# DEVELOPMENT OF A FRAMEWORK FOR EVALUATING THE RECYCLABILITY INDEX OF TEXTILE PRODUCTS


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## KEYWORDS

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## ABSTRACT

Due to its substantial contributions to pollution and resource depletion, the fashion and textile industry's environmental footprint has drawn growing attention. A paradigm change towards sustainability and circularity is necessary to address these issues. With the rising importance of policy regulations requiring to communicate on product recyclability, the need for a deeper understanding of textile recycling becomes needed. This study presents an in-depth analysis of factors influencing the recyclability of textile products within the fashion and textile industry. A structured and iterative systematic scientific literature review on the topic of recyclability in the fashion industry reveals critical dimensions affecting textile recyclability, including design, material composition, production methods, and end-of-life options.

This study delves into specific findings and discussions from the literature review, providing insights into various facets of textile recyclability using the Ecological Product Lifecycle. Design for disassembly and recyclability emerges as an effective approach, alongside circular business models. Materials used in the textile industry, including natural and synthetic fibers, present challenges in recycling due to their diverse properties and compositions. The research further reveals challenges in fiber recovery and separation for blended textiles as well as the effect of production chemicals on recycling procedures. The article examines several textile recycling techniques, including mechanical, chemical, and physical recycling, with a focus on the recyclable nature of mono-materials. The research also covers the relationship between recyclability, durability, circularity, and traceability.

The study further proposes the use of the Textile Product Recyclability Index (TPRI) to objectively evaluate the possibility for recycling textile clothing. This index considers a number of variables, including as design, raw materials, production processed, and end-of-life concerns and procedures. This paper proposes a scientific and practical contribution synthesised as the TPRI providing a tool that empowers stakeholders and players across the textile value chain – from designers and manufacturers to policymakers and consumers – to make informed decisions that prioritize recyclability support a more sustainable fashion sector.

## 1. INTRODUCTION

The fashion industry is one of the largest contributors to environmental pollution, and with the increasing awareness of sustainability and environmental issues, it has become imperative for the industry to adopt a more sustainable approach (Niinimäki, 2006). The circular economy has emerged as a crucial framework to achieve sustainable production and consumption of textiles, with the three pillars of circularity (Reduce, Reuse, and Recycle) serving as guiding principles (Ellen McArthur Foundation, 2017) that according to a study by Paulien Harmsen et al. (2021) can be presented by a four-layer model (Rethink, Reuse, Recycle and Recover) where recycling comes in play when the product cannot be reused anymore. While recycling is an essential aspect of the circular economy, a comprehensive framework for evaluating the recyclability of textile garments is still lacking. Today, out of 48 million tonnes of discarded clothes, only 14% go to recycling, of which one million tonnes are lost in collection (Ellen McArthur Foundation, 2017). Across the entire fashion industry, less than 1% of materials used in the production of clothing are recycled into new clothing, and as little as 12% are effectively recycled into other products after use (Ellen McArthur Foundation, 2017).

Policies on recyclability are becoming increasingly important and constraining for companies in all sectors. According to a recent French decree, producers, importers, distributors, or other market players of waste-generating products intended for consumers are required to provide information on the environmental qualities and characteristics of their products (Ministère de la Transition Écologique, 2022). Textiles play an integral role in the fabric of daily existence, encompassing apparel, furnishings, medical gear, protective attire, architectural components, and vehicular elements. Within the European Union (EU), the ecological ramifications of textile consumption are markedly substantial. Notably, textile consumption ranks as the fourth most impactful contributor to environmental and climate repercussions, following food, housing, and mobility (European Union, 2023). Correspondingly, textiles emerge as the third highest sector concerning water and land utilization, while concurrently occupying the fifth position with regard to the utilization of primary raw materials and the emission of greenhouse gases (European Union, 2023). International rules on waste management are becoming increasingly strict, forcing producing companies to become more aware of the impact from production to the disposal of the products. Today, the mission of the European Commission for 2023 is that “all textile products placed on the EU market are durable, repairable and recyclable, to a great extent made of recycled fibers, free of hazardous substances, produced in respect of social rights and the environment”.

Examining strategies to sustain the growth of textile products while mitigating their impact on natural systems goes beyond mere expansion. This research aims to alleviate stress on natural systems and minimize environmental effects. Achieving this goal necessitates embracing a recyclability mindset, emphasizing the recyclability of our products. The concept of textile and garment recyclability is multifaceted and complex, and depends on several factors such as design, material composition, processing and end-of-life disposal of a product. In order to develop a framework for evaluating the recyclability index of textile in the apparel industry, it is important to identify and organize these key concepts and variables. To this date, no unified index of recyclability has been developed for textile. Therefore, this paper aims to review the existing literature and use this for the purpose of developing a recyclability index for textile in the fashion industry.

