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LIFE CYCLE AND DURABILITY ASSESSMENT OF COTTON AND RECYCLED COTTON T-SHIRTS: IMPLICATIONS FOR SUSTAINABLE CONSUMPTION

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Abstract. *The environmental footprint of textiles has become a central concern in sustainable consumption and production strategies, with cotton garments representing one of the most resource-intensive product groups. Cotton cultivation requires large amounts of water, fertilizers, and pesticides, while subsequent manufacturing processes such as spinning, dyeing, and finishing are highly energy- and chemical-demanding. Moreover, the use phase of garments, particularly repeated washing, drying, and ironing, contributes significantly to their life cycle impacts. Considering this, a series of pilling tests have been conducted, using the M235 Martindale Abrasion Testing Machine, in order to identify which of the two products is more prone to develop pilling on their surface, and thus give informations about the product's durability. In order to receive clear information about the environmental efficiency of the analyzed products, this study also compares the life cycle performance of the two functionally equivalent T-shirts: one produced from 100% virgin cotton and another containing 30% mechanically recycled cotton blended with 70% virgin cotton. The assessment was carried out using a footprint calculator to evaluate cradle-to-grave environmental impacts. System boundaries included raw material production, textile manufacturing, distribution, consumer use, and end-of-life. Impact categories considered included climate change, water consumption, eutrophication, and energy demand. The functional unit was defined as one T-shirt worn until the end of its usable life, with results normalized by the number of wears. To complement the LCA model, fabric samples from the two products were subjected to a standard pilling resistance test. The 100% cotton T-shirt exhibited visible pilling earlier than the recycled cotton blend, suggesting a shorter effective lifespan. This empirical evidence was integrated into the functional unit definition to reflect differences in garment durability. The combined results indicate that incorporating 30% recycled cotton reduces environmental burdens in the production phase while also improving performance in the use phase through enhanced durability. When impacts are calculated per wear, the recycled cotton T-shirt outperforms the virgin cotton alternative. These findings highlight the dual role of recycled fibers in both resource efficiency and lifespan extension, supporting their broader adoption in sustainable textile strategies.*

Keywords: *carbon footprint, durability, pilling, recycled cotton blend, product lifespan*

1. INTRODUCTION

The textile industry is among the most resource-intensive sectors, with cotton garments playing a central role due to their widespread use and high production volumes. Cotton cultivation demands significant water, fertilizers, and pesticides, while downstream processes such as spinning, dyeing, and finishing consume large amounts of energy and chemicals [1]. Beyond production, the use phase of cotton garments—including repeated washing, drying, and ironing—contributes substantially to their environmental footprint [1, 2].

The adoption of recycled fibers has been promoted as a key strategy to minimize the environmental impacts of textiles by reducing dependence on conventional cotton. Cotton recycling feedstocks fall into pre-consumer (off-cuts, spinning wastes) and post-consumer (used garments) streams. Pre-consumer wastes are generally cleaner and yield higher-quality reclaimed fibers for spinning; post-consumer textiles require sorting and contamination control and typically produce shorter, weaker fibers after mechanical recycling. These feedstock differences strongly determine which recycling route and blend ratio are feasible for knitting yarns. [3] In order to have a clear picture of the recycling possibilities of the cotton that is used in producing knitted items, a brief review has been mapped within table 1:

Table 1

The recycling options for the cotton fibers, used for knitting yarn

Mechanical recycling (fiber recovery)	Mechanical recycling (shredding/tearing → carding → re-opening → blending → spinning) is the most mature and widely used route for cotton. It physically opens fabrics into staple fibers that can be re-spun alone (in limited proportions) or blended with virgin fibers to produce yarn for knitted fabrics. [3] However, the limitations involve fiber length reduction (due to shredding) by 30-40% [4], as well as contamination and color variability (a thorough sorting process is mandatory prior to recycling) [5]
Chemical / regenerative recycling	Chemical recycling dissolves cellulose from cotton-rich textiles and regenerates it into new cellulosic fibers. The main advantage consists in the production of fibers with renewed length and uniform properties — better for high-quality knitting than mechanically recycled short fibers [6]
Enzymatic / biorecycling	These emerging approaches (cellulase-driven hydrolysis to glucose, then re-polymerization) are promising for valorizing cotton cellulose into platform chemicals or feedstocks for regenerated fibers, but technology readiness is lower than mechanical or solvent routes [7]

Comparative LCAs have shown that substituting part of virgin cotton with recycled cotton leads to reductions in greenhouse gas emissions, water use, and land occupation [8]. For example, Gonçalves et al. (2024) demonstrated that T-shirts with 50% recycled cotton content had consistently lower cradle-to-grave impacts than those made entirely from virgin cotton [9].

