve a circular textile value chain, automation of the sorting step will be needed [12,34,35]. Textile sorting of recycling qualities consists of three main stages that can be automated to a certain degree: (i) feeding of the textiles to the sorting line or equipment, (ii) identification of materials and colour, and (iii) separation of the textiles based on the identified classes of materials and colours. Despite some remaining limitations, near-infrared (NIR) spectrometry is, at present, the most advanced material recognition technology. Until recently, (automated) textile sorting via NIR technology was still under development, but today, several automated lines are operational across Europe [34].

The sorting sector is seemingly on the verge of a breakthrough towards industrialisation with also partnerships such as the one between **Andritz Laroche**, **Pellenc ST**, and **Nouvelles Fibres Textiles**, as well as **Wastex**, aiming to further speed up the process. Nouvelles Fibres Textiles, in partnership with ANDRITZ Laroche (leader in mechanical fibre recycling technologies) and Pellenc ST (developer of optical sorting machines), is currently installing an industrial pilot for automated sorting and unravelling of End-Of-Life (EOL) textiles. The line will be able to sort garments automatically by composition and colour and will also be able to remove hard parts and to (pre-)unravel garments with a throughput of 1 tonne per hour [36,37]. Wastex is a joint venture between a textile manufacturing company specialised in recycled fibres, **Coleo**, and the sorting technology developer **Picvisa**. They provide the physical and digital infrastructure to enable proper and accurate garment sorting, traceability throughout the entire value chain via blockchain-enabled technologies, and additionally, a collaborative platform [37,38]. Over the last years, the use of blockchain technology for traceability purposes has captured the attention of many supply chain stakeholders. The reader is referred to a case study of a blockchain traceability solution adopted by the Lenzing group [39]. Table 9 provides a (non-exhaustive) list of companies involved in manual and automated textile sorting, including sorting companies and material identification or sorting equipment development companies.

Table 9. Non-exhaustive list of different companies involved in manual and automated textile sorting.

Company + Technology	Type	Status	Website
Manual			
BASF TrinamiX (Ludwigshafen, Germany)	Technology development		https://trinamixsensing.com/textiles *(accessed on 24 October 2023)*
Gut mIRoGun V4 (Walheim, Germany)	Technology development		http://www.gut-stuttgart.de/en/products/mirogun-40-mobile-nir-plastic-detection-from-gut-environmental-technologies.html *(accessed on 24 October 2023)*
Matoha Fabritell *(London, UK)*	Technology development		https://matoha.com/fabrics-identification *(accessed on 24 October 2023)*
Senorics SenoCorder Solid *(Dresden, Germany)*	Technology development		https://www.senorics.com/ *(accessed on 24 October 2023)*
Spectral Engines Nirone *(Steinbach, Germany)*	Technology development		https://shop.spectralengines.com/products/nirone-device-d1-4-d1-7-d2-0-d2-2-d2-5?variant=36643865821349 *(accessed on 24 October 2023)*
Valvan Fibersort *(Menen, Belgium)*	Technology development		https://www.fibersort.com https://smartfibersorting.com/ *(accessed on 24 October 2023)*
Lounais-Suomen Jätehuolto Oy (LSJH) *(Turku, Finland)*	Sorting		https://lsjh.fi/ *(accessed on 24 October 2023)*
TEXAID *(Schattdorf, Switzerland)*	Sorting		https://www.texaid.ch/en/ *(accessed on 24 October 2023)*
Automatic			
HKRITA *(Hung Hom Kowloon, Hong Kong)*	Technology development		https://www.hkrita.com/en/our-innovation-tech/projects/smart-garment-sorting-system-for-recycling *(accessed on 24 October 2023)*
Pellenc Mistral+ CONNECT *(Pertuis, France)*	Technology development		*https://www.pellencst.com* *(accessed on 24 October 2023)*
Picvisa Ecopick, Ecopack, Ecosort Textil *(Barcelona, Spain)*	Technology development		https://picvisa.com/en/ *(accessed on 24 October 2023)*
Steinert *(Köln, Germany)*	Technology development		https://steinertglobal.com *(accessed on 24 October 2023)*
Tomra Autosort *(Mülheim-Kärlich, Germany)*	Technology development		https://www.tomra.com/en/solutions/waste-metal-recycling/applications/textiles *(accessed on 24 October 2023)*
Valvan Fibersort *(Menen, Belgium)*	Technology development		https://www.fibersort.com *(accessed on 24 October 2023)*
Wastex—Picvisa *(Barcelona, Spain)*	Technology development		https://www.wastexrecycling.com/ *(accessed on 24 October 2023)*
Cetia—Fibersort *(Hendaye, France)*	Sorting		https://cetia.tech/home-en/ *(accessed on 24 October 2023)*
Coleo Recycling—Picvisa *(La Coruña, Spain)*	Sorting	5000 t/year	https://coleo.es/ *(accessed on 25 October 2023)*
LSJH *(Turku, Finland)*	Sorting	Planned for 2025	https://poistotekstiili.lsjh.fi/en/home/ *(accessed on 25 October 2023)*
New Retex *(Bjerringbro, Denmark)*	Sorting	Pilot installation of 10 t/week, 40,000 t/y planned for 2025	https://newretex.dk/ *(accessed on 20 December 2023)*

