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CIRCULAR ECONOMY AND RECYCLING IN THE TEXTILE INDUSTRY

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Abstract: *The paper analyses the transition from a linear economy paradigm to a circular economy model in the textile industry, which is one of the most polluting industries in the world. The linear model involves a large consumption of raw materials and generates waste, while the circular economy model focuses on the regeneration of raw materials and recycling. This includes the 5 R's of textile waste management: rethink, reduce, reuse, recycle, and reintroduce. The circular economy is characterized by close cycles, in which waste is minimized or converted into valuable inputs. Textile recycling process can be mechanical, thermal, chemical and biological. A series of recycling methods for different fiber-based materials: cotton, wool, synthetic, which are proposed in scientific papers is presented, contributing to the promotion of a zero-waste world.*

Key words: *sustainability, sorting, textile waste*

1. INTRODUCTION

In the current context of the growing importance of environmental protection in parallel with the sustainability of production activities and beyond, the textile industry is facing a change in strategies and process approaches in relation to the purpose and the profit obtained. A number of textile companies implement sustainable production systems, and others take into account principles such as sustainable sourcing of materials from suppliers who use ecological practices. Modern manufacturing processes enable harmful substances to be caught and repurposed as opposed to being dumped into the environment. At the same time, a new business model is used in the fashion industry, the circular economy (see fig. 1).

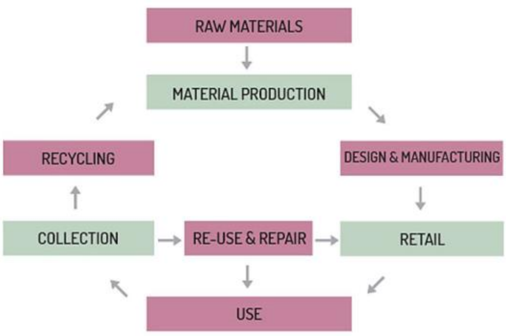

Fig.1: Circular economy in textile and apparel industry [1]

2. LINEAR AND CIRCULAR ECONOMY MODEL IN TEXTILE INDUSTRY

Clothing manufacturers also involve consumers in using sustainable consumption practices. By promoting ecological products, consumers learn about the benefits of circular fashion, which involves reusing and recycling of apparels. The 5 R's of textile waste management, which are rethink, reduce, reuse, recycle, and reintroduce, are crucial strategies for addressing the issue of textile waste. These tools enable us to conserve natural resources, reduce the amount of waste sent to landfills, and save energy [2].

Due to the fact that the textile sector ranks second in terms of pollution, contributing 10% of yearly worldwide greenhouse gas emissions and 20% of global industrial water pollution [3], it attempts to replace the traditional linear textile business model, which involves a large consumption of raw materials and the generation of waste [4]. To this practice is also added the Fast Fashion behaviour (the manufacturing and consumption of a lot of inexpensive, low-quality clothing with widespread use of micro plastics and other cheap raw materials [5]) which could be observed until the 2020s and which had the effect of doubling sales and decreasing the number of wearing of clothing products [4].

Limited natural resources, the polluting effects of waste, also utilizing non-renewable energy, represent environmental protection issues that are critical in approaching the linear economy. The solutions to these problems are given by the circular economy model, which focuses on the regeneration of raw materials and recycling. Clothing recycling increases the circularity of products and increases the life of textile materials. Textile fibers remain in the cycle longer and it is no longer necessary to be incinerated or stored [6] as waste as in the linear model. The circular economy is characterized by close cycles, in which waste is minimized or converted into valuable inputs, contributing to increasing productivity, optimizing the using of natural and human resources.

The management of the circular flow of materials must take the product's life cycle under consideration. Innovative strategies include item resale, rental, peer-to-peer sharing, collecting and exchange systems. As the product's life cycle is finished, its decommissioning is done by deconstructing and recovering the components without contaminating the ecosystems. If the garment can no longer be worn, textile resources are recovered by separating the fibers and regenerating them to new fabrics, as buildings materials [7].

