TEXTILE RECYCLING: SCENARIOS AND STATE OF THE ART

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Foreword

The report aims at offering an overview of the scenario of initiatives the textile machinery industry deploys to increase the sustainability and circularity of the textile and fashion segment. Considerations focus on textile recycling systems and basic technologies of an approach to circularity, which, however, do not cover all objectives. In fact, goal of a sustainable industry, no matter the sector, is avoiding or, at least reducing waste production and ensuring that goods become waste as late as possible. That is when recycling proves to be by far preferable rather than incineration and landfilling, as mentioned on the waste hierarchy defined by the European Commission.[1]

Such a high-flying claim was suggested not only in literature about environmental transition of economic systems since the historic report *The Limits to Growth*, through which in 1972 the Club of Rome sounded a warning against the unsustainable use of global resources. It also characterizes the current debate about politics, with the 2030 Agenda[2], promoted by UN in 2015, together with the commitment to keep global warming increase within 1.5°C and the European Green Deal[3], all of them major milestones on the path.

In fact, the introduction to the report covers European policies that, in the latest few years, mentioned the industry as beacon industry on the global scenario thanks to its economic and social role. However, it is also as a sector that deserves a continuous attention because of the environmental impact of its processing and of logistics as well as because of effects due to the use of products. All this is demonstrated by the dispersion of microplastics during washing of garments. The situation appears worse particularly due to the continuous production of enormous volumes of waste often difficult to manage. As mentioned even by the European Commission, '*in the European Union alone, we throw away about 5.8 million tonnes of textiles every year. That is nearly 11 kilos per person'*[4]. Meanwhile, *'in the world, this means that the equivalent of a rubbish truck full of clothes ends up on landfill sites or in an incinerator every second'*[5]. Separate waste collection aiming at finding new uses for textile waste is still inadequate. ***'****On average, 38% of used textiles placed on the EU market are collected separately in the European Union. It turns out that the remaining 62% is disposed of as a mixed waste fraction''*[6]*.*

Both the EU governance and players supporting the environmental transition of the fashion industry, as well as enterprises and their representatives, research centres and analysis labs, chemical producers, textile machine manufacturers, movements, standardisation and certification bodies, just to name some stakeholders directly called upon, are aware of the need to face the problem from different sides. They range from design to production processes, from goods handling to use, to management at end of life. There is now a widespread belief that environmental issues are interwoven with social issues and that the whole fashion value chain is being reconsidered.

However important it is to indicate any critical issues, the efforts should be acknowledged, launched by this industry in the last few years to reduce its environmental footprint.

In fact, the whole supply chain was and is a key player of substantial change covering energy saving, chemical safety, selection of materials and suppliers, supply chain check, measuring of the carbon footprint, experimenting business patterns based on principles of circular economy. Such performances have been made possible through dialogue and synergies that technology producers have built up with customers; they cover circulation of working methods and sustainable, circular business patters in the whole value chain.

Hence, the report does not only cover recycling; it considers some emergent strategies of this industry: preventing waste production through support of new generation technologies, regenerating biomass to obtain materials for the textile and fashion industry. A 360° vision that puts technology producers at the centre of strategies the EU is phrasing to accelerate the transition of the textile industry towards more sustainable patterns.

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1 https://eur-lex.europa.eu/legal-content/IT/TXT/HTML/?uri=LEGISSUM%3Awaste_hierarchy.

2 All 17 goals are inspired, though in different ways, on the subject of defence and accurate, equal use of the resources. In particular, goal 12 'Ensuring sustainable consumption and production targets' under goal 12.5 mentions 'By 2030, substantially reduce waste generation through prevention, reduction, recycling and reuse'.

3 The Green Deal goals launched in 2019 were acknowledged on 24th June 2021 as the Parliament approved of the European law on climate that makes legally binding the goals to reach 55% emissions reduction by 2030 and net-zero emission by 2050.

4 European Environment Agency (EAA), Textiles and the environment in a circular economy, 2019

5 Ellen MacArthur Foundation (EMF), A New Textiles Economy: Redesigning fashion's future, 2017

6 Journal of Cleaner Production (JRC), Circular economy perspectives in the EU Textile sector, 2021

1 The European Regulatory Framework

As indicated by the EU Commission in its document dated 30th March 2022, Strategies for Sustainable and Circular Textiles, 'world production of textiles has almost doubled from 2000 to 2015[7] and consumption of garments and footwear should increase by 63% by 2030, from today's 62 million tons to 102 million tons'[8]. A trend that implies intensive use of raw materials, chemicals, water and energy, likely to increase the volume of pre- and post-consumption waste. The leading cause of this situation is stated to be the *fast fashion* pattern pushing consumers to repeated purchases to frantically renew one's wardrobe and businesses in this industry to develop, beside a traditional season range, a growing set of collections, in turn generating overproduction and adopting non-sustainable practices in order to get rid of unsold goods. The European Union declares the objective to consider '*fast fashion* out-of-fashion', as reiterated in a press release dated 6th April 2023 'to fight over-production and excessive consumption of clothing and footwear. The Committee invites the Commission and EU Countries to take measures to put an end to *fast fashion*, starting from a clear definition of this term based on *"high volumes of lower quality garments at a low price*". Consumers should be better informed in order to make responsible and sustainable choices, even with a digital product passport[9]. However, it is not just a question of quantity of garments put to market, as its low quality limits a product life, making it difficult to be reused and even recycled.

The subject of the reduction of textile waste is not new to the European political debate that now suggests it in an integrated vision challenging economic patterns responsible of this phenomenon. In fact, the subject is clearly part of EU Directive 2018/851, that requires Member States to ensure the separated collection of the textile fraction by 2025; the subject is repeated in the 2020 '*New Circular Economy Action Plan*' confirmed in most recent proposals of environmental transition of the textile industry (2022-2023) still the main topic of discussion of interested parties. All documents confirm that the obligation to separately collect waste, though indispensable, is not sufficient to ensure reaching the goal of the supply chain circularity: an integrated system should be built able to manage and prevent the issue.

1.1 Key Steps to Define a Circular Transition for the Textile and Fashion Industry

The approval of Directive 2018/851 by the European Parliament sets targets that directly call upon the textile and fashion industry. In fact, the directive involves several industrial products and segments, however not disregarding the textile industry.

Targets laid down:

- by 2035 not more than 10% of waste shall go to landfills;
- by 2035 65% of urban waste shall be recycled (55% by 2025 and 60% by 2030);
- by 2030 70% of waste from *packaging* shall be collected and recycled;
- by 2023 obligation to separately collect the wet fraction of biodegradable waste; by 2025 this obligation concerns textile waste and hazardous household waste.

Whereas waste collection, management and recycling are central in the EU approach, the Directive calls for specific measures to prevent the formation of waste and promote the re-use of goods and stimulate the "industrial symbiosis". These should be integrated systems to manage pre-consumption waste (scraps, industrial waste, overproduction), to be able to convert a by-product of an industry into raw material of a different production unit.

The EPR regime (*Extended Producer Responsibility*) is central to this concept: the one who produces is called up to provide for the management of a product that reaches the end of life, but also to design it based on *ecodesign* principles.

In particular, a manufacturer is responsible for designing and making products with an adequate temporal duration: in fact, a built-in planned obsolescence is prohibited while calling for repairs and regeneration of goods. Further, the item shall be designed to be easily re-valued once it reaches the end of life (reuse,

7 Ellen MacArthur Foundation (EMF), A New Textiles Economy: Redesigning fashion's future, 2017
8 European Environment Agency (EAA), Textiles and the environment in a circular economy, 2019
9 https://www.europarl.europa.eu/news/it/press-room/20230424IPR82040/ending-fast-fashion-tougher-rules-to-fight-excessive-production-and-consumption

recycling or, whenever possible, biodegradation and composting); for this purpose the item shall be easily disassembled.

In order to promote a correct waste management, reduce its volume, study technical and management solutions promoting regeneration, interested parties, producers, the government, companies in the recovery and recycling segment shall work in synergy and associate in consortia by categories of waste to be managed.

The shift of the European economic system to circular patterns is outlined by the European Commission within a wider scenario covering the review of Directive 2010/75 on industrial emissions and the integration of circular economy practices in BAT reference documents (*Best Available Techniques)*[10]. All this is defined in a document dated March 2020 mentioning what the Commission intends to develop in subsequent years.

In particular, they recall the great significance of:

- facilitating the establishment of a communication and certification system promoted by the industry, hence implementing the industrial symbiosis;
- promoting a sustainable and circular bio-economy;
- promoting the use of digital technologies to track, source and map resources;
- promote the use of green technologies thanks to an accurate control system with registration of the EU system that checks environmental techniques with an EU certification mark.

Further, they recall the need to define conditions and criteria under which a waste ceases to be a waste and becomes a secondary raw material for new production processes, and the need to eliminate the illicit trafficking of waste from Europe to Third Countries.

The document also covers the development of new products and defines *ecodesign* as a design practice aiming at realising products with the following requirements:

- product durability, reusability, reparability, no built-in planned obsolescence;
- free from hazardous chemical substances;
- high recycled content;
- recyclability or biodegradability at end of life;
- low environmental impact and a carbon footprint measured applying scientific methods.

These goals are mentioned in the document dated 30th March 2022 ‘The EU Strategy for Sustainable and Circular Textiles[11], which summarizes the 360° vision of the European Commission.

The proposed change of pattern, from waste to saving and resource regeneration, in the EU vision, generates not only environmental effects, but also extremely positive social benefits: ‘*applying the principles of a circular economy within the EU economy could increase the GDP by 0.5% by 2030, while creating 700,000 new jobs. There exists a clear commercial benefit even for individual firms: on average, EU manufacturers allocate approximately 40% of expenditure to purchase of materials; hence, close cycle patterns can increase profitability while protecting them from resource price fluctuation”.*

10 The Best Available Techniques - BAT define the most efficient technologies available to reduce the environmental impact of production processes.

