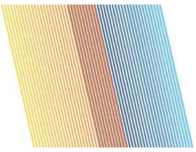

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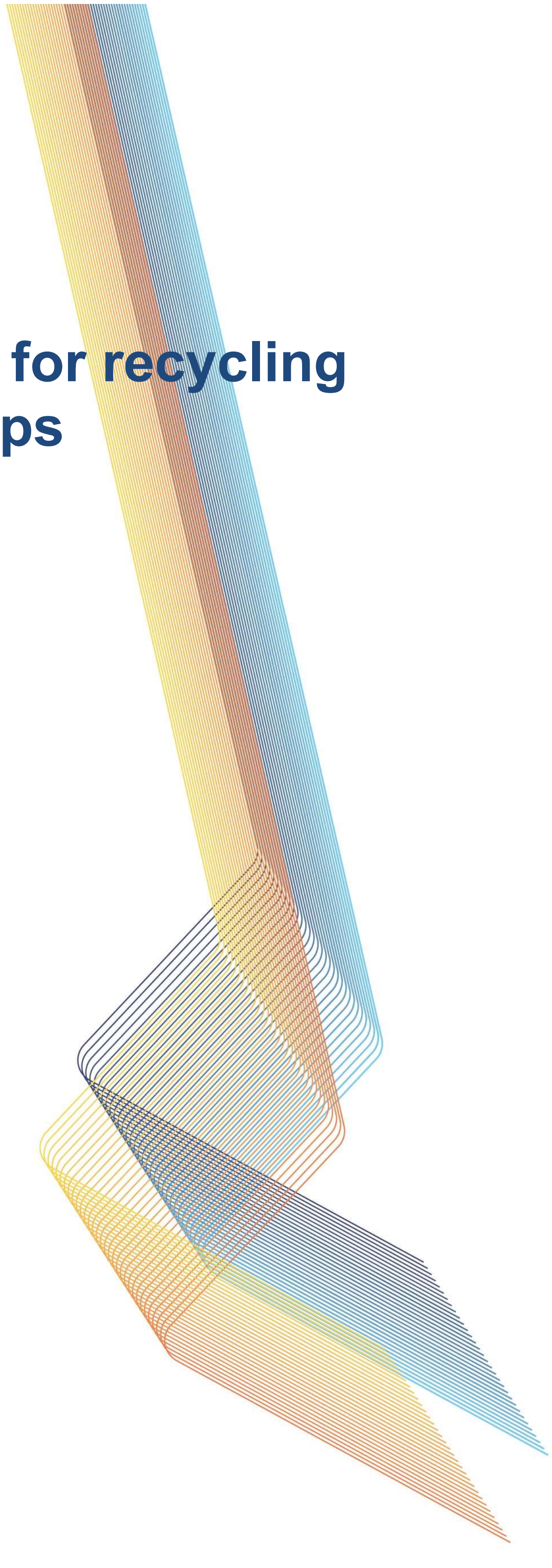


A Study on technologies for recycling and re-use of textile scraps

Summary

1. Overview

The great population growth, improvement of living standards and decreasing life cycle time of textile products are generating a significant amount of post-consumer and post-industrial textile waste in the world[1–3]. In addition, with the emergence of fast fashion, clothes became true fast moving consumer goods, easily accessible in great quantities and replaced frequently.

In Europe, about 75% of textile waster is disposed of in landfills, 25% is reused or recycled, and less then 1% is recycled back into clothing[3]. In this respect, advancing reuse and recycling technologies for textile waste in diverting waste from landfills is critical.

The Waste Framework Directive ((EU) 2018/851) obliges Member States to set up separate collection schemes for textiles waste by January 2025. The Directive (article 11(6)) also mandates the Commission to, by December 2024, consider setting up targets for re-use and recycling of textile waste. Ensuring ambitious textile re-use and recycling targets and enabling effective recycling at an industrial scale requires preparation of the companies. Ensuring ambitious textile circular economy targets and enabling effective recycling at an industrial scale requires preparation of the companies across the entire value chain, from fibers production to mechanical or chemical recycling of textiles and support in addressing existing bottlenecks. Recycling in textile can take place through different methodologies, like mechanical, thermal, or chemical recycling, which apply different technologies, and from different sources figure 1.

The mechanical approach is based on physical forces and may be used in isolation for fabric or fiber recycling or as pre-processing for other recycling processes. The mechanical recycling technology is currently at Technology Readiness Level 9 (TRL 9) and is a well-established technology in the market with decades of experience, for example, for wool in the Prato region in Italy or other natural fibers (cotton, jute, sisal, flax, etc.) and synthetic fibers (polyester, polyamide, acryl, viscose, PP, etc.) in various European regions (Belgium, France, Germany, Sweden, etc.). The principal advantage of mechanical recycling is that it can process any kind of textile waste, it can handle relatively small quantities of waste material, requires a relatively low level of investment and low skilled staff. The outputs of the mechanical recycling process are spinnable fibers, fluff, filling materials and dust. The fraction of spinnable fibers, which are fibers long enough to be spun into new yarn, is 5-20% of the textile material input in case of natural fibers and 25-55% of textile material input in case of polycotton or polyester. Spinnable fibers from mechanical recycling need to be blended with virgin material to reach a yarn of an acceptable quality.

Thermal recycling is based on thermal treatment with the aim to recover polymers or monomers from polymeric fraction of textile waste. A distinction is being made between thermo-mechanical recycling and thermo-chemical recycling. Thermo-mechanical recycling is a process used to melts the thermoplastic polymers in textile waste (e.g., polyester, polyamide, polypropylene), to allow the polymers recycling. Thermo-chemical recycling is a 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 raw material for the chemical industry. It is considered a mature technology but not much used and there are only few industrial plants with TRL 9[4].

Chemical recycling is a process using chemical reactions or chemical dissolution to carry out the polymer separation and recycling. There are many possibilities within this technology and three major technologies can be identified: polymer recycling of cotton via pulping process, monomer recycling of PA and PET, and recycling of polycotton blends. The advantage of chemical treatment is that the output products are most often the same in quality as their virgin counterparts, with no loss in physical properties through the recycling process. This is much superior to mechanical recycling when it comes to technology with the use of chemicals, enzymes, and controlled environment.

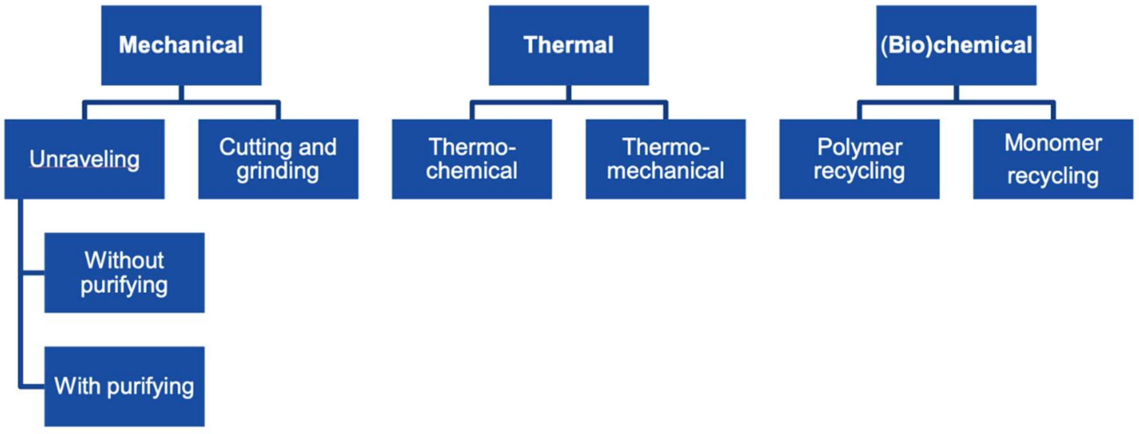


Figure 1: Categorization of textile recycling technologies.

2. Mechanical Recycling Processes

2.1. Input

Mechanical recycling processes have the advantage of being able to work basically with any kinds of textile waste, material type (synthetic, natural or blends), types of textile products (carpets, yarns, fabrics, used garments) and structures (knitted, woven or non-woven). However, the material type, in combination with the textile texture determines the required machinery and the potential output. An example is the mechanical recycling of aramid fibers (e.g., Kevlar®) or other high strength fibers for which specialized machinery are needed. Moreover, knitwear is in general very easily opened with tearing machines, while woven fabrics are a tighter construction which is more difficult to open and will lead to shorter fibers. To guarantee a higher quantity and quality of the fibers, inputs as homogeneous as possible are necessary. Because of this, textile wastes are preferably sorted by material and color before the process.

Unfortunately, several technology owners have indicated the lack of good-quality waste available in the market and more specifically, the scarcity of mono-streams. Another recurrent comment is the lack of traceability of the origin of the input. End-of-life consumer textiles with different fiber blends and of unknown origin will mostly lead to fluff material with an undetermined content that can only be used as filling material (e.g., for insulation in the construction industry) or in non-woven production.

Laminated and coated products are undesirable in the inputs to the process: coatings and glues keep the textile structure together and as such complicate the unravelling of textiles into individual fibers. Spinnable fibers cannot be obtained from mechanical recycling of these materials. Another undesirable is textile waste with the presence of 10% by weight or more of elastane. This elastomeric fiber is more difficult to shred or unravel and greater forces are needed to destroy the fabric and obtain individual fibers. However, some technology holders claim to be able to process textile with the presence of elastane without problem[5] .

