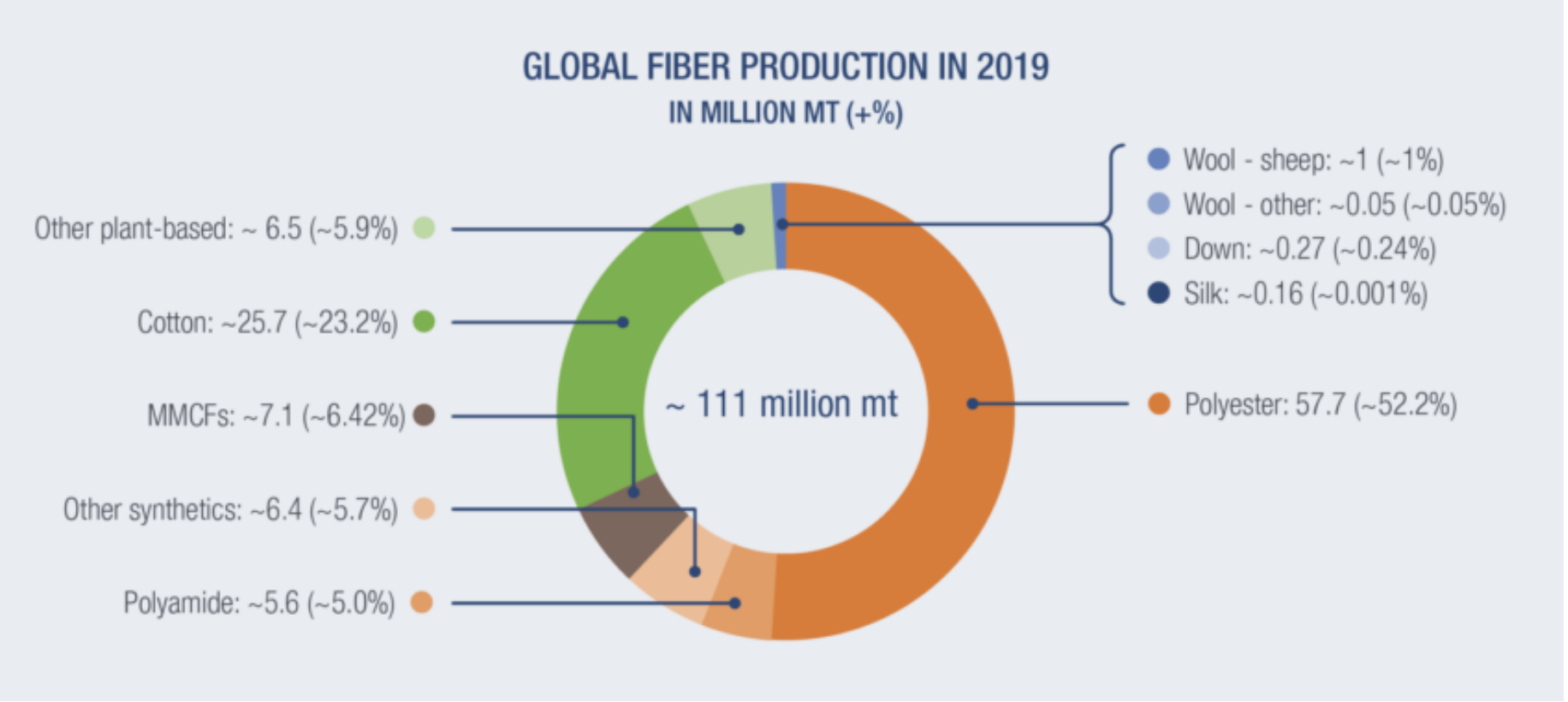
Circular options in textile materials – PART A

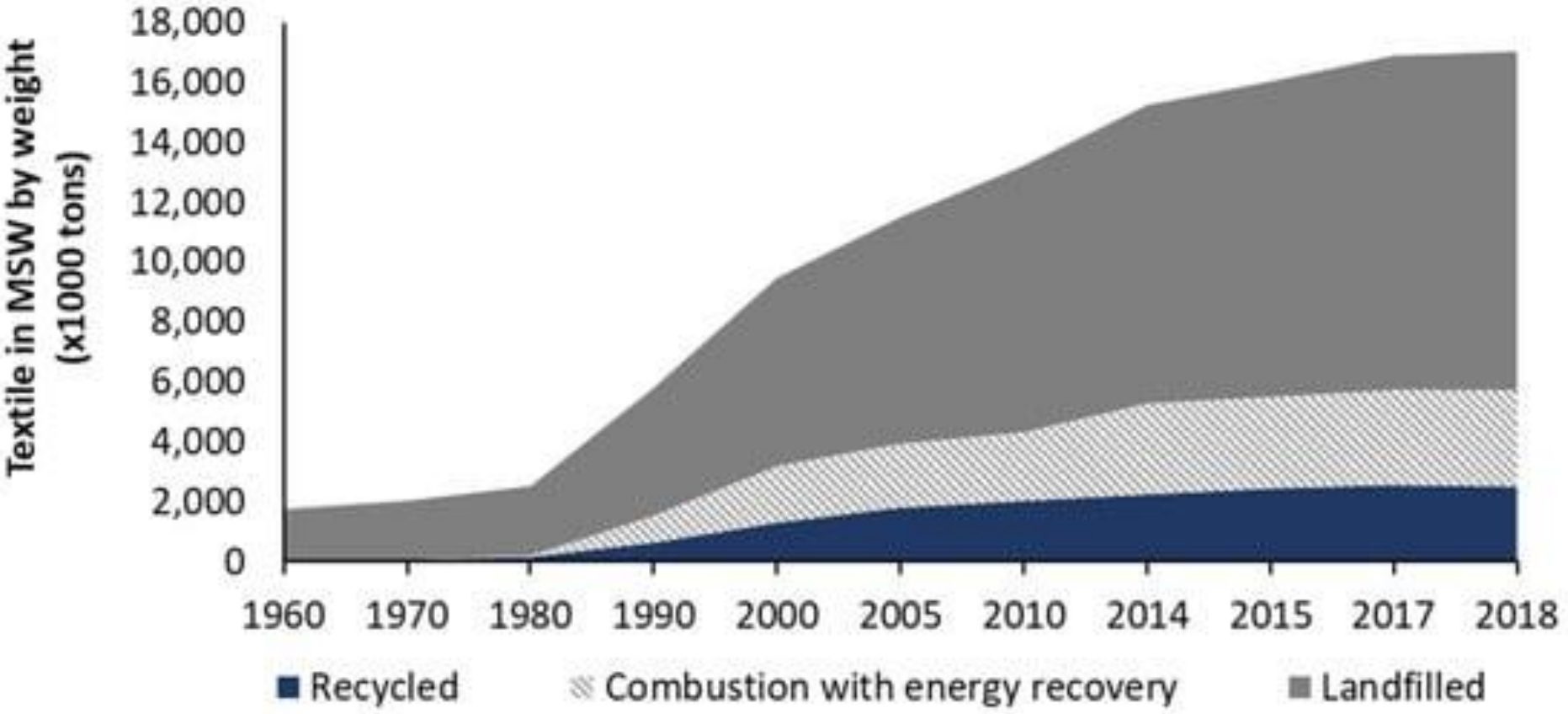


The starting points



https://textileexchange.org/2020-preferred-fiber-and-materials-market-report-pfmr-released-2/

The starting points



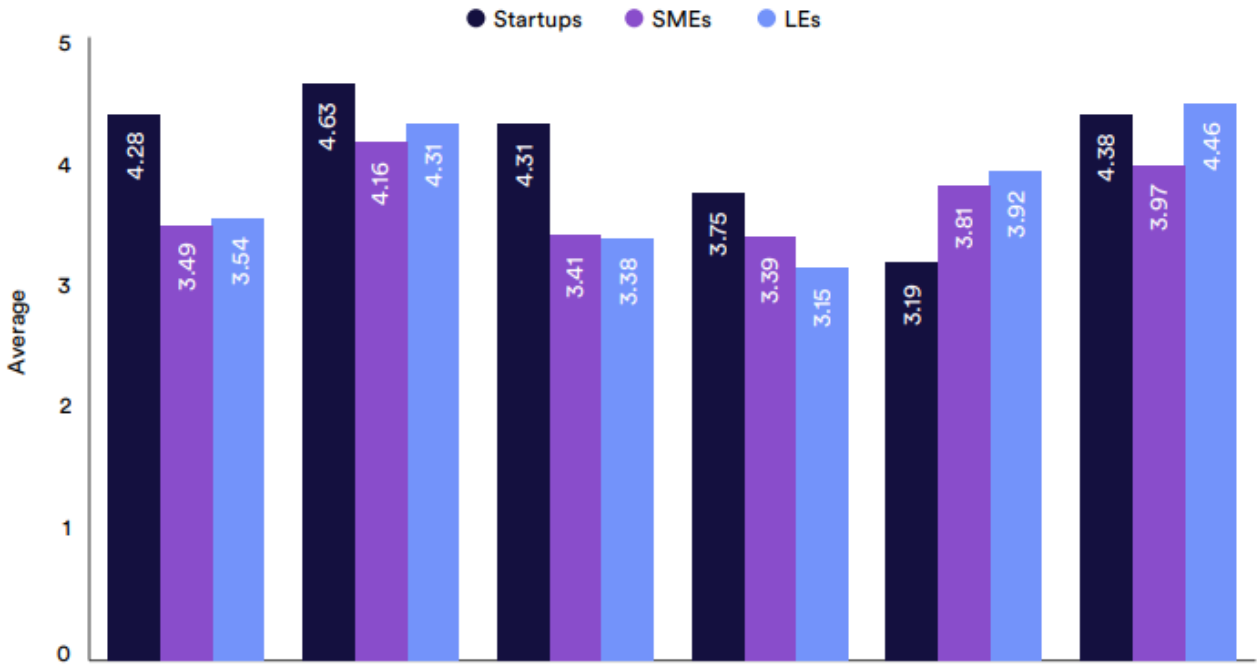
End of life of textiles

Source of the figure: Textiles 2022, 2, 174–188 https://doi.org/10.3390/

Perception about the Circular Economy in Italian fashion companies

Survey among Italian fashion company

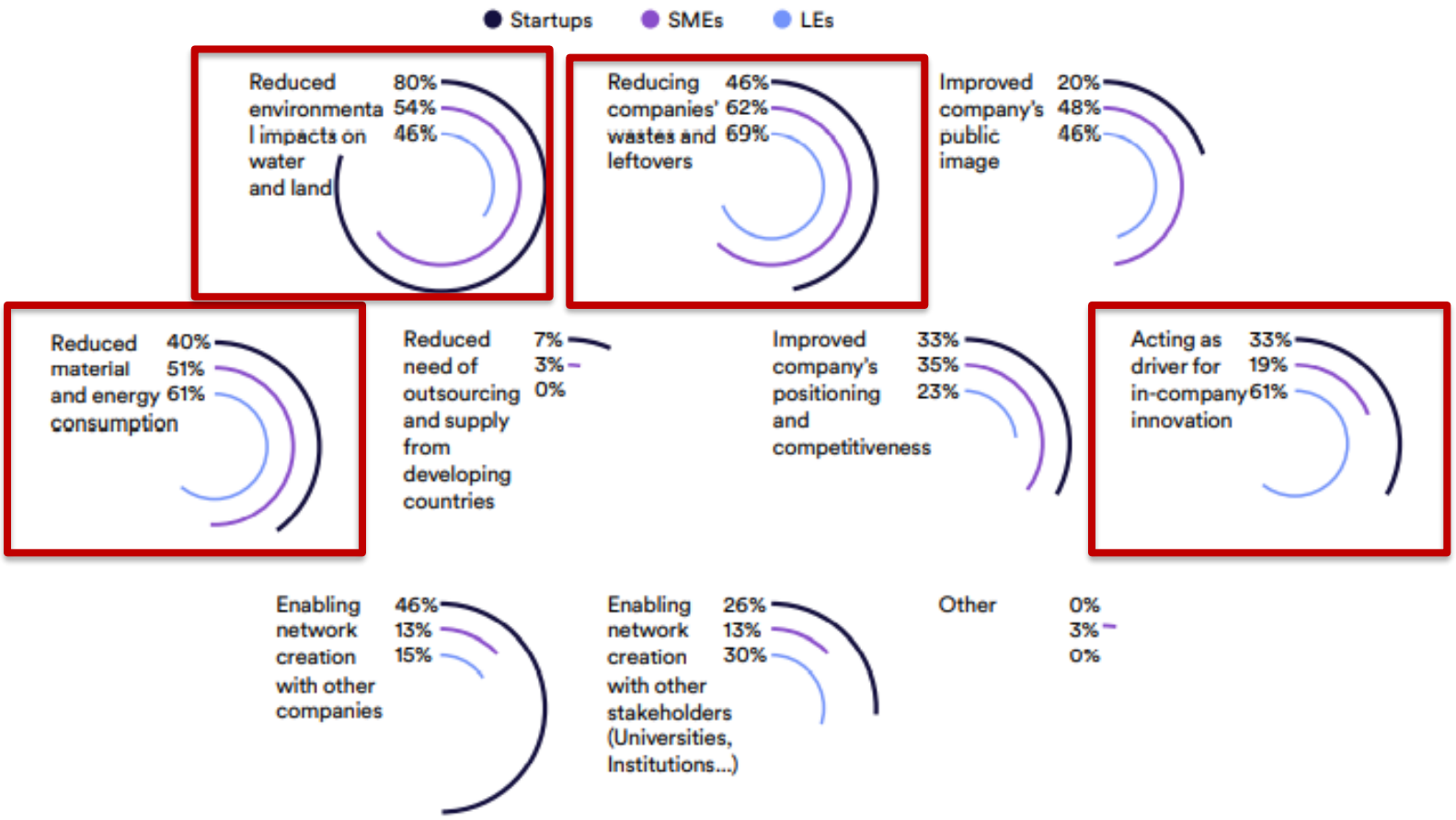
Circular Threads - A sectorial study of the Textile and Fashion Industry in the North of Italy, Tondo, Milano 2021