Section 2 will cover the research methodology followed by Section 3 which will provide an explanation of the development of the index and its factors as well as a brief discussion of the aspects of circularity, durability, and traceability. Using this framework, Section 4 reviews and discusses the findings from the literature review, based on which section 5 will discuss the textile recyclability index. Section 6 will thereafter cover the limitations and future opportunities for research. Lastly, section 7 completes the research paper with a conclusion.

## 2. RESEARCH METHODOLOGY

The methodology of this thesis will consist of an iterative systematic scientific literature review on the topic of recyclability in the fashion industry. According to Fink (2019), a systematic literature review can be defines as a systematic, explicit, and reproductible design for identifying, evaluating, and interpreting the existing body of recorded documents. The review includes a comprehensive search and review of peer-reviewed articles and other relevant grey literature, such as books, reports and policy documents from NGOs and industry associated establishments. The search was conducted using electronic scientific databases and search engines, such as Google Scholar and ScienceDirect. The review utilizes a thematic analysis framework to identify the key themes, concepts, and theoretical approaches used in the literature. A first literature review allowed to identify the parameters within the Ecological PLC that will affect recyclability. These parameters were then individually searched again to identify the measures of the parameters within the recyclability maturity model. The search was conducted using the keywords 'recyclability', 'apparel', 'textile', 'clothing', 'design', 'materials', 'production', 'end-of-life', 'disposal', 'use', 'traceability', 'circularity', and 'durability'. The selected literature was analyzed using an analysis framework that synthesizes the different levels and dimensions of recyclability throughout the Ecological Product Life Cycle. The framework includes design, materials, production, distribution, use, and end-of-life disposal. Traceability, circularity, and durability were also be reviewed in relation to recyclability.

The final analysis identifies the main indexes, indicators, and measures of recyclability in the fashion industry, and evaluate their strengths and limitations.

Considering the aim of this research paper is to identify all factors influencing the recyclability of a textile product, the review was be guided by the following research questions:

1. What are the parameters and criteria influencing recyclability throughout the Ecological Product Life Cycle?

2. How do those parameters affect the recyclability and how can they be measured?

Finally, the results of the analysis were be synthesized to provide a comprehensive overview of the state of knowledge on recyclability in the fashion industry and its implications for sustainability.

## 3. DEVELOPMENT OF A TEXTILE PRODUCT RECYCLABILITY INDEX (TPRI)

According to the UNSD/UNEP Questionnaire, recycling is defined as "Any reprocessing of waste material in a production process that diverts it from the waste stream, except reuse as fuel. Both reprocessing as the same type of product, and for different purposes should be included" (UN Stats, n.d.). The Waste Framework Directive defines recycling as "any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes" (Consolidated TEXT DIRECTIVE 2008/98/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL, 2018).

### 3.1. Recyclability and the environmental Product Life Cycle

Deducting from the above definition of recycling, we can define recyclability as the ability to recover waste materials and reprocess them into products, materials or substances whether for the original or other purposes. Stemming from the Lifecycle Assessment (LCA), a standardized framework methodology to quantify the impact of products, processes and services on the environment (Jhanji, 2023) the Environmental Product Life Cycle or PLC defines the stages that a product goes through throughout its lifetime, from the design to the final stage of disposal. In the scope of this research, the PLC consists of 6 stages: Design, Raw Materials, Production, Distribution, Use and End of Life. Each stage has an environmental impact that can be associated with it. In order to look at recyclability, it is relevant to look at what role it plays throughout the Environmental PLC. The following sections will try to explain the relevance of each stage preceding the literature review.

#### 3.1.1. Design

In an industry where aesthetics and design are dominant in consumers decisions, the design stage is indubitably important (De Angelis et al., 2017). When examining the apparel and fashion industry, garments frequently exhibit intricate designs and intricate material compositions. It's the consequences of decisions made at the design stage that determine around 80% of environmental impacts (Ellen McArthur Foundation, 2021). To enhance the potential for increased possibility for recyclability during the terminal phase of the product lifecycle, it becomes imperative to formulate and manufacture products in a manner conducive to their disassembly, subsequent reconstitution, and recycling. This necessitates a comprehensive contemplation of the construction techniques (shapes of garments, layers and embellishments) employed in crafting products, together with meticulous evaluation of the materials used and components present therein (Ellen McArthur Foundation, 2021). For example, the Closed the Loop platform identifies 5 different strategies for design including design to last, design for rebirth, design to minimize waste, design to reduce the need for rapid consumption and design with new technologies in mind (2023).