Table 9. *Cont.*

Company + Technology	Type	Status	Website
Salvation Army—Fibersort *(Kettering, UK)*	Sorting	500 t/year	https://www.satcol.org/fibersort *(accessed on 24 October 2023)*
Soex *(Bitterfeld-Wolfen, Germany)*	Sorting		https://www.soex.de/en/ *(accessed on 24 October 2023)*
Synergies TLC—Pellenc *(Albertville Cedex, France)*	Sorting	3000 t/year, 25,000 t/year planned for 2025	https://synergies-tlc.com/ *(accessed on 25 October 2023)*
Sysav—Siptex/Tomra *(Malmö, Sweden)*	Sorting	24,000 t/year target	https://www.sysav.se/en/siptex/ *(accessed on 24 October 2023)*
TEXAID—ReHubs project *(Schattdorf, Switzerland)*	Sorting	50,000 t/year planned for 2024	https://www.texaid.ch/en/ *(accessed on 26 October 2023)*

In the present report, a short summary is provided. The reader is referred to the Terra study "Technical monitoring of optical sorting, recognition, and disassembly technologies for textiles at European scale" for a detailed description of sorting technologies, including identification techniques, pros and cons, additional technologies (such as colour sorting, artificial intelligence, etc.), machine suppliers, and sorting lines [34].

4.2. Facilitated Disintegration of a Textile Product

Textiles typically consist of different components, including non-textile/hard parts (buttons, zippers, etc.) and textile parts of different materials (labels, patches, linings, etc.). They can also be coated (water, oil, or dirt repellent, etc.), laminated, or printed on. Disassembly and removal of certain parts is, thus, another important part of the pre-treatment of textiles for recycling. Again, this can be performed manually, by cutting up the textile products into uniform pieces of fabric without disruptors. However, as illustrated in Table 10, several technologies have been and are being developed to facilitate this process. These technologies are briefly discussed in the current section.

Table 10. Non-exhaustive overview of companies that have developed facilitating technologies for textile recycling, including an estimation of the current TRL.

Company	Technology	TRL	Website
ANDRITZ Laroche (Cours, France)	Garneting/tearing lines with integrated automated trim removal	9	https://www.andritz.com/products-en/nonwoven-textile/recycling/textile-recycling *(accessed on 24 October 2023)*
Dell'Orco & Villani (Capalle, Italy)	Garneting/tearing lines with integrated automated trim removal	9	https://www.dellorco-villani.it/en/ *(accessed on 24 October 2023)*
Valvan (Menen, Belgium)	Trimclean™ Automatic cutting and trim removal machine	7	https://www.valvan.com/en/solutions/textile-sorting-recycling *(accessed on 17 October 2023)*
Resortecs (Brussels, Belgium)	Smart Stitch™ melting threads and Smart Disassembly™ thermal disassembling ovens	8	https://resortecs.com/ *(accessed on 9 November 2023)*
Wear2 (Valkenswaard, The Netherlands)	Wear2® Ecostitching sewing thread combined with microwave technology for disassembly	7	https://wear2.com/en/ *(accessed on 24 October 2023)*
Fraunhofer IVV (Dresden, Germany)	Creasolv®-adapted process for delamination or dissolution of coatings from PET and PA textile substrates	7	https://www.ivv.fraunhofer.de/en/recycling-environment/recycling-plastics-creasolv.html *(accessed on 29 September 2023)*
Rescoll (Pessac, France)	INDAR Inside® debonding technology	6	https://rescoll.fr/rescoll-presents-indar-debonding-primer-a-solution-for-circularity-of-multimaterial-assemblies/ *(accessed on 29 September 2023)*
PVC separation (Tonsley, Australia)	PolySep	7–8	https://www.pvcseparation.com/ *(accessed on 7 November 2023)*