11 https://eur-lex.europa.eu/legal-content/IT/TXT/HTML/?uri=CELEX:52022DC0141&from=EN

Here is a summary of bullet points of the Proposal dated 30th March 2022

Action	Objectives/Modes
Ecodesign	Design goods to last longer, biodegradable or recyclable at end of life Reduce resources required for production, select raw materials based on sustainability criteria while ensuring the use of recycled material. Establish connection with the New European Bauhaus, meant to be a movement aimed at circulating and realising a culture of sustainability, innovation and social inclusion[12].
Chemical safety	Critical chemicals in materials to be recycled prevent a possible treatment. Hence the REACH regulations shall be reconsidered to prevent the *'presence of hazardous substances in textiles brought to the EU market, many of them being cancerogenic, mutagenic or toxic for reproduction'.*
Prohibition of the destruction of unsold garments or returns	In order to deter this practice, the Commission suggests an *'obligation of transparency: bigger firms shall make public the amount of products they destroy, including textiles, and its subsequent treatment to prepare them for reuse, recycling, incineration or landfilling'.*
Support for digitalisation	A very interesting issue for technology and digital systems producers. *'The Commission will evaluate together with the industry, in particular within the transition path for a textile ecosystem, how emerging technologies, like precision digital technologies, could reduce the high percentage of returns of garments bought on-line, encourage production on demand and made-to-measure, improve the efficiency of industrial processes and reduce the carbon footprint of e-commerce'*.
Fight against microplastics	Specifications will be defined to become part of the regulations on environment-friendly design of sustainable products and measures covering *'manufacturing processes, pre-washing in industrial plants, labelling and promotion of innovative materials. Other possible options include filters for washing machines, able to reduce the release during washing by as much as 80%[13], development of mild detergents, guidelines for care and washing, treatment of textile waste at end of life and regulations to improve the treatment of waste water and sewer sludge'.*
Fight against Greenwashing and Green Claims	The Commission will introduce a requirement to submit information like sustainability and circularity parameters, size of products and, if necessary, the Third Country where the product is made ("*made in*"). In the context of the above proposals, the Commission will also consider the opportunity of introducing a digital label (Digital Product Passport). Voluntary sustainability marks on environmental or social aspects shall refer to an independent check or be established by public authority. Further, the Commission will review the EU Ecolabel for textiles and footwear. They will study how to penalise sustainability statements, which might cause the consumer to buy a product based on untrue e non documented information.
Recycling of Polyester	The use of recycled PET to make textile garments is not in line with the EU principles as it takes away subsequently recyclable polymers from packaging to put them into presently non-recyclable textiles. The Commission encourages firms to give top priority to their efforts in terms of recycle of closed cycle fibres and to state results obtained in this important challenge of circularity of textiles.

12 https://new-european-bauhaus.europa.eu/

13 I.E. Napper et al., The efficiency of devices intended to reduce microfibre release during clothes washing and HK, 2020; McIlwraith et al., Capturing microfibers – marketed technologies reduce microfiber emissions from washing machine, 2019.

EPR - Extended Producer Responsibility	The obligation to organise a separated collection of textile waste by 1st January 2025 is confirmed. Producers, gathered in consortia, are obliged to support initiatives aiming at reducing and managing waste. The Commission will propose harmonised regulations on the extended producer responsibility covering textiles, with eco-modulation of fees.
Zero Pollution	A revision of the directive on industrial emissions[14] is foreseen, as well as of the current review of the BAT Reference Document (BREF) on the Best Available Techniques (BAT) for the textile industry[15].
Circularity Technologies	A common target roadmap will be defined for industrial technologies applicable to circularity, aiming at promoting industrial research and innovation, even in the textiles recycling sector. Innovation trends shall be coherent with the idea of a circular bio-based Europe" [16] which purpose is, inter alia, to promote the development of new types of textile fibres from biomass.

It is clear that the individual subjects covered in the 2022 document are in fact closely linked and that circularity and reduction of the environmental footprint of processes and products are feasible objectives only if they are managed in synergy.

What is substantive is a sort of mosaic where the unifying element is circular economy; this subject emerges both in design stages (*ecodesign*) and in the management of products at end of life and of waste generated in the production process, up to the statement of green claims endorsed by scientific evidence.

The subjects outline the holistic approach of the EU that tends to regulate what have been up to now voluntary initiatives of firms more sensitive to this issue. Even environmental certifications (too many and not always adequately solid, as it has already been said) shall meet the requirements of environmental statements pursuant to ISO 14024 of first type and consequently be validated by a third agency with reference to the Ecolabel certification. The question of when and how to calculate the *carbon footprint* of products and the role of methods like LCA and PEF has still not been answered; however the strict approach addressed by the European Commission on this subject is obvious.

In addition to that, the Commission intends to address the demand side, guiding consumers towards more aware consumption patterns, as demonstrated by #ReFashionNow, started within the European Bauhaus, as well as mobilising public spending towards the purchase of sustainable products by means of mandatory criteria for public supply contracts inspired on circularity modules through CAM (Environmental minimum criteria). All the signs are that the demand of recycled materials will significantly increase in the next few years.

Seen from this angle, one can guess that, in the eyes of the legislator, implementing the Green Deal means not just trusting the capacity of the market to award environmentally virtuous businesses and product, but regulating the conduct of economic operators.

After the Proposal dated 30th March 2022 was published, the EU Commission started a participatory process (*cocreation*) with plans and schedules whose outcomes are summarized in the document *Transition pathway for the textiles ecosystem* June 2023.

This recent document covers several thematic blocks, each of them offering operational guidelines (subjects involved, schedule). Each area of the transition pathway includes specific actions and an implementation calendar: short-term, medium-term (by 2030) or long-term (by 2040).

In particular, the document recalls the great significance of sustainable and digitalised processes to make Europe more competitive on the international stage, while outlining the governance that shall allow the EU to manage the *green* transition by 2023.

Furthermore, the document recalls the social dimension of the existing strategy, considering that the textile system is labour intensive and mainly made of SME: in fact, the green and digital transition will positively

14 https://ec.europa.eu/environment/industry/stationary/ied/evaluation.htm
15 https://eippcb.jrc.ec.europa.eu/reference/textiles-industry
16 https://www.bbi.europa.eu/about/circular-bio-based-europe-joint-undertaking-cbe-ju

influence employment, the development of skills and work conditions, above all in connection with the circular economy.

Hence, an important role is accorded to research in order to develop innovative, sustainable, circular, high quality products without disregarding the structural changes needed, e.g., to ensure efficient management and recycling processes of textile waste. Some important EU funding instruments will address research, infrastructures and development of the skills needed.

The close connection between sustainable transition and technological development is emphasized in the *Transition pathway*: 'the assessment of digital, circular technologies and solutions in the textiles ecosystem shows different level of maturity. Many of the technologies (such as post-consumer recycling by adding cellulose-based fibres, chemical recycling, bio-based raw materials) are at medium Technology Readiness Level. Various circular technologies, such as recycling technologies and replacement of raw materials with recycled content demonstrate higher Technology Readiness Level. Some of the technologies (such as material separation, plastic micro-fibre release reduction, and digital authentication/passport for textile products/materials) are at relatively low Technology Readiness Level and need further experimentation. The same applies to Artificial intelligence (AI). To take full advantage of the enabling power of digitalisation the industry needs to embrace new technologies: take up cloud processing technologies, explore the potential of AI, ensure the skilling of employees in the use of these technologies: more generally, be prepared to benefit from current and future waves of technologies in order to improve efficiency, productivity, and overall competitiveness'.

1.2 Exporting Textile Waste: from Reporting the Issue to Launching New Business Models

In this context, the topic of textile waste export from Europe to Third Countries is of paramount importance as an easy way to reduce the volumes of used garments under the illusory banner of humanitarian operations.

In reality, everybody knows that, largely, it is an irresponsible trade, which has the effect of creating large areas of waste left behind, altering the landscape and threatening biodiversity of the involved areas. The extent of the phenomenon has become untenable and now requires legislative action. As mentioned in the EU Proposal dated 30th March 2022 '*in 2020 exports of textile waste to non Eu-Countries are steadily increasing, amounting to 1.4 million tonnes*[17]*. Based upon the recent proposal by the Commission on new EU regulations on shipments of waste*[18]*, export of textile waste to non-OCSE Countries would be authorised only provided such Countries inform the Commission about their intention to import some specific types of waste and demonstrate to be able to manage it in a sustainable way*'. The ETC/CE – European Topic Centre on Circular Economy Report, published early 2023 offers a closer examination of the subject: *EU exports of used textiles in the Europe's circular economy*[19]'.

17 https://ec.europa.eu/eurostat/fr/web/products-eurostat-news/-/ddn-20210420-1
18 COM, 709 final, 2021.
19 https://www.eea.europa.eu/publications/eu-exports-of-used-textiles

The most significant key points of the report are reviewed below:

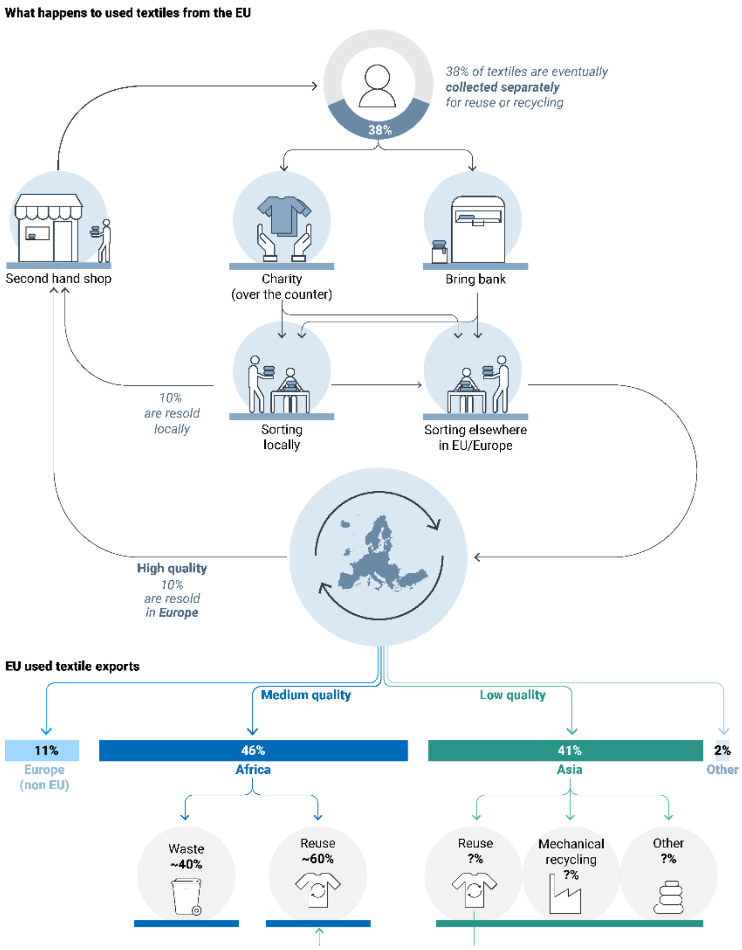

Figure 1: Source: ETC/CE – European Topic Centre on Circular Economy

❖ Textiles are the fourth-highest source of pressure on the environment and climate change;