3. TEXTILES RECYCLING

Waste is generated in the textile industry, both during the manufacture of textiles and the usage of the products, as post-industrial (pre-consumer) or post-consumer waste as shown in table 1. Pre-consumer waste refers to fibers, yarns, fabrics made of wool, acrylic, nylon, polyester, cotton and other materials, which originate from various operations of textile production, such as spinning, weaving, knitting, sewing, etc. Post-consumer waste originates from used textile products.

By recycling, the textile waste is eliminated from the stream, reprocessed and reintroduced it into the market to be used for creating new textile or non-textile goods. Pre-consumer waste is derived and used for automotive, aeronautics, housing, furniture, mattresses, coarse yarn and clothing, as post-consumer waste consists in textile that the user evaluates to no longer require and decides to throw away because they are worn, damaged or out of date [8].

Textile recycling can be mechanical, thermal, chemical and biological [9]. Mechanical recycling breaks down waste into fibrous forms which can be re-spun into yarns or processed into nonwoven, to use for decoration, construction, agriculture and gardening. Mechanical recycling has the advantage of being able to process fabrics made from any type of fiber and fiber mix.

Mechanical recycling is typically used for pre-consumer textile waste, which does not suffer wear and tear and is of better quality than post-consumer waste [10]. Recycling of unwearable, ripped, or stained clothing can be done by breaking down the fabric into fibers by shredding, cutting, carding etc. The fibers will then be used for other textile products such as padding, automotive outlines and coverings, building materials such as insulation and roofing felt, as well as blankets, carpeting, furniture upholstery, insulating materials and toys.

Table 1: Textile waste

Waste	Type of textile waste	Source of waste (section)
Post-industrial (Pre-consumer, production)	Blending, carding, dropping wastage, sliver, draw and ring frame waste	spinning
	Weaving, sizing, knotting, beam residual, auxiliary selvage wastage	weaving
	Samples, fabrics with stains, bareness, stripes, hole, thick, thin yarns	knitting
	Shade variation, crease	dyeing
	Cutting, sewing, finishing, printing, embroidery waste	garmenting
Post-consumer	Garments, home textiles, technical textiles, nonwoven	final consumer

Closed-loop mechanical recycling is a process that involves breaking down waste textiles into individual fibers without compromising their mechanical properties such as rigidity and strength. On the other hand, open-loop mechanical recycling entails cutting fibers prior to undergoing the melt-blowing process where they are disintegrated into individual fibers. The resulting fibers are then web formed and dried to produce the final product. This method is commonly used in manufacturing individual pads for mattresses.

Thermal recycling refers to the conversion of thermoplastic waste, typically polyester flakes, into fibers through the melt extrusion fiber production process. Recycled polyester fibers from plastic bottles are obtained through thermal recycling [10].

Chemical recycling has two variants: synthetic polymers fibers are depolymerized into monomers and then repolymerized into polymers, as well as regenerated cellulosic fibers are created by wet spinning natural or recycled cellulosic fabrics that have been dissolved in a solvent.

Chemical recycling involves the depolymerization of polymers, such as polyester, or the dissolution of materials like cotton and viscose. Through this process, fibers of similar quality to virgin materials can be produced [11]. Through chemical treatment, textile waste with protein-based fibers can be used to make adhesives for wooden panels, and those with cellulosic fibers used for bioethanol process [12]. The products obtained from glycolysis of PET waste will serve as building blocks for the synthesis of degradable co-polyesters. By performing amylolysis in the presence of amino acids, nylon 6 and nylon 6.6 are transformed in other substances. Hydrolysis is a versatile process that can be employed to treat mixed fabrics such as cotton, wool, and polyester. While there are various types of hydrolysis, enzymatic, alkali, and acid hydrolysis have gained more popularity in recent times.

To enable thermal and chemical recycling of textiles composed of fiber blends, it is essential to ensure a high degree of material purity, which necessitates the sorting and separation of such materials.