	Std. Dev.	Std. Dev.	Std. Dev.	Std. Dev.	Std. Dev.	Std. Dev.
Startups	0.50	0.81	0.60	1.06	1.05	0.62
SMEs	0.84	0.73	0.76	0.97	0.88	0.95
LEs	0.66	0.48	0.65	0.69	0.76	0.78

- 17 Start-ups
- 37 Suppliers Small Medium Enterprise (SMEs)
- 13 Suppliers Large Enterprises (LE)

Perceived benefits of the Circular Economy



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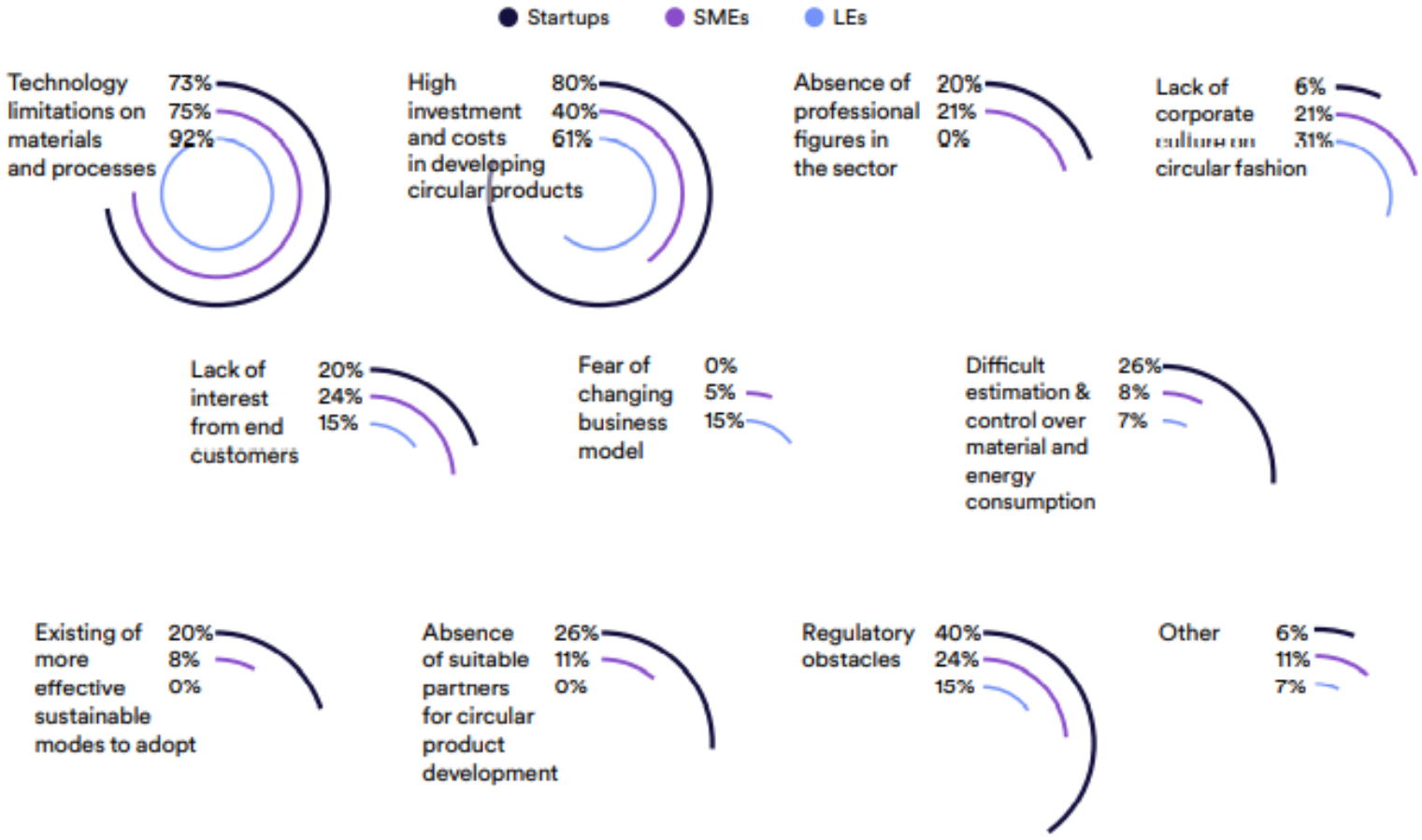
Circular Threads - A sectorial study of the Textile and Fashion Industry in the North of Italy, Tondo, Milano 2021
Survey among Italian fashion company

Perceived obstacles of the Circular Economy



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Survey among Italian fashion company Circular Threads - A sectorial study of the Textile and Fashion Industry in the North of Italy, Tondo, Milano 2021

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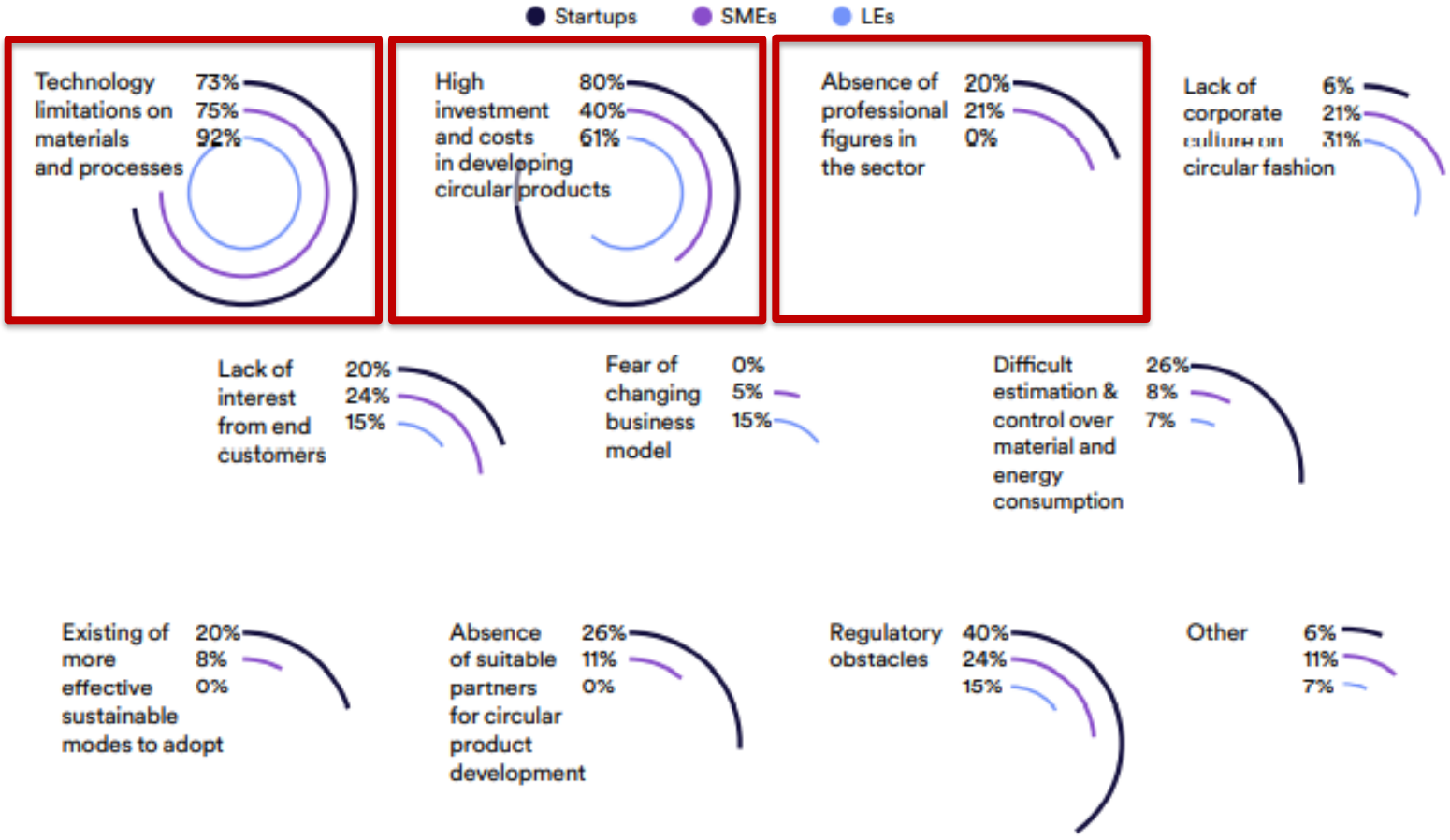

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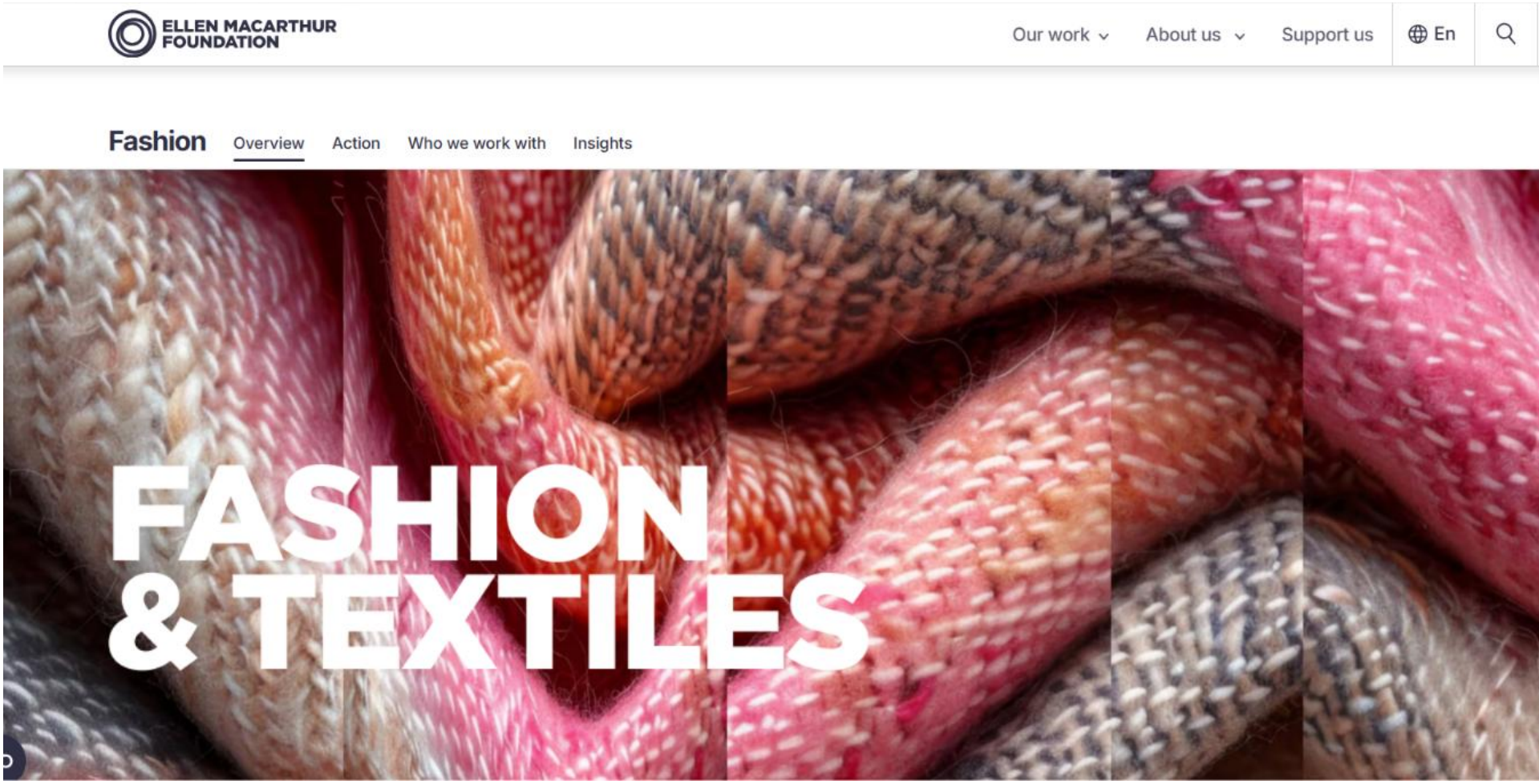
Survey among Italian fashion company Circular Threads - A sectorial study of the Textile and Fashion Industry in the North of Italy, Tondo, Milano 2021

Circular options in textile materials: sources



Circular options in textile materials: sources



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Circular options in textile materials

The (fast) fashion industry of today

Changing the system will unlock billion dollar economic opportunities.

Source: https://www.ellenmacarthurfoundation.org/fashion-and-the-circular-economy-deep-dive

Globally, the USD 1.3 trillion clothing industry employs more than 300 million people along the value chain; the production of cotton alone accounts for almost 7% of all employment in some low-income countries.

Clothing represents more than 60% of the total textiles used and in the last 15 years, clothing production has approximately doubled, driven by a growing middle-class population across the globe and increased per capita sales in mature economies.

At the same time, clothing use has declined by almost 40%.
Both developments are mainly due to the '**fast fashion**' phenomenon, with quicker turnaround of new styles, increased number of collections offered per year, and often, lower prices.

By moving to a circular system the industry can unlock a USD 560 billion economic opportunity. Realising this opportunity requires new business models and collaboration across the value chain (e.g. production, marketing, and after-sales care), to keep safe materials in use.