❖ The amount of used textiles exported from the EU has tripled over the last two decades from slightly over 550,000 tons in 2000 to almost 1.7 million tons in 2019;

❖ Twenty five percent of the approximately 15 kg. of textiles consumed per person each year in the EU is intended for export as waste. In 2019, 46% of used textiles ended up in Africa. Imported, used textiles on this continent primarily go towards local reuse as there is a demand for cheap, used clothes from Europe. What is not fit for reuse mostly ends up in open landfills and informal waste streams with serious effects to the environment. 41% of used textiles ended up in Asia. Mostly to dedicated economic zones where they are sorted and processed, down cycled into industrial rags.

❖ Textiles that cannot be recycled or re-exported are likely to end up in landfills.

❖ Germany is the largest exporter of textile waste (36% of total export volumes) followed by the Netherlands (14%), while Italy percentage reaches 10%;

The segment confirms a loss of value of textile waste: once the best part of it is subtracted, which often stays in the origin Countries supplying the second-hand and vintage market, the export amount is frequently of poor/no quality; being unusable it is released in the environment on illegal landfills;

Hence an alarm signal is given:

❖ Due to the obligation to collect textile waste as a separate fraction in all EU Countries by 2025, the amounts of used textiles collected may increase further, highlighting the limited reuse and recycling capacity of the European textile system.

If on one hand one has to prevent export of waste to Countries with a lacking conditions of efficient textile waste management, on the other hand a circular economy suggests new business patterns to allow the global fashion supply chain to redesign itself in a responsible perspective.

An example comes from the Switch/MED[20] Programme promoted by UNIDO (United Nations Industrial Development Organisation) and financed by the EU, aiming at creating integrated supply chains to enhance the value of textile waste in Egypt, Morocco and Tunisia, with a larger number of European brands.

In a study carried out by the Italian company Blumine srl and the Estonian company Reverse Resources textile waste was measured and mapped, generated from textile production in both Countries, broken down by fibre type and production phase. The mapping shows an extraordinary development potential of a circular economy. They calculated that the yearly volume of pre-use textile waste in spinning, weaving, cutting and apparel making processes in both Countries exceeds 114 thousand tons (83 thousand tons in Morocco and 31 thousand tons in Tunisia). Waste is mostly generated during cutting and garment making, whereas the amount of recycled or exported materials to be recycled is limited to a few isolated cases. Based upon the data

20 https://switchmed.eu/

collected, experimentations are going on involving both local players, i.e. manufacturers and recovery and recycling firms, as well as global fashion brands whose supply chain operates in the area.

A pilot project is particularly interesting, developed in Tunisia thanks to the Nudie Jeans trademark to manage denim waste. Through the involvement of the Diesel brand they launched a plan to recover waste with a high content of cotton from production lines to obtain a top quality yarn (thirty percent from recycled material, seventy percent virgin material) destined to new collections. Lower quality materials, i.e., with mixed fibres goes to the production of non-woven to make items for humanitarian projects (mattresses and blankets). Some managers from Tunisia, Egypt and Morocco, recently visiting ITMA 2023 in Milan, confirmed their interest to invest in technology to support the local textile recycling economy.

Some interesting signals come also from Asia.

The Bangladesh Garment Manufacturers and Exporters Association (BGMEA), asked for immediate government provisions to stop export of pre-consumer waste from Bangladesh to other Countries. The present estimates show that less than 5% of textile waste is being recycled locally, whereas 35% is incinerated in boilers or on landfills with the remaining 60% exported to India, Hong Kong, Sweden and other Countries to be recycled into new yarns. The Association registered approximately 20 plants processing recycled fibres all over Bangladesh with a recycling capacity of 2,400,000 tons/year, a significant detail in a country where the apparel making industry stands for 80% of export and employs over 4 million people. At the end of 2022, the trade press mentioned the interest of the British government to support the Bangladesh textile and agricultural recycling industry with investments.

Again, in Asia, in October 2022, the Vietnamese association Hanoi Textile and Garment JSC (Hanosimex) and Hansae Group from South Korea signed an agreement to start an integrated textile recycling system with an approximate output estimate of 4,000 tons of recycled fabric destined to the EU market. In the summer months of 2022 even China stated to be willing to increase its recycling capacity: with the paper *'Implementation Opinions on Accelerating the Recycling of Waste Textiles'*, the Chinese government launched the objective to build by 2030 a textile recycling industrial system able to regenerate 30% of textile waste and produce 3 million tons/year of recycled fibre. In 2020, China produced approximately 22 million tons of textile waste obtaining approximately 20% recycling and approximately 1.5 tons of recycled fibre.

1.3 Social Aspects of Circular Fashion

As mentioned in the EU 2022 Proposal 'Most clothes and home textiles consumed in Europe are imported from Third Countries. In 2019, EU was among the top clothing importers in the world with a total value of 80 billion Euro[21]. Promoting more environmentally friendly and equal value chains at world level will help ensure that textiles consumed in the EU and elsewhere are made taking full account of social and environmental aspects all over the world'.

This important approach leads to the approval by the EU Parliament of the draft law Corporate Sustainability due Diligence Directive[22] on 31st May 2023. The Directive regulates the social policy of businesses, providing to oblige firms in the EU to shoulder their responsibility for violations of human and environmental rights in own sourcing chains. Companies are obliged to identify, face and remedy critical aspects of their value and supply chain that could violate human rights including those connected with union representation, cause environmental damage (e.g., pollution and deforestation) or encourage corruption and bribery. Among qualifying aspects, the law mentions the commitment to reduce potential adverse impacts and stop actual adverse impacts through a "*preventive action plan*", providing for monitoring based on indicators to measure the effects of actions carried out. The supply chain control includes specific contract guarantees to ensure compliance with its own code of conduct.

Though not expressly mentioned, the approach refers both to standard production chains and to materials recycling chains, a business carried out in Third Countries under often very critical environmental and social conditions,

21 https://ec.europa.eu/eurostat/web/products-eurostat-news/-/edn-20200424-1
22 https://www.europarl.europa.eu/RegData/etudes/BRIE/2022/729424/EPRS_BRI(2022)729424_EN.pdf

2 Textile Waste Management in Italy

First, how can we define textile waste?

In Italy, urban textile waste includes textile fractions (EER 200111) and clothing (EER 200110), even though materials are usually collected by companies in charge of separating them to identify and exploit items to be resold along *second hand* trade channels.

Both the trade literature and insiders distinguish collected fractions into post-consumer waste (urban fraction) and pre-consumer, referring to materials discarded during the manufacturing process as defective or damaged, excess inventory, unsold items, scraps (off-cuts, selvedge, proof print, etc.). From a formal point of view, it would be better to talk about by-products (materials that have never been classified as waste, originating from production and complying with the requirements of art. 184*bis* of TUA (Waste Identification Code), and *end of waste*). Such materials have *become*end-of-waste pursuant to art. 184*ter* of TUA[23].

The final outcome of potential textile waste, whether to be sent for landfilling, to a waste to energy plant or to a new production cycle, often depends not just on a material's characteristics, but on trade relations and skills that can assess it and introduce it into circular circuits. Hence the importance to put waste management in a network, able to assess its characteristics and decide about the destination and use, including companies that can operate with technological as well as commercial solutions to gain value (industrial symbiosis). Even more difficult is the identification of alternatives to landfilling for so-called special waste. It is the case of materials with codes EER 04, which in 2019 reached 643 thousand tons, slightly over 0.4% of the total waste from businesses or from non-domestic users. To the family of codes 04 (*composite materials* – EER 040209 – and *waste from raw textile fibres* – 040222) one should add *packaging made of textiles* (EER 150109) and *textile waste from mechanical processing of waste* (EER 191208).

According to the latest data from ISPRA[24] covering urban waste management, in 2021 the separate waste collection amounted to 154.2 thousand tons of textile waste, slightly more in previous years. The exception regards 2019 (the total amount was 157.7 thousand tons) with peaks in Northern areas (over 77 thousand tons) followed by Southern areas (42.1 thousand tons) and Central areas (34.9 thousand tons). According to ISPRA, approximately 4% goes to reuse (about 75 thousand tons) of which only a minimum portion, between 5% and 10%, stays in Italy to be resold in point of sales and on-line as *second hand* items. On the other hand, the remaining portion goes mainly abroad, above all to Eastern Europe and Northern Africa. Of course, there is a 'grey' area, difficult to quantify, covering re-used waste, however in a way that reduces its value: such as cleaning rags in workshops or rags to protect floors and furniture during painting and refurbishing operations. As a whole, the quantity destined to recycling, that is fabrics and yarns brought back to fibre state and woven again or re-used to make nonwoven is less than 1%.

Hence, it is easy to understand, how textile waste can really be an enormous wealth if managed in the right way, thus balancing the lack of raw material and reducing CO_2 responsible for production processes of virgin materials. In fact, wool-recycling chains profit from import of cloths ready to be recycled, for example free of buttons, zip fasteners, labels, that would limit recycling. This kind of activity is marginal in Italy.

The way to change this situation is a topic both in the textile industry as such and in the whole waste management chain, summoned in the decree law DL 116 to be operative and involving public agencies, contracting firms, firms operating in recovery and recycling, *second hand* retailers, charities/third sector.