The process of biodegradation involves the natural recycling of waste and the breakdown of organic materials by microorganisms like fungi, bacteria, worms and insects. Biochemical transformation by fermentation is a way of using recyclable cotton textile waste into new products. Utilizing solid waste from the textile industry for biogas production via anaerobic digestion presents an alternative approach [9]. Enzymes function as biocatalysts, accelerating the rate of chemical reactions. They exhibit remarkable specificity, selectively acting on particular substrates to produce desired products. One example of this is cellulose, which can be sourced from fungi and bacteria, and is utilized in cellulose hydrolysis.

Medical textiles can currently be recycled completely through various methods such as chemical treatment, incineration, and autoclaving. However, the latest and most inventive solution for recycling medical textiles involves molecular tagging of fibers [13].

4. THE SORTING PROCESS

The sorting of post-consumer waste begins with the selection of heavy items from the lightest, followed by the separation by product categories, fabric and gender, raw material (wool, cotton, linen), conditions (tear, missing buttons and wear), quality and degree of use [14]. Following collection, textiles are sorted by color and material to enable efficient processing. Fabrics or garments with similar characteristics are grouped together and processed in batches. Components that are not made of textiles, like zippers and buttons, are extracted, and the remaining material is cut into uniform sizes to facilitate processing. To ensure smooth machinery operation, waste is blended with oils. Depending on the type of material, suitable methods such as physical or chemical techniques are used to further break down the material. The resulting fibers are then carded and/or spun into yarns, which are used to create value-added products.

The mechanical recycling of thermoplastics, such as polyolefin, polyester, polyamides, and other plastic products and textile materials, involves melting, shredding, or granulation of the waste. To achieve efficient mechanical recycling, it is essential to maintain the purity of the final product, and therefore, sorting of waste materials before recycling is necessary to prevent contamination that may considerably decrease the value of the recycled fibers. Sorting of plastic waste is typically based on color and chemical structure and can be carried out manually or by machine. Manual sorting consumes time and is not very rigorous, which is why automatic sorting is a better alternative. Various techniques, as X-ray fluorescence, near-infrared spectroscopy, flotation and electrostatics are introduced to sort plastics automatically [15]. In recent times, hydrocyclones, which were originally employed in mineral separation and other industries, have found application in plastic separation processes.

The Pyramid Model in fig. 2 specifies the categories that will determine which processes will be supported next: recycling or reuse of the textile material. These categories are: textiles for used clothing markets, conversion textiles, wiping and polishing clothes, textiles sent to landfills and incinerators and diamonds [16].

Diamonds (1-2% of recycled textiles) are older clothing items from well-known brands: couture, Levi's, Ralph Lauren, Dona Karan, Harley Davidson, and expensive fibers, as cashmere and camel hair. There is significant demand for second-hand clothing, which can be sold online, in vintage or retail boutiques. Only around 7% of recycled textile products are either incinerated or sent to landfills. Textiles that end up in landfills lose their value and cannot be repurposed, making it important to avoid incineration and minimize losses. This practice is applied especially in Europe, aiming to increase the efficiency of incineration and reduce the harmful by-products of incineration.

About 17% of used textiles are included into the category of wiping and polishing cloths, being considered unwearable. This group encompasses blends of hydrophilic and oleophilic fibers that are frequently beneficial in industrial settings. It also includes T-shirts made of cotton fibers renowned for their high absorbency.

Approximately 29% of textile waste is repurposed into new products if it is considered unsuitable for further use. The terms "shoddy" (for knits) and "mungo" (for woven garments) refer to the process of converting fabric into fibers through mechanical means. The shoddy method involves creating new yarn products from old materials and is often utilized in producing knit blankets. The term "mungo" pertains to the process of utilizing textile waste to produce cloths in cold climate countries. Shoddy and mungo fibers are used for cashmere sweaters, the filling material used for furniture, automobiles, and punching bags.