2.2. Process steps

The main stages of the mechanical recycling process are represented in the block diagram in figure 2

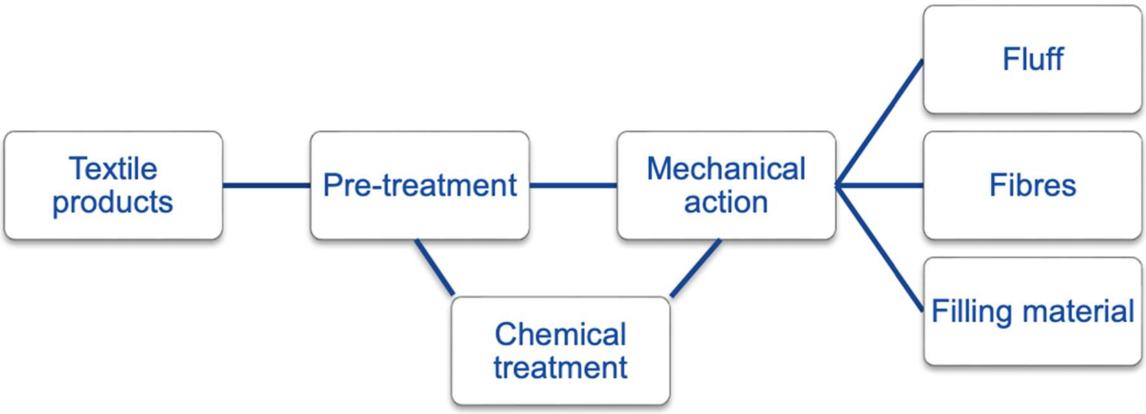


Figure 2: General process scheme for the mechanical recycling of textiles

The principal steps consist of a pre-treatment followed by a set of mechanical actions. However, the specific actions needed to obtain a useable output strongly depend on the nature and characteristics of the input material.

2.3. Pretratment

The textile waste will be dismantled and cut to an appropriate dimension. This phase can include automatic or manual removal of unwanted accessories. Coating, prints and labels are to be avoided because they can cause visual variation (different color of the labels), lower the quality of the output, or hinder further processing. Hard parts like bottoms and zippers, can damage the machines during the process and metallic parts especially pose a risk of fire: a spark caused by a metal part like a press fastener hitting machine parts could cause the cotton to ignite. In case of manual removal of these parts, a fraction of the textile material is lost as it is economically unviable to spend a lot of time on the precise removal of the part. Some metallic components can be easily removed thanks to their magnetic properties by a magnet, while non-ferro hard parts can be separated based on density by means of centrifugal force after fragmentation

For contaminated textile like post-consumer clothes, carpet, and unwashed textile, the pre-treatment step may include sanitation by industrial washing process. These processes include cleaning with detergents or liquid carbon dioxide (CO_2), and sanitation with ozone (O_3). Generally, for industrial/pre-consumer waste, the washing processes are not needed.

2.4. Mechanical action

The mechanical process consists of a series of consecutive actions. First, the material is cut into smaller pieces, typically with a characteristic length of 4-6 cm[6] but some technologies work with larger dimensions, improving the fibers length of the output. After cutting step, the smaller pieces are fed into a textile tearing machine, which consist of a sequence of high-speed rotating cylinders or drums covered with saw or steel pins to tear the textile. Under this action, the structure of textile opens, releasing the individual fibers. The first cylinders have coarse spikes and when the opening is sufficient, the fibers will pass through a series of cylinders with more and finer spikes or saw wires in every step. In figure 3 it is shown a typical tearing line, consist of 3 to 6 (sometimes up to 9) cylinders[6,7]. Different terminology is used to describe this process, such as opening, tearing, pulling, garneting, and unravelling.

Figure 3 Tearing line from LAROCHE. (https://www.laroche.fr/en/domaines-dactivites/recycling.html)

After the tearing machines, the baling presses will compress fibres into bales for transport. Additional to the cutters, tearing machines and baling presses, pre-openers and fine-openers, blending boxes and cleaning drums can be included. Pre-openers perform a first opening of the textile before entering the actual tearing machine, while fine-openers are used at the end of the line to open the last unopened yarns/pieces. Moreover, in order to ensure the recycling into yarn, the opened fibres are carded, a process that disentangles, orients, cleans and intermixes fibres, producing a continuous web or sliver. The opened fibres can also pass through extra steps in order to remove the fraction of fibres which are too short for spinning. Blending boxes can be used in order to ensure a more consistent input by blending the fibres or fabric input intensely so that the quality of the output is more consistent. This is also possible later in the process when mixing the recycled fibres with other virgin or recycled fibres. A cleaning drum can be included in the recycling line for automatic removal of remaining contaminations (metal or plastic parts, stones, seeds, etc.) that were not removed during pre-treatment.Larger textile pieces can yield longer fibres but are more difficult to open. However, the size of the textile input is not the only factor determining the final length of the output fibres as the mechanical tearing will cause a reduction of the fibre length. The extent of this length reduction depends on the nature of the fibre (natural vs. synthetic) and the structure of the textile (loosely knitted vs. tightly woven) . The machinery and process steps will often be tailored to maintain the fibre length as much as possible to obtain a high-quality output suitable for respinning into yarn. Some technology holders implement a novel chemical treatment, without altering the fibre to large extents (e.g., cotton remains cotton). This can enable a more gentle recycling process or make the fibres more resistant to the process, resulting in stronger fibres with a length almost comparable to virgin ones. Contaminations such as dust, unwanted particles or fibre fragments, etc. are sometimes chemically removed from the fibre mass in order to obtain a higher purity and better fibre quality. The chemicals used, such as for example organic solvents, will depend on the exact contamination one wants to remove. Knowledge of the input composition is thus extremely important, because you want a selective removal without influencing the fibres one wants to regain. Different textile wastes might require a different line-up of machinery. How various machines and technologies are combined depends firstly on the input material and secondly on the intended output. Moreover, process parameters such as speed of material transport and speed of drum rotation, can be adjusted to optimize productivity and fibre quality [8] Therefore, not all technology holders are able to process all kinds of textiles and choices must be made. This leads to specialisation in certain waste streams and an increased need of knowhow. For textile that has a structure that can’t be opened or for technical fibres such as aramid and carbon, milling or precision cutting can be performed to obtain short fibres or particles that can be used as filling material in compounding applications for example.

2.5. Output

During mechanical recycling the overall fibre properties (including material content and colour) are retained, apart from the fibre length and strength. Due to the tearing process materials can suffer severe damage, leading to a significant reduction in fibre length compared to virgin fibres. This means that the quality of the output depends both on the input material and on the recycling process. The better the process is adapted to the input material the higher the quality of the output. The process yields a variety of fibre lengths, including a considerable share of short fibres and dust. Pieces of fabric and threads can be present as well, in that case, the material requires another (or several) pass(es) through the tearing machine in order to obtain single fibres [9,10]. Due to the decrease in fibre quality, blending with virgin fibres is necessary to enable respinning into yarns . It has been estimated that current tearing technologies generate between 25% and 55% of fibres longer than 10 mm (Gulich 2006). When the fibre length has become too short, respinning will be impossible. These short fibres are also referred to as flock or fluff. The minimum fibre length required for spinning depends on several factors (i.e., the spinning technology: ring yarn vs. rotor yarn, the desired yarn properties: strength, fineness, evenness, etc.). Generally, fibres longer than 15 mm are preferred, while fibres with lengths from 10 to 15 mm can be spinnable but they will not or rarely contribute to the yarn strength. Unfortunately, the majority of the recovered fibres (i.e. about 80 - 95% for cotton) are currently not respun into yarn but processed into non-wovens instead. Although no prove was delivered, some technology holders claim to be able to recover 90% of spinnable fibre in specific cases of cotton waste, this is due to the use of larger pieces of textile, improved technology and better performing machinery. There is a believe amongst experts that this might be the case for stronger fibres like polyester fibres. Nonetheless, the industry is clearly still working on developments to increase the output of spinnable fibres. Alternatively, the short fibres can be used as filling material or for non-woven production to produce insulation material or technical nonwovens for the automotive industry. Therefore, mechanical recycling is sometimes seen as downcycling. Moreover, any substances, including hazardous ones, remain in the material

In terms of fibre content, the output purity solely depends on the input material. In case of material blends the output is very difficult to identify and might also be very inconsistent, depending on the number of different blends that are processed together or even in the same line. A textile input of 100% cotton fibres (e.g. when using 100% cotton denim only) will lead to a certain amount of spinnable fibres that are 100% cotton. However, when other materials were previously processed in the processing line, residues might remain in the machinery and contaminate the 100% cotton batch. The same applies for colours. The possible outputs are delivered to producers in the form of a bale or in containers. We can categorise the different outputs as spinnable fibres, fluff material or flock for non-woven production, fillers and additional waste streams of non-textile materials.