Circular fashion – background, definition and 16 key principles

Anna Brismar coined the term ‘circular fashion’ while preparing for a sustainable fashion event in central Stockholm, as lead organizer and developer of the event.

To start planning for the event, Anna and the other three team members met and Anna asked the others: “What shall we call the project?” In the absence of other suggestions, she shared her own proposal: “What about ‘circular fashion project’?”. The others agreed positively to the name. Upon returning home, Anna searched widely on the Internet for the term “circular fashion” to see if it had been used prior to this, but the term was nowhere to be found. A couple of days later, Anna decided to go public with the term.

By pure coincidence, some days later Anna learned that the concept of circular fashion *in its Swedish wording* (as ‘cirkulärt mode’) had been used by a few sustainability staff members at H&M headquarters in Stockholm for about a month or two prior. Yet, H&M did not go public with their Swedish version until some years later, nor did they provide any definition for many years. Instead, it was used primarily internally at H&M.

In autum 2014, Anna began building up the website **circularfashion.com*** and launched a network called **Circular Fashion Network** (with around 100 members, primarily Swedish). For the network, Anna arranged various meetings on different topics, from a film event (with a discussion of the 16 Circular Fashion principles), an Ocean plastics co-hosted event, to an event on Biomimicry. (*The website was later merged with greenstrategy.se, but there is an intention to built it up anew in late 2026.)

https://greenstrategy.se/produkt/circular-fashion-background-definition-and-16-key-principles/

Circular fashion – background, definition and 16 key principles

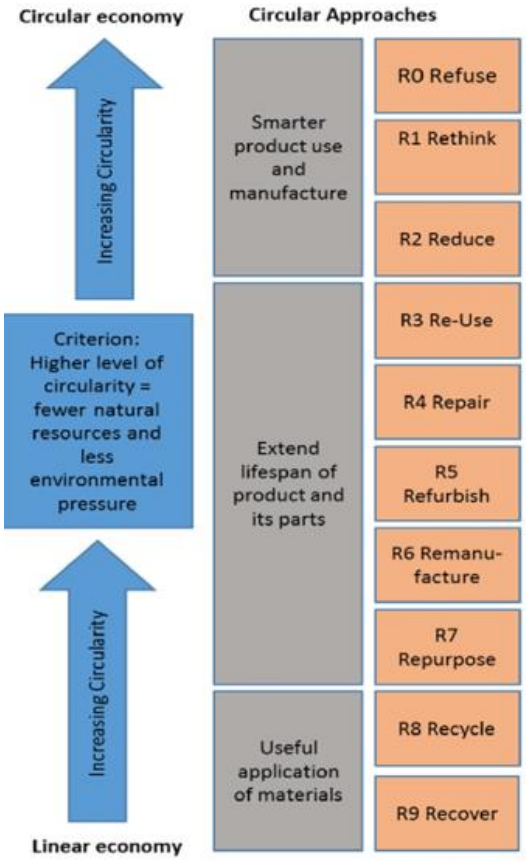


Your task: find some circular fashion example and prepare 1 slide on it (by 17.11.2027, send me n 16.11.2027)

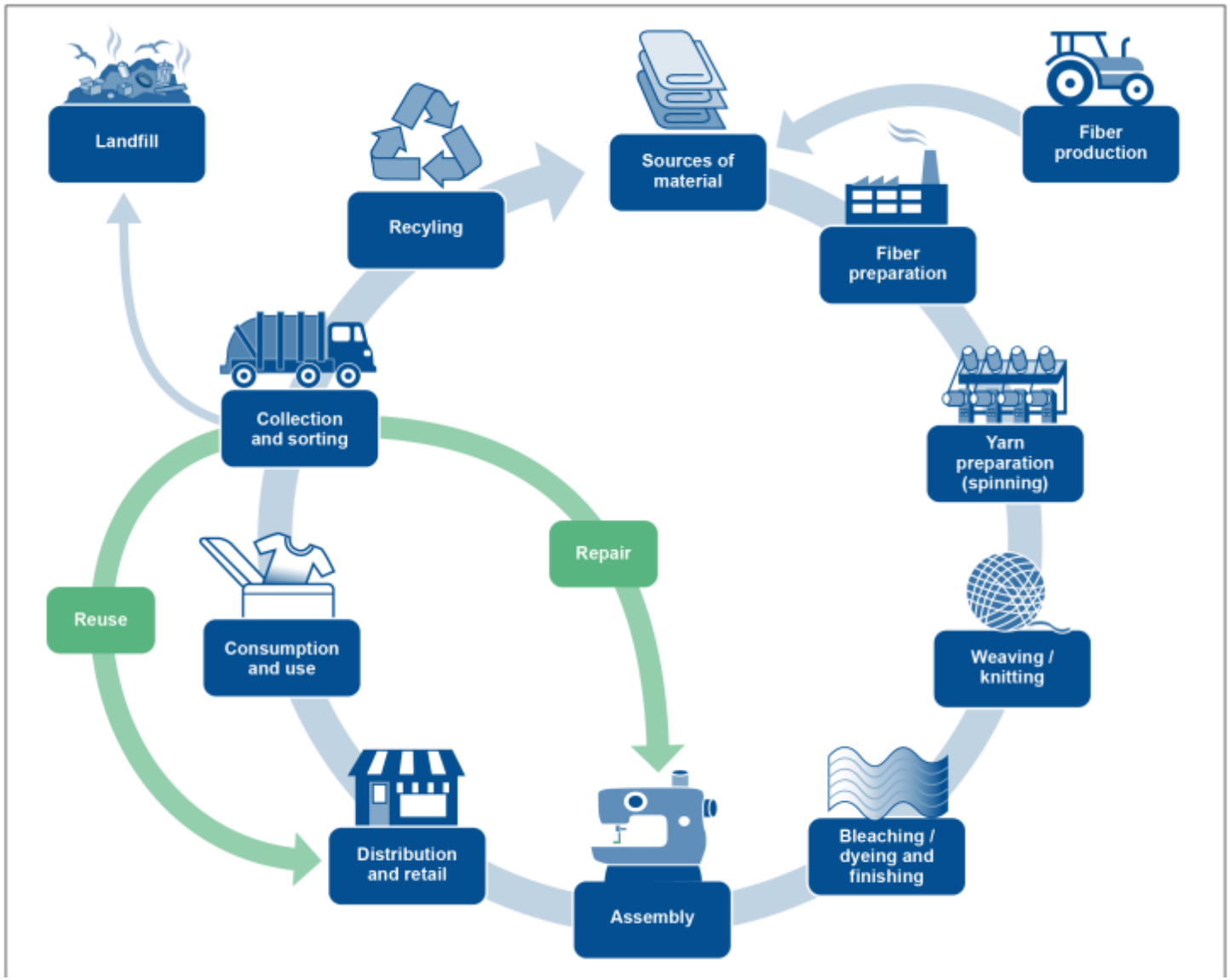
https://greenstrategy.se/produkt/circular-fashion-background-definition-and-16-key-principles/

Circular options in textile materials

- designing apparel and garnments to reduce complexity and facilitate disassembly and recycling at the end of life (e.g. zip, metallic parts, buttons etc)
- resort to more sustainable (less energy/raw materials demanding) materials, also reducing their amount and complexity
- reuse (second hand)
- life cycle extension through transformation and refurbishment
- repurpousing
- recycling/upcyclying of materials (when technically affordable)
- downcycling in other valuable applications
- recover as thermal energy (incineration)



Circular options in textile materials: the value chain



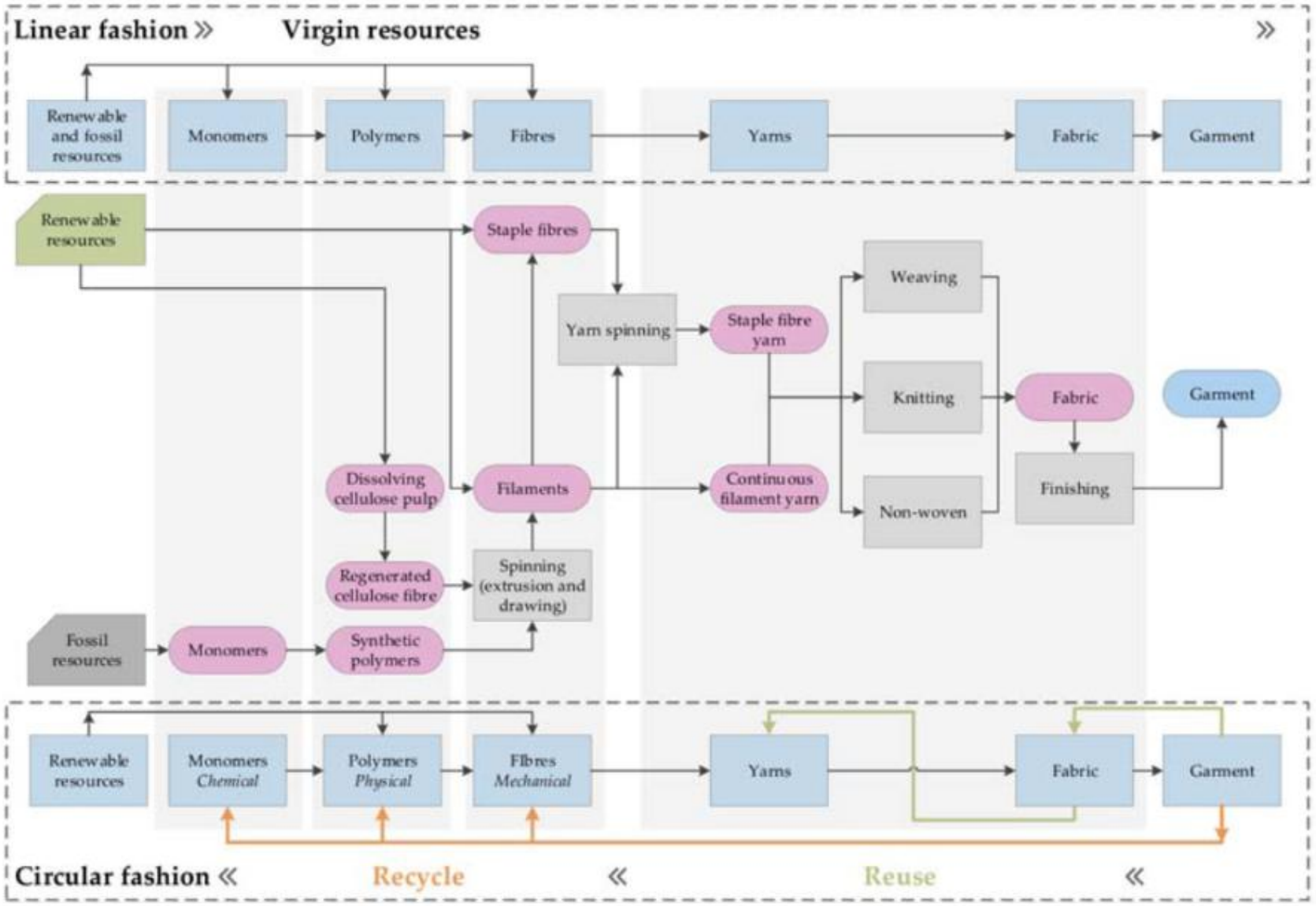
Circular options in textile materials

Textile recycling sector is underdeveloped compared to domestic plastic waste recycling.

- Complex textile structures make material identification challenging.
- Fabric waste often includes buttons, zippers, labels, and blended fibres.
- Multiple components & contaminants hinder single-material recycling.
- Manual sorting is the industry norm, making the process slow and costly.