3.1.2. Raw materials

The lifetime of a product depends strongly on technical product characteristic such as the choice of material, textile composition and textile quality. Changes in material choices can improve the recyclability of a product at the end of the Environmental Product Life Cycle. According to a study by Paulien Harmsen et al. (2021) textiles exhibit a rising prevalence of diverse fiber compositions, as textiles solely composed of single fibers frequently fail to meet the demands of contemporary fashion. The technique of fiber blending, involving the combination of two or more distinct fiber types into novel yarns or fabrics, emerges as a strategic response. This process facilitates the harmonization of the finest attributes inherent in each constituent fiber thereby culminating in an elevated fabric functionality. A common example of this is the presence of elastane in jean to make the garments more stretchy and comfortable (Radhakrishnan, 2017). Elastane may cause problems during recycling as it has limited recycling options. It is typically not recycled but is rather removed during the recycling process as its recycling methods are not advanced enough and still being developed (Harmsen et al., 2021). This means that blended textiles tend to me more negative as the different types of fiber need to be separated which has been proven to be difficult or in some cases even impossible (Harmsen et al., 2021).

3.1.3. Production

As identified in a study by the European Commission, two separate but consecutive steps can be identified in the production stage. Firstly, a finished sheet of fabric must be made, which refers to the textile or fabric production. Subsequently, for a product to become a textile garment, the textile must go through product confection (European Commission. Joint Research Centre. Institute for Prospective Technological Studies., 2014). How a product is produced can determine de recyclability of a product. Chemical processes, textile dye or coloring and other embellishments or procedures such as pesticides, solvents, surfactants, plasticisers, water and stain repellents, flame retardants and biocides (EMF adapted from CHEMSEC, 2017) can affect the final disassembly and recyclability opportunities of a product.

3.1.4. Distribution

Although distribution does not impact the final recyclability of a garment, keeping the distribution process clean adds an extra advantage to a products carbon footprint and overall environmental impact. As mentioned, for the purpose of this paper the distribution will overall be disregarded.

3.1.5. Use

A distinction ca be made between post-consumer textile waste and industrial waste. Post-consumer waste is typically harder to recycle due to the usage phase that will affect its recyclability. The use of a garment refers to the wearing, washing, tumble drying, ironing but also repairing, rental and resell of a product (Laitala & Klepp, 2020). This phase also includes contamination of fibers as pointed out by Harmsen and al. (2021). Additionally, challenges in the use phase involves removal of labels, meaning important information regarding the material composition of product is lost, hindering a smooth recyclability process at the End-of-Life. Furthermore, as highlighted in a study by Wilting and van Duijn (2020), inaccuracies, or variations that occur compared to the initial composition following the use phase also obstruct the effective evaluation of product sustainability as well as raising concerns about the reliability of product information in the post-use lifecycle stages.

Post-Industrial textile waste on the other hand are often easier to recycle as they have not been used and are usually more well defined and more homogeneous, facilitating the recycling process as they can be collected as fibers, yarns or fabrics (Harmsen et al., 2021).

Although studies exist regarding the average use in years of a textile garment and their estimated carbon footprint, how a garment will be used and what condition it will be in at the End-of-Life phase is something that cannot be pre-determined when selling a product and can therefore not be included in a Textile Product Recyclability Index (TPRI). However, it can be safely assumed that garments with a high level of usage will consequently be more complicated to recycle as the fiber will be more fragile.

3.1.6. End-of-life

The conclusive and ultimate stage in a product's lifecycle is its end-of-life phase. In the prevalent linear system of today, this phase primarily involves methods of disposal, such as incineration or landfilling. However, an assessment conducted by the European Union in 2014 encompasses both recycling and reuse within this phase (European Commission. Joint Research Centre. Institute for Prospective Technological Studies., 2014). Before final disposal or recycling of textiles, several actions can be taken to extend the life of the product and reduce waste. These include repairing and mending garments, repurposing, or upcycling textiles into new products, and donating or reselling items that are still in good condition. By extending the life of textiles, we can reduce the amount of waste generated and the need for new materials. Downcycling, on the other hand, involves breaking down the material into its component parts and using it to create lower-value products. While downcycling is not as desirable as true recycling, it is still a valuable way to recover materials and reduce waste (Ellen McArthur Foundation, 2017).

Considering the three relevant stages of the Ecological Product Life Cycle, the End-of-Life phase will depend on the factors of Design, Raw Material and Production to understand the options of recyclability that lay ahead for a garment. Depending on these factors and measure, a product will be considered as recyclable or not recyclable.