A. Spinnable fibres / fibres of high quality and length

The spinnable fibre fraction is the output fraction made of long fibres of a good enough quality to be used in a spinning process. This output can only be obtained when the fibres from the textile input are of a good quality and the textile material is easy to open in the tearing process. Mechanical recycling of laminated, coated, printed or contaminated input will not result into fibres for spinning. These materials, once mechanically recycled, will result in fluff or filling material. In case of natural fibres, between 5 – 20% of a good quality textile inputs can be recovered as spinnable fibres. As mentioned before, some technology holders claim to be able to recover a much higher percentage of cotton fibres from end-of-life textile. It is needless to say that the more fibres can be used as spinnable fibre, the lower the environmental impact will be when taking into account the replacement of virgin material. For synthetic fibres such as polyester, the amount will be higher but never 100% of the total material. There will always be a part of the textile material that will be recovered as short fibres or dust and thus cannot serve as input for a spinning process. The removal of contaminants upfront of the recycling process might increase the amount of spinnable fibres but certain contaminants e.g., paint stains, are not removable. Therefore rags used to clean up paint or clothing of a professional painter will have a lower output of spinnable fibres than hospital clothing. Depending on the nature and amount of contaminants, mechanical recycling is not an option for some textiles and they should be recycled with another technology that can purify the textiles of this contamination.

B. Fluff / un-spinnable fibre material

This output is still a fibre but they are too short and/or too entangled to be used in a spinning process. Fluff material is typically used in the non-woven industry to produce filling products like insulation for the construction industry or technical non-wovens for the automotive industry.

C. Fillers

In some processes (e.g. milling) the fibre shape is drastically altered, leading to small particles instead of fibres. This is not always intentional but due to the disintegration of the fibre during the recycling process. For example, cotton fibres that are present in a garment that is washed over 100 maintenance cycles can become so fragile that it pulverises, resulting in cotton dust. This fraction is now mainly compressed and used as burning fuel but could also potentially serve as raw material for a viscose process resulting in a viscose-type fibre. Depending on the shape, size, and material, these particles can be used as filling or reinforcements in plastics and composites. Regarding dust production, one technology holder estimated that more or less 20 kg dust is produced for each ton of input material. Another technology holder indicated 50 to 250 kg/h of dust leading to 80 to 400 tonnes a year.

D. Additional waste streams

Non-fibrous material is unwanted for further processing and thus removed. These are especially hard parts, such as coatings, backings, buttons, zippers or prints, or contaminants present on the textile product such as sand, dried paint or washing residues. Since these parts could also damage the machines, they will be removed resulting in metal and plastic waste fractions. One technology holder estimated this is less than 10% of the total weight in the case of a garment. The cleansing processes will lead to contaminated cleansing mediums like organic solvents, water, etc.

2.6. Advantages

Mechanical recycling technologies require a relatively low level of investment and space, and less highly skilled personnel than chemical recycling technologies .

As mentioned before, practically any textile waste stream (material and structure) can be processed via mechanical recycling. Hence, textiles that are not recyclable via other (i.e., chemical or thermo-mechanical) technologies can most probably be recycled mechanically. This leads to additional materials finding their way to new products replacing virgin material instead of going to incineration or landfill. For natural fibres, mechanical recycling is the only way to preserve the fibre type, for example cotton fibres remain cotton without being converted into regenerated cellulose fibres such as viscose, which is the case in a chemical recycling process .This means the original properties of the fibre remain although this might be altered depending on the state of the fibre. The process uses a relatively low number of resources. Interviews with the technology holders revealed that between 0.3 to 0.5 kW per kg input material is used. Also, the water usage is limited as this is only related to an occasional cleansing process as pre-treatment, but this is not always needed, e.g., production waste like cutting scraps form the confection industry.Another advantage is that relatively small quantities of waste material can be processed with this technology. However, these small quantities may have as a disadvantage that material can stay behind in the machinery contaminating the following productions leading to quality issues.

2.7. Disantvantages

There are two main disantvantages:

- the output consisting of mostly textile fibres of a (much) lower quality than virgin fibres or worse, non-fibrous material which is unsuitable for textile production without further processing. The use of the spinnable recycled fibre fraction will have an inevitable impact on the quality of the final textile product and blending with virgin material might be needed to reach an acceptable quality.
- Textile might become contaminated with chemical substances during use. For example, research has shown that firefighter suits contain a high amount of polyaromatic hydrocarbon (PAH) substances that can’t be washed out with a conventional cleansing process [12].These PAH substances remain in the textile when mechanically recycled. Since the output can be very inconsistent depending on the input material it is practically impossible to guarantee the compliancy via testing of batches. Only a watertight supply chain could potentially solve this. One would need to know the complete history of the input materials.

Due to practical reasons it is hard to check the fibre content of every product that goes into the process (fibre contents might have changed during use, labels are removed…) and it is too costly and time-consuming to test every product. This problem can be tackled by having full knowledge on the input.New developments will concern the increase in the amount of spun fiber spinnable fibre and improving the quality of the fibres that are recycled. These developments mainly focus on adjustments to the machinery or recycling line set-up, additional (chemical) treatments and better sorting of the input material. When the input is highly pure and of good quality, it could be a first step to obtain a fraction of spinnable fibres that are (partially) used in a new textile product at a low cost and probably also at a lower environmental footprint. The other fractions could be used as input for other recycling technologies, for example, cotton dust for a pulping process. Thanks to the improving technology and machinery, the amount of spinnable fibres will probably increase in the future.

3. Thermal recycling process

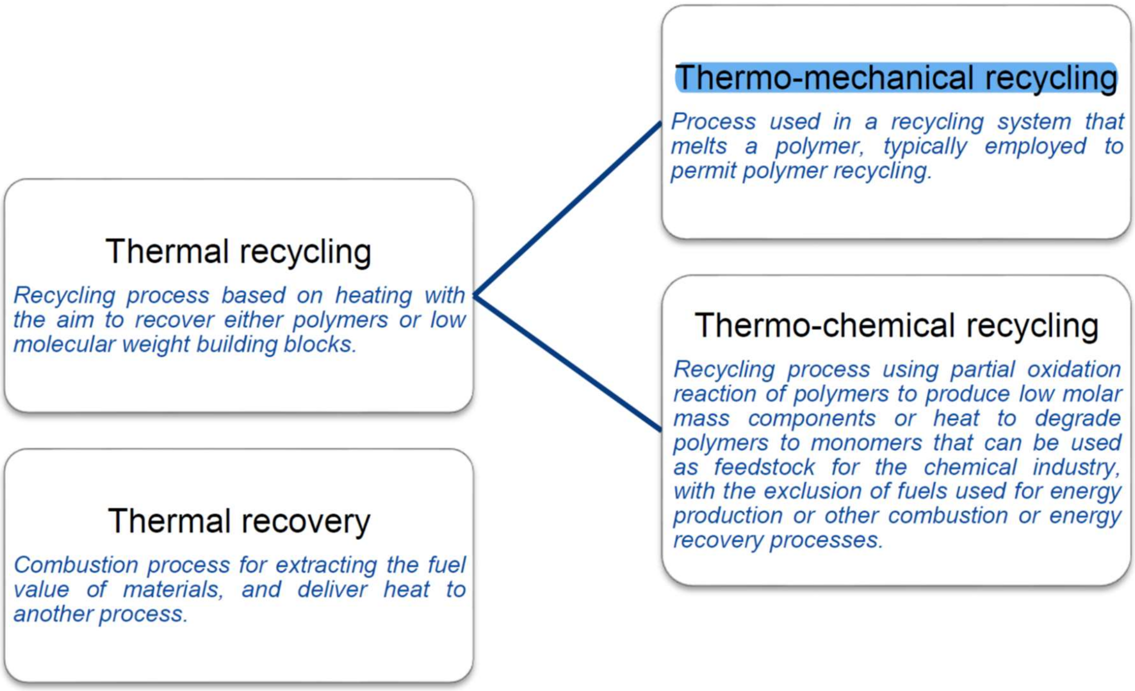
Under thermal recycling, a key distinction should be made between thermo-mechanical and thermo-chemical processes (i.e. gasification, pyrolysis, cracking).The thermo-mechanical process will merely melt the polymer, keeping the chains intact, while the thermo-chemical process will break them down into low molecular weight building blocks. There are two differences definition for thermo-mechanical recycling, and for Thermo-chemical recycling.

3.1. Thermo-mechanical recycling process

The processi s used in a recycling system that melts a polymer, typically employed to permit polymer recycling. These are technologies for recycling thermoplastic textiles, e.g. polyester, polyamide, polypropylene, etc. by melt processing them into a regranulate and/or new fibres. However, recently also thermo-chemical processes are gaining attention for material recovery, more specifically for the recovery of base molecules (e.g., monomers, syn gas, oils) that serve as feedstock for the chemical industry. The ISO 15270 Plastics – Guidelines for the recovery and recycling of plastics waste, already includes cracking and gasification as chemical recycling technologies for conversion of plastic waste into monomers or new raw materials (excluding energy recovery and incineration as well as conversion into fuels for energy purposes). The processes are in theory also applicable to textiles and some research as well as larger scale initiatives are considering textiles as input material.

3.2. Thermo-chemical recycling process

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.Thermo-chemical recycling could be considered a chemical recycling process, but due to the high temprature needed, it was decided that the thermal part is the main influence in the process. An overview of the definitions of thermal recycling and recovery processes is presented in Figure 4.



Thermal recycling

Recycling process based on heating with the aim to recover either polymers or low molecular weight building blocks.

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.

Thermal recovery

Combustion process for extracting the fuel value of materials, and deliver heat to another process.

Figure 4: Overview of definitions regarding thermal recycling and recovery.

4. Thermo-mechanical recycling

Thermo-mechanical recycling is a process using heat to melt thermoplastic textiles and recover the polymers in the form of regranulate or fibres.