As regards the domestic legislative context, in Italy the EU 2018/851 directive was implemented through the law decree DL 2020/116 which anticipated on 1st January 2022 the achievement of objectives scheduled by the EU to be achieved by 2025. Useless to say that they did not respect the date and that today the debate is still mainly theoretical.

End December 2022 the Italian Ministry of Environment and Energy Security (MASE) sent a draft decree for consultation, regulating the introduction of an EPR scheme covering clothing, footwear, accessories, leather ware and home textiles. The draft would directly involve producers, dealers, urban waste collection operators, citizens, cooperatives and no-profit entities and anticipates the establishment of a Centre to coordinate textile recycling (Centro di Coordinamento per il Riciclo di Tessuti - CORIT), based on the experience gathered in waste management by means of electric and electronic equipment (WEEE Coordination Centre).

23 https://www.gazzettaufficiale.it/
24 https://www.isprambiente.gov.it/it

As regards the targets of consortia, the proposal attaches great importance to activities that can ensure to some extent a longer life to products, from re-use to repair, without forgetting the need to take actions in order to make consumers aware of a more responsible conduct to let a product last longer. However, there is a risk of a sort of role overlapping among consortia and entities charged with direct collection and management of waste; in fact, the draft law requires producers to ensure the establishment of a doorstep waste collection on the whole country, coherent with the geographical coverage of the product distribution.

Another issue within the MASE proposal covers the type of companies that shall also finance the consortia.

EPR identifies producers only as those subjects who put on the market a finished product, destined to be consumed by citizens, regardless of the fact that the product was actually made by them or not, whereas exporters are not considered as producers. However, some consortia aim at extending the participation to manufacturers of semi-finished products, as priority subjects in the value chain.

Until now, some aspects are still to be clarified, like the amount of funding contributions and the calculation system of the same that will presumably be based on the weight class of clothes involved.

Certainly, the targets specified by the Presidential Decree (DPR) are ambitious: by 2025, at least 25% in weight of textile volumes shall be prepared for re-use or recycling; by 2023 the target is at least 40% in weight, so as to reach 50% by 2035. It is not clear how the volumes of unsold goods are part of this scheme; for them the EU requires to prohibit the destruction; similarly not clear is the sort of clothes illegally entering our Country or counterfeited, seized by the Italian Finance Police every year.

Meanwhile a debate has emerged in Italy on the scopes of consortia; specific aggregations are being promoted by aggregating promoters (this is the case of Retex.Green, promoted by Sistema Moda Italia, and of Ricrea promoted by the National Chamber of Italian Fashion) or by local synergies (Corertex and Cobat in Prato). To all these we can add the Ecoremat and Eco tessili consortia (started by Federconsumatori to manage end-of-life mattresses and upholstered items) and Erino. It should also be stressed that, at European level, Euratex, the European Apparel and Textile Confederation, set in motion the ReHubs project, aiming at recycling from fibre to fibre 2.5 million tons of textile waste in Europe and generating over 15,000 new jobs by 2030. At Community level there is also ECESP, European Circular Economy Stakeholder Platform, in Italy ICESP - Italian Circular Economy Stakeholder Platform, coordinated by ENEA (Italian National Agency for New Technologies, Energy and Sustainable Economic Development) that identified in-depth study areas about textiles. Finally, for a further completion of the map of subjects involved (at least up to now) let us add UNIRAU - Unione Imprese Raccolta Riuso e Riciclo Abbigliamento Usato (Union of firms active in the collection, re-use and recycling of apparel). It is not excluded that additional initiatives may follow in the next few months.

This pathway shall be framed in a more complex effort to adapt installations that will practically manage this action. A measurement included in the National Recovery and Resilience Plan on the so called circular economy *beacon projects,* assigned lines of funding for a total amount of 150 million Euro to textile waste management. Reference is made to the D course of action "*Development of the collection of pre-consumer and post-consumer textile fractions, modernisation of installations and building of new textile fraction recycling plants in a root and branch approach, so called Textile Hubs*[25]". As regards the allocation of funds, 82% goes to enterprises in the North-Western and Central areas in Italy, where important textile districts are located.

The role of Consortia - Summary:

a) To promote and encourage the creation of a network of municipal re-use centres;

b) To facilitate repair of used textiles, promoting national and local networks of experts;

c) To promote new skills and professionals of repair;

d) To ensure that, when purchasing a textile product, consumers are offered a guaranteed reparability and information on repair;

e) To support re-use through exchange and sale on the second hand market, even on digital channels;

f) To encourage the development of national and local second-hand chains;

g) To organize environmental communication campaigns targeted at the citizens, to promote prevention and re-use.

25 https://www.mase.gov.it/pagina/linea-d-infrastrutturazione-della-raccolta-delle-frazioni-di-tessili-pre-consumo-e-post

3 Textile and Fashion, Bio-economy and New Materials

Extending the scope and considering also EU broadest strategies on bio-economy and biodiversity, the production of materials for textiles and fashion could become part of a wider context connecting this industry to agri-food, forest economy and biomass management, be it the result of targeted crops or agricultural and food industry waste. We need to understand how the textile and fashion universe could benefit from the processing of biological materials otherwise managed as under-products of no value.

From this perspective, producing yarns or structures used as alternative to leather and plastics to make accessories, footwear and furniture, is a full-fledged recycling operation[26] and a most interesting potential development area to redesign the segment.

This is a 'very old' process, in which artificial fibres from wood pulp are processed to obtain filaments by means of chemical solvents and extremely polluting processes. It goes back to the 19th century and consolidates as an industry mainly in the first part of the twentieth century until, starting from the Second World War, bigger and bigger portions of the market were transferred to synthetic fibres obtained from fossil fuel[27].

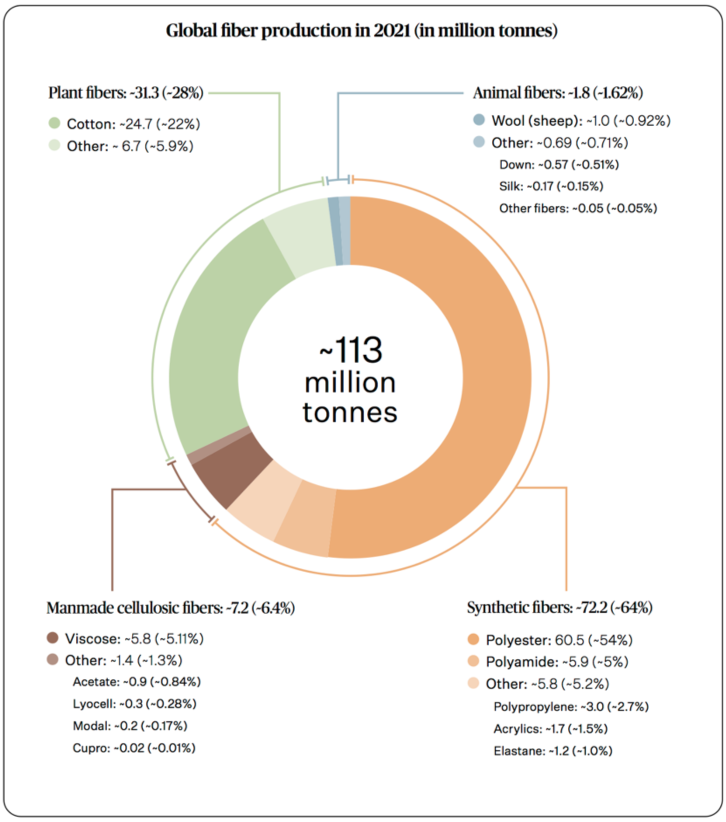

Figure 2: Textile Exchange

Today, the production and use of textile fibres show an important upward trend, confirming the role textile materials play not only in mass consumption, but also in the production of other goods, from automotive to building & construction, from healthcare to sportswear and in the wider economy.

Textile Exchange estimates that 113 million tons of fibres have been produced in the world in 2020. In this scenario, cellulosic *man-made* fibres, on one hand limited to a smaller size if compared with synthetic *man-made* fibres, account for approximately 7%. The latter are estimated at approximately 70% with a predominant role of polyester, on the other hand are going through a relaunch phase thanks to closed-loop and low environmental impact production systems as well as to support actions of research and testing of ways to revitalise cellulosic waste.

It is the case of the Lenzing group which significantly reduced the environmental footprint of the transformation process thanks to controlled production processes and the use of the cellulose solvent NMMO (N-methyl-morpholine-N-oxide) as an alternative to carbon disulfide in the Lyocell process, a solvent being recovered and recycled. The Lenzing pattern is interesting not just for being environmentally efficient, but for being able to include the experience of start-ups and smaller companies, which otherwise would risk not to be scalable. Collaborations have been set up with companies that supply Lenzing with cellulose from recycle processes, as it is the case with Renewcell, of the REFIBRA technology, and of Södra.

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26 The recent study *Global Eco Fibers Market Size, Share, and COVID-19 Impact Analysis, By Type (Regenerated fibers, Recycled fibers, Organic fibers,* conducted by the research company Spherical Insights, expects 'sustainable' fibres to grow considerably in the next few years, from 46.22 billion dollars in 2022 to more than 98 billion dollars in 2023, at an annual growth rate of 7.8%. It also defines cellulose man-made fibres as 'regenerated', thus distinguishing them from traditionally recycled materials. Such a definition highlights the importance of adapting the terminology of textile fibres to the present production context.

27 On the other hand, producing artificial filaments from milk processing waste - see Lanital made by SNIA in a self-sufficiency regime - has been an interesting though not very lucky experience.

3.1 The case of Finland

In the last decade the Finnish economy targeted a bioeconomy pattern based on the development of value chains that connect the forest/agro-industry segment to the bio-technological industry and research. A political and economic choice that aims at transforming the Country's natural resources into a growth potential. In fact, as mentioned on the website of the VTT Finnish research centre '*the Finnish textile industry, reorganised on sustainability and research, could be worth 1.2 billion Euro of investment, approximately 17,000 new jobs and a better global reputation as a leader Country in sustainable development*'.