However, the sustainability of recycled fiber garments depends not only on resource efficiency but also on product durability. Garment lifespan—the number of times a product can be worn before disposal—has been identified as a critical factor influencing environmental performance per use [10]. Studies emphasize that washing frequency and the number of laundering cycles that a garment can withstand play a decisive role in the overall life cycle footprint of clothing [2].

To complement the life cycle assessment with empirical evidence on durability, a standard pilling resistance test on fabric samples from the two T-shirts under study has been conducted. The results revealed that the 100% cotton T-shirt developed pilling earlier than the blend containing 30% recycled cotton. Since pilling affects both garment aesthetics and the likelihood of continued consumer use, this result suggests that the recycled cotton T-shirt has a longer effective lifespan. Integrating this durability data into the functional unit definition allows for a more realistic comparison of environmental performance per wear.

The present study therefore conducts a cradle-to-grave LCA comparing a 100% cotton T-shirt and a T-shirt containing 30% recycled cotton. The analysis is carried out using the footprint calculator, with particular emphasis on lifespan and consumer efficiency. By combining LCA modeling with experimental durability testing, this work aims to determine which option provides a more sustainable choice for consumers when impacts are normalized over the actual number of uses. This way, the pilling test becomes a bridge between durability (real-world performance) and the LCA model (environmental performance per use).

2. EXPERIMENTAL PART

The objective of this study was to compare the environmental performance and effective lifespan of two functionally equivalent T-shirts: one composed of 100% virgin cotton and the other containing 30% mechanically recycled cotton blended with 70% virgin cotton. Both T-shirts are produced by Malfini, a company that uses both GOTS certified organic cotton, as well as recycled cotton sourced from post-

industrial textile waste. A cradle-to-grave system boundary was applied, encompassing raw material production, textile manufacturing, distribution, consumer use, and end-of-life.
Two commercially available short-sleeved T-shirts of the same weight (measured 246 g), same size (4XL) and same design were selected. T-shirt A consisted of 100% virgin cotton fibers, while T-shirt B was composed of a blend of 70% virgin cotton and 30% mechanically recycled cotton fibers. Both products were manufactured in Europe, Czech Republic, and distributed to the Romanian market.

2.1. Life Cycle Analysis: Goal and Scope definition, Inventory Analysis

Recent studies on recycled cotton blends [8] showed that blending 30% recycled cotton with 70% virgin cotton (cradle-to-gate) can reduce environmental impacts (GHG, water use, land use, etc.) by several percents (table 2). Based on recent peer-reviewed cradle-to-gate results [11], replacing 30% of virgin cotton with mechanically recycled cotton (a 70/30 conventional/recycled blend) typically yields small-to-moderate reductions in production-stage impacts — but the size of the reduction is highly variable depending on system choices and data.

Table 2
Environmental impact of using recycled cotton blends [8]

Impact factors	Reduction [%]
GHG emissions (CO_2-eq)	~2.2 - 8.6
Water footprint	~0.3 to 27.7
Air-pollution indicators	~3.3 to 6.8
Land use	~1.4 to 26.4

For this study, the life cycle inventory (LCI) was constructed using primary product specifications and secondary data obtained from the Ecoinvent v3.8 database. Inventory data included inputs of raw materials, water, energy, and auxiliary chemicals for fiber cultivation, spinning, knitting, dyeing, cutting, and sewing. Transportation distances were indicated specifically, from Prague (Malfini manufacturing location) to Cluj (main warehouse in Romania) and from Cluj to Iași. The consumer use phase included machine washing, drying, and ironing, based on average Romanian household energy mixes and water use data. End-of-life scenarios reflected the Romanian context, where most post-consumer textiles are landfilled or incinerated, with limited recycling.

However, all three end-of-life scenarios have been taken into consideration, to highlight their impact on the product's overall carbon footprint. The LCA modeling and impact assessments were performed using the footprint calculator, applying the ReCiPe 2016 midpoint method. The impact categories considered included climate change (global warming potential), water consumption, eutrophication, energy demand.