4.1. Input

Theoretically, any thermoplastic fibre or textile, both pre- and post-consumer, can be reprocessed into a new fibre via thermo-mechanical reycling. Examples include PET, PA6, PP and PA6,6. However, it is important that the input material consists of only one polymer type or of compatible polymer types. Incompatible polymers will not blend properly which will cause problems in processing, resulting in fibres of lower strength or even prevent fibre production altogether. It should be noted that one fibre type or name can refer to different types of polymers. For example, “polyester” is typically used to refer to fibres or textiles made from polyethylene terephtalate (PET), however it can also refer to polybutylene terephtalate (PBT) or polytrimethylene terephtalate (PTT). Blending these different types of polyester can also adversely affect the processing and the quality of the output. Fibre spinning is a very delicate process and the presence of even a small amount of an incompatible polymer can cause problems in processing and reduce output properties. Other contaminants such as pigments, prints, wash residues, flame retardants, coatings, etc. that are present in or on the fibre or textile, can also hinder the spinning process and/or result in severely reduced output quality.

4.2. Process steps

The general process diagram for thermo-mechanical recycling is presented in Figure 5. It is very similar to the extrusion process of virgin thermoplastic polymers with the exception of the pre-treatment step.

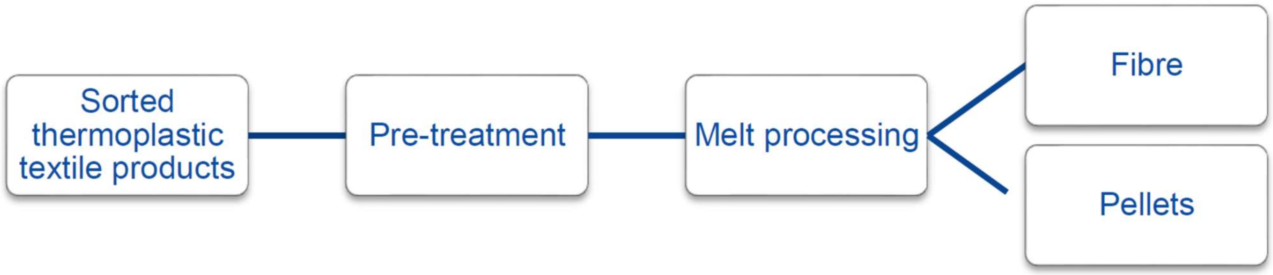


Figure 5 General process scheme for thermo-mechanical recycling

4.3. Pre-treatment

Removal of non-textile parts, washing/cleaning, drying and shredding/grinding to fibres is needed. This can be done in the same way as for mechanical recycling (Process steps). For moisture sensitive materials such as polyester and polyamide, the drying step is very important to avoid material degradation due to hydrolysis during processing at increased temperatures.

4.4. Melt processing

Similar to mechanical recycling of solid plastic waste, thermoplastic textile waste is processed via compounding and regranulation. This involves reprocessing into a granulate which can be further processed into fibres via melt spinning or other processing techniques [10].It should be noted that processing of fibre/textile fluff is generally more challenging because of the low bulk density. Therefore, specialized shredding, feeding and/or compacting equipment is often required to maintain a constant supply of textile or fibrous input.

4.5. Output

Textile yarn (continuous filaments in case of high-quality input: no contamination or degradation, or staple fibre in case of lower quality input) or thermoplastic polymer pellets (regranulate) for other applications (in case fibre spinning is not possible).

Contaminants such as pigments, dyes and other chemicals remain in the material. The output colour is thus dependent on the colours of the input materials and of possible colour changes during processing due to degradation or thermochromic dyes. Hence, to avoid irregular and unwanted colours either the input textile should be colour sorted or a dark dye or pigment should be added. Moreover, some remaining contaminants.

4.6. Advantages

The process is similar to melt processing of virgin material (with the exception of shredding, cleaning, feeding and degassing steps), even more similar to the more established mechanical recycling of solid plastic waste. It is also a cost-effective, efficient and well-known process which means it can be easily implemented.

Next to this there are little emissions that could emerge during the process, only volatile contaminants (e.g. from disperse dyestuff or polymer degradation). The output are fibres can be used in various textile applications, depending on the quality. High quality materials can be used in a higher amount when blended with virgin polymer and/or lead to filament yarns. The lower quality can be blended with virgin material which leads to staple fibres.

4.7. Disadvantages

The polymer/fibre properties deteriorate after each cycle. So, despite the similarities with the melt processing of virgin or waste plastics, specialised equipment or components are required to ensure a stable and continuous process. This depends on the material and state of the material that is being processed. For example, equipment for the polycondensation of polyester might be implemented to increase the quality of the output. In addition, the technology is very sensitive to even low levels of contamination and the state (molar mass/viscosity) of the polymer. Technology holders have also indicated that they are only willing to use production waste or large batches of known origin because of this reason. Since the colorants remain in the polymer material, only dark colours are possible, unless the input is colour-sorted and no colour changes occur during processing: some colorants are thermochromic, meaning that they change colour at a certain temperature.

4.8. Prospect

The process is very interesting for the recycling of production waste. It is estimated that in the next few years the process will reach to TRL 7 soon for post-industrial textile waste.

5. Thermo-chemical recycling

The thermo-chemical recycling processes pyrolysis and gasification differ from one another and from combustion in several ways. Combustion is performed at temperatures in between 800 and 1200°C with sufficient oxygen in order to completely oxidize the material and is mainly used to generate steam for electricity production or for heating. Hence, it is not considered a recycling/material recovery process. Gasification occurs typically at 700-1100°C with insufficient oxygen or steam to achieve partial oxidation and pyrolysis at 350-700°C in the absence of oxygen [12,13] The output products (gas and oil) generated by gasification and pyrolysis can be used for heat and power purposes, however, with subsequent purification/upgrading steps these can also be converted into chemical intermediates and therefore serve as feedstock for the chemical industry.The pyrolysis technology is already used to convert plastic waste into solid, liquid and gaseous fuels (Miandad, et al. 2019). Moreover, several industrial players are developing new or modified pyrolysis processes with the intention to produce not only fuels but also raw materials for the chemical industry [12].

5.1. Input

In theory any waste can be processed via thermo-chemical recycling as long as it consists of organic/carbon-based material, including biomass, plastics (thermoplastics as well as thermosets) and textiles. The ability to treat heterogeneous and contaminated waste is one of the main advantages of gasification, the flexibility of feedstock is higher than for other recycling technologies. In the gasification process the targeted molecules are carbon and hydrogen, and as most commercially produced polymers contain high amounts of carbon and hydrogen, they are optimal feedstocks for forming syngas through gasification. However, the overall composition of the feedstock can incluence the product mix when it carries high amounts of inorganic material. An example of an inorganic component is nitrogen present in polyamide, which will influence the process to the extent that the amount of polyamide in a production batch will be limited. Moreover, as with any chemical process, depending on the input, the process conditions need to be adjusted to ensure a well-functioning process and high yield.

Therefore, also for this technology, it is imporant to know the composition of the input material. One of the questioned technology holders is capable of processing practically all plastic types (PET, HDPE, LDPE, PP, PS and other) with the exception of PVC (plastic type 3) and other plastics with high halogen content due to existing processing limitations, and not technology limits. The gasification process is capable of dealing with small amounts of PVC, however, due to the corrosive nature of chlorine, it is not a desirable feedstock. Nevertheless, some processable materials (like polyamide) are only wanted in limited quantities and they mainly focus on plastics and textiles made from polyester and blends with polyester, as of today. In addition to plastics they are also able to process cellulosic materials. Technology holders have stated that contamination with certain chemicals can influence the process but it is generally not a main concern as most contaminants don't cause major problems. Hence, the input textiles don't require washing or cleaning. Nevertheless, extra gas treatment/cleaning steps might be necessary depending on the desired chemical intermediate, which will increase the investment and operational costs. Therefore, feedstock requirements can also be guided by economical concerns.

In addition to textile feeds, further input materials for the gasification, such as fossil fuel, industrial CO2 or other organic sources, are currently used for scale. In the future, more fossil input will be replaced with waste. In addition, energy, both from external sources and a portion that is captured from the process itself (auto-consumption), and air,oxygen or steam (depending on the type of gasifier) are needed to run the process.

5.2. Process steps

The general process scheme for thermo-chemical recycling via gasification is shown in Figure 6.

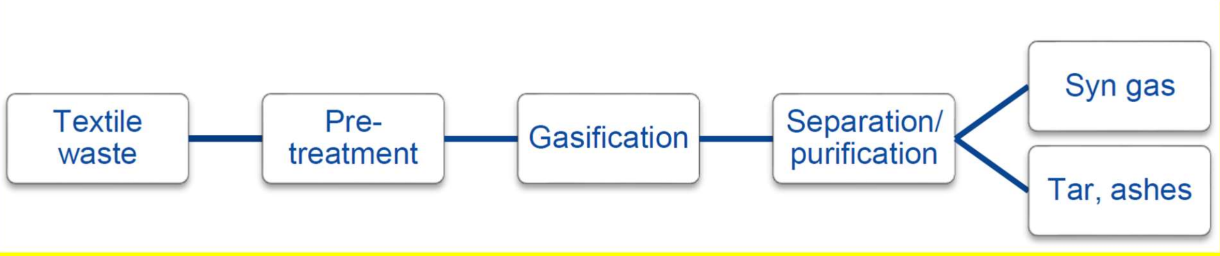


Figure 6: General process scheme for thermo-chemical recycling via gasification.