Completely rethink our approach



Circular options in textile materials

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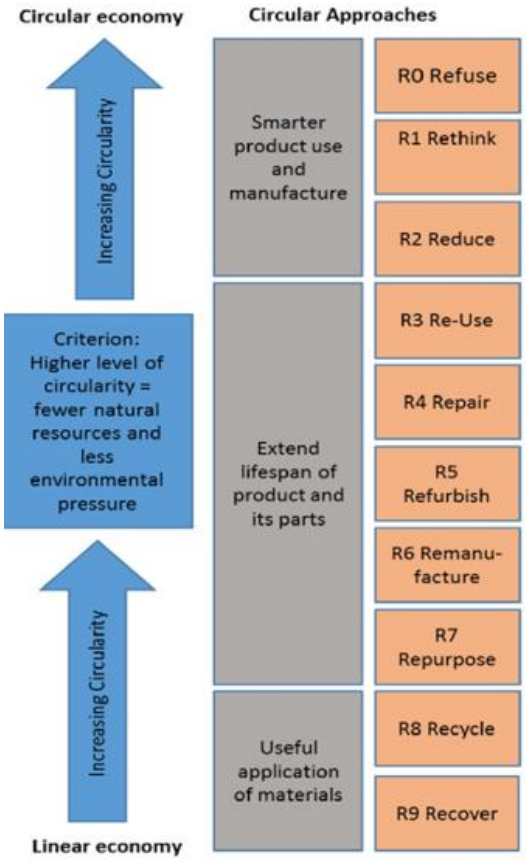
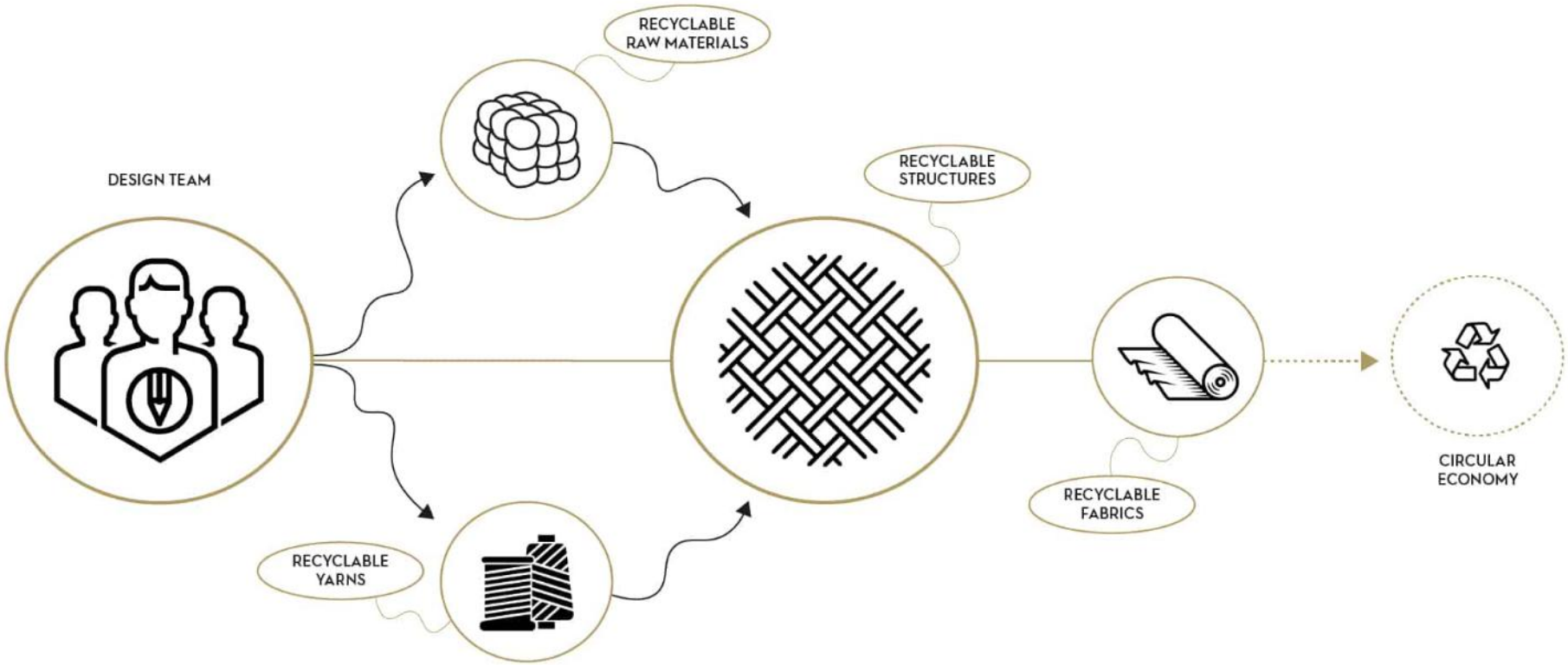


Circular options in textile materials: design



Source of the figure: https://manteco.com/project/sustainable-design/

Circular options in textile materials: sources



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sustainability
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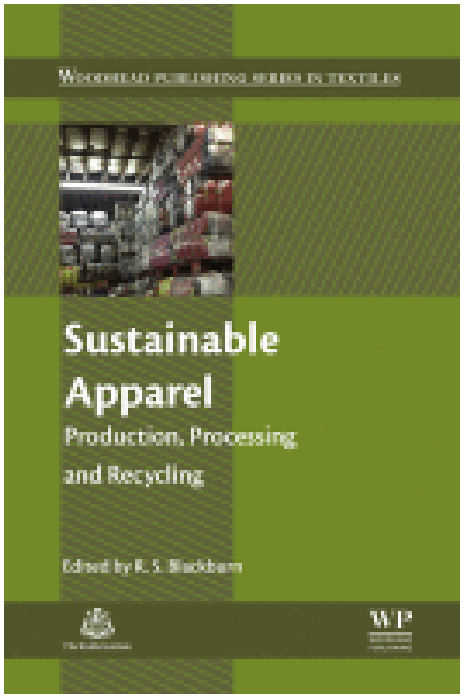
Article

Material-Driven Textile Design (MDTD): A Methodology for Designing Circular Material-Driven Fabrication and Finishing Processes in the Materials Science Laboratory

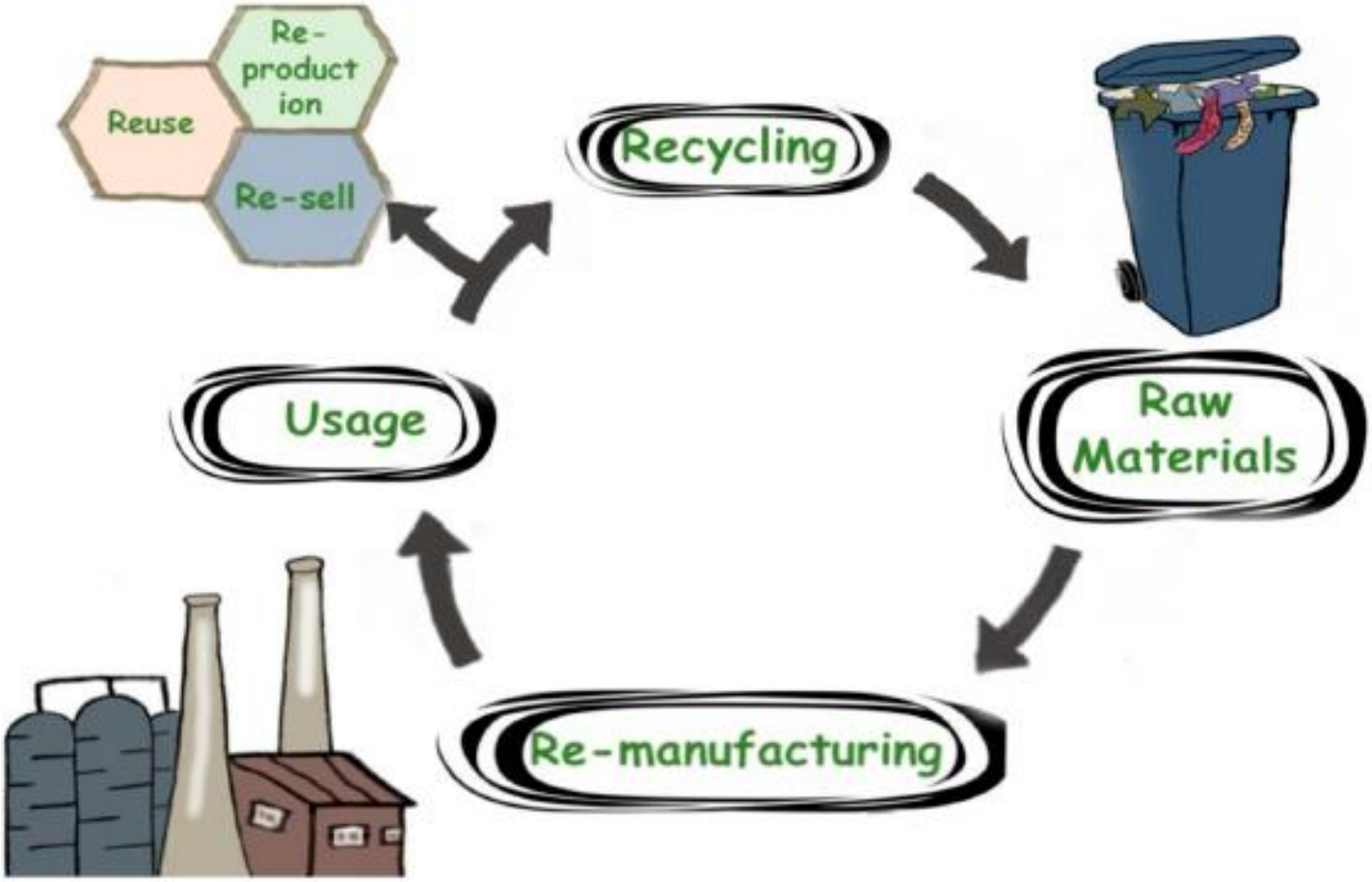
Miriam Ribul [1,*], Kate Goldsworthy [2] and Carole Collet [3]

Circular options in textile materials: design

- Durability (selection of starting materials)
- homogeneity of composition (selection of starting materials)
- compatibility with industrial recycling processes (zips, buttons..)
- yarn and fabric structure
- coatings and printed surfaces
- adhesives and lamination
- joint selection
- disassembly time, and labelling
- small design modifications in clothing to facilitate automated disassembly for the removal of labels, logos, buttons, and zippers without damaging the surrounding fabric

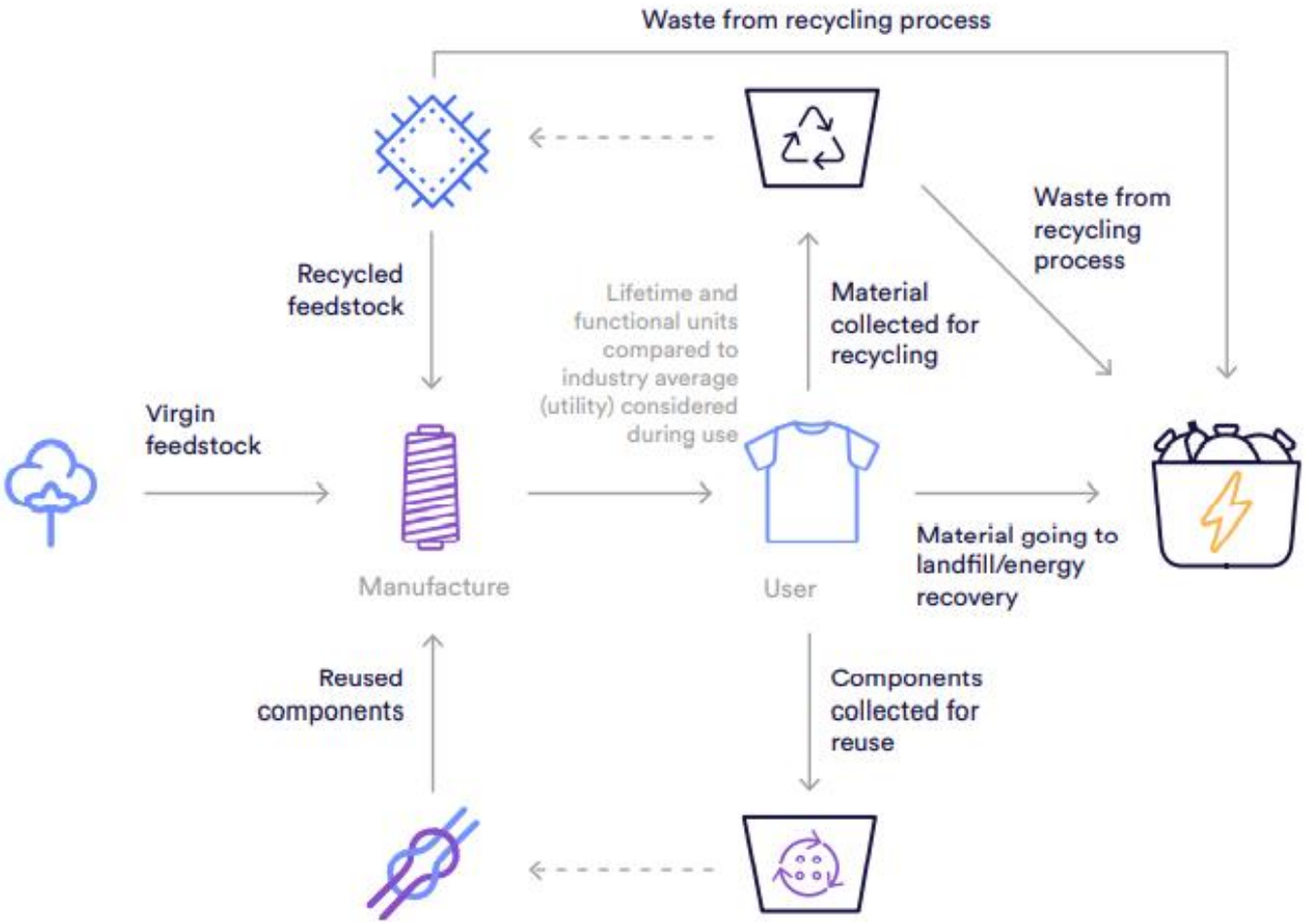


Circular options in textile materials



Schematic representation of the possible circular options for textiles
Source of the figure: Polymers **2021**, 13, 3834 7