For example, one of the best known businesses, Spinnova[28], claims that '*by 2030 the production of cellulose based fibres different from cotton and sustainably produced shall grow to balance the growing demand for fibres while also becoming a real alternative to cotton whose cultivation is not sustainable*'.

The steps to promote the transformation of the Finnish industry are described in a document presented by VTT and the Finnish Textile & Fashion '*Finland as a forerunner in sustainable and knowledge-based textile industry – Roadmap for 2035*', published in August 2021. It is an interesting approach connecting bioeconomy with circular economy; furthermore, the separated collection of textile waste will be mandatory from 2023 and the Country has tooled up to provide textile components recycling facilities, some of which already operating, in particular the centre managed by Rester OY and Lounais-Suomen Jätehuolto Oy (LSJH), aimed at recycling pre- and post-consumer textiles.

Among some significant experiences let us recall Spinnova, mentioned above, established in 2009 on the initiative of Jula Salmela, a VTT researcher. The company produces and trades fibre from FSC or PEFC certified wood pulp cellulose or agricultural waste like wheat and barley straw, whereas the process has been recently extended to post-consumer leather and cotton waste. It is a closed-loop process without chemicals or solvents and with a low water usage; the result is a biodegradable material. The promoters have estimated a 65% reduction of CO_2 eq. as against cotton. They started cooperation agreements with Adidas, Lenzing, H&M, Bestseller.

On the other hand, the system developed by Infinited Fiber Company[29] starts from undifferentiated textile materials (agri-food waste, but also post-consumer paper and textiles) that are ground, with separation of metallic non-recyclable components. After fibres are sorted out according to their type, the cellulose portion is transformed in dust by means of a urea treatment, hence into a viscous, spinning liquid from which impurities are filtered. This process too raised the interest to some global fashion brands. Norratex[30] is a fibre made by Nordic Bioproducts, a *spin-off* of the Aalto University, owner of the patented AaltoCell technology. Cellulose obtained from the dissolution of forest, textile and paper waste, is first hydrolysed, and then converted into a textile fibre similar to viscose. They are in search of partners to develop novel low carbon print applications.

Finally, the Fortum bio-refinery studied the possibility of obtaining textile fibres from agricultural waste of poor regions in the world. They are starting the first bio-refinery in India to produce bio-ethanol and bio-chemicals; production should start in 2023.

The Finnish picture is coordinated and interesting, however difficult to be reproduced in Italy, unless based upon bold decisions- If it is true that artificial fibre installations which our Country operated in the twentieth century no longer exist, on the other hand new generation chemical and bio-technological companies engaged on the field of bio-fuels, *bio-chemicals* and bio-polymers can open the way to a new possible industrial development in that direction[31].

3.2 The Textile Sustainable Transition Includes (also) Biopolymers

Research connected to the production yarns and surfaces from natural sources and applying low impact methods places the textile and fashion industry in the wider universe of bioplastics from biomass. These products are obtained from fermentation of organic materials subject to the action of enzymes, bacteria or

28 www.spinnova.com
29 https://infinitedfiber.com
30 https://nordicbioproducts.fi
31 An interesting case story is that of the Prime project, coordinated by Novamont and involving 26 partners (firms and research centres) financed by the Piedmont Region, as part of the Technological Platform for Bioeconomy. The project promotes the development of various sectors and strategic markets in the Piedmont area, generating a significant impact on the agri-food, automotive, bioplastics, bio-stimulants, cosmetics, nutraceuticals and textile sectors.

yeasts in targeted industrial plants, called bio-refineries, that can process e.g., maize starch, wheat, potatoes, (Polylactic acid/PLA, Polyhydroxialcanoates/PHA, Poyhydroxybutyrate/PHB), sugars (PHB, bio-Polyethylene Terephtalate/PET, PHA), cellulose (for example, cellophane), chitin (PHA, Chitosan).

Biomaterials can be obtained processing purpose cultivated like oil seed rape, maize, sugar beets and the '*bio-degradable fraction of products, waste and bio-based residues from agriculture including vegetable and animal substances, forestry and related industries, including fishing and aquaculture, as well as the biodegradable portion of industrial and municipal waste*'[32]. This second approach is preferable, because it avoids diverting soil and water from foodstuffs cultivation, while enabling the regeneration of otherwise devalued waste. With this in mind, collaborations could be organised between firms and territories, but also among different players interested to experiment connections[33].

Today, bio-plastics accounts for less than 1% of over 390 million tons of plastic produced every year[34]. After the 2020 stagnation, mainly caused by Covid-19, the total world production has increased again since 2021. This development is driven by increased market demand combined with more sophisticated emerging applications and products. According to the latest market data processed by European Bioplastics in collaboration with nova-Institute, the worldwide production capacity of bio-platics should increase from 2.2 million tons in 2022 to approximately 6.3 million tons in 2027.

Under this scenario, the textile component of bio-polymers, including non-woven, is estimated to account for 329,000 tons in 2022, a volume likely to continue to increase. This is still a niche scenario, though dynamic and involving various industrial players: there are some start-ups generated by university spin offs that, in pilot installations, produce volumes of materials considered negligible for the market; these are interesting pilot examples and veritable developments on an industrial scale[35].

4 The Role of Technologies in the Circular Transition of the Fashion Industry

As pointed out at several instances both in documents of the European Union mentioned in this context, and in the extensive literature on the subject, certainly circular economy does not only mean recycling, though important, at least in the collective imagination.

In fact, a sustainable and circular fashion is part of a much wider project concerning resource management, energy and even industrial policies.

With the recent Green Deal Industrial Plan12 and the Net-Zero Industry Act13[36] proposition, the European Commission aims at scaling up manufacturing of clean technology and making sure the EU and its industry are well equipped for the clean energy transition. The Net-Zero Industry Act will support the implementation to reach the climate neutrality and a transition towards clean energy, while strengthening the resilience of the EU energy system in line with REPowerEU14[37].

Hence, recycling is part of a broader approach.

A circular economy does not produce waste or, at least, works to reduce it to a minimum level, a concept, which applies in any industry segment; however, due to the attributable waste volumes and to the difficulty to manage it, this is true above all in the fashion industry.

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32 European Directive 2009/28/CE

33 Bio-polymers from biomass have been recently complemented by new generation materials obtained through the *Carbon Capture and Utilisation* (CCU) approach, as an important development of the management of CO_2. The system concerns first the production of bio-fuels using aquatic algae that can process CO_2 and return them in the form of biogas; however, the aim of research centres and enterprises is to obtain a range of high value added products like uronic acid, as well as probiotics and bio-polymers. According to nova-Institute by 2030, the estimated capacity as regards CO_2 based products should exceed 6 million tons per year of CO_2 based products.

34 STATISTICA, Annual production of plastics worldwide from 1950 to 2021, 2023.

35 Let us consider the case of a yarn known as spider silk (used, among others, by Adidas to make sports footwear), bio-fabricated by AMSilk in a bioengineering process to obtain complex proteins in bio-industrial plants. Microsilk by Bolt Threads has the same properties and a biological base mostly made of sugar, water, salts and yeast. Also, Spiber's Brewed Protein™ is made of sugars from sugar cane, corn or saccharification of cellulose. After a 12 years' R&D period, Spiber now focuses on mass production.

36 https://ec.europa.eu/commission/presscorner/detail/en/ip_23_1665

37 https://www.consilium.europa.eu/it/press/press-releases/2023/02/21/eu-recovery-plan-council-adopts-repowereu/

Not by chance, the EU strategies mentioned above aim at moving away from the *fast fashion* model as a major cause. This is a fight with a strong cultural and social dimension, that is aiming at changing purchasing patterns through the introduction of different value categories (*being is better than appearing, choose beautiful, well done products, made a purchased object last longer, know its story, replace possession with use of goods, et.*). Technologies that should make of this change a model play an important role. The production of waste has to be reduced, improving quality and shifting from volume production to customised products based on a real demand of the market.

An important change.

In the last decades, technological research has focused on introducing automation able to accelerate and increase the production yield of every manufacturing step, on control of performance in order to correct defects in real-time and avoid downtime resulting in loss of productivity. Today, technology is requested to make the production flow qualitatively and quantitatively functional to the demand dynamics, while offering "customised" products within a *time to market* shorter than the competition. The fourth industrial revolution - Industry 4.0 - helped make this production pattern possible, implementing enabling technologies to support design, production, logistic and organization processes. [38].

The vision of a more sustainable economy gives new value to mere process efficiency raising. Use of raw material, water, energy and chemicals has to be reduced, avoiding production residues and waste, producing on demand with no provisions stored in warehouses where they will be rapidly devalued, rationalising logistics, quickly capturing consumers' expectations while directly involving them in the design process, and so forth. Without pretending to be exhaustive, we can outline macro-areas where technologies play a key role, modifying a company organisational set-up and generating the need for new skills and knowledge.

- *Simulating instead of Producing*

In the design activity, simulation systems allow the virtual development of new products, hence preventing waste and consumption, while reducing the risk margin connected with the operations. In fact, virtual models are not just a technical support to product design and engineering that can speed up and enhance design stages and the sharing of ideas with the customer. They can also save materials, usually employed for prototyping, while detecting critical steps in time, preventing waste and introducing changes in real time.

The textile and fashion segments are intended to benefit more from the following concept: 'simulation is better than production'. The range goes from systems to develop a textile structure graphically (fabric, lace, embroidery and jacquard) to prototyping, from a wearability test on virtual models to the digital presentation of a collection. Digital technology has already been for some time an indispensable partner of companies and engineering offices thanks to CAD systems to develop a 2D and 3D design, CAE – *Computer Aided Engineering* simulation systems and to transfer technical information to production machines needed to make the designed item (CAM – *Computer Aided Manufacturing*). Over the years, a broad technology base, widely used by styling departments and designers, has been streamlined with the contribution of digital printing and additive technology (3D printing), developed with the aim to make the prototype engineering phase quicker and less expensive and, in many instances, to integrate, if not to replace the ordinary industrial production process. However, we should not forget that designers work in a context where a new product is given shape with the help of function technologies for an effective management of single stages of activity. They work surrounded with a network of information and digital supports and can consult sources in cloud, store, transfer and share documents accelerating the execution time with the opportunity to collaborate with subjects either remote or operating at different points of the value chain.