5.3. Pre-treatment

Non textile parts such as metal buttons are removed as they can cause problems during processing. This can be done in the same way as for mechanical recycling. Drying can be necessary when the input material is wet. Size reduction to homogenize and compact the input textiles is required as well.

5.4. Gasification

The actual gasification step entails heating the waste to temperatures of 700 to 1100°C with a controlled amount of oxygen, air, oxygen enriched air and/or steam [12.] During the process a series of complex endothermic chemical reactions occur, resulting in the production of volatiles (i.e. gases and tars) and a solid residue (i.e. char or ash). The composition of the resulting volatiles depends on the polymer reaction mechanisms, which in turn determines the subsequent cracking and reforming reactions happening in the gaseous phase. The gasifying agent is also an important determinant for the output. Air gasification will result in a syngas mainly suitable for energy production, while steam gasification leads to nitrogen free syngas with a composition appropriate for chemical synthesis applications [14.]The process can be performed in different types of reactors, such as bubbling fluidized bed (BFB) gasifiers; circulating fluidized bed gasifiers; dual fluidized bed gasifiers; plasma gasifiers; and entrained flow gasifiers. The general design includes the gasification reactor with feeding system and the difference between the various types lies in the heating mechanism, the inlet for gasification agents and the location of the syngas output [12,15]. The ideal reactor design depends on the input and output, for example gasifiers for plastic waste need other features than biomass/coal gasifiers. More specifically, they need to be able to provide high heat transfer rates to promote fast depolymerisation, be able to handle the sticky nature of plastics, allow an appropriate residence time distribution to favour tar cracking, and so on. Fluidized bed reactors are mostly used for waste plastics, altough other reactors have been used as well [16].

5.5. Separation/Purification

A series of traps/separators each collect a fraction of the reaction products. This can be achieved via condensation by cooling in ice-water, using liquid nitrogen, etc. (e.g., for the tar) or the simple capture of the gasses (e.g., for the syngas). In order for the syngas to meet the requirements for the production of chemical intermediates, components containing sulfur, halogens, nitrogen, etc. need to be removed. Hence, a very efficient gas cleaning system is needed [16].

5.6. Output

Different fractions coming out of the process can be viscous liquids (also called oil or tar fraction), condensable and non-condensable/permanent gases (syngas) and inorganic residue such as carbon soot, metals and minerals (also called ash). The specific output of the gasification process depends on the input waste (type and composition), the reactor type and process parameters (gasifying agent, temperature, heating rate, residence time, etc.), meaning that fractions might have a different content and the quantities might also shift [12]. The obtained fractions can serve as feedstock for the chemical industry, but also as fuel. Syngas is a mixture of hydrogen (H2) and carbon monoxide (CO) including lower concentrations of carbon dioxide (CO2), methane (CH4) and potentially other hydrocarbons. After purification it can be further refined to chemical intermediates via different steps. Figure 9 illustrates how syngas can serve as feedstock for the chemical industry through various refining steps [12],[17]. For this purpose conditioning of the syngas may be required, for example by water-gas shift (i.e. adjustment of the H2/CO ratio) and CO2 removal (H.S.Tay, T.L.Ng en K.S.Ng 2012). One of the main products derived from syngas is methanol, which in turn can be converted into a range of chemical intermediates [17]. Steam gasification results in a N2-free syngas with high H2/CO ratios which is better suited for chemical synthesis than the syngas produced by gasification from direct air [12,18] .Gasification with pure oxygen (O2) combines the advantages of both gasifying agents, resulting in a high-quality syngas but is more complex and expensive due to the need for air separation.A possible technology of process foresees polyester textile material be degrad in CO and H2 is subsequently converted into methanol. The methanol is converted into acetic acid later used in combination with wood pulp to produce cellulose acetate which is dry spun into fibres for textile applications.

Research on the gasification of textiles in a fluidized bed reactor showed that 100% cotton produced high yields (0.8-0.9 kg/kgdaff; kg dry ash free fuel, excluding all moisture and ash) of permanent gas (the non-condensable fraction of syngas) suitable for chemical synthesis, while 100% polyester yielded not only permanent gas (0.7-0.8 kg/kgdaff) but also aromatics

(0.1 kg/kgdaff), making valorisation of benzene, toluene, xylene and styrene (BTXS) an option as well. Altough textile blends resulted in lower yields (0.5-0.7 kg/kgdaff permanent gas and 0.1 kg/kgdaff BTXS), the uncoverted fraction could be utilized to produce the energy required for the gasification process (Vela, Maric en Seemann 2019).

5.7. Advantages

The main advantage of this technology is the ability to process more complex, heterogeneous waste streams, including fibres and blends of fibres that can't be recycled by any other technology or would be downcycled as best option (e.g., thermosets, composites, coated and laminated textiles…). Hence it does not need high-quality, sorted textile waste. It is also more tolerant to contaminants compared to thermo-mechanical or chemical recycling technologies and therefore does not require thorough cleaning and decontamination pre-treatment of the input textiles. Unlike mechanical and thermo-mechanical recycling, gasification is less sensitive to material degradation happening during the product lifetime or recycling [19].The input doesn't need to consist solely of textiles material. Materials from different industries (biomass, plastics, textiles…) can be blended, as the carbon and hydrogen content are the molecular targets. This gives a significant advantage as the larger scale of waste material allows to set up an economically viable recycling process. In this way also smaller textile fractions that can't be processed by another technology because it is economical not feasible to develop and scale up a production process, could still be treated. The technology leads to pure, uncontaminated, virgin-like feedstocks, making it ideal for textiles containing compliant chemicals that cannot be removed via other recycling technologies.

5.8. Disadvantages

The process of thermo-chemical recycling is energy consuming due to the high temperatures needed.Together with the required separation and purification steps, the enviromental impact is expected to be higher compared to mechanical and thermo-mechanical recycling of thermoplastic polymers. However, processing (textile) waste requires less energy than processing fossil input, hence the environmental impact is lower than for the traditional gasification of fossil feedstock.Most gasification plants are optimized for energy recovery and fuel production from biomass or plastic waste and need adaptations and additional purification steps in order to be suitable for textiles as input and clean syngas for chemical synthesis as output. These additional cleaning steps increase investment and operational costs. Moreover, there is a risk for greenwashing when gasification is claimed for recycling because a major part of the input material can go to fuel production instead of feedstock for the chemical industry. This is technology dependent so clarification is required to ensure credibility of claims. It is important to note that this technology is still evolving and developments are focusing on increasing the yield of output suitable as chemical feedstock.The fact that the output can serve many applications and is not limited to the textile industry, can be seen as an advantage, but it also makes it more difficult to make solid claims on the actual recycled content in the final product.

6. Chemical recycling process

A process using chemical dissolution or chemical reactions which is employed in polymer or monomer recycling. There are several possibilities within this recycling technology.

- 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

Three major technologies can be identified in this respect: Polymer recycling of cotton via a pulping process, Monomer recycling of PA6 or PET via (partial) degradation into oligomers or monomers, and technologies focusing on the recovery of both cellulose and PET from polycotton blends. Due to the large differences between these technologies, they will be treated separately in the following sections.We want to note that some technology holders only pulp the cellulosic materials by grinding the cellulose into nano cellulose and dispersing it in a liquid without breaking down the cellulose into However, from this point on, the pulp needs chemical processing to obtain a regenerated cellulose fibre. In addition, the outcome is a different fibre when the cellulose comes from cotton or other natural fibre. Therefore, it was decided to categorise also this type of pulping under chemical recycling. single polymers chains. This could be seen as mechanical recycling. However, from this point on, the pulp needs chemical processing to obtain a regenerated cellulose fibre. In addition, the outcome is a different fibre when the cellulose comes from cotton or other natural fibre. Therefore, it's is classifiched also this type of pulping under chemical recycling.

6.1. Polymer recycling of cotton via a pulping process

Cellulosic fibres such as cotton can be chemically recycled via a pulping process. This process can be categorized as polymer recycling, as the cellulose chain is not broken down to monomer level (i.e., glucose), although it can be partially degraded. Regenerated cellulosic fibres are produced from the pulp via solution spinning processes (e.g., viscose, lyocell, ioncell-F process, etc.). These fibres should have the same properties as other regenerated cellulose fibres (e.g., from wood pulp or other cellulosic sources).Theoretically, any cellulosic material could be recycled into regenerated cellulose fibres via a pulping process. However, as cellulose from different sources (e.g., wood, cotton, viscose, cardboard) can differ in chemical structure and viscosity, most technology holders indicated that changing the source would require adaptations to the pulping process or pre-treatment. Hence the need for a pre-treatment step or independent/specific pulping process for processing cotton waste, compared to wood as input material. Moreover, if the viscose or in general all regenerated cellulose fibres would be recycled via pulping, adaptations to the pre-treatment or pulping process would be required as well. Technology holders prefer textile waste with a cotton content of at least 50%, preferably as high as possible. Most processes could technically handle lower cotton levels, however this would not be economically feasible. Some technologies can separate PET from cotton, but most are still working on the recovery of PET and currently only the cotton fraction of blends can be recycled. In contrast to mechanical recycling, the fabric structure (knitwear, woven, non-woven…) has no influence on the chemical recycling process via pulping. The tolerance to dyed textiles depends on the process, but most technologies include a decolouring and/or bleaching step, although with varying efficiencies. The colorant which is present in the material determines if bleaching is possible. The removal of any hard parts (buttons, zippers…) is required and can be done in the same way as for mechanical recycling . Most technology holders indicated that both pre- and post-consumer textile waste can be handled. The efficiency of the recycling process depends highly on the purity of the input material as any contamination (i.e. non-cellulosic content) will reduce the yield or require additional separation or purification steps, which increase both the economic and environmental cost. The application of sorted textile waste is thus very important Knowledge of the applied dyes and additives would allow a more efficient removal.

