



RECYCLED COTTON FIBERS: PATHWAYS AND APPLICATIONS

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Abstract: *The global textile industry faces significant environmental challenges due to high resource consumption and growing volumes of post-consumer waste, particularly from cotton, one of the most widely used natural fibers. This paper examines the pathways and applications of recycled cotton fibers within the framework of a circular economy. Mechanical recycling, the most established method, involves shredding and fiber reconstitution, enabling the production of blended yarns and nonwoven materials, though it reduces fiber length and strength. Chemical recycling techniques, including solvent-based dissolution and regeneration, allow the production of high-quality cellulose fibers comparable to or exceeding virgin cotton in performance, suitable for demanding textile applications. Emerging biological and hybrid approaches, such as enzymatic treatments and combined mechanical-chemical processes, provide sustainable alternatives, preserving fiber integrity while reducing chemical and energy usage. The study highlights the influence of recycling methods on fiber, yarn, and fabric properties, showing that optimized blends containing up to 30% recycled cotton maintain adequate mechanical performance for apparel and home textiles. Advanced applications of recycled cotton, including nanocellulose, composites, and functional materials, demonstrate its potential beyond conventional textiles. Finally, recycling cotton fibers contributes to resource efficiency, waste reduction, and the development of sustainable, high-value materials, supporting the transition toward environmentally responsible textile production.*

Key words: *cotton, textile waste, circular economy, mechanical recycling, chemical recycling*

1. INTRODUCTION

The global textile industry is a major contributor to environmental degradation, driven by high resource consumption and increasing volumes of post-consumer waste. Cotton, one of the most widely used natural fibers, is associated with significant water usage, pesticide application, and land exploitation. As sustainability becomes a central concern, the transition toward circular economy models has emerged as a critical strategy for reducing the environmental footprint of textile production. Recycled cotton fibers offer a viable solution by diverting textile waste from landfills and reducing reliance on virgin cotton. Advances in recycling technologies have enabled the transformation of cotton waste into a variety of products, ranging from low-grade insulation materials to high-performance regenerated fibers and advanced functional materials. However, challenges remain in maintaining fiber quality, ensuring economic viability, and scaling recycling processes. This paper aims to analyze current recycling pathways for cotton fibers, evaluate their impact on material performance, and assess their environmental benefits within a circular framework. It also identifies key challenges and outlines future directions for research and industrial implementation.



2. RECYCLING TECHNOLOGIES FOR COTTON FIBERS

2.1 Mechanical Recycling

Mechanical recycling is the most established method for processing cotton waste and involves sorting, cutting, shredding, and opening textile materials into reusable fibers. This process is relatively simple and cost-effective, making it widely adopted in industry. However, mechanical recycling significantly affects fiber properties. The repeated mechanical stress shortens fiber length and reduces strength, which in turn impacts yarn quality and limits the proportion of recycled fibers that can be used in high-performance textiles. The quality of the recycled fibers strongly depends on the characteristics of the input waste, including fabric structure, blend composition, and previous processing history. Although recycled cotton fibers generally exhibit inferior properties compared to virgin cotton, particularly when produced by shredding fabric waste, this has historically limited their use in clothing production [1].

As a result, recycled cotton has mainly been directed toward coarser yarns through blending with other fibers. The paper [2] highlights key advancements in textile recycling, focusing on improving circularity for cotton, polyester, and their blends. Spectroscopic techniques, particularly Near-Infrared Spectroscopy (NIRS) combined with color sorting, are used to accurate and efficient classification of textile waste. Once properly sorted, materials undergo mechanical and/or chemical recycling, including decolorization when necessary. The authors have pointed out that for cotton, understanding the degree of polymerization (changes from virgin fiber through various recycling stages) is essential. This knowledge helps select the most suitable recycling processes and maximizes the number of useful lifecycles for cotton fibers.