The words '*digital twin*' are frequent in the common language to mean the virtual simulation of products as well as of processes to test and prototype new ideas in the safe environment of a digital dominion or an infrastructure effectively and in a preventive way[39]. The *Cloud* system is part of this framework to help transfer, store data and remotely access calculation capacities.

Managing a coordinated flow of information, as it is the case when designing a collection, is rather critical and raises issues related to privacy, protection of the intellectual property, cyber-security and requiring continued attention and preventive, defensive strategies.

38 The European Commission defines key enabling technologies as 'knowledge intensive and associated with high R&D intensity, rapid innovation cycles, high capital expenditure and highly skilled employment' (Horizon 2020).

39 L. Cappannari, Metaverso 2023: che cosa cambierà nel business e nella tecnologia, EconomyUp, 5th January 2023 (Metaverse 2023: what is going to change in business and technology).

At the design stage, additive technologies like – *Additive Manufacturing* (AM), play an important role and are applied in production as an approach of 'evolved handicraft culture'. This production mode is alternative to the traditional technique based on the removal of exceeding material to obtain the desired shape: based on data supplied by the graphic CAD, the machine makes the object depositing layers of materials on a pre-defined surface. While on one hand in standard processes one risks to generate a lot of waste, on the other hand, in this case, the advantages are high efficiency of resources, reduced consumption and reduced waste of material and control of energy use. The additive printing process will be more sustainable when making use of materials with a low environmental impact like biopolymers[40] or recycled materials obtained even from waste of the same printing process. Once again, it is worth pointing out that this technology reduces the risk of unsold finished products as it allows manufacturing on demand.

- *Increasing the Environmental Effectiveness of Production Systems*

Of course, digital technologies deploy their potential in production systems both making the information and process flow effective and strengthening automation. However, the textile and fashion industry often goes for human intervention to ensure the hand-made and tailor-made approach, which remains a strong point of this industry, where each single garment is customized with great attention to details.

Reference is made to *Industrial IoT - Internet of Things*, an environment based on technology and information, in which the machines, thanks to computer connections, can interact with other machines, while facilitating the interchange of data and stimulating the learning process. Just to give an example, this makes it possible to monitor and correct a process depending on data and inputs acquired and transferred from devices on the machines as well as on workpieces by means of RFID, sensors, tags continuously controlling the implementation of the production and of the logistic process. The environmental benefit is evident: a continuous control of the production flow, a wise management of energy use in the production halls, no waste and no reprocessing, efficient resetting of the machines. Data gathered in relation to the type of information processed (performance of the machine, events occurred, consumption, etc.) and managed with techniques of *Big Data Analytics* helps derive useful information to evaluate the running process, to further develop it (as it is the case with a preventive maintenance to predict failures of the plant) while helping the management to make the right decision.

A robotic approach, mainly in handling systems and logistics, as a role of *Advanced Manufacturing Solutions*, improves the degree of safety of workers thanks to machines that work autonomously or can support the operator carrying out risky or laborious work (collaborative robots).

On the other hand, *Augmented Reality* is a multi-level instrument. Thanks to electronic devices, mainly worn by the operator, the latter receives additional information. In the meantime, other information, connected with the perception of the five senses, may be removed to allow an immersive experience - with effective learning - or just an emotional experience. Hence, Augmented Reality plays an increasingly important role in marketing strategies. Known to the general public mainly in entertainment and cultural or promotion activities, indeed it is a useful tool to train engineers and operators. It looks particularly promising in production bays to repair and maintain the machines also with the help of a remote tutor.

While opening up new opportunities to industrial models, these new technologies should not be taken as separated areas, but as allies in an effort to increase the environmental efficiency of industrial systems. Hence, one should not misunderstand the take-up of better-consolidated technologies and methods in the textile industry; on the contrary, the take-up should be enhanced as it can reduce consumption and avoid waste. This view is supported by the EU Commission report "*ERA industrial technology roadmap for circular technologies and business models in the textile, construction and energy-intensive industries"*[41], published in December 2022. E.g., with reference to finishing processes by way of '*electro-chemical deposit of pigments into recycled materials to extend the life cycle, to recover dyestuff from dyeing waste water, for dyeing processes without water by means of super critical CO_2 supercritical, plasma treatments, ozone technology*'.

40 Tanase-Opedal, M., Espinosa, E., Rodríguez, A., & Chinga-Carrasco, G. (2019). Lignin: A Biopolymer from Forestry Biomass for Biocomposites and 3D Printing. Materials (Basel, Switzerland), 12(18), 3006. https://doi.org/10.3390/ma12183006.

41 https://op.europa.eu/en/publication-detail/-/publication/32f12c4b-9d89-11ed-b508-01aa75ed71a1/language-en/format-PDF/source-279513935

Bottom line

The task of technologies, though important, in not to give means to recover and recycle raw materials otherwise expected to go to a waste to energy plant or to a landfill. It is also to support the effort of industrial segments to avoid the generation of waste and to save raw materials, water and energy.

Providers of technology for the textile industry have always paid attention to these issues, considering the need to offer their customers economic benefits. Today, they are even more driven by sustainability.

5 Technology to Recycle Textiles

With globally growing consumption, an increasing demand of fibres on one hand and increasing textile waste, difficult to be managed, on the other raise the urgent problem of developing and circulating methods and technologies to select and recycle textiles at end of life and pre-consumption waste.

According to a study carried out by the consultancy company McKinsey, the potential of a recycling process, though urgently needed, is actually limited because of objective facts, such as a wide range of materials in a single garment, often not easy to separate, and the lack of an effective recycle preparation chain. The study reads: '*Advanced, accurate, and automated fiber sorting and preprocessing are not yet developed. Finally, to reach their full potential, the fiber-to-fiber recycling technologies must further expand their ability to handle fiber blends, lower their costs, and improve their output quality—these bottlenecks prevent the circular textile economy from scaling. Our analysis indicates that by overcoming these barriers, fiber-to-fiber recycling could reach 18 to 26 percent of gross textile waste in 2030. To reach this scale, we estimate that capital expenditure investments in the range of €6 billion to €7 billion are needed by 2030. Our analysis indicates that this industry could—once it has matured and scaled—become a self-standing, profitable industry with a €1.5 billion to €2.2 billion profit pool by 2030'.*[42]

According to this forecast, should technical and organisation constraints be duly taken into account, results would be socially and environmentally encouraging: *'about 15,000 new jobs could be created and CO2e emissions could be reduced by approximately 4 million tons, equivalent to the cumulative emissions of a Country the size of Iceland'.*

The impact on the economy should be positive. By quantifying into monetary terms several other impact dimensions like the secondary effects to GDP from job creation, CO2 emission reduction, and water- and land-use reduction, the industry could reach 3.5 billion Euro to 4.5 billion Euro in total annual holistic impact by 2030, coming to an annual holistic impact return on investment of 55 to 70 percent'. Such results, as the analysis indicates, needs great support with suitable investments: '*Several parts of the value chain must be built out almost from scratch, which requires significant capital expenditure. Our analysis indicates that sufficient economic value can be realized to make up for the required risk. Private investors would lead this journey by taking initiative to finance building out the value chain'.*

The need to increase investment in the search of technological solution suitable to step up recycling is confirmed also in a document of the UEERA Commission on *Industrial technology roadmap for circular technologies. "Assuming investment up to 50 million Euro, 5 to 10 million should go to the research on recycled materials, 10-20 million to chemical recycling and the study of innovative recycling. There is a special need of funding of pilot plants/demonstration platforms (estimated cost: one million Euro per research structure), given the importance of sorting and recycling infrastructures".*

Meanwhile there exist some projects aimed at developing, testing and implementing technological and organisation models to ensure the optimal management of textile recovery and recycle both as regards private consumers, and through financing plans provided by the European Union.

5.1 Digital Technologies to Support System Measures

Technology will play an important role both in preventing the production of waste and, of course, in recycling. The same applies to the fight against illegal conduct and misbehaviour, for example in supporting the identification of unlawful textile landfills. The illegal dispersion of textiles in the environment requires aimed measures in accordance with the polluter-pays principle launched by the EU. In Italy, this fight will require

42 McKinsey, Scaling Textile recycling in Europe, turning waste into value, 2022

investment in advanced technology, while maintaining control over the territory even my means of satellites, drones, and artificial intelligence systems[43]. This experience already exists, though occasionally, in specific environmental projects aimed at detecting plastics left on the beach.

However, it is in production process where digital technologies are intended to play a very important role. Just to give an example, in collecting, sorting and selecting materials to be reused and recycled and, in particular:

- in the implementation of platforms to support industrial symbiosis plans aimed at helping to bring together demand and supply of textile residues. This formula was already tested in plans supported by the EU, such as the *Material Match Making* platform, implemented by UNIVA and Centrocot, together with some partner companies within the Life M3P programme;
- in monitoring collection flows and transformation of materials to be recycled, hence making the process effective and documented, also in order to assign a reliable value to the percentage of recyclable components in new products and to the relevant environmental product declarations;
- in developing business models based on circularity and sharing of goods: from a sharing economy to on-line selling of second-hand apparel and accessories;
- in actions in order to make consumers aware and to involve them in a responsible behaviour when purchasing and until disposal of goods.

5.2 Collection and Preparation for Recycling

Summary of the stages textile waste must go through to enter the re-use chain[44]:

- collection of the textile fraction (through a door to door collection or in containers on the street);
- temporary storage;
- first sorting: resp. opening of bags brought by users and first sorting by item type;
- second sorting, mainly carried out by hand by skilled operators who separate apparel by type and quality in order to take up the most valued fraction and build homogeneous lots of re-usable products;
- sanitation of re-usable products.

The portion of urban textile waste discarded during the sorting process as non -suitable to be re-used, is further sorted by type of material and shipped to:

- production of rags for the industry, used in cleaning and maintenance operations (rags, absorbent and washing pads) in the metal sector, in printing houses and to protect floors;
- textile recycling;
- as an alternative to recycling: incineration/waste to energy plant.