A. Input

Theoretically the cellulose recovery process can be repeated several times, however the polymer chain degrades with each repetition [20]. Hence the quality of the input should be monitored closely. Additional input that is required besides cotton textiles are chemicals for dye removal and bleaching, water for washing, water and chemicals for pulping, electricity, and steam. Some technologies process 100% waste but most of them add at least 50%

virgin wood pulp to 50 the cotton pulp to achieve better fibre properties or because the process requires a too big adjustment/optimization to be viable for higher cotton pulp contents.

B. Process steps

The general process diagram for the recycling of cotton (or other cellulosic textiles/materials) into man-made cellulose fibres is presented in Figure 7.

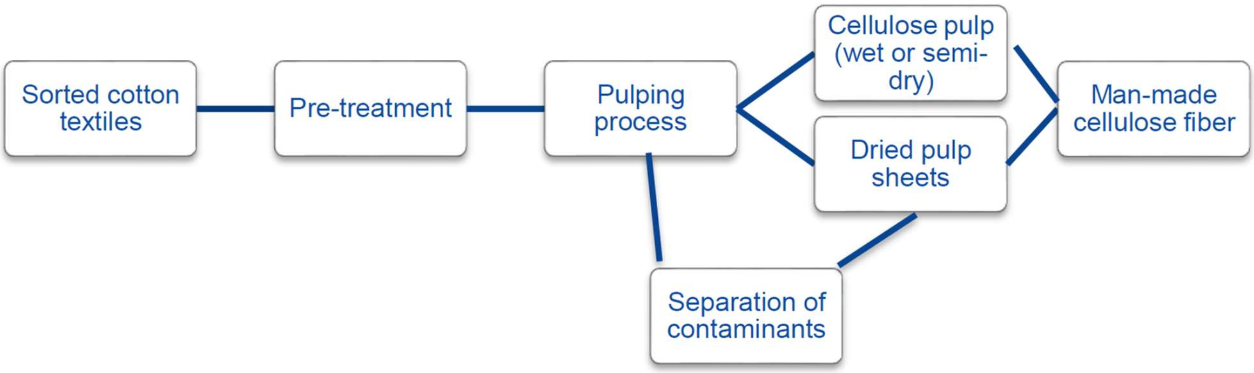


Figure 7:: General process scheme for the recycling of cotton textiles via a pulping process.

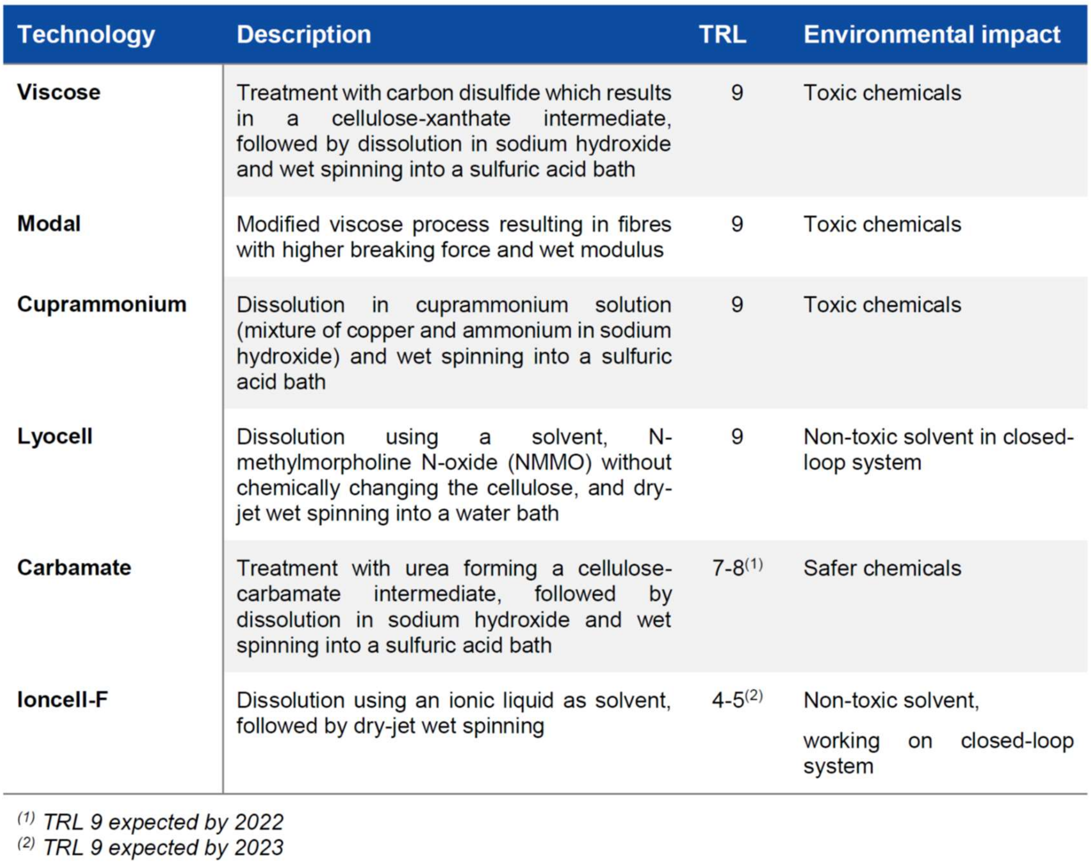
C. Pre-treatment

Like for the other technologies, mechanical removal of non-textile parts and shredding/grinding to a fibrous material is needed.

D. Pulping process

The cotton cellulose is suspended in a liquid with chemicals and can be depolymerized to a certain extent depending on the specific technology, turning the material into a slurry/pulp called dissolving pulp. This can include several steps to adjust the viscosity and reactivity of the cellulose. The process often includes a chemical treatment to remove dyes and finishes as well as a bleaching step It should be noted that there are various processes for spinning regenerated cellulose fibres of which the newer technologies (Lyocell, carbamate and ioncell) use more environmentally friendly and safer chemicals, often in closed-loop systems. These processes should be considered separately from the pulping process of cellulose textile waste because they are similar to the virgin regenerated cellulose fibre production. The pulping of the cellulosic textile waste is the actual recycling step. A non-exhaustive overview of such spinning processes is provided in Table 5. of which the latter is similar to the traditional wood pulp production process.

Table 5: Overview of spinning processes for the production of regenerated fibres from cellulosic pulp.



Technology	Description	TRL	Environmental impact
Viscose	Treatment with carbon disulfide which results in a cellulose-xanthate intermediate, followed by dissolution in sodium hydroxide and wet spinning into a sulfuric acid bath	9	Toxic chemicals
Modal	Modified viscose process resulting in fibres with higher breaking force and wet modulus	9	Toxic chemicals
Cuprammonium	Dissolution in cuprammonium solution (mixture of copper and ammonium in sodium hydroxide) and wet spinning into a sulfuric acid bath	9	Toxic chemicals
Lyocell	Dissolution using a solvent, N-methylmorpholine N-oxide (NMMO) without chemically changing the cellulose, and dry-jet wet spinning into a water bath	9	Non-toxic solvent in closed-loop system
Carbamate	Treatment with urea forming a cellulose-carbamate intermediate, followed by dissolution in sodium hydroxide and wet spinning into a sulfuric acid bath	7-8(1)	Safer chemicals
Ioncell-F	Dissolution using an ionic liquid as solvent, followed by dry-jet wet spinning	4-5(2)	Non-toxic solvent, working on closed-loop system

(1) *TRL 9 expected by 2022*
(2) *TRL 9 expected by 2023*

At present, most technologies have already reached a high TRL of 7 to 9, at least for pure cotton textiles as input material. The TRL 7-8 technologies are expected to reach TRL 9 by 2025 at the latest. Process capacities range from 10 kg/day to thousands of tonnes/year. The main requirements for further upscaling are more production time and customer feedback for optimization of the process and continuous deliveries of suitable textile waste (in terms of purity and composition) as feedstock. Some technology holders have indicated that they are exploring the recycling of polycotton blends, however it is currently less appealing economically due to the additional separation and purification steps that need to be implemented/developed.

6.2. Monomer recycling of PA6 and PET

Chemical recycling via depolymerization implies that the polymer chains are completely broken down into monomers and is thus classified as monomer recycling. These monomers are separated and purified before entering the polymerization process again to produce new virgin-quality polymers. In theory many polymers can be depolymerized, but efficient, practical processes have not (yet) been developed, e.g. for PA6,6 a polymer with similar applications as PA6. Therefore the following sections focus on PET and PA6 (nylon 6) as these are the only synthetic fibres that are currently recycled via depolymerization on a commercial, though still limited, scale.

A. Input

In theory any PA6 or PET textiles or plastics can serve as input. However, in practice:

- For PET: generally post-consumer food packaging materials and (pre-consumer) industrial waste , PET textiles recycling is still under development.
- For PA6: mainly post-consumer PA6 from carpets, also fishing nets and industrial waste (oligomers+plastic waste generated by polymer industries)

Depending on the process, “light” contamination with other materials is allowed, generally dyes and prints and even certain finishes and coatings can be accepted. Nevertheless, most technology holders request a minimum of 80-90% PET or PA6 content for economic reasons. Knowledge of the composition and adequate sorting of the input is thus of great importance.