Circular options in textile materials



Schematic representation of the material flows for textiles

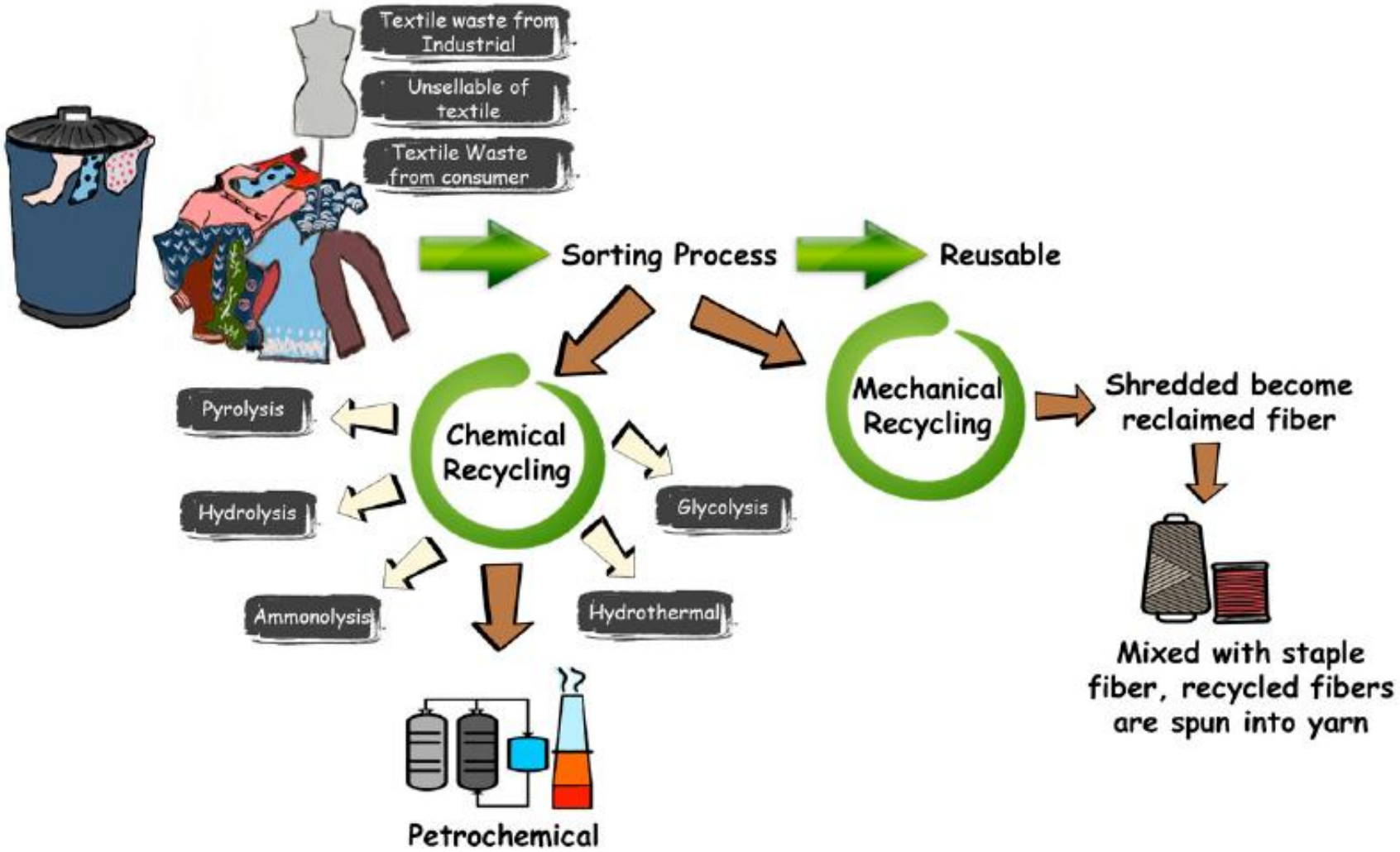
Source of the figure: Circular Threads - A sectorial study of the Textile and Fashion Industry in the North of Italy, Tondo, Milano 2021

Textile wastes

TYPE OF TEXTILES	TYPE OF WASTE	SOURCE OF WASTE
Industrial	fibre, filament, yarn, woven, textile surface (woven, knitted, nonwoven, braided etc.)	fibre & filament production, spinning, weaving, knitting, nonwoven, finishing, garmenting
Pre-consumer	garments, hometextiles (incl. carpets), technical textiles, nonwoven	brands, retailers, distributors
Post-consumer	garments, hometextiles (incl. carpets), technical textiles, nonwoven	final consumer

Schematic representation of the material flows for textiles
Source of the figure:https://kohantextilejournal.com/euratex-unveils-rehubs-a-joint-initiative-to-upcycle-textile-waste-and-circular-materials/

Circular options in textile materials: recycling



Mechanisms of possible textile waste recycling routes.
Source of the figure: Polymers **2021**, 13, 3834 7

Levels of Textile Recycling

Various Levels of Textile Recycling utilized in **open-loop recycling** (different applications) or **closed-loop recycling** (same application). See dedicated slide

1.Recycling Fibers:

1. Fibers remain intact.
2. Achieved through **mechanical methods** that disintegrate cloth while preserving fibers.

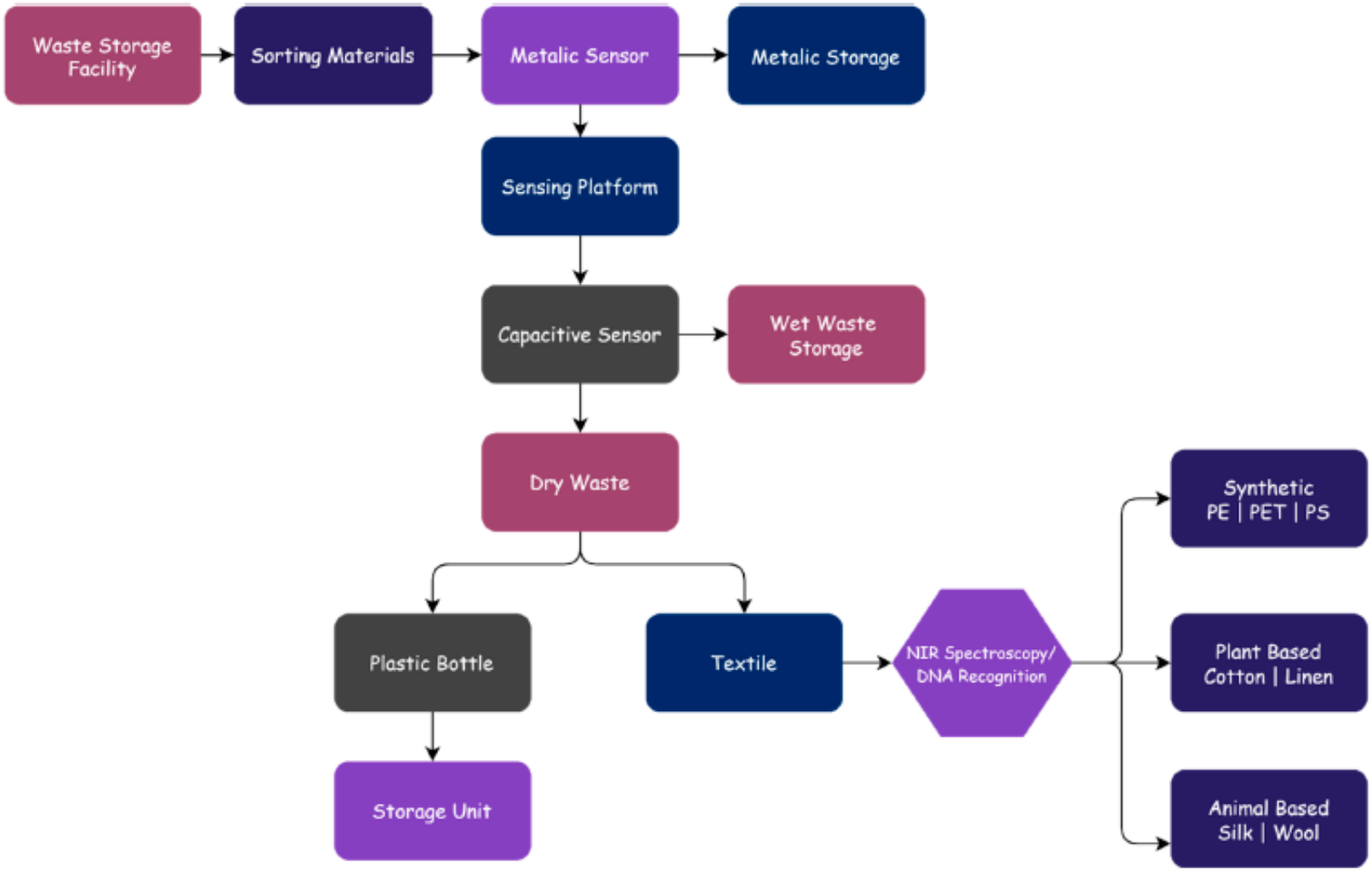
2.Polymer Recycling:

1. Fibers are disassembled, but polymers remain intact.
2. **Mechanical shredding** followed by **chemical or physical dissolution methods**.

3.Monomer Recycling:

1. Fibers and polymers are broken down into **chemical building blocks**.
2. Achieved through **chemical recycling methods**.

The first step: Sorting of textiles



The sorting and identification of textiles

Source of the figure: Polymers **2021**, 13, 3834 7 of

Sorting of textiles

- near-infrared (NIR) spectroscopy (also implemented automatically by convolutional neural network machine learning)
- chemometrics (= computer assisted data processing) for textile analysis
- the cotton component, which comprises mixed cotton and polyester, is determined by genetic algorithms
- nuclear magnetic resonance (NMR) has been used to predict the proportion of cellulose and polyester in textile blends

Source://kohantextilejournal.com/euratex-unveils-rehubs-a-joint-initiative-to-upcycle-textile-waste-and-circular-materials/

Sorting of textiles

Textile	Analyzer	Mathematic Algorithms	Recognition Rate, %	Ref.
Pure (polyester slash; wool; cotton; polyester normal; nylon). Mix (polyester/nylon; polyester/wool; polyester/cotton slash; polyester/cotton).	NIR	SVM, MLP + CNN	92–98	[74]
Cotton, polyester, polyamide, acrylic, silk, wool.	NIR	SIMCA	93–97	[79]
Polypropylene, polyethylene terephthalate, polylactic acid, cashmere, Tencel, cotton, wool	NIR	PCA + SIMCA	100	[80]
Wool	NIR	PLS, ECR		[81]
Satin, twill, plain	ResNet-50	CNN	99.3	[82]
Satin, twill, plain	Epson Scan V330	TILT, HOG, FCM clustering, histogram equalization data	94.5	[83]
Non-woven fabric, plain weave, twill weave, double jersey, satin weave	Canon scanner 9950F, Self-organizing map (SOM) network	CIE + Co-occurrence matrix	92.6	[84]
Cotton, polyester, viscose	NIR	NA	76–100	[85]

CIE: C-Illuminant (light source C), FCM: fuzzy C-means, HOG: histogram of oriented gradients, PCA: principal component analysis, SIMCA: soft independent modeling of class analogy, SOM: self-organizing map, SVM: support vector machine, TILT: transform invariant low-rank textures. PLS: partial least squares. ECR: elastic component regression. NA: not available.

The recognition rate with different types of analyzers
Source of the figure: Polymers **2021**, 13, 3834-7

Sorting of textiles

- ATR-FTIR spectrometer (Attenuated Total Reflection–Fourier Transform Infrared) to sort and classify textiles based on the type of polymer materials in textiles.
- Mathematical modeling applied to more accurately predict the data from the IR spectrum.
- The recognition rate percentage achieved by the mathematic algorithms (principal component analysis, canonical variate analysis, k-nearest neighbors algorithm (k-NN algorithm)) could detect synthetic and natural fibers, such as polyamide, viscose, polyester silk, linen, cotton, and wool, with an accuracy of up to 100%
- FTIR is a good approach for analyzing many textile samples quickly, easily, non-destructively, and non-invasively

Table 1
Most characteristic infrared bands for the studied fibers. Produced from (Peets et al., 2017) and (Vigo, 1994).

Band frequency (cm^{-1})	Type of bond-vibration	Type of fiber
3500–3000	O–H stretching	Cellulosic fibers (N and A)
3500–3000	N–H stretching	Polyamide(S), wool(N), silk(N)
1750–1715	C=O stretching (ester)	Polyester(S)
1680–1630	C=O stretching (amide)	Polyamide(S), wool(N), silk(N)
1570–1515	N–H bending (amide)	Polyamide(S), wool(N), silk(N)
1250–1150	C–O stretching (ester)	Polyester(S)
1100–1000	C–O stretching	Cellulosic fibers (N and A)
730–700	C–H aromatic ring wagging	Polyester(S)

(N) natural fibers; (A) artificial; (S) synthetic.

Source of the figure: J.-R. Riba et al. / Journal of Cleaner Production 272 (2020) 123011

Sorting of textiles

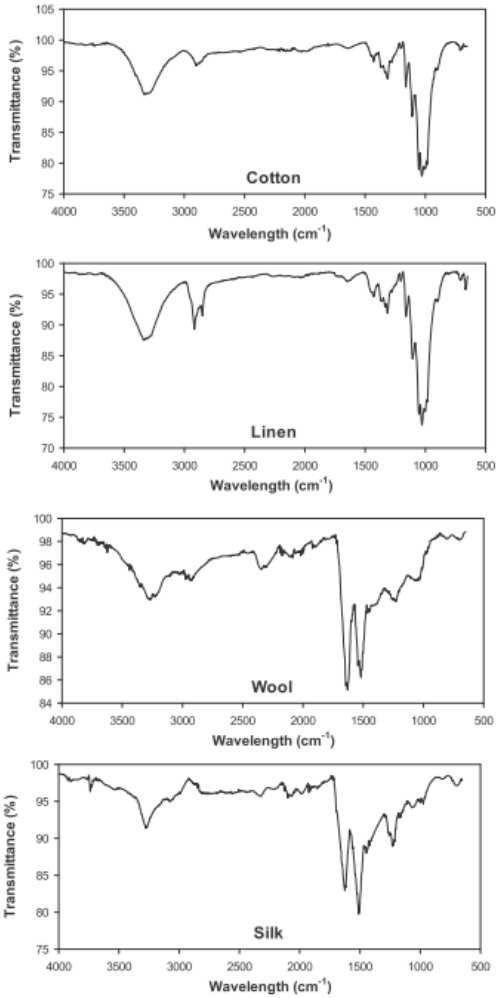


Fig. 3. ATR-FTIR spectra of representative natural fibers.