A substantial portion of the technological research has focused on the sorting and selection of materials. The objective being to replace or, at least, integrate the sorting by hand with technical solutions to speed up the process and make it more reliable. This way helping the segment to go from manual work/craftsmanship to more industrialised patterns. These mostly include materials reading systems based on the Near-Infrared Spectrum (NIR) to identify the colour and composition of textiles, considering that each single cloth has spectrum features useful to classify a product. In fact, the chemical and molecular structure of natural, artificial or synthetic fibres is different and they react in different ways to electromagnetic waves. Usually, dedicated machines include a conveyor belt on which materials run to be subject to optic vision, while separating belts convey the materials to aggregations based on types in order to recycle them.

Just to give an example, let us mention recent experience gained on the field: SIPTex, a Swedish consortium led by IVL, the Swedish Environmental Research Institute, developed a pilot plant sorting textiles by means of the VIS-NIR technology to identify and separate textiles by prevailing colour and fibre composition; compress air blows the collected fibres into the correct container. Next Technology Tecnotessile, a company based in Prato (Florence), has developed the prototype of a semi-automatic machine that detects materials on an automatic conveyor belt by structure (knit, orthogonal fabrics, warp-knit fabrics), colour (they identified seven reference colours) and fibre composition. The machine consists of a detection station with advanced cameras

43 Decree 27th January 2023 Reallocation in lines B and C covering the European Economic Recovery Plan PNRR M2 C1 I 1.2 investment of remaining resources not allocated for lines A, B, e D related to the same investment (23A01536).
44 Ecomondo, https://www.ecomondo.com/blog/20917792/prevenzione-rifiuti-tessili, 2022.

using hyperspectral technology in the near-infrared, assisted by an artificial intelligence system with self-learning algorithms and storage of spectral images acquired, a conveyor belt and baskets to collect garments.

Before starting the recycling operations, if not yet accomplished, difficult parts have to be removed, which might cause problems during the recycling operation. It is the case of soft plastic coatings or metallic parts like buttons or zippers. Whereas soft/rubber-like components may bind to fibres being recycled making them not suitable, hard components may damage the machine during the process. There exists also a potential risk of fire: a spark caused by a metallic piece, like a snap hitting the machine, can ignite highly flammable fibres like cotton.

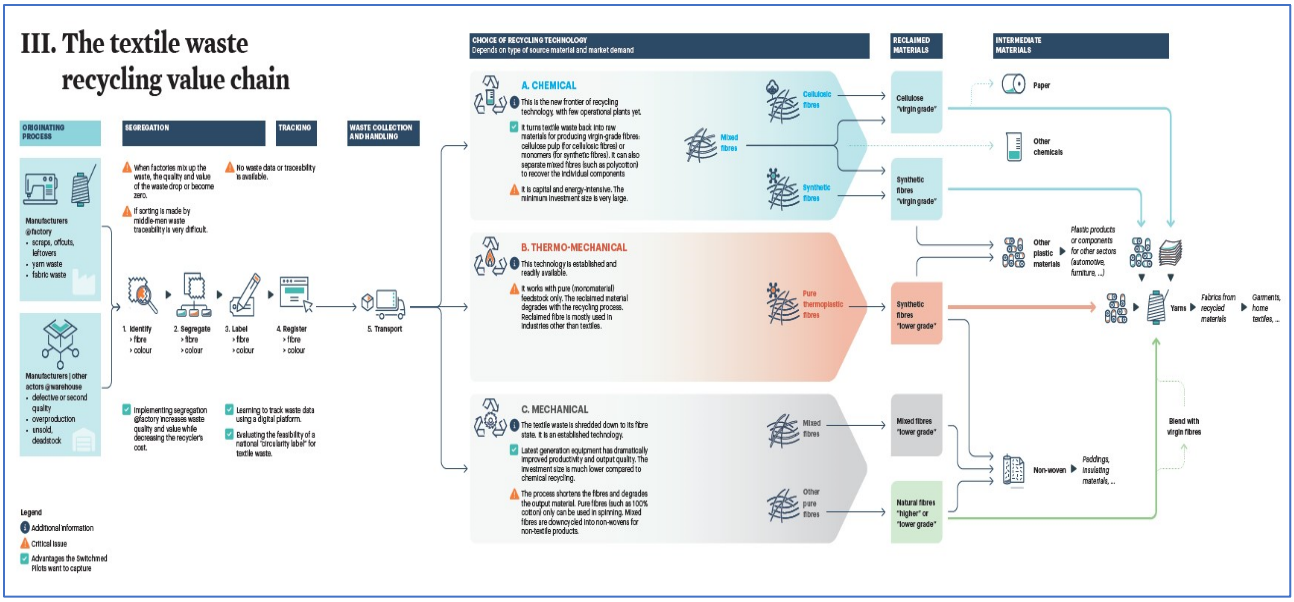

Figure 3: The textile pre-consumption waste recycling process, source Blumine for Unido project

Short glossary of recycling

- Closed loop recycling: materials are recycled to obtain a product more or less identical to the type of material processed;
- Open loop recycling: materials are recycled to obtain a different product category with integration of virgin raw material;
- *Upcycling*: the product resulting from recycled materials has got a higher value than the original one;
- *Down-cycling*: the product resulting from recycled materials has a lower value than the original one.

5.3 Recycling

This chapter of the report covers various types of textile recycling. To this aim, reference is made to recycling types mentioned by the European Commission in its document '*Study on the technical, regulatory, economic and environmental effectiveness of textile fibres recycling'*[45]*:* mechanical, thermo-mechanical, thermo-chemical and chemical recycling process.

❖ **Mechanical Recycling:**

The mechanical recycling has a long history. This technology has been in use for decades, mainly in wool cloth processing, as one can see in the Prato area. It is a well consolidated process. Once free from any metallic parts or lining, fabrics are sorted by fibre composition and shade (this will help reduce if not avoid the use of dyes on the recycled yarn). Wool cloths are carbonized in a chemical treatment to remove any cellulose fibres that would jeopardize the quality of the regenerated product. Materials are torn and defibrated in order to detangle and loose the fibres. The result is a material ready to be carded in a machine that parallelizes fibres and lines them in strips to be converted later in yarns through drawing and twisting. The final yarn shade can be obtained selecting and mixing fabrics based on the original shade or through an finishing process to be carried out both on pre-spinning materials and on the product at the end of the process. This system to regenerate materials can be applied both to obtain yarns ready to be put on the market and as preliminary stage for a further thermal or chemical process. In the case of mixed fibres or low quality fibres the system will fray the material to obtain fibres for upholstery, fillers and to reinforce materials for composites.

While on one hand mechanically processed wool maintains a good quality grade, processing of other fibres may be more critical. A mechanical action will keep the properties of a fibre unchanged, though resulting in a lower quality to a point that requires introducing virgin fibres to raise the quality of the yarn obtained. Maintaining dyestuff and chemicals in the mechanically recycled material may be an advantage (when sorting the waste flow by colour you do not need to dye the material); however, undesired contaminants may still be there making it difficult to claim the compliance of the material with the REACH regulation provisions. In any case, mechanical recycling, though in terms of d*own-cycling*, can process a wide range of materials and fabrics not recyclable through other technologies. Further, this is a low energy use process (between 0.3 and 0.5 kW per kilogram of material entering the process) and featuring a low water consumption, limited, if necessary, to a pre-treatment cleaning process. As against chemical recycling, the mechanical recycling needs a lower investment and a medium level of technical expertise of operators.

Technological research projects focus mainly on improving the quality of materials obtained and retrofitting the machines according to the subsequent stages of thermal and chemical process starting from a more effective sorting of entering materials. The above study mentions European companies applying this kind of recycling with production capacities ranging from 5,000 to 10,000 tons/year, to as much as 36,000 tons/year.

❖ **Thermo-Mechanical Recycling**

As it is the case with the mechanical recycling, thermo-mechanical recycling is a low cost, consolidated process. Based on grinding and melting of materials, it is especially interesting to recycle waste from the production of man-made fibres and some specific types of consumer waste that has been collected in specialised centres (e.g.plastic bottles), however it is not suitable to recycle thermosetting polymers. The presence of polymers non-compatible with the recycling process may cause problems in the processing and reduce output properties; hence, an accurate sorting of input materials is an important pre-requisite.

Research on this type of recycling focuses on mitigating the immiscibility of polymer blends. The same applies to colours; pigments and other contaminants remain in the materials wash residues, flame-retardants, coatings, etc. in or on the fibre and on the fabric (potentially not consistent with the REACH regulation).

Further, the polymer/fibre properties deteriorate after each cycle. Hence, though similar to virgin or waste plastics melting, this process requires suitable equipment and components in order to ensure a stable and continuous process without altering the viscosity of the polymer obtained. Since dyes remain in the polymeric material, one can only obtain dark shades, unless the input is sorted by colour, exploiting the property of some thermochromic dyes to alter a colour at a given temperature.

45 EU Commission, Study on the technical, regulatory, economic and environmental effectiveness of textile fibres recycling, 2021.

❖ Thermo-Chemical Recycling

The process uses partial oxidation reaction of polymers or heat to degrade polymers to monomers that can be used as feedstock for the chemical industry. It is a useful technology to reduce textile waste that cannot be processed with other methods, however not to recover fibres from fibres. It is considered a mature technology, although there are some very recent developments to allow the production of raw materials for the chemical industry, as opposed to energy recovery or fuel production. Syngas, the main output of this process, is useful for many applications in chemical synthesis reactions resulting in a full range of products.

The energy requirements for thermo-chemical recycling are very high. In thermo-chemical recycling processes through pyrolysis and gasification, combustion takes place at temperatures ranging from 800°C and 1200°C with enough oxygen to fully oxyde the material. The output (gas and fuel) of gasification and pyrolysis can be used for produce heat and energy. However, through subsequent purification/upgrading steps, they can be converted into intermediates as raw materials for the chemical industry.

❖ Chemical Recycling

Chemical recycling is a process using chemical dissolution or reactions to disassemble used fibres, extract polymers for new uses or break them down to their constituent monomers to rebuild new polymeric fibres.