B. Process steps

The general process diagram for the recycling of synthetic fibres like polyamide and polyester into the same synthetic fibres is presented in Figure 8.

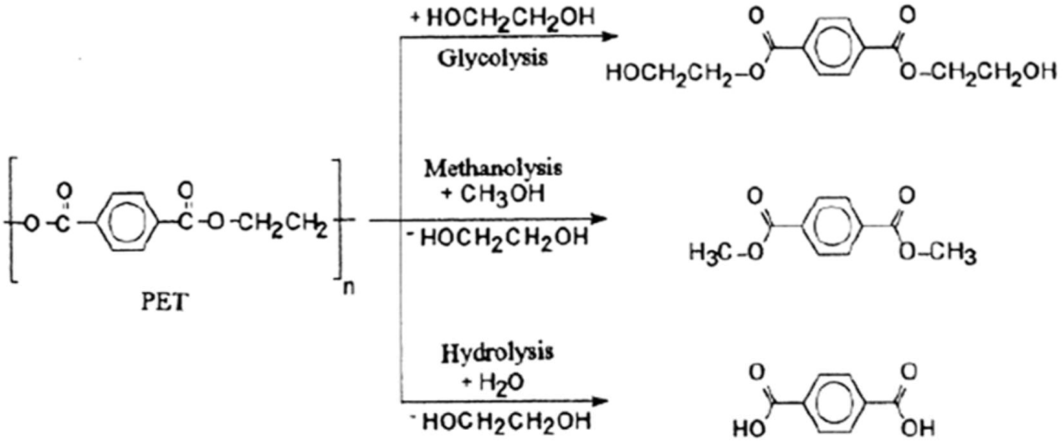
Figure 8: General process scheme for the recycling of synthetic fibres like polyamide and polyester into the same synthetic fibres

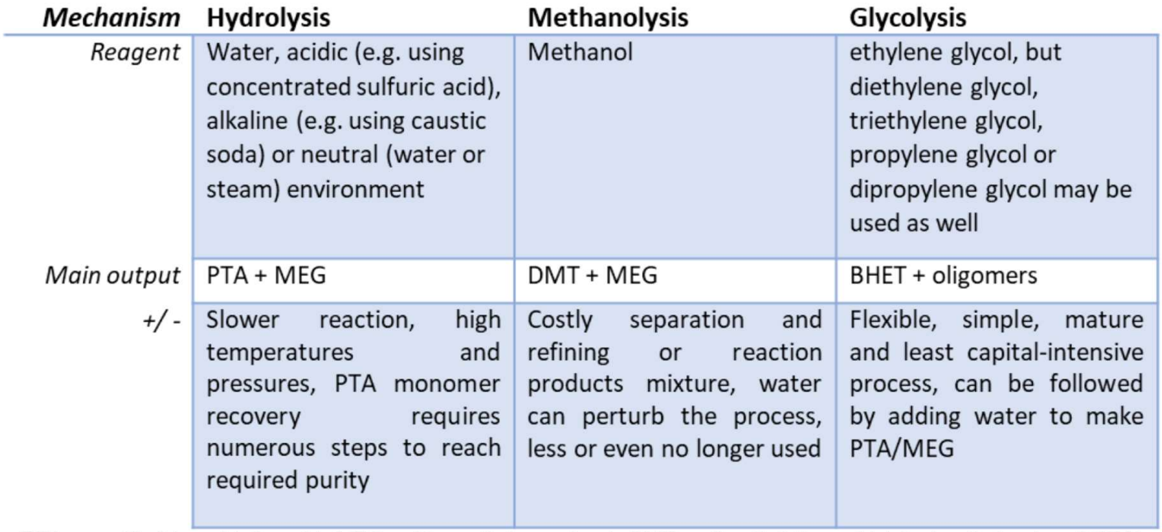
C. Pre-treatment

The pre-treatment can include several of the following steps, depending on the type and shape of the waste: cleaning, sorting, mechanical removal of non-textile parts and by extension non-PET or -PA6 parts (e.g. the backing of carpets), shredding/grinding, washing, granulation and/or pelletizing [21]

D. Depolymerization

The PA6 or PET materials are depolymerized, some after first dissolving the polymer, via different technologies and various reaction conditions (temperatures/ pressures/ time/ catalysts). PA6 and PET polymers contain functional groups that can be cleaved by certain reagents also acting as the solvent of the reaction. These types of chemical reactions in which the solvent is one of the reagents and is present in great excess, are called solvolysis reactions. The applied solvents are typically water (i.e., hydrolysis), alcohols (i.e., methanolysis) or glycols (i.e., glycolysis) [22]. In practice PA6 is generally depolymerized via hydrolysis, e.g. using high pressure steam [23], via acid hydrolysis and super-heated steam[24,25], or via glycolysis . For PET all three of the reaction mechanisms, being hydrolysis (alkaline, acid or neutral), methanolysis and glycolysis are used for depolymerization, although the latter is the most common. The final output depends on the reagent [27]. The most important characteristics of each process are presented in Figure 9.





Mechanism	**Hydrolysis**	**Methanolysis**	**Glycolysis**
Reagent	Water, acidic (e.g. using concentrated sulfuric acid), alkaline (e.g. using caustic soda) or neutral (water or steam) environment	Methanol	ethylene glycol, but diethylene glycol, triethylene glycol, propylene glycol or dipropylene glycol may be used as well
Main output	PTA + MEG	DMT + MEG	BHET + oligomers
+/ -	Slower reaction, high temperatures and pressures, PTA monomer recovery requires numerous steps to reach required purity	Costly separation and refining or reaction products mixture, water can perturb the process, less or even no longer used	Flexible, simple, mature and least capital-intensive process, can be followed by adding water to make PTA/MEG

PTA = purified terephtalic acid, MEG = Monoethylene glycol, DMT = dimethyl therephtalate (methyl ester of PTA), BHET = Bishydroxylethyleneterephtalate (bis(hydroxyethyl) ester of PTA, PTA with 2 MEG)

Figure 9: Illustration (top, (Janssen and van Santen 1999) and characteristics (bottom, (Bartolome, et al. 2012)) of the different methods for the depolymerization of PET.

It should be noted that in addition to the three solvolysis methods, recently a fourth method has become available, namely an enzymatic depolymerization reaction. With this technology, the polymer chain is broken down into monomers using an engineered PET-depolymerase enzyme. It allows the recycling of all forms of PET plastics and fibres, even in mixtures as the enzyme is selective for PET. The process runs at low temperature, at atmospheric pressure and without solvents [28,29]. The enzymatic depolymerization technology can be considered a biochemical recycling process since the chemical reaction is mediated by a biological catalyst, the enzyme.

E. Post-treatment

The post-treatment typically includes one or more of the following steps:

- Purification

1)Separation of contaminants (e.g., removal of insoluble substances via (micro)filtration)

2)Removal of colorants (e.g., using activated carbon, activated clay minerals such as clay, bentonite, montmorillonite, zeolites)

- Separation

1) Distillation of caprolactam or removal of solvent via evaporation. Not in all processes a solvent is used. When there is no solvent used this implicates there is also no need to remove it.

2) Crystallization of BHET/PTA

- Drying

F. Output

PTA and MEG are the traditional monomers obtained from PET, but the final output depends on the reagent. The main output options are regeneration of base monomers (in case of the methanolysis mechanism for dimethyl terephthalate (DMT) and hydrolysis or enzymatic mechanism for producing pure terephthalic acid (PTA) and ethylene glycol (EG));conversion into oligomers and bis(hydroxyethyl) ester of PTA (BHET) (via glycolysis) [30]. See Figure 12 (bottom) for the specific output per process. These monomers can be repolymerized to obtain high purity, virgin grade PET. Concerning PA6 recycling, the output is caprolactam which can be repolymerized to virgin grade PA6. Just like the pulping process of cellulose fibres, the efficiency of the chemical recycling of synthetic fibres depends highly on the purity of the input material. The waste that is generated is a non-PET/PA6 solid residue or sludge consisting of other synthetic or natural fibres, dyes, chemicals from finishings/coatings/prints, etc. depending on the input composition.

G. Prospect

Chemical recycling of PA6 textiles via depolymerization is already an established technology, being at TRL 9 for a decade. For PET textiles the TRL-levels vary from 4 up to 7, with 500 tonnes/year being the largest available production capacity to date . The first technologies are expected to reach TRL 9 by 2023 as currently an industrial production line is being built. For the lower TRL technologies, funding and more R&D at the pilot level are mainly needed to make further progress.

Moreover, there have been new developments in order to improve the solvolysis processes:

- Depolymerization by microwave technology: Hydrolysis process using microwave radiation instead of traditional heating which claims to be an economically efficient chemical recycling method for PET. This technology is currently at TRL 6, a demonstration plant with capacity of 60 kg/h is being constructed.
- Ionic liquid technology: accelerated solvolysis process based on a catalyst complex consisting of a magnetic ionic liquid. It claims to be able to remove colorants and other additives, allowing the upcycling of all types and colors of PET waste into feedstock for virgin-quality recycled PET [31]. The technology has reached TRL 8.

6.3. Recycling of polycotton blends

Several technologies focus on the recycling of both cotton and PET from polycotton blends via different approaches.