Fig.2: The Pyramid Model for textile recycling categories [16]

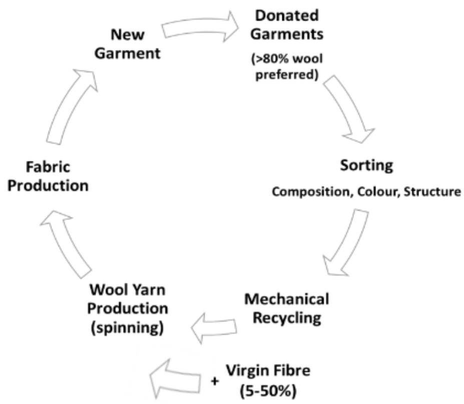

Fig. 3: Recycling of wool closed - loop [29]

48% of textiles are classified in the category of used clothing markets. Western countries engage in the exportation of used textiles to developing countries or use them for humanitarian aid purposes during times of crises or emergencies.

5. CATEGORIES OF TEXTILE RECYCLING

5.1. Cotton fibers

Polyester and cotton are the most common fibers used worldwide. Cotton is a natural fiber which can be recycled mechanically, chemically, or biologically. However, cotton recycling can be complicated by the presence of contaminants such as dyes and finishes, and mechanical recycling can weaken the fibers.

During the production of cotton garments, there is an estimated global generation of approximately 11.6 million metric tons of waste cotton each year. The cotton recycling process refers to the mechanical processing and re-spinning of residual waste. Due to the fiber-breaking nature of the mechanical process, the quality and strength of the recovered fiber are typically diminished. Consequently, the recovered fiber must be blended with either virgin cotton fibers or other types of fibers to enhance its strength. Cotton as a raw material is used in non-woven surfaces for insulation, automotive felts, and oil absorbent films. Recycling cotton fibers offers ecological benefits, including 20% lower water and energy consumption, a reduction in chemical use, and fewer emissions generated. The elimination of agricultural operations associated with conventional cotton production also leads to a decrease in the consumption of natural resources [17].

Several studies have been conducted on recycling of cotton waste. In [18], the authors explored various techniques for recycling pre-consumer and post-consumer cotton waste, including chemical and mechanical processes. They also compared the applications of waste cotton to their virgin counterparts from technical, environmental, and economic viewpoints. The study also included non-conventional applications of waste cotton, as biofuels and composites, which could open up alternative markets for waste cotton that do not conflict with the use of virgin cotton.

Paper [19] investigates the feasibility of recycling cotton waste into usable yarns for textile production. The study involved the collection of cotton fabric scraps from a local garment factory and the processing of the scraps into yarns using a semi-industrial machine. The authors examined the effect of different processing parameters, such as carding, combing, and drafting, on the quality of the recycled yarns. They analyzed the physical properties of the yarns, such as thickness, strength, and elongation, and compared them to those of virgin cotton yarns. The results showed that the recycled yarns had similar physical properties to those of virgin cotton yarns, indicating that cotton fabric scraps could be successfully recycled into usable yarns.

The authors of [20] used a mechanical recycling process in optimizing the recycling process of waste cotton yarn and spinning of reclaimed fibers to produce value-added products. They tested various spinning parameters to optimize the production of yarn. The optimal spinning conditions for the reclaimed fibers were a draft ratio of 1:9 and a spindle speed of 12000 rpm.

The Cotton Waste Recycling for Regenerated Cellulose Fibers is the subjects of [21] and [22]. In [21], the physical properties of the resulting fibers, such as their tensile strength, elongation at break, and thermal stability, are evaluated, being found as a potential alternative to traditional textile fibers. Paper [22] proposed a process for recycling post-consumer cotton waste into regenerated cellulose fibers, which involved several steps, including pre-treatment, dissolution, regeneration, and spinning. The authors investigated the effect of a chelating agent use during pre-treatment, which improved the purity and mechanical properties of the regenerated cellulose fibers.