Table 1: Main recycling routes and end uses for waste cotton

Pathway / Product	Typical Outputs and Uses	Citations
Mechanical -> yarns/fabrics	Knit & woven apparel, denim, mélange yarns	[1], [2], [3], [4]
Chemical -> regenerated fibers	Rayon/lyocell-like fibers, often equal/better than wood-based	[5], [6], [7], [8], [9]
Nonwovens & insulation	Building, clothing, acoustic/thermal panels	[27], [28], [29]
Advanced materials	CNCs, adsorbents, biofuels, electronics, composites	[30], [31], [32], [33]

Up to 25–30% mechanically recycled cotton can be blended into 30 Ne ring-spun yarn suitable for knit tops, with acceptable strength loss. In this sense, the paper [3] shows that recycled cotton fibers from pre- and post-consumer textile waste can be successfully reused by blending them with virgin cotton. Although the blend yarns exhibited higher unevenness, more imperfections, and reduced strength compared to 100% virgin cotton, they enable attractive mélange-style fancy yarns, with the environmental benefits of recycled materials outweighing the slight drop in quality and garment lifespan for today's sustainability-conscious consumers. Despite these limitations, mechanical recycling remains suitable for applications such as blended yarns, denim, and nonwoven products, particularly when optimized sorting and processing conditions were applied. Fabric studies show recycled-cotton woven fabrics can match mechanical properties and drape of carded cotton, suggesting real apparel potential. The study in [4] evaluated several key properties of woven fabrics made from recycled cotton yarns compared to conventional carded cotton yarns. Recycled cotton fabrics demonstrated superior tensile strength in the weft direction, likely due to higher weft yarn density, and showed significantly better abrasion resistance, with no yarn breakage even after 20,000 cycles, unlike



carded cotton fabrics which failed earlier. In terms of bending rigidity, recycled cotton plain woven fabrics exhibited lower values, indicating softer handle and better drapability. However, due to the higher hairiness and short fiber content of recycled yarns, these fabrics displayed poorer pilling performance, especially in twill constructions.

2.2 Chemical Recycling

Chemical recycling processes involve the dissolution of cotton fibers and their regeneration into new cellulose-based fibers. Technologies such as lyocell-type processes use solvent systems (N-Methylmorpholine N-oxide or emerging alternatives like Ioncell®) to produce regenerated fibers with properties comparable or superior to those derived from wood pulp [5], [6]. This approach overcomes the limitations of fiber shortening associated with mechanical recycling, enabling the production of high-quality fibers suitable for demanding textile applications. However, chemical recycling is more complex and requires careful management of solvents, energy consumption, and processing costs. The regenerated fibers [6] showed very high wet and conditioned tenacities (about 54–62 cN/tex) with elongations at break of 9–13%, due to high molecular orientation that increases hydrogen bonding but slightly reduces flexibility and stretch. The authors suggest further optimization of cellulose degree of polymerization, scaling up the process, and exploring advanced applications such as composite or carbon fiber production.

Paper [7] describes the process of cellulose filaments obtaining by dissolving industrial cotton residue in two ionic liquids, [Emim]Cl (1-ethyl-3-methylimidazolium) and [Emim]OAc, with Dimethyl Sulfoxide as a cosolvent, followed by regeneration in water or ethanol. The resulting filaments were homogeneous and dense, retaining additives like optical brighteners. All filaments had reduced thermal stability, with the worst performance observed for the [Emim]Cl - ethanol combination, which also showed poor mechanical properties due to low polymerization and crystallinity. In contrast, other filaments had elastic moduli comparable to viscose and modal fibers (10 - 13 GPa). The [Emim]OAc - ethanol system provided the best balance of mechanical, thermal, and structural properties.

For cotton/polyester or cotton/elastane blends, selective dissolution or hydrolysis separates the components. Ionic liquids, deep eutectic solvents, switchable hydrophilicity solvents, acids, enzymes, and hydrothermal treatments are key tools. The paper [8] reviews chemical separation technologies for polyester/cotton blended textiles, focusing on methods to separate components through polyester depolymerization and cellulose dissolution. It analyzes key polyester depolymerization approaches, and cellulose separation via acidic hydrolysis and dissolution in non-derivatizing solvents. The authors of [9] examine the separation of cotton and polyester and elastane using methods such as dissolution, acidic hydrolysis, acid-catalyzed hydrothermal treatment, and enzymatic hydrolysis, followed by approaches for isolating elastane from other fibers through its selective degradation or dissolution. Recent developments focus on improving process efficiency, reducing environmental impact through closed-loop solvent recovery systems, and enabling the recycling of dyed and blended textiles.