The selection of impact categories, category indicators, and characterization models is guided by the framework requirements outlined in ISO 14040/44: defining the goal and scope, the inventory analysis, the impact assessment and lastly, interpretation.
To respect the structure of the manuscript, these elements have been equally divided. Thus, the first two elements (the goal and scope definition, and the inventory analysis) will be elaborated within this chapter, whereas the latter will be presented within the following chapter.

Inventory analysis

According to the ISO 14040/44 framework, the second stage encapsulated the need to list and quantify the main materials that are found within the analyzed products. The first step consisted in drafting the 2D patterns of the T-shirt. This phase was needed to identify the necessary amount of main textile fabric that is needed to manufacture one T-shirt unit. Therefore, once the patterns have been drafted, they have been nested on a standard 150 cm fabric width. The width and the length of the layplan (Figure 1) have been used to calculate the number of square meters of fabric that are needed for one T-shirt. This determination is viable for both items analysed.

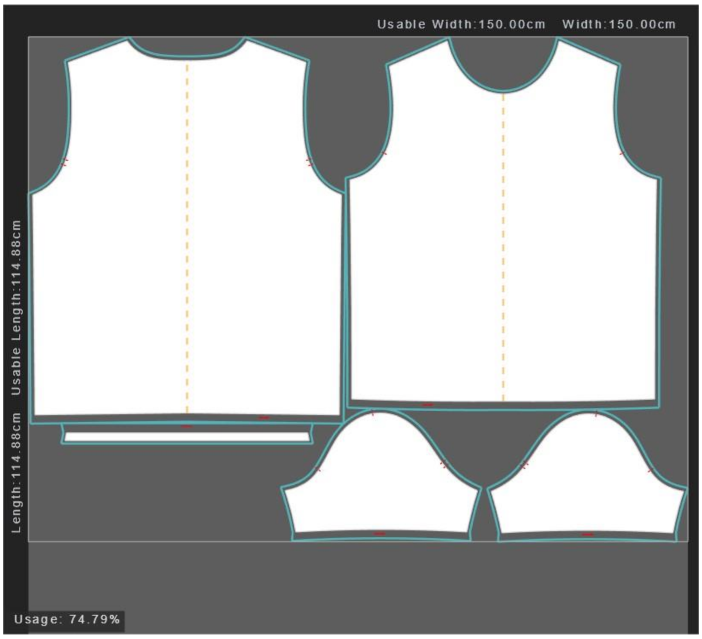


Figure 1. The layplan for 1 T-shirt unit, size 4XL

The data collected allowed for the analysis to go further, which implies identifying the amount of cotton fiber that is required for spinning the threads and consequently for knitting the 1.72 m^2 of textile fabric, that is needed for manufacturing 1 T-shirt unit. The next step was to calculate the amount of sewing thread needed to assemble and finish the garment item (table 3). It has been established that the sewing thread used is made from 100% polyester. At the same time, for the use phase of the product's life cycle, a number of 50 washing cycles has been assigned. The inventory analysis (textile fabric demand, the fabric to fiber conversion, sewing thread demand) has been organized and illustrated within table 4.

Table 3

The sewing thread demand for 1 basic T-shirt unit

Stitch class	**f(F) – thread thickness [mm]**	**P – stitch loop length [mm]**	**G – layer thickness [mm]**	**T – Stitch width [mm]**	**Thread demand for 1 stitch step [mm]**
504 Overlock	0,2	3	3,28	5	$l_{504} = 3P+4G+2T+2\sqrt{P^2+T^2} + f$ (F) [12]
					43,98
602 Coverstitch	0,2	2	3,28	7	$l_{602} = 6P+4G+T+3\sqrt{P^2+T^2} + f$ (F) [12]
					54,16

Stitch class	**Stitch placement on the garment**				**Total measured length [cm]**
504 - overlock	Armhole contour	Sleeve line	Side line	Shoulder line	275.2
602 - coverstitch	Garment's hemline	Sleeve hemline	Neckline contour		220

Sewing thread demand

Stitch demand [cm] for 1 stitch loop		Stitch loops count per cm	Sewing thread demand for 1 cm stitch [cm]	Total seam length [cm]	Sewing thread demand for total seams[cm]	Sewing thread demand for the entire product [m]
Seam 504	4,39	3	13,17	275.2	3.624	95.64
Seam 602	5,41	5	27	220	5.940	