From a general point of view, recyclability will ultimately not only depend on the garment but also on 2 important factors being (1) the capacity of collecting the clothing from a territorial point of view and (2) the capacity for the collected garments to be efficiently sorted to be recycled (Refashion, 2022). While brands often possess some knowledge of their target markets during garment production, it's essential to acknowledge the uncertainty regarding the end-of-life journey of these garments. They may traverse various routes for numerous reasons after being sold, potentially impacting the collection and sorting processes. However, as these aspects extend beyond the immediate scope of this research, they will not be further discussed.

3.2. Recyclability and traceability/durability/circularity

3.2.1. Recyclability, circularity and durability

According to Ashby (2018), circularity can be defined as the concept of keeping resources continuously flowing in a closed loop, which can be achieved through redesigning products, manufacturing procedures, and supply chains. The current economic system can be described in terms of linear material flows, in which resources are repeatedly utilised from a natural system (take), altered during production (make), used for various purposes within the human system (use), and then eventually disposed of back into the environment (waste), typically with negative results. Value is added to the extracted resources during production in that linear process, although it is often generated and acknowledged just once (Keßler et al., 2021). Durability is part of the Circular Economy. Durable and long-life fashion utilises high-quality, long-lasting materials along with (aesthetical and material) design for longevity with the goal of prolonging the use phase of the textile itself through reuse (Keßler et al., 2021). Although durable products lead to enhanced brand value (Goworek et al., 2020), having long lasting and durable materials or product designs will decrease the ability to recycle a product at the end of its lifecycle. Recyclability which is also part of circularity but will never be a 100% circular due to the amounts of textile waste lost during recycling processes (Ellen McArthur Foundation, 2021). This means recyclability only slows down the loss of valuable materials throughout time until they eventually cannot be used or do not exist anymore. Higher durability is seen to be beneficial for prolonging a product's lifespan, although it is not necessarily compatible with recyclability. This frequently results in trade-offs between creating something with a lengthy lifespan and enhancing recycling options once it has served its purpose (Ghisellini et al., 2016).

3.2.2. Recyclability and traceability

Defining recyclability relies heavily on the traceability of a product throughout its supply chain. It is necessary to have transparency and traceability about the percentage of fibre composition and recycled fibres, as well as their origin and quality. Beyond the fibre, there is sometimes a "lack of knowledge regarding chemicals and hazardous substances in textile products."(European Union, 2008). According the a study by Sandvik & Stubbs (2019) the Scandinavian fashion industry encounters several impediments in establishing effective textile-to-textile recycling systems. These challenges primarily revolve around technological limitations, substantial research and development expenses, and the intricate nature of supply chains, marked by a myriad of stakeholders engaged in product development. Nevertheless, opportunities for progress exist through the adoption of innovative materials in design and utilization, along with augmenting garment collection rates and fostering collaborative initiatives. In light of these challenges and opportunities, the study advances that integrating digital technologies can serve as a pivotal enhancement in sorting and recycling processes. The incorporation of digital solutions has the potential to yield benefits such as enhanced transparency, traceability, and automation within the recycling ecosystem.

## 4. FINDINGS AND DISCUSSION OF THE LITERATURE REVIEW

Table (1) summarizes the literature reviewed in section 4. The table delineates the focal points of each article by outlining the dimensions described earlier.  Following from this we can deduct the need for a recyclability index in the literature.

Synthesis of the topics discussed in the selected literature.

| | | | | | PLC | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Publication Year | Author(s) | Recyclability | Apparel | Textile | Lifecycle | Design | Materials | Production | Distribution | Use | End-of-Life | Disposal | Durability | Traceability | Circularity | Recyclability index |
| 2006 | Gulich, B. | x | | x | | | x | | | | x | | | | | |
| 2006 | Niinimäki, K. | | | x | | x | | | | | | | | | | |
| 2012 | Muthu, S. S., Li, Y., Hu, J. Y., & Mok, P. Y. | x | | x | | | x | | | | | | | | | |
| 2016 | Ghisellini, P., Cialani, C., & Ulgiati, S. | x | x | | x | | | | | | | | x | | | |
| 2017 | De Angelis, M., Adıgüzel, F., & Amatulli, C. | | x | | | x | | | | | | | | | | |
| 2017 | Radhakrishnan, S. | x | x | x | | | x | | | | | | | | | |
| 2017 | Ellen McArthur Foundation | x | x | x | | | | x | | | x | x | | | x | |
| 2018 | Ashby, A. | | | | | | | | | | | | | | x | |
| 2018 | Lihong, C., Hong, Y., & Xinfeng, Y. | x | x | | | x | | | | | | | | | | |
| 2018 | Nimkar, U. | x | | x | | | | x | | | | x | | | | |
| 2019 | Sandvik, I., & Stubbs, W. | x | | | x | x | | | | | | | | x | | |
| 2020 | Goworek, H., Oxborrow, L., Claxton, S., McLaren, A., Cooper, T., & Hill, H. | x | | | x | x | x | | | | x | | x | | | |
| 2020 | Laitala, K., & Klepp, I. G. | x | x | | | | | | | x | | | | | | |
| 2020 | Wilting and van Duijn | x | | | | | | | | x | | | | | | |
| 2021 | Harmsen, P., Scheffer, M., & Bos, H. | x | x | x | | | x | | | x | x | x | | | | |
| 2021 | Keßler, L., Matlin, S. A., & Kümmerer, K. | x | x | | x | | | | | | x | | x | | x | |
| 2021 | Ellen McArthur Foundation | x | x | | | x | x | x | | | | x | x | | x | |
| 2022 | Juanga-Labayen, J. P., Labayen, I. V., & Yuan, Q. | x | x | x | | | x | | | | x | x | | | | |
| 2022 | Refashion | x | x | | | | | | | | | x | | | | |
| 2023 | Jhanji, Y. | | | | x | | | | | | | | | | | |
| 2023 | Riemens, J. | x | x | x | | | x | x | | | | x | | | | |
| Totals | | 17 | 12 | 9 | 5 | 6 | 8 | 4 | 0 | 3 | 6 | 7 | 4 | 1 | 4 | 0 |