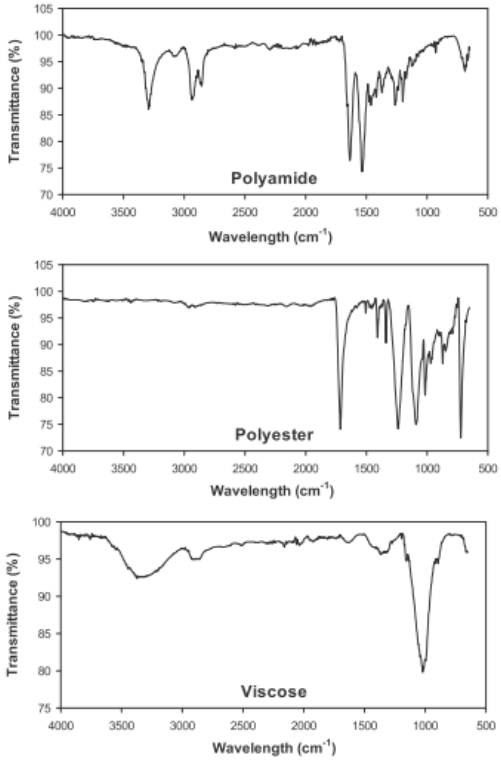


Fig. 4. ATR-FTIR spectra of representative artificial or synthetic fibers.

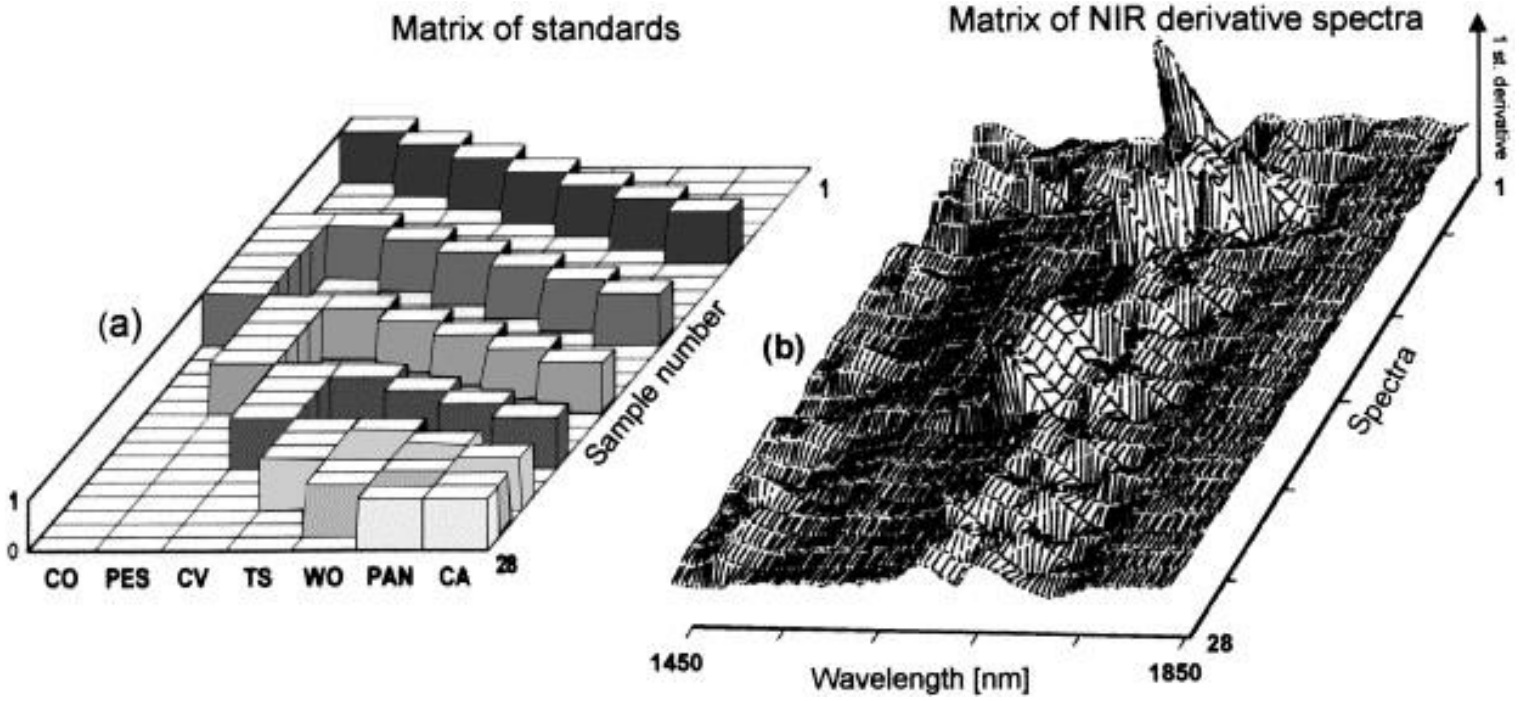
Table 2
Classification success rate of natural versus synthetic fibers following the PCA + CVA + k-NN approach over the 175 prediction samples.

Preprocessing type	$k = 3$	$k = 4$	$k = 5$	$k = 6$
Raw spectral data	175/175	175/175	175/175	175/175
First derivative of spectral data	175/175	175/175	175/175	175/175
Second derivative of spectral data	175/175	175/175	175/175	175/175

FT-IR spectra of most common fibres

Source of the figure: J.-R. Riba et al. / Journal of Cleaner Production 272 (2020) 123011

Sorting of textiles



cotton (CO), polyester (PES), viscose (CV), silk (TS), wool (WO), polyacrylonitrile (PAN) and acetate (CA)

Schematic representation of the matrix *C*, of standards (a) and the matrix *E* of the NIR derivative spectra (b) of the 28 textile samples. The figure shows which of the fibers were used in each of the samples. If the fiber was used, it is described in the diagram with the value 1 and if not with the value 0; for example, sample 1 contains only CO and sample 28 contains PAN and CA. After calculation of the parameter matrix, unknown fabrics were identified from the measured NIR data.

Source of the figure: Analytica Chimica Acta 420 (2000) 163–167

Sorting of textiles



TOMRA

David Rüßmann
Mülheim-Kärlich
March 2023

Interactive seminar on Moodle

Sorting of textiles



Sorting approaches
Source of the figure: Dr. Ruessmann, Tomra

Sorting of textiles

Resources, Conservation & Recycling 180 (2022) 106157

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journal homepage: www.elsevier.com/locate/resconrec



Efficient Recognition and Automatic Sorting Technology of Waste Textiles Based on Online Near infrared Spectroscopy and Convolutional Neural Network

Wenqian Du [a], Jiahui Zheng [b], Wenxia Li [a,*], Zhengdong Liu [c], Huaping Wang [d], Xi Han [e]

The current issue and full text archive of this journal is available on Emerald Insight at:
https://www.emerald.com/insight/1560-6074.htm

Artificial intelligence (AI) in textile industry operational modernization

Monica Puri Sikka, Alok Sarkar and Samridhi Garg
Department of Textile Technology,
Dr. B R Ambedkar National Institute of Technology, Jalandhar, India

Artificial intelligence

67

Received 11 June 2021
Revised 2 August 2021
24 September 2021

Sorting of textiles

CNN = convolutional neural network

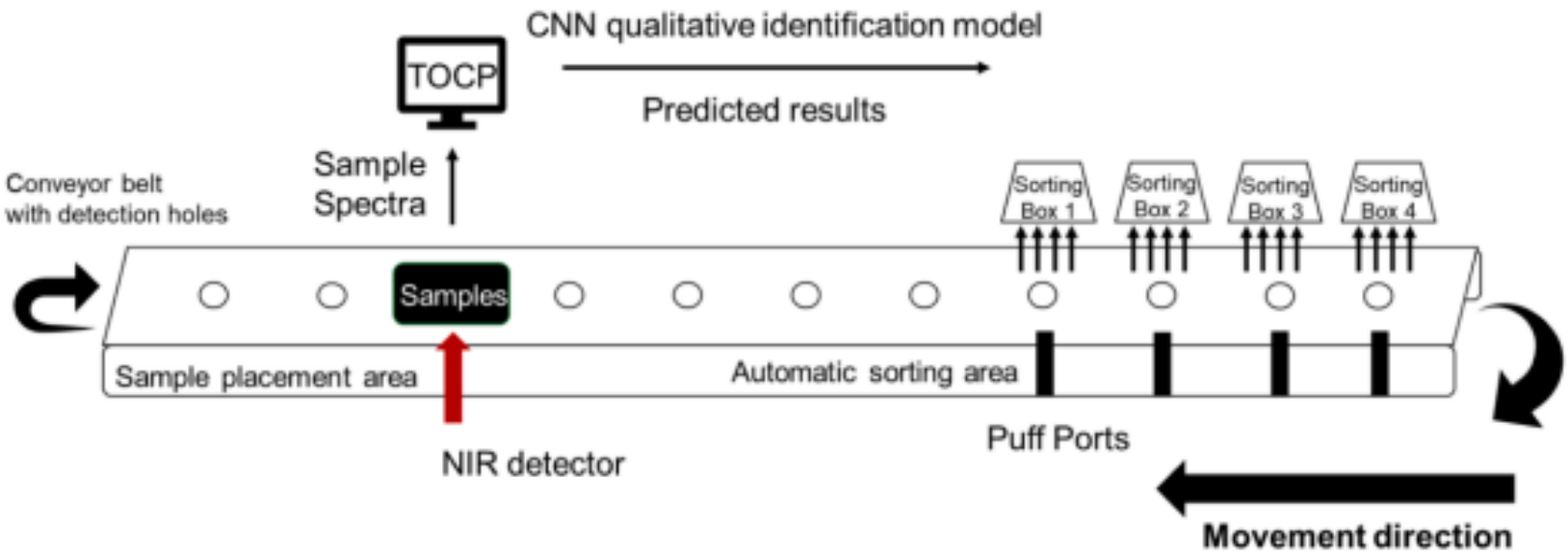


Fig. 1. Online NIR device and sorting process

Challenges for recycling

- lack of commercially viable recycling technologies for a low-grade textile fraction;
- lack of mainstreamed, up-scaled processes and know-how to separate fiber types from the mixed blends and composite structures;
- sorting low selectivity (complex structure of textile polymers and fibres)
- costly recovery process;
- the fact that the recycling end-market is dominated by low-quality materials and blends
- costly logistics and the low availability of textile recycling plants on both local and regional levels
- the market for recycled textile products is still limited and there is a lack profitable circular business models on the market;
- the quality of recycled textile is typically low

Challenges for recycling

• Mechanical methods break down the fabric and retain the fibres by cutting, tearing, shredding or carding. The fibre length is reduced as an unwanted side effect, thereby affecting the spinnability and yarn strength. The fibres will have a shorter fibre length than the original fibres, and some dust will be generated.

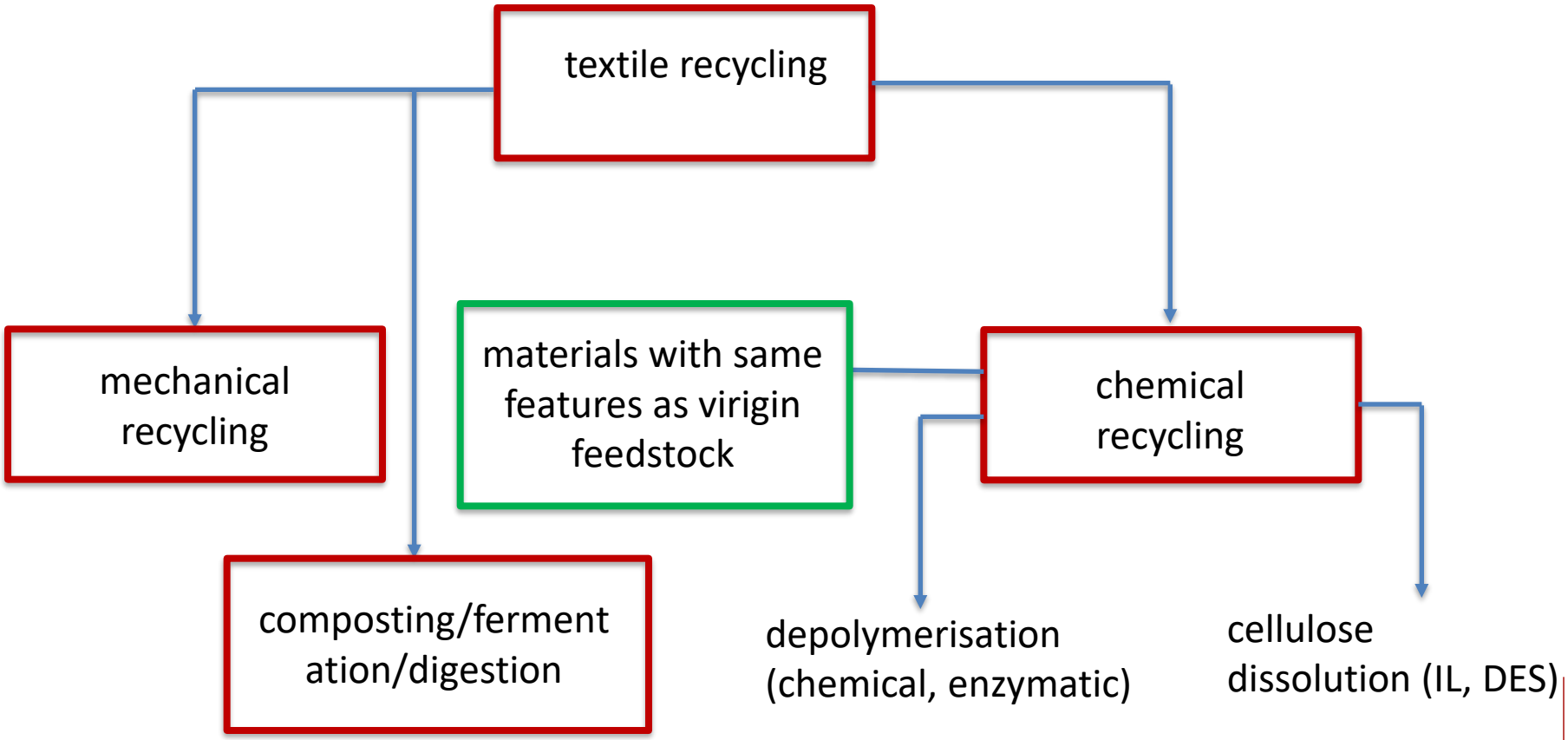
• Physical methods use physical processes to make the fibres or polymers suitable for reprocessing, either by melting or dissolving them. With physical recycling, the structure of the fibres is changed, but the polymer molecules that make up the fibres remain intact. After melting or dissolving, either melt spinning or solution spinning can be used to form a new filament (i.e., a fibre of infinite length).