Table 4
Inventory analysis for 1 basic T-shirt unit

Raw material	
T shirt mass [g]	246
Layplan dimensions: length x width [m]	1.14 x 1.5
Layplan area [m^2]	1.71
The fabric's weight [g/m^2]	160
Polyester sewing thread demand [m]	95.64
Packaging and distribution	
Polybag [piece/ unit]	1
Prague → Cluj → Iasi [km]	1.250 km
Use	
50 wishes/shirt	

It's important to mention that a value of 50 L of water per washing cycle was used to represent the laundering phase, reflecting the typical consumption of modern European front-loading machines (35–50 L per wash; Washing Machines in Europe – Detailed Assessment of Consumption and Performance) [13]. Although this allocation exceeds the real per-garment share in household use, it was applied to ensure experimental consistency, as samples were washed individually under controlled conditions for reproducibility and comparability.

2.2. Pilling Resistance Test

To experimentally assess garment durability, fabric samples were collected from both T-shirts and subjected to a Martindale pilling test (ISO 12945-2:2020). Circular specimens (diameter 38 mm) were mounted on a Martindale abrasion and pilling tester and rubbed under controlled pressure against standard wool fabrics. Each specimen underwent up to 500 cycles, with intermediate evaluation at 125 with a 71.3 rpm.

Figure 2. The Martindale pilling test made for the two products analyzed

3. RESULTS AND DISCUSSION

3.1. Life Cycle Analysis: Impact Assessment and Interpretation

This section evaluates the environmental performance of both T-shirt types using life cycle assessment (LCA) methodology. The analysis considers the entire product lifecycle, from raw material extraction through production, use, and end-of-life disposal. Each impact category previously mentioned (global warming potential, water consumption, eutrophication, energy demand) was assessed based on normalized data per functional unit. To highlight the differences between them, they have been illustrated as follows:

- a bar chart (figure 3) that is meant to illustrate the life phases of the two products that generate the most amount of CO_2 equivalent, while also considering the different end-of-life scenarios (recycling, incineration and landfill disposal);
- A series of tables show: the water footprint for both products (table 5), the eutrophication potential (table 6), as well as the energy demand (table 7), highlighting the water demand per each life stage.

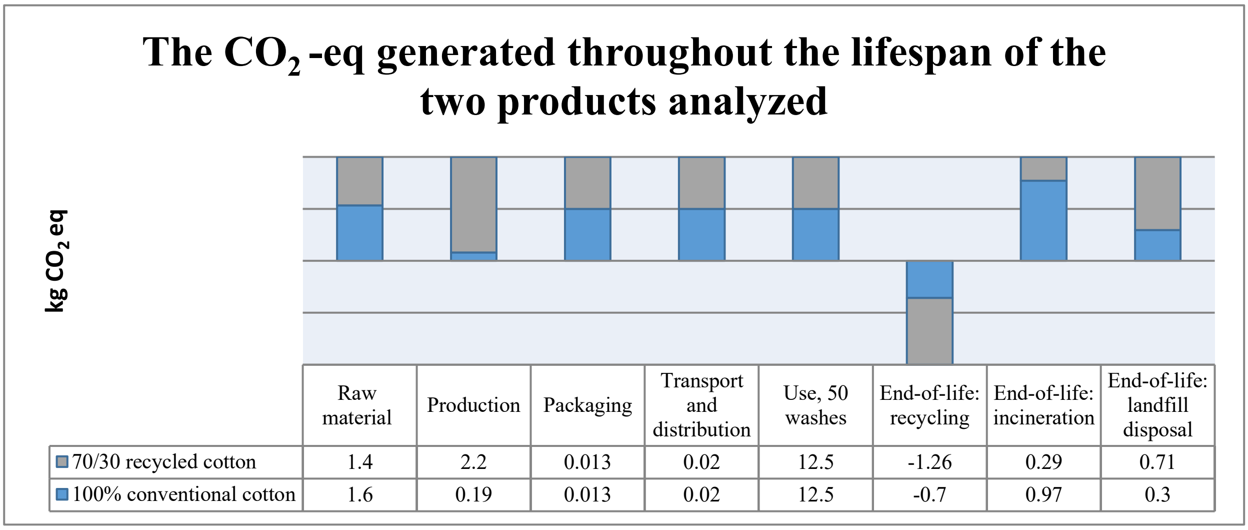


Figure 3. The carbon footprint for the two products analyzed

The first aspect that stands out is the amount of CO_2 equivalent that is generated during the use phase, due to the number of washing cycles that have been adopted for this life stage.