Table (1) Synthesis of topics discussed in the selected literature

4.1. Design and recyclability

According to the literature, design for disassembly and design for recyclability are two methods that can improve the recyclability of garments (Lihong et al., 2018). Design for disassembly involves designing a product so that it can be easily taken apart and its components can be reused or recycled, while design for recyclability involves designing a product so that it can be easily recycled at the end of its life cycle.

Circular business models that prioritize recycling and remanufacturing can help mitigate the waste impact. By designing products so that they can be disassembled, and their components and materials remade or recycled into new products, fashion players can prevent waste and maximize positive environmental outcomes. According to the Ellen McArthur Foundation, the potential environmental benefits of implementing circular business models in the fashion industry could be significant, including a reduction of $CO_2e$ emissions by more than 16% per year (Ellen McArthur Foundation, 2021).

One approach is to use mono-materials or materials that are easily separable, as this simplifies the recycling process. Additionally, designing products with fewer components and using standardized fasteners and connectors can make disassembly easier. Designing for durability and repairability can also extend the product's lifespan and reduce the need for disposal.

Finally, incorporating recycled materials into the product design can help close the loop and reduce the need for virgin materials. These design considerations can improve the recyclability of products and contribute to a more circular economy (Ellen McArthur Foundation, 2021). By incorporating these design principles, garments can be made with better reuse potential and the negative impact of safety on apparel reuse and recycle can be minimized.

4.2. Materials and recyclability

When talking about the textile and apparel industry, materials rely on two important components constituting textile: polymers and fibers. Polymers are large molecules made up of repeating units called monomers, while fibers are thin, thread-like structures used to make textiles.

Textile recycling is a complex process that involves the separation of different types of fibers and chemicals. The textile industry uses a wide variety of fibers, including natural fibers such as cotton, wool, and silk, as well as synthetic fibers such as polyester, nylon, and acrylic. These fibers can be blended together to create fabrics with unique properties, making the recycling process challenging (Riemens, 2023). Table (2) shows an exhaustive list of natural and synthetic fibers.

| Natural | Synthetic |
|---|---|
| Cotton<br>Wool<br>Silk<br>Linen<br>Viscose<br>Lyocell<br>… | Polyester<br>Nylon<br>Acrylic<br>Elastane<br>Polyethylene Terephthalate (PET)<br>Polypropylene (PP)<br>Polyethylene (PE)<br>Acryl<br>Modacryl<br>… |

Table (2) Classification of materials into natural or synthetic fibers

Different recycling methods have been proposed to address this issue, including mechanical, chemical, and thermal processes (Riemens, 2023) . The level of disassembly and the polymer structure of the fibers have also been used to classify textile recycling methods (Harmsen et al., 2021). However, sorting is a manual and costly phase, and there is a need for an economically viable and effective way to recognize and sort textile materials, to further advance textile-to-textile recycling as requiring homogenous feedstocks (Riemens, 2023). Therefore, further research is needed to develop efficient and cost-effective recycling methods that can handle the diverse range of textile and chemical compositions used in the fashion industry.

There are different methods of textile recycling, including mechanical and chemical recycling. Mechanical recycling breaks down textiles into fibers, which can then be used to create new yarns and fabrics. Chemical recycling, on the other hand, breaks down polymers into individual monomers or other constituent materials that can then serve as feedstock to produce virgin-quality polymers (Harmsen et al., 2021).