2.3 Emerging Biological and Hybrid Approaches

Emerging recycling methods incorporate biological and enzymatic treatments to selectively break down cotton fibers or remove impurities. These approaches offer the potential for gentler processing, preserving fiber integrity while reducing chemical usage. Enzymatic treatments, particularly those using cellulases, enable the controlled breakdown of cotton fibers into valuable intermediates such as glucose or regenerated cellulose, while minimizing harsh conditions and environmental impact. The review paper of [10] emphasizes that chemical and biotechnological



approaches, such as acid hydrolysis, achieving up to 70% glucose recovery, and enzymatic recycling, which can reduce energy consumption by around 20% compared to conventional methods, enable the effective conversion of textile waste into valuable resources, while scalable technologies including advanced solvent recovery systems, optimized pretreatment processes, and fluidized-bed pyrolysis (increasing bio-oil yields by up to 25% over fixed-bed reactors) are essential for enhancing efficiency, sustainability, and industrial applicability.

Advances in microbial fermentation further allow these sugars to be converted into bio-based chemicals, fuels, or new polymer precursors, supporting circular material flows. Emerging technologies such as Biocelsol, which utilizes dissolving-grade pulp to produce regenerated cellulose fibers [12], along with processes like bioethanol production via enzymatic fermentation, biogas generation through anaerobic digestion, biochar formation by carbonization, and biodegradable composting, represent promising biological routes for textile recycling; however, due to the complexity of textile waste compositions [13].

Hybrid systems combining mechanical, chemical, and biological steps are also being explored to optimize both efficiency and product quality, enabling the production of novel materials, including high-performance cotton fiber fragments and nanostructured cellulose products. They integrate these biological methods with green solvents or mild chemical pretreatments to enhance dissolution, improve fiber separation in blended textiles, and increase overall process efficiency. Together, these approaches offer promising, more sustainable alternatives to conventional recycling, though challenges remain in scaling, cost optimization, and maintaining material quality (see fig. 1). The authors of [11] emphasize the need for hybrid models combining these methods to address their individual limitations, such as integrating technological sorting for mechanical recycling or developing non-toxic green solvents for chemical recycling.

3. FIBER AND YARN PERFORMANCE

3.1 Fiber Properties

Recycling methods strongly shape the properties and performance of recycled fibers. Mechanical recycling, which relies on shredding, grinding, or repeated extrusion, typically shortens fibers and degrades their strength, because fibers are broken by shear and impact during processing, as presented by the authors of [14],[15]. In many fiber-reinforced composites and textile systems, higher screw speeds, higher fiber volume contents, and aggressive size-reduction steps are all linked to more severe fiber length reduction and loss of mechanical properties [16]. This is why mechanically recycled textile fibers and composite reinforcements often need blending with virgin fibers or are downcycled into lower-value products. By contrast, chemical or solvent-based recycling of fiber-reinforced polymers and textiles can preserve or restore the underlying polymer or cellulose structure, enabling the production of more uniform, high-quality recycled fibers. In carbon-fiber systems, solvolysis or optimized pyrolysis can remove the matrix while largely retaining fiber stiffness and much of the tensile strength, especially when followed by appropriate surface sizing, so the recovered fibers approach virgin performance [17]. Reviews of textile waste management similarly note that polymer recycling by melting or dissolving, as well as chemical depolymerization of synthetics, tends to yield recycled materials with more consistent quality than purely mechanical routes, albeit at higher energy and process complexity [18].

Because recycling routes and parameters so strongly affect fiber length, strength, fineness, and surface condition, the properties of recycled fibers are inherently variable. Studies across glass, carbon, natural, and textile fibers emphasize that careful control of recycling conditions (temperature, screw speed, number of cycles, repulping/refining severity) and thoughtful selection of feedstock and

additives are essential to obtain reproducible properties and ensure reliable performance in downstream applications such as yarns, nonwovens, or structural composites [18], [14].