The chemical recycling of cotton materials and other cellulosic textiles to produce high-quality regenerated textile fibers is a new process that aims to address concerns related to the growth of the population, scarcity of resources, and adverse environmental effects caused by the textile industry. The authors of [23] present an overview of the various chemical recycling techniques, such as hydrolysis, pyrolysis, and solvolysis, and their respective advantages and disadvantages.

In [24] researchers have developed a new method for depolymerizing cotton waste textiles to form a glucose solution using sulfuric acid as a catalyst, with a high yield of over 70%. The method is applicable to various types of cellulosic fibers; the high concentration of glucose produced (>100 g/L) reduces the cost of purification, making the process more economically viable. This method has the potential to not only reduce textile waste but also to create a closed-loop system within the textile value chain, retaining the value of waste textiles and reducing the industry's reliance on virgin materials. The methods proposed in [25] and [26] refer to solubilizing cotton post-consumer textile waste in the cellulose-dissolving ionic liquid ([DBNH]OAc) to be transformed into continuous filaments. However, due to the heterogeneous nature of the raw material, it was necessary to pre-treat the waste cotton to modify the degree of cellulose polymerization by acid hydrolysis, enzyme hydrolysis, or mixing with birch pre-hydrolyzed kraft pulp to improve spinnability. In comparison to native cotton fibers and other commercially available fibers such as viscose and lyocell, all of the regenerated fibers during Ioncell® process [26] display considerably higher tenacities of approximately 60 cN/dtex with a 10% elongation. Fibers produced from dyed cotton experienced a decrease in color intensity and a minor reduction in crystallinity after spinning, but no notable changes in the chemical structure were observed.

Paper [27] presented a reuse of waste cotton fibers method by milling them into fine powders with particle sizes of approximately 30 µm and dyeing them for use as pigments. The study used several methods, including dynamic mechanical analysis, scanning electron microscopy, Fourier-transform infrared spectroscopy and X-ray photoelectron spectroscopy to explore the properties of the powders and indicated that the material underwent primarily viscous deformation. Using similar assessment methods, the proposed approach from article [28] refers to the woven cotton fibers degradation at 50°C with low concentrations of urea, citric acid, sodium hydroxide ammonium hydroxide and sodium nitrate which successfully separates the component fibers besides depolymerization of the cellulose structure. The study proves that it is feasible to recycle waste fabric effectively through non-chemical intensive procedures, as it is possible to recover the staple fibers and reuse them in the production of new textiles.

5.2. Wool fibers

Wool is a natural fiber that can be recycled mechanically or chemically. Wool fibers have unique properties such as elasticity and moisture management, but they can be challenging to recycle because they can become damaged or matted during processing. Additionally, wool recycling can be complicated by the presence of additives and finishes.

Recycling wool fibers in a closed loop system is possible, and traditional methods can transform recycled wool yarns into high-value apparel products. The process of wool recycling is similar to mechanical cotton recycling (see fig. 3) [29], [30].

Paper [31] aimed to determine the environmental and market impacts of the recycled wool blend clothing production. During a cradle-to-grave life cycle assessment, the study emphasis that by using best practices for garment maintenance; a recycled wool blend sweater can decrease environmental impacts by 66-90% in comparison to a new pure wool sweater. Furthermore, if the closed-loop recycling rate were increased to 50%, it could potentially reduce impacts on the wool sweater market by 7-24%, depending on the specific impact category.

The products of recycled wool may be of lower quality than the original materials, but they can still be used in various applications such as insulation, carpeting, or padding. Other applications, including biomaterials, resins, and adhesives, are created by extracting the keratin protein from pre- and post-consumer waste. Researchers have also explored using recovered proteins from recycled or waste wool like functional treatments in wool fabric manufacturing. For instance, Smith and Shen [32] separated polypeptides from waste wool of low quality to change the surface properties of wool fibers and enhance shrink resistance. Similarly, Du et al. [33] designed a finishing method for wool fabric that prevents felting and pilling through the use of keratin polypeptides separated from recycled waste wool, which also improved the softness, dyeability, and hydrophobicity of the treated fabrics.