Mono-materials, or textiles made from a single type of fiber, are generally easier to recycle than those composed of multiple fibers. Good recycling options for mono-materials include mechanical recycling, which involves shredding and re-spinning the fibers, and chemical recycling, which breaks down the fibers into their chemical components for reuse. However, textiles composed of more than one fiber are more difficult or impossible to recycle as the fibers must be separated for recycling. This is particularly true for post-consumer textile waste, which is more complex due to the variety of fibers and materials used in the garment. Industrial textile waste, on the other hand, is often easier to recycle as it is typically made up of a single type of material and is generated in large quantities, making it more economically viable to recycle (Riemens, 2023).

Some fibers are easier to recycle than others due to their properties of production methods. For example, fibers like wool, nylon and polyester are easier to recycle than cotton, hemp, PP, acrylic or viscose (Muthu et al., 2012). This will also affect the recyclability potential of a textile product.

4.3. Production and recyclability

Chemicals used in textile production and processes include pesticides, solvents, surfactants, dyes and pigments, plasticisers, water and stain repellents, flame retardants and biocides (EMF adapted from CHEMSEC, 2017). The presence of substances of concern during recycling has the potential to disrupt the recycling process and result in the continued circulation of these substances, leading to potential exposure. The extent of exposure depends on the recycling methods employed. In order to enable healthy flows of materials in a circular system, elimination of these substances would be ideal to be able to capture the full value of a closed-loop system. The presence of substances of concern in textiles placed on the market before current regulations can also pose a challenge to recycling, as they may contain significantly higher amounts of these substances than virgin materials where their use is restricted. This makes the material value more difficult to recapture.

The use of certain chemicals in textile production, such as dyes and finishing agents, can make it difficult to separate and recover fibers during recycling. Some chemicals can also degrade the quality of the fibers, making them unsuitable for reuse. Additionally, the presence of toxic substances, such as heavy metals, can hinder composting and reduce the nutritional value of the resulting compost. These factors can make it harder to recycle textiles and reduce their value in the circular economy (Ellen McArthur Foundation, 2017). According to Nimkar et al, up to 90% of the initially introduced chemicals are still present in the post-use phase and contaminate recycled fibres (2018) causing even more problems with recycling. Chemicals hinder various recycling processes by lowering output value or restricting end markets (Riemens, 2023). However, from the current literature and research, it is unclear exactly which chemicals interrupt the process and to what degree.

4.4. End of life and recyclability

Pre- or post-consumer textiles that enter the recycling stream are processed into different goods in two steps: (1) disassembly and (2) reassembly (Keßler et al., 2021). Firstly, ease of disassembly will depend on the design stage. As mentioned earlier, this stage is probably the most important one as it represents 80% of a products environmental costs (Ellen McArthur Foundation, 2017). The combination of elements such as zippers, buttons, fibre blends and appliqué render effective sorting and separation into pure fractions almost impossible (Keßler et al., 2021).

There are several recycling methods available for textiles, at different levels of the textile structure. These include fabric, yarn, fiber, polymer, and chemical monomer recycling.

Fabric recycling involves breaking down textiles into smaller pieces and reusing them to create new fabrics. Yarn recycling involves unravelling old garments to create new yarns. Fiber recycling involves breaking down textiles into their component fibers and reusing them to create new textiles. This is typically what happens during mechanical recycling. Polymer recycling takes fibers back to the polymer level, destroying the fibers but keeping the chemical structure of the material intact. Chemical monomer recycling breaks down polymers into individual monomers or other constituent materials that can then serve as feedstock to produce virgin-quality polymers. Chemical recycling can happen both at the monomer and polymer level (Ellen McArthur Foundation, 2017).

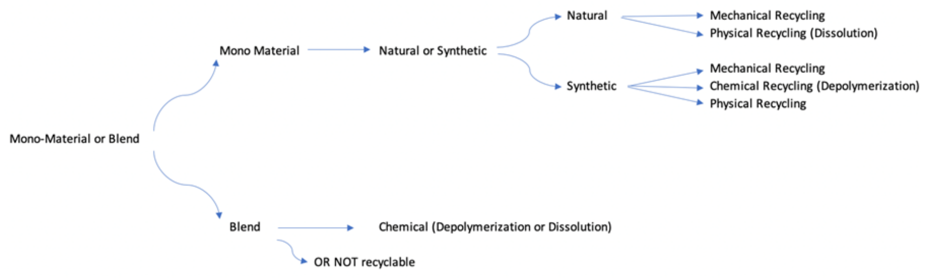
Depending on the level in textile structure at which a garment is being recycled, textile recycling is typically classified as mechanical or chemical recycling (Juanga-Labayen et al., 2022), although a recent study by Harmsen et al. (2021) identifies physical recycling as a third way of recycling.