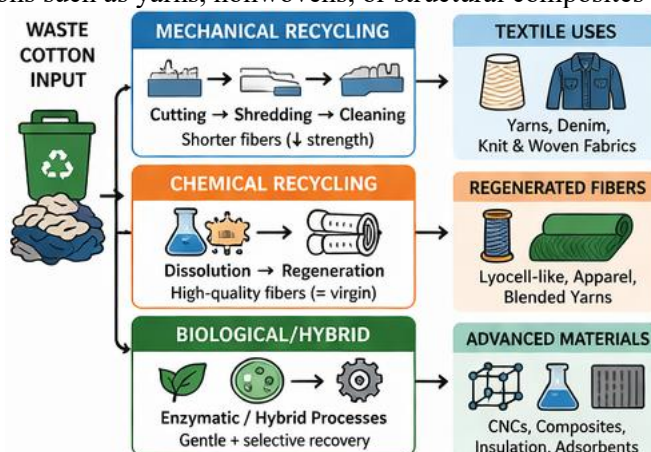


Fig. 1: Recycling pathways and applications

3.2 Yarn and Fabric Performance

The integration of recycled cotton fibers into yarns and fabrics is a key strategy for advancing sustainability in the textile industry, but it requires careful blending to maintain product quality. Research consistently demonstrates that blends containing up to 25–30% recycled cotton can be used in ring-spun yarns without significant loss of performance, making them suitable for mainstream applications such as knitwear and woven apparel [5],[19]. At the fabric level, studies show that textiles made with recycled cotton can achieve comparable abrasion resistance, drape, and comfort to those made from virgin cotton, especially when optimal spinning methods and finishing processes are employed [20]. These findings highlight the potential for recycled cotton to be widely adopted in apparel manufacturing, provided that blending ratios and processing techniques are optimized.

4. APPLICATIONS OF RECYCLED COTTON

4.1 Textile Applications

Recycled cotton is now used across many textile product types, from everyday knitwear to denim and nonwovens. Its shorter, more variable fibres are managed through blending, spinning, and finishing strategies that allow functional and aesthetic performance comparable to virgin cotton in many cases. Knit tops such as T-shirts and polos can be effectively produced using ring-spun 30 Ne yarns that incorporate up to approximately 25–30% recycled cotton derived from both pre- and post-consumer waste. Fabrics made from blends of recycled cotton and recycled polyester (r-PET), for example in a 60/40 ratio, demonstrate bursting strength and pilling resistance comparable to those of standard commercial T-shirt materials [21].

When appropriate finishing processes are applied, knitted fabrics containing even higher proportions of recycled cotton up to 80% can achieve satisfactory performance in terms of bursting strength, abrasion resistance, and pilling. This is particularly effective when compact yarns are used in combination with optimized wet finishing techniques such as bio-polishing and controlled stripping and dyeing [20]. Additionally, single-jersey knitted fabrics developed from recycled denim waste, using ring-spun blends with ratios as high as 75/25 recycled to virgin fibres, have shown promising results in both tensile strength and abrasion resistance, making them a viable option for durable



knitwear applications [22]. Denim fabrics, both in warp and weft directions, can successfully incorporate rotor-spun yarns with high levels of recycled cotton, making them suitable for large-scale commercial weaving. In the case of stretch denim, elastic core-spun yarns can include up to 60% recycled cotton while still maintaining adequate strength, elongation, and compatibility with high-speed loom operations [21].

For handloom applications, rotor yarns containing up to 75% recycled cotton have demonstrated no significant decline in key performance characteristics such as pilling resistance, abrasion durability, or air permeability, even in plain and twill woven structures [23]. More broadly, mechanically recycled cotton is widely utilized in general woven fabrics and home textiles, particularly in the form of coarser rotor-spun yarns in the 10–20 Ne range. These yarns are well-suited for products such as denim, towels, and various home furnishing materials, where durability and texture are essential.