The above mentioned study indicates three cases of recycling processes with three major technologies.

- ❖ Cotton recycling through a pulping process to obtain cellulose pulp to be used as input (in a viscose or lyocell process) via processes with sulphate, sulphite and sulphur-free. Sorting textile waste is very important: in order to optimize the process the cotton percentage must be high (minimum 50%). The tolerance to dyed textiles depends on the process, but most technologies include a decolouration/ bleaching step. The cellulose paste obtained can be blended with wood pulp before going to a spinning process.
- ❖ Monomer recycling of PA6 and PET is a de-polymerization process, where polymer chains are broken down in monomers via different technologies and reaction conditions (temperatures/pressure/time/catalysts). The applied solvents are typically water (i.e. Hydrolysis, for PA6), alcohols (i.e. methanolysis) or glycols. For PET, all three of the reaction mechanisms are used, with glycolysis being the most common. In addition to the three methods mentioned, recently a fourth method has become available, namely an enzymatic de-polymerization reaction. A biological catalyst mediates the chemical reaction. Although the final output depends on the reagent, PTA (terephtalic acid) and MEG (ethylene glycol) are the traditional monomers obtained from PET, which can be depolymerized to obtain high purity, virgin grade PET, while for PA6, the output is caprolactam which can be re-olymerized to virgin grade PA6. The efficiency of the chemical recycling of synthetic fibres depends to a high degree on the purity of the input material. For economic reasons, the PET or PA content in the input should be around 80-90%. Hence, current practices proceed from packaging waste PET and industrial waste PET to obtain recycled polyester fibres. However, the use of PET to obtain textile fibres removes polymers from a repeated recycling cycle; in fact, polyester is not easily recyclable, hence the EU Commission encourages a fibre-to-fibre recycling process. On the other hand, polyamide is usually obtained from textile flooring, fishing nets and other plastic waste with an estimated recovery around 65% of the total input.

❖ Recycling of Poly-cotton

Via solvent-based dissolution and filtration processes different materials can be separated extracting the desired components. The recovered cellulose can be applied in the mentioned process to obtain man made cellulose fibres, while PET polymers remain largely intact and can be respun to filaments; however, in today's practice, they are incinerated for energy recovery. A second type of technology consists of a hydrothermal approach to degrade (partially) either cotton or PET or both. These processes rely on water, pressure, temperature and chemistry. A third approach focuses on partial degradation via an enzymatic process resulting in glucose (that can be used in other industrial applications), cellulose powder and PET. In order to obtain PET fibres, via a melt-spinning process, which are suitable for textile applications, virgin grade PET has to be added to improve quality.

- **Recycling via Biotechnology**

The biological recycling is based on resources that can disintegrate and build nutrients to be converted into novel renewable resources. Processes can be classified as biological, that is a biological decomposition at end of life, in which micro-organisms metabolise textile materials in simple molecules (compost and anaerobic digestion; biochemical, via enzymatic depolymerization using enzymes to deconstruct polymers in monomers and fermentation via micro-organisms.

Textile waste can be considered raw material rich with cellulose for second generation bio-refinery in an open loop recycling process (from cotton to man-made cellulose fibres) although contaminants in elastomers and chemicals used in the dyeing and finishing process, as well as a high degree of crystallinity of cotton fibres, could be a constraint in the recycling process. Wool and silk are made of keratin, a protein whose recycling has been studied in the food industry to recover biopolymers from post slaughter plumage. However, for the time being, high costs associated and the negative environmental impact have discouraged this research. Studies are being conducted to obtain enzymatic recycling of PET, though such an approach would be difficult to apply to textiles. However, it is more and more accepted that methods developed in bio-technology based management of materials from renewable and non-renewable sources may represent the path to follow or be functional to chemical recycling processes, e.g., in pre-recycling steps. This is one of the most advanced sides of the research on recycling of textiles, although not yet industrially scalable.

6 Final Notes

Nobody has to explain to anyone that the demand of recycled fibres is increasing. In their report on sustainability number of brands mention the aim of increasing secondary raw material in their collection and the EU contributed asking contracting entities to introduce the second life component into the EMC - Environmental Minimum Criteria. In a study carried out to measure the use of key words connected to sustainability in the report on sustainability of 12 global fashion brands, the words ‘recycled’ and ‘recyclable’ are the most recurrent, confirming the importance of the topic in the strategies of those brands[46].

Some trade shows like Première Vision and Milano Unica confirmed this trend. The latter offers each time data on sustainable innovation trends that characterise the materials selected and shown in the sustainability section of the exhibition. At the event held in February 2023, almost 500 samples (42%) were presented with the “recycled material” label. It is also striking that in excess of 73% of 166 exhibitors participating in the project, presented at least one sample including recycled material, as against 71% at last year’s event[47].

However, circularity cannot be improvised. First, materials and products shall be designed to last for a long time and be easily recycled, once they have fulfilled their function. They have to be chemically safe; if made of different materials, these shall be compatible in the recycling process or easily separable. The demand of recycled materials shall stimulate the necessary investment to produce them; the supply shall ensure technical and aesthetic performances required as well as the volumes needed to feed industrial streams. There exists also a non-negligible aspect: information supplied with the purchased products shall refer to evidence-based data, scientifically documented; all that requires an active involvement of the whole supply chain.

We are facing an epoque-making change that involves different subjects, on whose cooperation depends the effectiveness of the achievements; manufacturers of materials and finished goods, companies involved in collecting and sorting waste, recycling agents, logistics, research entities, test laboratories, regulators and certification agencies. And, of course, the manufacturers of processing systems and machines.

Under this scenario, technology is expected to offer a fundamental contribution. Manufacturers of machines, systems, equipment and software are called upon to feed the new and complex supply chain both with technologies to be applied to single process steps (from detection of materials to separation, to preparation for recycling, recycling process, spinning, building of surfaces, finishing, logistics and traceability) and with support to the build-up of networks and the management of data from the supply chain. All that applying those logics of energy and resource optimization that make the process not only environmentally effective, but also economically sustainable. There seems no doubt that the market will increasingly need technologies to manage and convert waste. Euratex estimated that by 2030 Europe will need in excess of 200 recycling plants to be added to those already working, that have to be updated and reinforced.

A research, experimentation and production approach is expected, able to involve the whole supply chain and ensure the necessary connections of all operation steps.

More specifically, we should overcome the objective constraints on the growth of industrial recycling starting from a still weak diffusion of systems to detect and sort materials made of different fibres and colours.

As regards recycling in itself, information gathered shows that, although mechanical recycling is a mature technology - as the business in the Prato area has been demonstrating for one hundred years - measures shall be taken to make processes effective and more versatile, actually able to manage different materials, while ensuring quality results. Pyrolysis is considered a most promising technology. It is a thermal depolymerization technique that allows obtaining a hydrocarbon or monomere blend, able to effectively process polyolefine fibres. However, chemical recycling is a focus of a growing interest. In fact, beside effectively processing man-made fibres, it is a valuable alternative to recycling of mixed waste where mechanical recycling may deteriorate the fibres. On this side, research shall accelerate the development of technologies able to process significant volumes of waste and allow transforming the materials into novel filaments.

Important signals are being sent from the chemical industry (also) in Italy. See the case of NextChem, a subsidiary of Maire Tecnimont operating in the green chemistry and energy transition segment, that in 2022

46 Blumine, Indicatori di sostenibilità nelle strategie dei marchi globali della moda, 2023. (Sustainability Indicators in Strategies of Global Fashion Brands, 2023).

47 https://www.milanounica.it/it/i-materiali-da-riciclo-pi-utilizzati-nel-tessile

started the DEMETO project, co-financed by the European Union within Horizon 2020 programme, aiming at the chemical recycling of PET and polyester textile fibres waste andobtaining pure monomers to be used in industrial processes to produce new polymers[48]. Another interesting technology has been developed by the Japanese group Teijin[49] on the use of a new system of depolymerisation catalyst, to chemically decompose polyester converting it into BHET, an intermediate raw material, before being repolymerised. The production process is simpler than using dimethyl terephthalate (DMT), hence with less energy consumption; also, the new technology reuses resources such as waste water, waste liquid and depolymerization catalysts**.**

A further barrier to the development of industrial textile recycling is due to chemicals in input materials not compliant with the Reach regulation, which may limit its recyclability. Whereas the regulation is being updated at European level, awareness is growing that the product and product's features documentation (Digital Product Passport) shall not only provide comprehensive information to consumers, but also provide information for a correct and safe management of an item at end of life.

Technical literature and the trade press rightly stress experiments applied to extremely complex product classes like composites, coated fabrics, fabrics containing elastomers[50], as well as items of general use like mattresses and geo-textiles, usually expected to be *downcycled*[51].

Of course, a culture of sustainability offers technology producers the opportunity to introduce their projects and products into a global value chain. With a growing demand of recycled materials, also the demand of process management technologies will grow. The provision of finance to support technological research will inevitably follow to help manage critical issues and eliminate limits that hinder an efficient closed loop recycling, 'from textiles to textiles'. In an integrated system aimed at managing a circular transition of the textile industry, different subjects are called to action. From recycling firms, to preparation and recycling in textile businesses, from research institutions to certification agencies. However, manufacturers of machines, systems and software are those required to put on the ground application instances, currently at an experimental stage, converting them into industrial processes.

48 https://www.industrychemistry.com/primo-impianto-di-riciclo-chimico-di-pet-e-poliestere-da-tessuti-in-italia/

49 https://www.teijinaramid.com/en/sustainability/recycling-and-circularity/index.html

50 Experimentation carried out in 2022 by Next Technology Tecnotessile, a Prato based research company, to separate elastomers, is an interesting step forward towards the solution of the problem. Also the Swedish Re:mi project is worth mentioning; it aims at making chemical recycling of man-made materials efficient.

51 In Italy some interesting solutions are being tested, demonstrating that waste can be effectively converted in to new materials. It is the case, for example of the waste treatment unit at Spresiano[51] with the first industrial plant of this kind in the world, developed in cooperation with Fatersmart; the plant can recycle use diapers converting them into cellulose, plastics and polymers to be re-used in various production processes.

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