4.2.1. Automatic Removal of Trims

Automated removal of hard parts has already existed for some time as a part of mechanical recycling (garneting/tearing) lines. Machinery manufacturers **ANDRITZ Laroche** and **Dell'Orco & Villani**, for example, offer tearing lines with integrated automated hard point separation modules [34]. Additionally, **Valvan** has developed an automatic trim removal machine, Trimclean^{TM}, with a maximum capacity of 1 t/h. It consists of a cutting line, where textiles are cut into small clippings, followed by a detection system based on optical cameras and metal sensors to detect both textile and non-textile trims (buttons, zippers, but also labels, patches, etc.). Clippings with trims are then pneumatically separated from other clippings, as illustrated in Figure 8 [40].

Figure 8. Clippings with trims (**right**) separated from untrimmed clippings (**left**) by Valvan's Trimclean^{TM} technology (https://www.valvan.com/en/solutions/textile-sorting-recycling).

4.2.2. Yarns for Facilitated Disassembly

Stitching/sewing yarns that disintegrate upon applying a certain trigger allow a stitched textile product or components stitched on a fabric to be separated. Currently, two types of disassembly yarns exist: thermal and microwave-based disassembly. **Resortecs'** Smart Stitch^{TM} and Smart Disassembly^{TM} (see Figure 9) technologies include stitching threads combined with industrial thermal disassembling ovens. The yarns can be bio-based or synthetic with melting points of 150, 170, or 190 °C and suitable for various applications, from apparel to workwear. Textile products manufactured with Smart Stitch^{TM} threads can be dismantled by heating in Smart Disassembly^{TM} ovens. These thermal disassembly ovens have a capacity of 1 up to 13 t/day [41]. The **Wear2**® Ecostitching Technology offers a sewing thread combined with microwave technology for disassembly of EOL textile products. A new Tunnel Disassembler is operational in a demo separation hub [42].

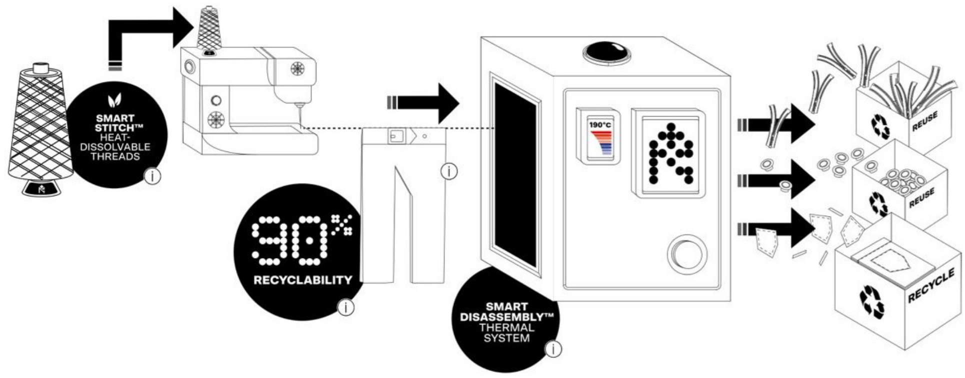

Figure 9. Illustration of Resortecs' Smart Stitch^{TM} and Smart Disassembly^{TM} technology for industrial-scale disassembly of textiles (https://resortecs.com/).

4.2.3. Coating Removal and Delamination

Different types of technologies have been and are being developed for the removal of coatings and laminated layers:

- Dissolution of the adhesive layer, coating, or textile,
- Triggerable smart polymer material systems,
- Reversible crosslinking–decrosslinking systems,
- Supramolecular polymer adhesives.

The Creasolv® process, developed and patented by **Fraunhofer IVV** and a registered trademark of **CreaCycle GmbH (Grevenbroich, Germany)**, allows the separation of different material components of films, plastics, textiles, etc. The process is based on dissolution of components but uses higher boiling 'greener' solvents, tackling the ecological and safety problems related to previously developed technologies (e.g., Vinyloop). As illustrated in Figure 10, the process consists of three main steps: (i) dissolution of the target polymer using a specific solvent, (ii) separation of contaminants from the recovered polymer solution, and (iii) precipitation of the target plastic from the purified polymer solution [43].