Mechanical recycling involves shredding and re-spinning the fibers of a material to create new products. This process is commonly used for mono-materials, or textiles made from a single type of fiber. The fibers are sorted by color and quality, then shredded and re-spun into new yarns or fabrics. Mechanical recycling is a relatively simple and cost-effective process (Harmsen et al., 2021). Approximatively 95% of recovered cotton fibers by mechanical recycling are directly processed and reused into non-wovens for the automotive industry, appliances, drainage systems and geotextiles (Gulich, 2006). However, it can generally be noted that mechanical recycling can result in a loss of quality and strength in the recycled material (Harmsen et al., 2021).

Physical recycling refers to the various physical processes to render fibers or polymers amenable to reprocessing, typically through either melting or dissolution procedures. It is done by recycling back to polymers. In the realm of physical recycling, alterations are made to the structure of the fibers, while the fundamental polymer molecules constituting these fibers remain undisturbed. Following the processes of melting or dissolution, subsequent steps may involve either melt spinning or solution spinning to fashion a novel filament, characterized by its infinite length, thereby facilitating the recycling process. Physical recycling is done by recycling back to polymers. (Harmsen et al., 2021).

Chemical recycling, also known as feedstock recycling, involves breaking down the fibers of a material into their chemical components for reuse. This process is typically used for mixed or contaminated materials that cannot be mechanically recycled. Chemical recycling can be achieved through a variety of methods, including pyrolysis, gasification, and depolymerization. These methods involve heating the material to high temperatures in the presence of a catalyst or solvent to break down the fibers into their constituent chemicals. Chemical recycling can be more complex and expensive than mechanical recycling, but it can result in a higher quality and more versatile recycled material (Harmsen et al., 2021).

From this, the following pathway or model can be deducted to determine the corresponding recycling methods for each type of material:




Scheme (1): Recyclability methods pathway

The table (Table 3) below offers a more comprehensive view of the possible recyclability methods for the textiles cited in table (1). Elastane, PP and PE are marked black as technology is not advanced and cost-effective enough to recycle these fabrics at this time.

| TEXTILE | Mechanical to Fibers | Physical to Polymers | Chemical to Monomers |
|---|---|---|---|
| Cotton | x | x | |
| Linen | x | x | |
| Viscose | | x | |
| Lyocell | | x | |
| PET | | x | x |
| Wool | x | | |
| Silk | | | |
| Nylon | | x | x |
| Elastane | | | |
| PP | | | |
| PE | | | |
| Acryl | x | | |
| Modacryl | x | | |

Table (3) Mono-textiles and their possible recycling methods adapted from (Harmsen et al., 2021)

## 5. THE TEXTILE PRODUCT RECYCLABILITY INDEX

Following the extended analysis of the factors impacting the recyclability of textile products, a general Textile Product Recyclability Index can be developed.

### 5.1. The concept of a recyclability index

A Recyclability Index cannot be decided by considering one single factor of a textile fiber or of any material. It is a combination of factors, taking into account numerous factors from various perspectives. Following the extended analysis of the factors impacting the recyclability of textile products, a general Textile Product Recyclability Index can be derived. This would mean that:

TPRI = Impact Design + Impact Raw Materials + Impact Production + Impact Distribution + Impact Use + Impact End of Life (disposal, collecting and sorting possibilities and recyclability options)

Considering the stages of Distribution and Use do not have a significant impact in the final recyclability potential of a textile garment (from a producer's perspective), the Textile Product Recyclability Index (TPRI) can be reduced to:
TPRI = Impact Design + Impact Raw Materials + Impact Production + Impact End of Life

Each factor will be attributed a defined weight (score out of x) that will be recalculated into a recyclability percentage to define de final Textile Product Recyclability Index (TPRI). This model will ultimately enable players to understand portant impact of recyclability. For sustainability reasons, natural fiber has also been added to the recyclability index. Lastly, since the importance of chemical processes and embellishments cannot accurately be measured at this time, a weight of 0,5 per element has been assigned.

Assuming the following factors can be traced back along the production chain, this model allows to calculate and define the recyclability potential of a textile product.