A first method applies solvent-based dissolution and filtration processes to separate different materials and extract the desired components. In principle the polymers chains should remain unaffected, hence this method is categorized as polymer recycling. The recovered cellulose can be applied in a typical pulping and wet spinning process, while the PET polymers remain largely intact [32].

A second type of technology consist of a hydrothermal approach to (partially) degrade either cotton or PET or both. These processes rely on water, pressure, temperature and green chemistry: the final output depends on the specific process applied

A third approach focuses on (partial) degradation of cotton from polycotton blends via an enzymatic route (i.e., biochemical recycling) resulting in glucose, cellulose powder and PET fibres Input

Any polycotton-polycellulose material, but depending on the technology also pure polyester and/or pure cotton/cellulose can be processed. Most technologies can deal with a certain percentage of contamination with other materials (nylon, acrylic, wool, elastane…), however hard/metallic accessories such as zippers and buttons and generally also coatings must be removed. Again, sorting of textiles waste is required as knowledge of the composition (e.g. 100% cellulose or PET or the cellulose/PET ratio for blends) is often required for a good process efficiency.

A. Process steps

B. Pre-treatment

The pre-treatment requires mechanical removal of hard, non-textile parts, cutting and shredding of the fabric to smaller pieces

C. Separation and recover

a) Cotton and PET polymer recycling via a dissolution process

Pure polyester and polycotton textiles enter the process together, but the PET/cotton ratio is balanced in order to ensure a good process yield. Almost any contaminant (dyes, elastane, TiO2) can be removed during the process. PET and cotton are both dissolved, each with a different solvent, used in a closed loop system. The PET pathway includes dye-removal, polymer solvent separation, purification and polymer restoration steps. Although the PET polymers are kept largely intact (i.e. no depolymerization to oligomer of monomer level), the final process step is meant to increase the molecular weight and achieve virgin quality. The output of the cotton pathway is cellulose pulp for man-made cellulose fibre production.

b) Hydrothermal recycling processes

A hydrothermal process can be defined as a process in an aqueous system under pressure and increased temperature. It typically involves subcritical water which is liquid water at a temperature between 100°C (i.e., the atmospheric boiling point of water) and 374°C (i.e., the critical point of water). Textiles are treated with water containing one or more green acids (e.g., an organic acid or sulfuric acid), no organic solvents, under increased temperature and pressure. Some technologies result in the decomposition of cotton which is recovered as cellulose powder. Next, the polyester fibres are separated via filtration with no depolymerization, retaining the quality of the fibres, ready for spinning.However, the fibres can also be melted, extruded and pelletized, while chain extenders and/or stabilizers can be added to obtain virgin quality PET pellets [33]. Final steps include water removal and drying. Other hydrothermal technologies result in the depolymerization of PET to TPA and ethylene glycol, and subsequent recovery of the cellulose fraction via a dissolution process or via a second subcritical water treatment. In order to improve the efficiency and reduce energy consumption, a co-solvent with or without phase transfer catalyst can be used during the subcritical water treatment. The exact processing conditions depend on the input: an acidic (e.g., using acetic acid or other organic acids) medium is used for cotton and cotton-polyester blends, while an alkaline environment (e.g., using sodium or potassium hydroxide) is required for PET and polyester-cotton blends. TPA is precipitated and crystallized after which it can be repolymerized and melt spun to PET filament. The recovered cellulose can be further treated to produce pulp for wet spinning of regenerated cellulose fibres .The different processes can include a colour removal/bleaching step as well.

c) enzymatic recycling process

The first step consists of a pre-treatment to modify the textile structure, more specifically to reduce the crystallinity of the cellulosic fibres and enhance its susceptibility to enzymatic hydrolysis. Next, a fungus is grown onto the textile waste. This fungus will secrete enzymes in situ through solid state fermentation or submerged fermentation. These enzymes are then recovered for use in textile waste hydrolysis. For the textile waste hydrolysis step the recovered enzyme solution is thoroughly blended with the pre-treated textile waste in a bioreactor. Cotton is hydrolysed into cellulose and soluble glucose, while PET (or another non-biodegradable material) remains intact and is separated as fibre via filtration. Finally, PET is re-spun into yarns, while the cotton hydrolysate is purified by activated carbon to obtain a glucose-rich syrup. This syrup can be converted into plastics, surfactants, and chemicals (via industrial biotechnologies) [34]

D. Output

The dissolution process results in PET resin (pellets) which can be respun to filaments and cellulosic pulp or powder which can be further processed into regenerated cellulose filaments. The different hydrothermal-type technologies have different outputs, including cellulose powder or pulp and either polyester fibres (applicable as such or remelted and granulated to PET pellets) or PET monomers that can be repolymerized to virgin PET resin. The enzymatic process produces cellulose powder and glucose syrup which can be converted into plastics, surfactants, and chemicals (via industrial biotechnologies) as well as PET fibres that can be re-spun [35]

E. Prospect

The solvent-based dissolution and filtration technology is currently at TRL 5 and is expected to reach TRL 6 in 2022 and TRL 9 in 2024/2025. A demonstration facility is currently being designed and will be built in 2022. The different hydrothermal technologies are at TRL 6 to 7, approximately. They are expected to reach TRL9 in 2023/2024 (Circ 2021) (Waste Management World 2021), while the enzymatic approach is at TRL 5, expected to reach the next TRL in 2021 Q3 and TRL9 in 2023.

F. Advantages

The main advantage is that the recycled material can be purified and separated to obtain a pure, colourless polymer of good or even virgin-like quality.This technology is the only option for degraded or contaminated polymers and heavily damaged fibres if they can’t be processed by other technologies such as mechanical or thermo-mechanical recycling. Chemical recycling can restore the polymer.

G. Disadvantages

Some technology holders claim that the cost of the chemical recycling process is more or less equal to the corresponding virgin production process. In addition, when the inputmaterial is heavily contaminated additional purification steps might be required, which will further increase the production cost. In addition, compared to the mechanical and thermo-mechanical recycling processes, chemical recycling technologies are more expensive.Looking at the environmental impact, chemical recycling processes are expected to have the highest impact due to the additives/chemicals/solvents needed in the dissolution or de- and repolymerisation processes. This is less of an issue for the enzymatic depolymerisation as enzymes are used for the depolymerisation process. However, it is still valid for the repolymerization. Like all other technologies, improvements of recycling of polycotton blends are being made, for example, solvent-free process

7. Conclusion

It should be noted that thermo-chemical recycling or other textile recycling technologies are not substitutes to one another. All technologies complement each other and, in the future, it is likely that the most sustainable solution to handle textile waste will be to integrate different technologies.

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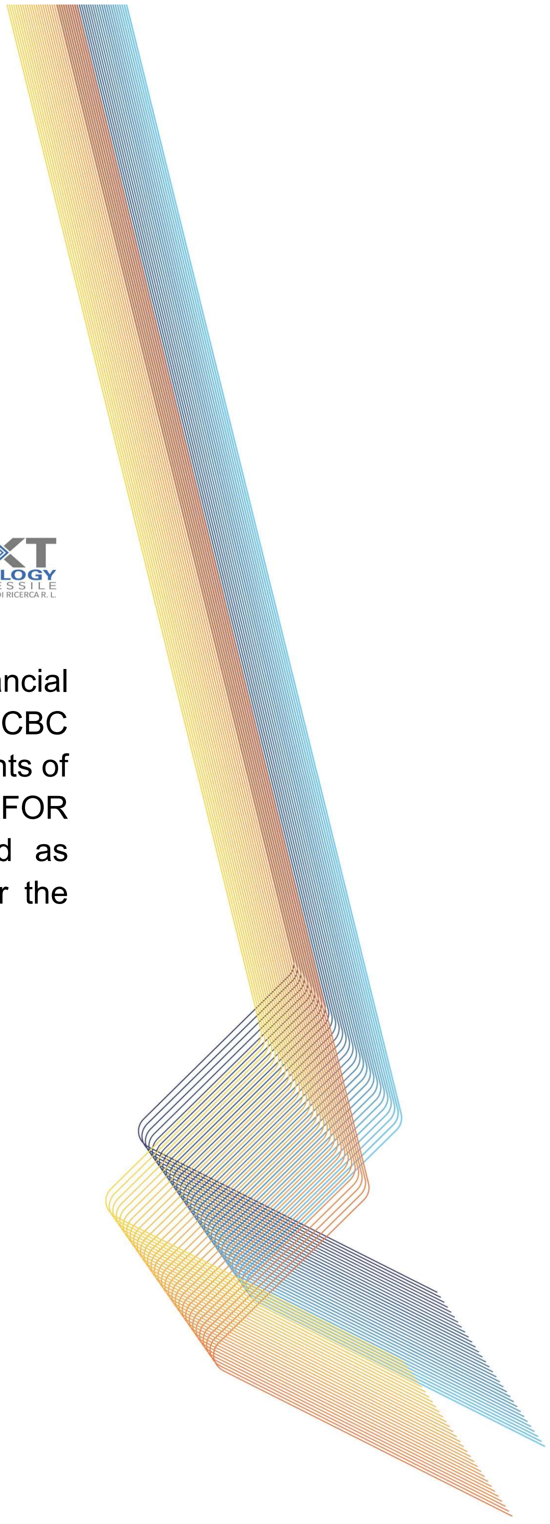

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This publication has been produced with the financial assistance of the European Union under the ENI CBC Mediterranean Sea Basin Programme. The contents of this document are the sole responsibility of TEXFOR and can under no circumstances be regarded as reflecting the position of the European Union or the Programme management structures.