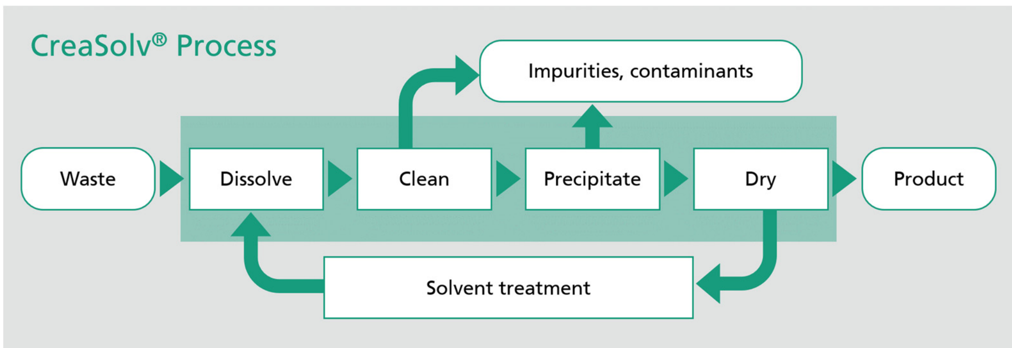

Figure 10. Illustration of the CreaSolv® Process steps [43].

In the H2020 project DECOAT (DECOAT was funded by the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 814505—https://decoat.eu/, 6 November 2023), the CreaSolv® process was successfully tested to delaminate or dissolve polyurethane, polyamide, PVC, and acrylate coatings from PET and PA textile substrates.

Rescoll Technological Center has developed and patented a debonding process, INDAR Inside®, that applies triggerable smart polymer material systems (see Figure 11) [44,45]. Specific additives, namely blowing agents, activated by heating at a certain temperature (130, 150, or 170 °C), allow the disassembly of structural bonds on command. This technology drastically reduces the dismantling time and fulfils the main characteristics required by this application: no change in processing (implementation, curing conditions, etc.) and no or slight modification of the mechanical properties.

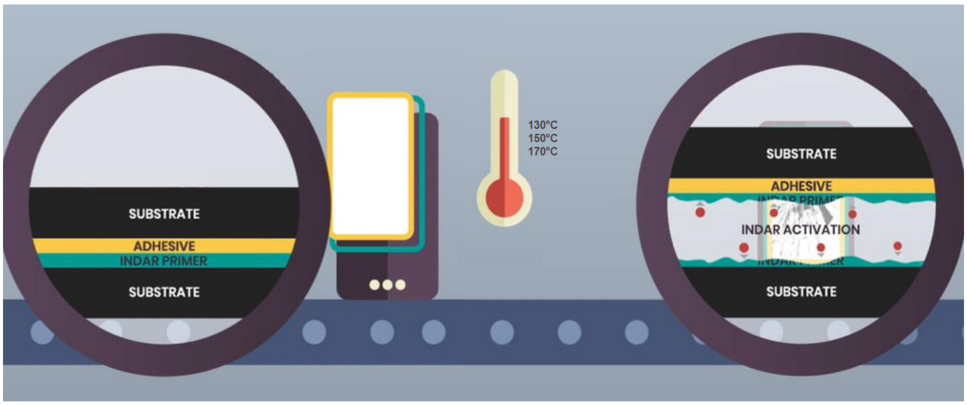

Figure 11. Schematic representation of the INDAR® debonding technology, reused with permission from [46].

The use of the INDAR-primer as an intermediate de-bondable coating layer has been successfully tested in the H2020 project DECOAT (DECOAT was funded by the European Union's Horizon 2020 research and innovation programme under Grant Agreement **No. 814505** - https://decoat.eu/). By applying a variation of the primer with a debonding triggering temperature of 180 °C in between a PU coating and A4-sized PET fabric samples, it was possible to achieve spontaneous and complete removal of the coating after thermal triggering.

Finally, the PolySep process is a batchwise process to separate multi-layered materials (see Figure 12). It was initially designed to remove PVC from PET. The input material is first shredded, and then soaked with solvent, which swells the PVC fraction. In the next step, the soaked material comes into contact with the catalyst, which is hot water or steam. This induces a flash evaporation of the solvent, leading to a popcorning effect. At this step, the PVC coating is detached from the PET substrate. Subsequent conventional separation steps (such as zig zag air separation) allow to obtain different individual streams (in this case, PVC and PET). The solvent is recuperated via a distillation process, and thus used in a closed loop. The process has been developed in Australia and has been patented (EP3504037A1), and a container-based demo line has been installed at the premises of Centexbel.