***Textile Product Recyclability Calculator***

| Is the product designed for disassembly / recyclability? | + | Is the product composed of more than 1 material? | + | Is the material mono-material? | + | Is it a natural fiber? | + | Is there any presence of the latter: | If yes |
|---|---|---|---|---|---|---|---|---|---|
| If Yes +2 | | If Yes +0<br>If No +1 | | If Yes +2 | | If Yes +1 | | Pesticides | +0,5 |
| | | | | | | | | Solvents | +0,5 |
| | | | | | | | | Surfactants | +0,5 |
| | | | | | | | | Dyes and pigments | +0,5 |
| | | | | | | | | Plasticisers | +0,5 |
| | | | | | | | | Water and stain repellents | +0,5 |
| | | | | | | | | Flame retardants | +0,5 |
| | | | | | | | | Biocides | +0,5 |

= / 10

Table (4) Simplified Score Board/Maturity Model for TPRI

Once a score has been obtained and converted into percentage, the same principle can be used as with the plastic recyclability index where the score will correspond to a level of recyclability. See table (5).

| Score | Recyclability |
|---|---|
| More than 95% | Recyclable |
| Between 80 and 95% | Mostly recyclable |
| Between 50 and 95% | Moderately recyclable |
| Less than 50% | Not Recyclable |

Table (5) Recyclability score if the TPRI

## 6. LIMITATIONS AND FURTHER RESEARCH

While this study provides valuable insights into developing a recyclability index for textiles in the fashion industry, there are several limitations that should be acknowledged. Firstly, the proposed index is based on a simplified model that primarily considers factors within the Environmental Product Life Cycle stages. While this provides a structured approach, it may not encompass all possible variables influencing recyclability. Therefore, further research can be done regarding the weight of each factor on the final recyclability of the product.

Furthermore, the proposed index assumes a relatively linear relationship between the identified factors and the overall recyclability score. However, interactions and dependencies between different factors could exist, impacting the overall outcome. This calls for more advanced statistical methods to accurately model and quantify these relationships. Additionally, aspects like the quality of the material and additional components or contaminants are not considered in their respective phases which will also have a significant impact on final recyclability possibilities of a product. Although this study offers clear identification of the factors affecting recyclability of textile products, a deeper dive should be done to identify the weight and measurements of the latter.

Lastly, this study predominantly focuses on the fashion industry. However, the principles of the proposed recyclability index could be extended to other sectors that heavily rely on textiles, such as medical and automotive industries. Investigating the applicability and effectiveness of the index in diverse contexts would contribute to its broader relevance.

In conclusion, while this study lays the foundation for a recyclability index for textiles in the fashion industry, there are various dimensions yet to be explored. Future research should aim to refine and validate the index using a more comprehensive approach that considers both technical and consumer-oriented aspects, leading to a more robust and practical tool for assessing textile recyclability.

## 7. CONCLUSION

The fashion and textile industry's impact on environmental pollution and resource depletion is undeniable, necessitating a paradigm shift towards sustainability. The circular economy, with its core principles of Reduce, Reuse, and Recycle, emerges as a promising framework to guide the transformation of textile production and consumption. Within this context, the development of a comprehensive recyclability index for textile garments has been a central focus of this study.

Through an extensive review of existing literature, this paper has unveiled the intricate interplay of factors influencing the recyclability of textile products. Design, material composition, production methods, and end-of-life options have been identified as critical dimensions that shape the potential for textiles to be reintegrated into the production cycle. These findings have been synthesized into a proposed Textile Product Recyclability Index (TPRI), providing a structured framework for evaluating and quantifying the recyclability of textile garments.

However, this study has also highlighted the complexity of the recyclability challenge. One of the biggest challenges in recycling that will become increasingly important is the recycling of blended textiles. Recycling processes are complicated and sometimes even impossible due to the current state of technology. Mono-materials prove to be more readily recyclable compared to mixed-fiber textiles and the presence of chemicals used in production can hinder recycling processes. The different recycling methods each have their advantages. While mechanical recycling is the most used, it can often reduce the quality of the recycled fiber. Technological advances will be needed in the future to meet the needs of the Circular Economy. Further, the interaction between different stages of the Environmental Product Life Cycle necessitates a holistic approach to assessing recyclability.

In the pursuit of a more sustainable future, the development of the TPRI represents a significant step towards fostering a circular economy within the fashion and textile industry. However, it is crucial to acknowledge the limitations of this study, including the simplified model of the index and the exclusive focus on technical aspects. To fully realize the potential of the TPRI, future research should expand its scope to encompass broader consumer perceptions, economic implications, and regional recycling infrastructure differences.

Ultimately, this paper proposes a scientific and practical contribution synthesised as the TPRI providing a tool that empowers stakeholders and players across the textile value chain – from designers and manufacturers to policymakers and consumers – to make informed decisions that prioritize recyclability. As the industry strives for a more sustainable and circular future, collaboration, innovation, and ongoing research will be paramount to unlocking the true potential of textile recyclability and minimizing the environmental footprint of fashion along its growth.

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