5.3. Synthetic fibres

Approximately 72 per cent of all materials used by the fashion industry are made from plastic [34]. 500000 tons of microfibres are released into the ocean each year from washing clothes - the equivalent of throwing 50 billion plastic bottles [4]. These fibres can take up to 200 years to decompose.

Synthetic fibers such as polyester, nylon, and acrylic are derived from petrochemicals and are not biodegradable in the standard conditions. Synthetic fibers can be recycled chemically or mechanically. Chemical recycling of synthetic fibers can be energy-intensive, and the process often requires high temperatures or strong solvents. Mechanical recycling can be more challenging for synthetic fibers because they are often blended with other materials, making it difficult to separate and recycle them [35].

Recent articles cover strategies and novelties in enhancing the biodegradability of synthetic textile fibers. In paper [36], the use of polylactic acid is proposed as a biobased and biodegradable alternative apparel textile fiber, while biological methods are suggested for addressing PET waste, such as industrial enzymatic hydrolysis for creating recyclable monomers. Although pure PET fibers do not biodegrade under standardized conditions, recent advancements in process intensification and engineered enzymes have shown greater enzymatic recycling efficiency for PET polymer in comparison to cellulosic materials. Also, the development of synthetic/natural fiber blends and novel waste management techniques like compost, anaerobic treatment, and biocatalyzed industrial reworking are opening up potential for new environmentally friendly and recyclable textile fibers.

The mechanical properties of recycled PET yarns are often inferior to those of virgin PET (v-PET) yarns due to impurities originating from non-PET sources like labels and caps of bottles. As a result of growing environmental concerns, the recycling of post-consumer plastic containers into textile fibers has made economically viable. In [37], the authors investigated the impacts of mechanical and chemical recycling processes on yarn properties such as photo-degradation, tensile strength, thermal behavior and hydrolysis. The virgin and chemically recycled yarns have related physical, mechanical properties and long-term degradation behavior. These results offer valuable insights into the processability and serviceability of recycled PET (r-PET) yarns, especially for high-end use applications.

Paper [38] consists in a study of the liquid moisture transfer properties of polyester and recycled polyester knitted fabrics, concluded in the r-PET fabric had better results than the PES fabric in terms of absorption rate, wettability, drying rate, and capillarity.

The authors of [39] propose a twisting technique to enhance the mechanical characteristics of the yarns made from recycled plastic bottles and make them more suitable for use in high-performance reinforced composites.

Fabrics that are often recycled contain cotton and polyester. Clothing products such as shirts, sportsuits, bags, coats etc. use recycled polyester. The study from [40] emphasis that the recycled PET fiber is a suitable component for cotton blended yarn production. The recycled PET yarn exhibits reasonable degrees of unevenness, hairiness, and elongation when compared to virgin PET yarn. However, the recycled PET yarn's decreased strength could be viewed as a drawback.

The paper by dos Santos Pegoretti et al. [41] presents a comparative life cycle assessment case study about the acoustic components used in the automotive industry, with a focus on the environmental effects of using recycled versus virgin materials. The authors also evaluated the economic feasibility of using r-PET fibers, concluding that the cost of using r-PET fibers was comparable to the cost of using virgin materials.

5. CONCLUSIONS

Recycling presents unique challenges and benefits for each material. Successful recycling depends on various factors, such as the presence of contaminants, availability of appropriate recycling facilities, and markets for recycled products. Despite the difficulties, natural fibers like cotton and wool are biodegradable and have a lower environmental impact than synthetic fibers, which are made from non-renewable resources and can persist for centuries. To close the fashion loop, brands must assume full responsibility for their products until their end-of-life, implementing sustainable solutions like reselling, clothes swaps, take-back programs, repairing schemes, and upcycling. These strategies can divert textiles from landfills, support decarbonization, and promote a zero-waste world.

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