• Chemical methods exploit chemical processes to break down fibres and polymers. The polymers that make up the fibres are either modified or broken down, sometimes to their original monomeric building blocks. This can be done by chemical or biological methods (e.g., with enzymes).

Circular options in textile materials

mechanical: textile fibres separation (based on NIR sorting or manually) then frayed with a variable percentage of the virgin textile

chemical: either chemical or enzymatic depolymerisation or by dissolution of cellulose with solvents (Lyocell process with NMMO)



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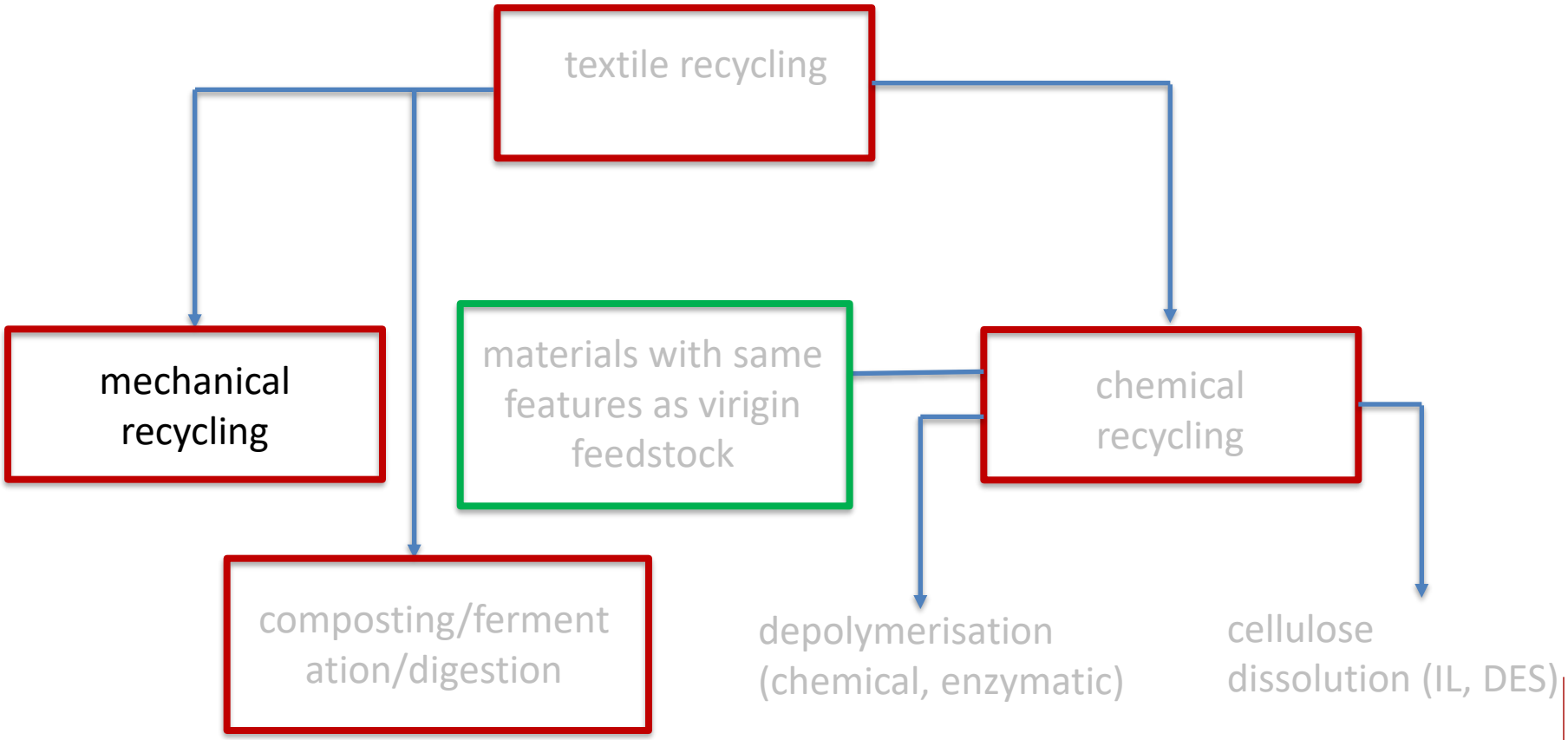


Mechanical recycling of textiles

•**Definition:**
Mechanical textile recycling involves the process of **recycling textiles into fibers** without using chemicals. It includes mechanical processes such as unraveling, garneting, ripping, cutting, grinding, and more.

•**Key Feature:**
Mechanical recycling **doesn't break down the polymer chains of the fibers**, allowing the material from textile waste to be reused and turned into new raw materials. This sets it apart from chemical recycling methods.

•**Cost-Effective:**
•Avoids the use of chemicals, reducing production costs reducing chemical waste. Cost-effective and widely used

Mechanical recycling of textiles: challenges

- there are few mechanical recycling options for post-consumer textile waste fabrics due to the variety and amount of fiber elements in one textile waste garment;

- the shredding (=sminuzzare, triturare) technique reduces the length of post-consumer textile waste garment fibers. The resulting short fibers are of a lower quality and strength than virgin cotton fibers, and they are frequently combined with virgin fibers to improve quality. Recycled fibers are shorter (up to 40% shorter) and of lower quality, often requiring blending with virgin fibers, with wool being the exception.

- **Mixed Textiles**: Blended fabrics are unsuitable for mechanical recycling due to difficulty in separating multi-material textiles, limiting options for post-consumer waste.

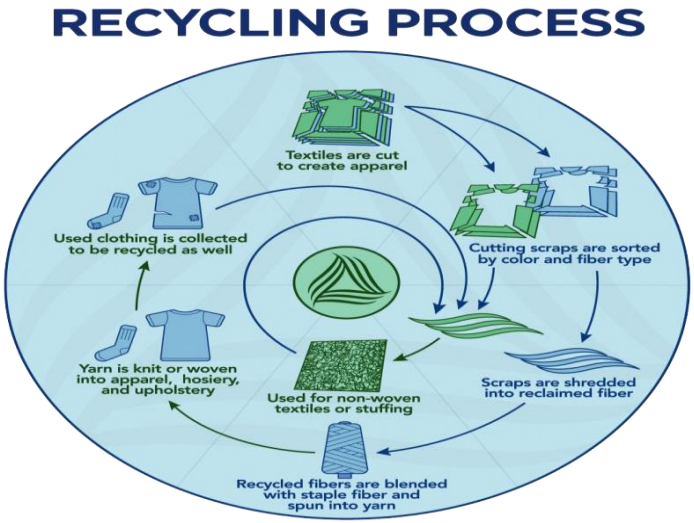
- **Contaminants**: Dyes must be removed during the process.

- **Limited Applications**: Recycled fibers may not be suitable for fabrics requiring high strength or durability

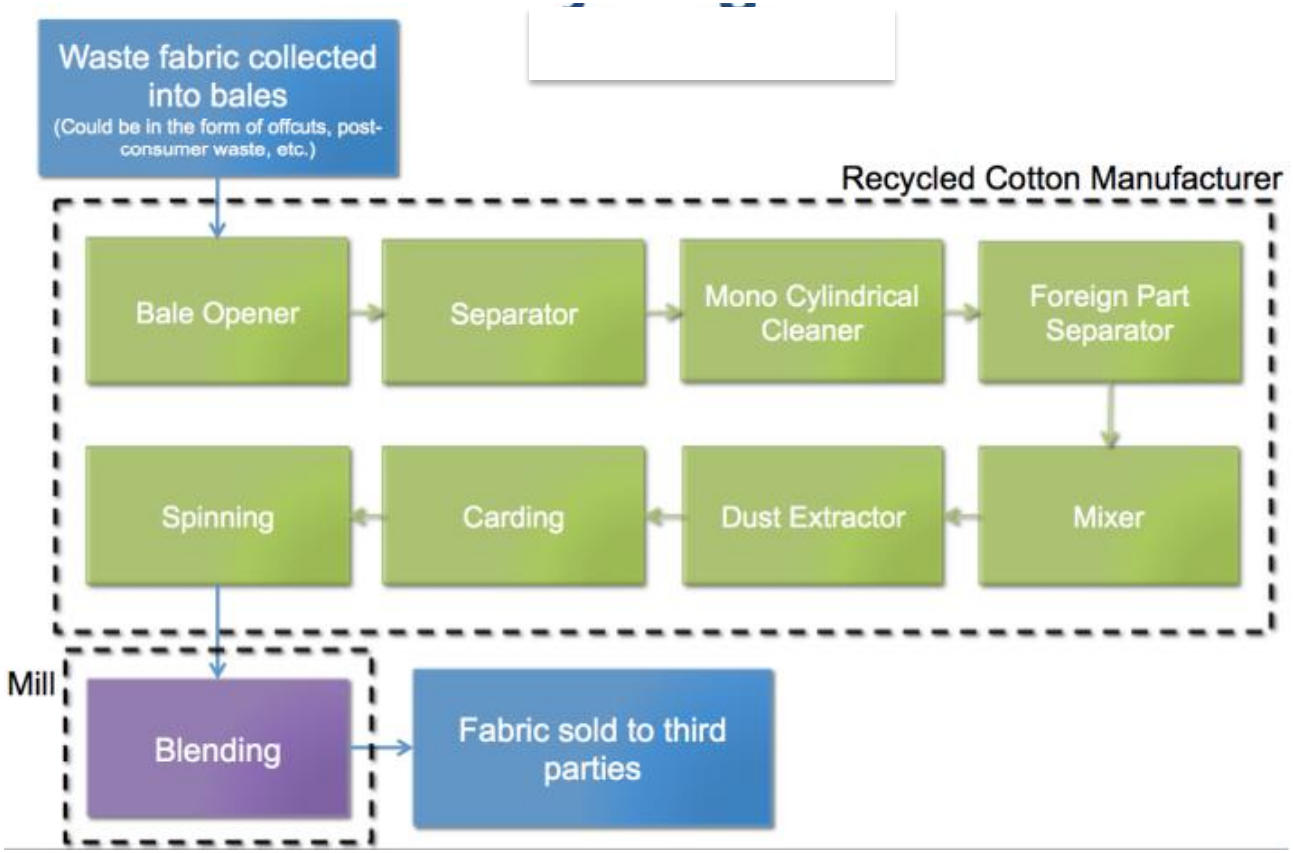
Mechanical recycling of textiles: steps

•**Steps:**

- **Remove** unwanted components (e.g., zippers, buttons).
- **Shred fabrics** into smaller pieces.
- **Tear fabrics** using high-speed cylinders or drums to release fibers.
- **Re-spin fibers** with virgin fibers into yarn, weave or knit into new fabrics, and produce recycled apparel.



Mechanical recycling of textiles



Mechanical recycling involves separating and re-spinning of fabric into yarn through mechanical action. First, the textiles are collected and put into bales (=balla). The bales are passed through a bale opener, which mechanically strips fibers from the fabric.
Source of the figure: MIT Sloan School of Management Strategies for Sustainable Business Final Report – Recycled Cotton for Gap Inc

Mechanical recycling of textiles: outpts

1.Cut Fabrics:

1. Shredded fabrics need further tearing to produce single fibers.
2. Blended with virgin fibers to re-spin into yarn due to quality degradation.

2.Spinnable Fibers:

1. Long fibers of sufficient quality for spinning into yarn.

3.Fluff:

1. Short or twisted fibers not suitable for spinning.
2. Used in insulation for the building industry or nonwovens for the automotive sector.