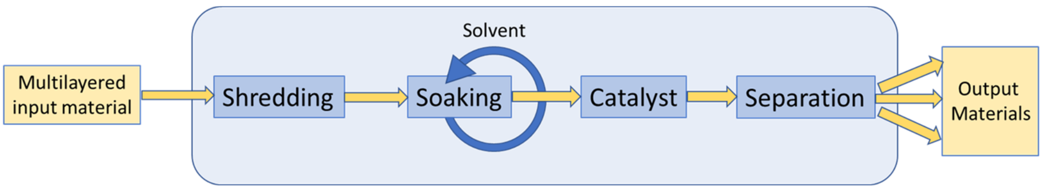

Figure 12. Schematic representation of the PolySep process.

5. Virtual Databases and Platforms

Transformation to a circular textile economy will require collaboration across the value chain. Different players, going from brand and retailers to garment makers to yarn and fabric producers, and waste collectors to recyclers, will have to work together in order to align processes and implement and scale the circular technologies. Some examples of partnerships have already been mentioned in previous sections. Virtual platforms such as **Ellie Connect**, **Reverse Resources**, and **Recycle Refashion** can help companies find the right partners.

In addition, the end user is also of key importance in the shift to a circular economy. They require knowledge on proper use, maintenance, and disposal of textile waste, and on environmental and social impacts of textile products. Moreover, finding sustainable clothing is not always easy and online platforms such as **COSH!** can guide consumers in their search.

The platforms are briefly presented in Table 11.

Table 11. Non-exhaustive overview of virtual platforms that help connect partners in the textile (recycling) value chain and inform customers.

Platform	Technology	Link
Ellie Connect by Ariadne Innovation	Digital platform for organisations looking for independent support, focused on finding a concrete next step. It is intended to help companies find new connections, knowledge, and expertise, and use cases for sustainability transformation in and with the textiles and fashion industry. Platform features include an actor database, offering database, challenges, trend monitoring, knowledge base (publications, reports, and documents), etc. Free membership available and paying membership for extra features as well as paid additional on-demand solutions.	https://ellieconnect.com/ *(accessed on 9 November 2023)*
Reverse Resources	A Software-as-a-Service (SaaS) platform to digitise, connect, and scale global textile-to-textile recycling. Reverse Resources is a portal to match textile waste with the best possible recycling solutions, enable predictive transparency, and build data-driven supply chains. Access point to 4 different types of "roles" on the platform: (i) waste suppliers, (ii) waste handlers, (iii) recyclers, and (iv) brands.	https://reverseresources.net/ *(accessed on 9 November 2023)*
Refashion Recycle	Platform connecting textiles and footwear recycling stakeholders in France and Europe. It is a tool dedicated to identifying materials from textiles and footwear recycling, to promoting recycling solutions and to connecting stakeholders. In just 3 clicks, professionals are able to obtain, in a region of their choice, non-reusable textiles and footwear feedstock potential, recycling solutions, and detailed stakeholder profiles corresponding to their request. Platform is freely accessible for professionals that use or produce materials made from recycled clothing/footwear and/or that provide an industrial solution contributing to the recycling of clothing and footwear in Europe. Access is subject to validation by Refashion depending on the applicant's motivations.	https://recycle.refashion.fr/en/ *(accessed on 9 November 2023)*
COSH!	Platform providing location-based sustainable shopping advice for consumers, with more sustainable alternatives to fashion, cosmetics, and lifestyle products from local shops and brands. Currently available for Belgium, the Netherlands, Spain, and Germany.	https://cosh.eco/en *(accessed on 9 November 2023)*

6. Conclusions

In this manuscript, an overview of existing textile recycling technologies, their current state, and projected developments has been put together. Information, comprising details about relevant companies and their present and expected production capacities, was presented. While fibre-to-fibre recycling is the preferable technology, the paper also included companies/initiatives that have not fully adopted a 100% closed-loop approach but are actively working towards it or express the intention to do so. Recycling technologies have clearly significantly evolved over the past years and many of them are expected to reach the industrial/commercial scale soon. In addition to textile recycling processes, the paper also provided insights into key facilitating technologies. Furthermore, it listed virtual platforms that aid companies in connecting with stakeholders and that inform consumers. With this manuscript, the authors hope to provide relevant information that empowers textile companies to take action and transform their linear business models to a circular model.

Author Contributions: Conceptualisation, B.S., S.V.V. and S.H.; investigation, B.S.; resources, S.V.V., S.H., and R.G.T.; writing—original draft preparation, B.S.; writing—review and editing, M.V. and

I.D.S.; funding acquisition, M.V. and I.D.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by VLAIO, TEX2CE-project, with grant number HBC.2021.0942.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflict of interest. The funding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

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