4.2 Nonwoven and Insulation Materials

Nonwoven fabrics made from recycled cotton are widely studied for use in thermal and acoustic insulation, especially in buildings and technical clothing, where fiber length and uniformity are less critical than in yarn-spun textiles. Research shows these materials can match or approach the performance of conventional synthetic insulators while adding moisture management and sustainability benefits.

Recycled cotton, often blended with polyester from post-consumer garment waste, has proven by the authors of [24] to be highly effective in the production of nonwoven insulation materials for buildings. Technologies such as chemical bonding and air-laid processing enable the formation of lightweight, porous structures with excellent sound-absorbing capabilities. These nonwovens can achieve sound absorption coefficients exceeding 70% across a broad frequency range (125 - 4000 Hz), making them particularly suitable for interior acoustic applications such as wall linings, ceilings, and partition systems. Importantly, their acoustic performance remains stable even under conditions of elevated humidity, which is a critical factor in real-world building environments [25]. From a thermal perspective, insulation panels and boards manufactured from textile waste, including significant proportions of recycled cotton—demonstrate thermal conductivity values typically in the range of 0.034 to 0.05 W/m·K. These values are comparable to those of widely used conventional insulation materials such as mineral wool and polymeric foams, indicating that recycled textile-based solutions can serve as viable, sustainable alternatives in building envelopes [26]. Additionally, post-consumer cotton fibers can be utilized in loose-fill insulation or incorporated into nonwoven mats. These forms exhibit similar thermal conductivity ranges, with their performance influenced primarily by environmental conditions such as temperature and humidity, while fiber orientation has a relatively minor effect. This makes them versatile for various installation methods, including cavity wall insulation and attic applications [25].

Insulation materials derived from recycled cotton not only contribute to waste reduction and circular economy goals but also offer competitive thermal and acoustic performance, supporting their growing adoption in sustainable construction practices.

4.3 Advanced materials

Recycled cotton is increasingly transformed from textile waste into advanced materials rather than just lower-value textiles. The authors of [27],[28] focus on extracting cellulose nanocrystals (CNCs) or nanofibrils from post-consumer garments, blended fabrics, and cotton process waste, using acid hydrolysis, deep eutectic solvents, or NaOH/urea systems. These nano-cellulose materials offer high crystallinity, aspect ratio, and surface area, making them attractive for nanocomposites,



electronics packaging, and functional films. CNCs from cotton waste have been used to reinforce poly(vinyl alcohol), PLA, methylcellulose, and polypropylene, giving large gains in tensile strength, modulus, and sometimes impact resistance, with potential uses in automotive and construction components, flexible films, and lightweight foams or nanopapers for electronic or packaging applications [29]. Surface-sulfated or citrated CNCs from waste cotton further improve flame resistance or transparency, enabling electronic packaging and conductive film possibilities. Beyond structural nanocomposites, recycled-cotton-derived cellulose is explored as adsorbents, biofuel precursors, and environmental materials. Activated or surface-modified cotton waste and CNCs show high adsorption capacity for dyes, heavy metals, oils and other recalcitrant pollutants in water, and can form improved membranes or aerogels for wastewater treatment. [30]

5. CONCLUSIONS

The recycling of cotton fibers constitutes a fundamental component in the transition toward a circular and sustainable textile industry. Mechanical recycling is the most established and cost-effective method for reintegrating cotton waste into textiles and nonwovens, albeit with fiber degradation, whereas chemical and emerging biological processes enable recovery of high-purity cellulose, producing regenerated fibers with properties comparable to or exceeding those of virgin cotton. The development of hybrid recycling systems, integrating mechanical, chemical, and biotechnological processes, further enhances process efficiency and material quality, contributing to the advancement of closed-loop recycling models.

Despite the challenges associated with variability in feedstock, process scalability, and economic viability, recent research highlights significant progress in improving the performance of recycled fibers and expanding their end-use potential. In particular, the valorization of cotton waste into high-value products such as nanocellulose, composites, and functional materials underscores the broader industrial relevance of recycling strategies beyond conventional textile applications.

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