4.Filler Materials:

1. Tiny fiber particles resulting from milling.
2. Used as reinforcements or fillers in plastics and composites.

European Commission; Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs; Study on the Technical, Regulatory, Economic and Environmental Effectiveness of Textile Fibres Recycling—Final Report; Publications Office: Luxembourg, 2021

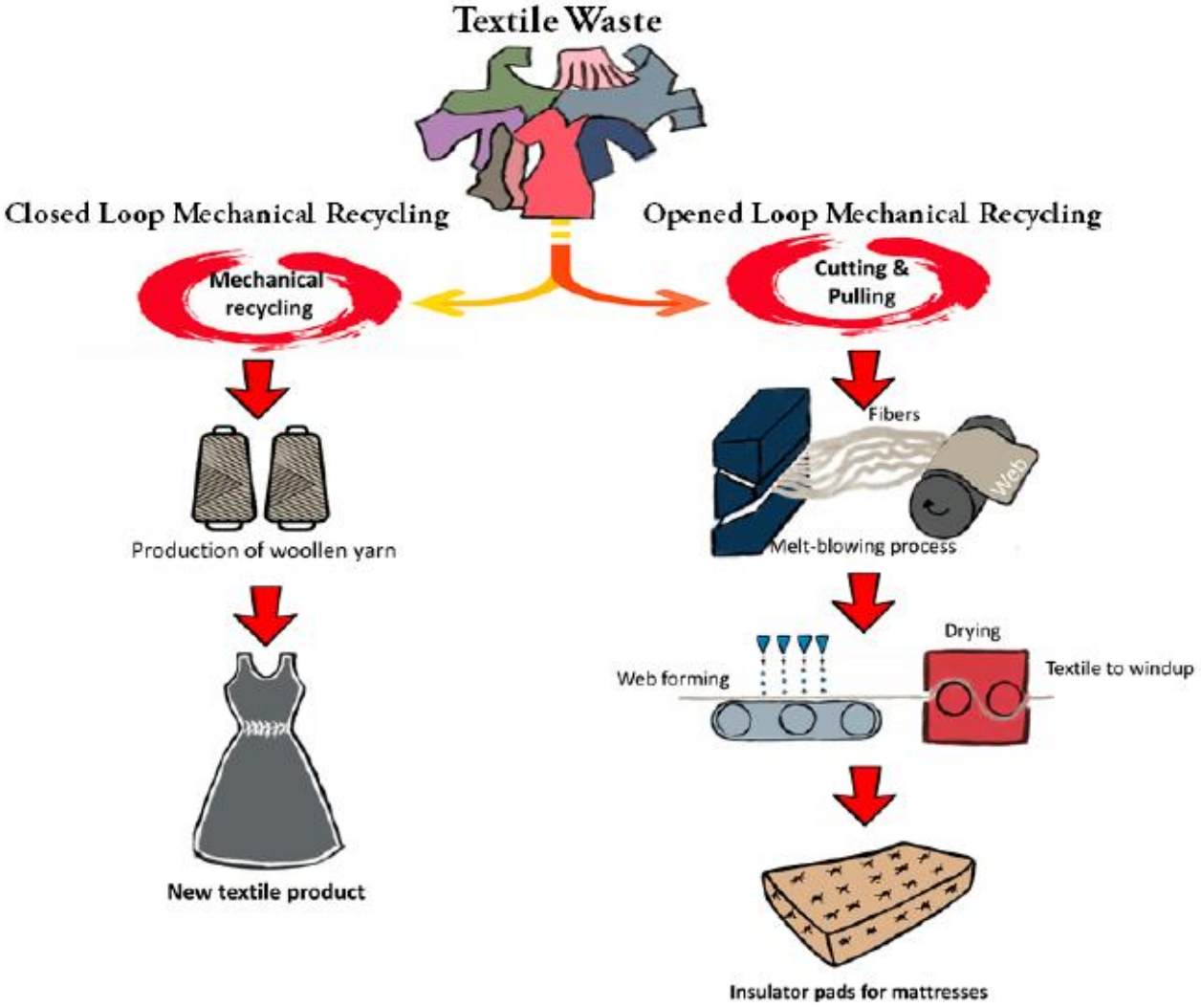
Mechanical recycling of textiles: applications

- **Natural Fiber Waste:**
  - Frequently shredded and used for non-woven sheets.
  - Applications include agricultural geotextiles, composite reinforcing materials, and insulation for noise and thermal applications.

- **Synthetic Materials (e.g., Polyester or Nylon):**
  - Melted, shredded into flakes or pallets, and re-spun into fibers.

European Commission; Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs; Study on the Technical, Regulatory, Economic and Environmental Effectiveness of Textile Fibres Recycling—Final Report; Publications Office: Luxembourg, 2021

Mechanical recycling of textiles



Mechanical processes applied in textile recycling
Source of the figure: Polymers **2021**, 13, 3834 7

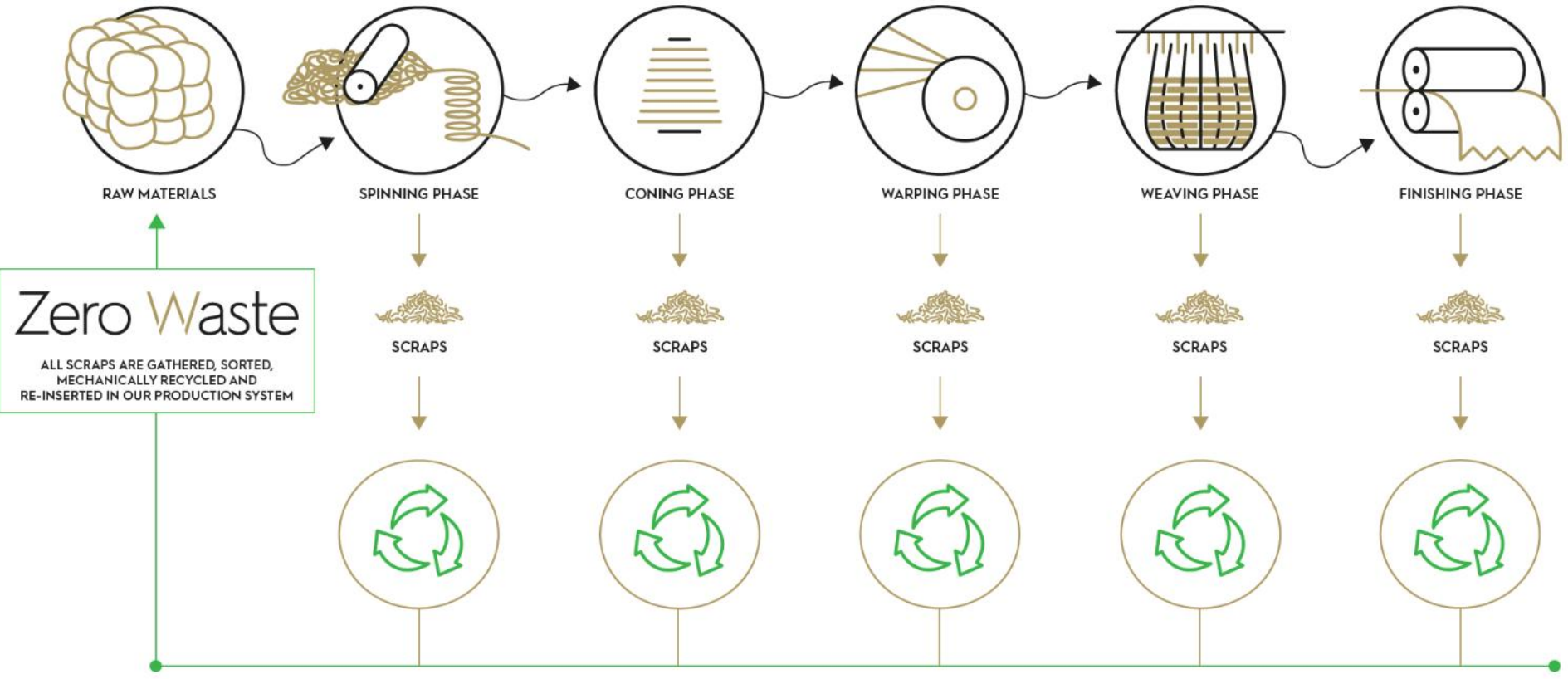
Mechanical recycling of textiles

CLOSED LOOP	OPEN LOOP
Closed-loop textile recycling refers to processes in which the recycled material is identical to the provided material. Both pre- and post-consumer mechanically recycled materials can be considered to be closed-loop recycled since the waste material or fiber re-enters the apparel generation chain.	Methods in which fabrics or textiles are used to make new and different products.
The fineness, length, polymer quality, and shading of the new fiber properties can determine the quality and to create the most appropriate final product. A closed loop conducts the recycling of wool fibers. Using traditional techniques, recycled wool yarns can be turned into very high-value apparel products. Woolen materials are mainly formed from long fibers that have been carefully treated, allowing for mechanical recycling to covert the wool into fibers.	Melt blowing process can be combined with polymer melt extrusion passed by the attenuation of the extrudate and orifices under extremely high-velocity air jets to generate nonwoven fibers in just one step.

Source of the text: Polymers **2021**, 13, 3834 7

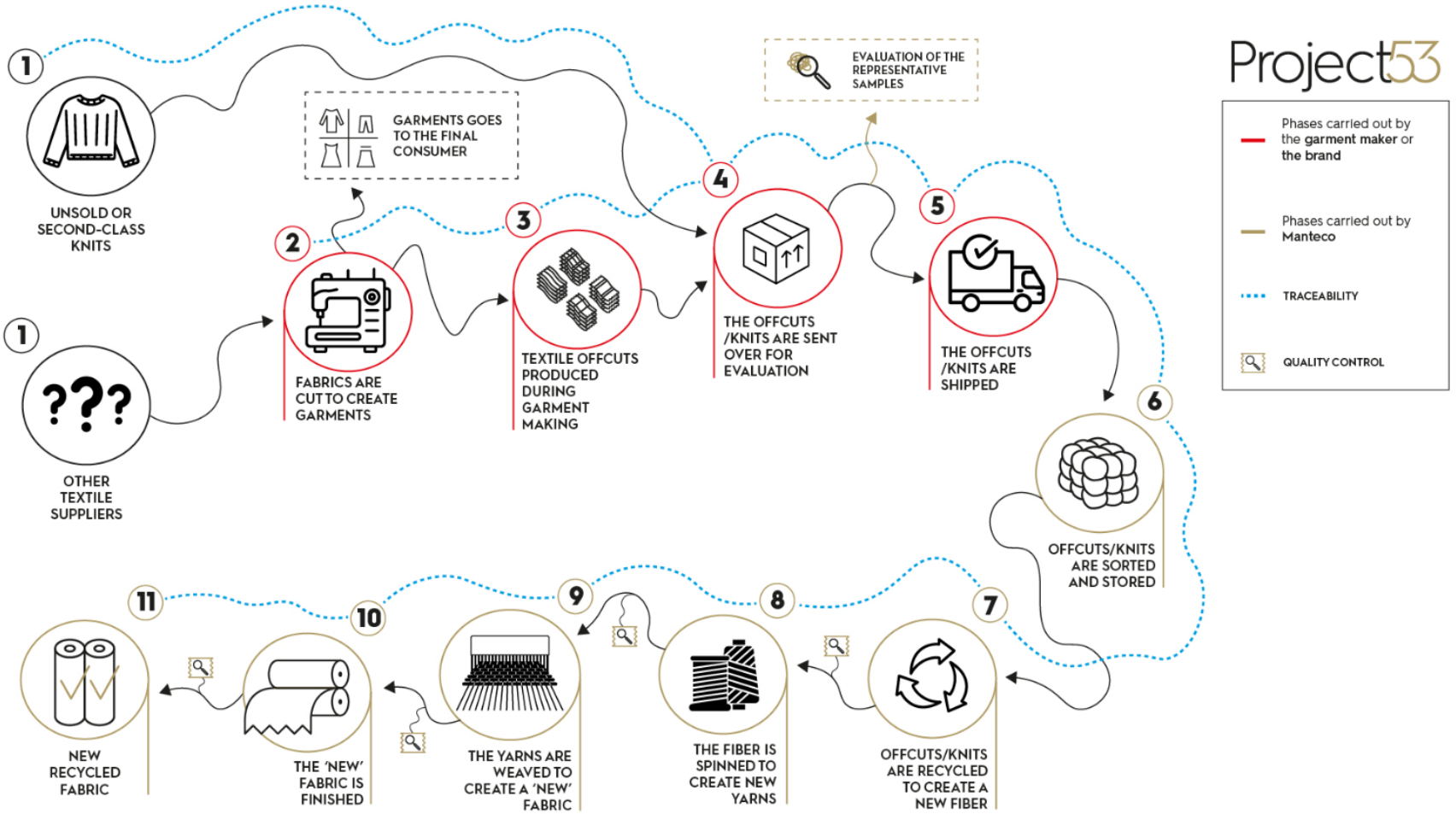
Mechanical recycling of textiles

Source of the figure: https://manteco.com/project/zero-waste/



A department of our company exclusively deals with the gathering of scraps and leftovers generated by our production network, from the spinning phase to the finishing processes. If we did not recover our spinning and coning scraps, as well as selvedges, weaving trials and sampling leftovers during our production processes, we would waste a significant amount of materials, thus interrupting our endless and green production cycle (text from website of the company)

Mechanical recycling of textiles



The purpose of Project 53 is to optimise and reduce to "Zero Waste" leftovers from garment making processes from any manufacturer, not just Manteco. This includes fabrics as well as other textile elements, such as knits. These materials are gathered and regenerated through a simple procedure, eventually creating a new luxury fabric.

Source of the figure: https://manteco.com/project/sustainable-design/

Mechanical recycling of textiles

"MWool® is a low-impact and high-end recycled wool that distinguishes itself for an accurate selection and deep testing of the best possible raw materials, a cutting-edge and low-impact mechanical recycling process of pre-consumer scraps and post-consumer garments , a masterful blending and color creation through our Recype Process (https://manteco.com/recype/)."

MWool®, compared to generic virgin wool fibers, impacts 99,2% less on climate change, 99,9% less on water use and 93,3% less on total energy consumption

resources
MDPI

Article

Life Cycle Assessment (LCA) of MWool® Recycled Wool Fibers

Isabella Bianco [1,*], Raffaella Gerboni [2], Giuseppe Picerno [3] and Gian Andrea Blengini [1]



Source of the text: https://manteco.com/mwool/

Mechanical recycling of textiles

Mechanical recycling of polyester, particularly PET, is well-studied, with PET flakes from bottles commonly used to produce staple polyester fiber for textiles. However, fiber-to-fiber recycling remains challenging due to polymer degradation during extrusion and injection molding.

High temperatures and shear forces break polymer chains, reducing molecular weight and altering properties like glass transition temperature, affecting dye absorption and leading to uneven dyeing.

Structural changes from remelting lower crystallinity and mechanical performance, making fibers more brittle, less flexible, and weaker under tension. To mitigate these issues, strategies include blending recycled polymers with virgin ones, using chain extenders to repair polymer chains, or adding cross-linking agents.

Typically, mechanically recycled fibers are mixed with virgin fibers of the same or different types, but fabrics can only contain up to 30% recycled fibers before quality declines (Baloyi et al. 2024).