Table 5
Water consumption [L] for the two products analyzed

	100% conventional cotton T-shirt		**70/30 recycled cotton T-shirt**	
Life cycle stage	**Water (L)**	**Share (%)**	**Water (L)**	**Share (%)**
Raw materials	2,460	**49.2 %**	1,726	**40.5 %**
Production	36.9	0.7 %	36.9	0.9 %
Transport and distribution	1.0	0.02 %	1.0	0.02 %
Use (50 washes × 50 L)	2,500	**50.0 %**	2,500	**58.6 %**
End-of-life (disposal)	0.5	0.01 %	0.5	0.01 %
Total	4,997	100 %	4,263	100 %

Analyzing the results, it becomes obvious that conventional cotton has a very high irrigation water demand, compared to the recycled cotton, thus the water use for the raw material phase is reduced by 29.8 %. Blending recycled cotton substantially reduces water use, yet responsible washing habits (full loads, lower frequency) can be equally impactful. An important detail that needs to be mentioned is that for the end-of-life phase, the landfill disposal scenario has been considered.

Table 6

Eutrophication potential, EP [kg PO_4^{3-} eq] for the two products analyzed

	100% conventional cotton T-shirt		70/30 recycled cotton T-shirt	
Life cycle stage	**kg PO_4^{3-} eq**	**Share (%)**	**kg PO_4^{3-} eq**	**Share (%)**
Raw materials	0.00295	12.5 %	0.00214	9.4 %
Production	0.00049	2.1 %	0.00049	2.2 %
Transport and distribution	0.00001	< 0.1 %	0.00001	< 0.1 %
Use (50 washes × 50 L)	0.02	85.1 %	0.02	88.1 %
End-of-life (disposal)	0.00002	< 0.1 %	0.00002	< 0.1 %
Total	0.0235	100 %	0.0227	100 %

Results highlight the significant amount of kg PO_4^{3-} eq that is being generated during the raw material extraction phase, which is an important contributor, due to fertilizer runoff. On a similar note, the use phase dominates eutrophication potential, mainly from phosphorus in detergents and wastewater nutrient discharge.

Table 7
Energy demand [MJ] for the two products analyzed

	100% conventional cotton T-shirt		70/30 recycled cotton T-shirt	
Life cycle stage	**MJ**	**Share (%)**	**MJ**	**Share (%)**
Raw materials	7.38	3.9 %	5.58	3 %
Production	3.69	2 %	3.69	2 %
Transport and distribution	0.25	0.1 %	0.25	0.1 %
Use (50 washes × 50 L)	175.5	93.7 %	175.5	94.6 %
End-of-life (disposal)	0.49	0.3 %	0.49	0.3 %
Total	187.3	100 %	185.5	100 %

The data illustrates that the use phase dominates the energy demand (>90%) due to repeated washing and tumble-drying energy. Substituting recycled cotton slightly lowers total energy demand (~1%) because fiber preparation is less energy intensive. However, the raw materials and production stages contribute marginally (<5%) in total but are more relevant for renewable energy sourcing strategies.

This analysis indicated that the raw material stage dominated impacts for both garments, while the use phase accounted for a substantial portion of water and energy consumption, consistent with previous literature. The end-of-life stage contributed minimally due to low recycling rates in Romania. When impacts were normalized per wear, accounting for the longer lifespan of the recycled cotton T-shirt, the environmental benefits became more pronounced.

3.2. Pilling Resistance: Assessing garment durability

Pilling formation was visually assessed and graded on a 5-point scale (figure 3) where grade 5 represents no pilling and grade 1 represents severe pilling. The 100% cotton T-shirt exhibited visible pilling at earlier stages (125 cycles), while the 30% recycled cotton blend maintained a higher grade over the same number of cycles. This result indicated a longer expected lifespan for the recycled blend garment, due to slower aesthetic degradation. Results are depicted within table 8.

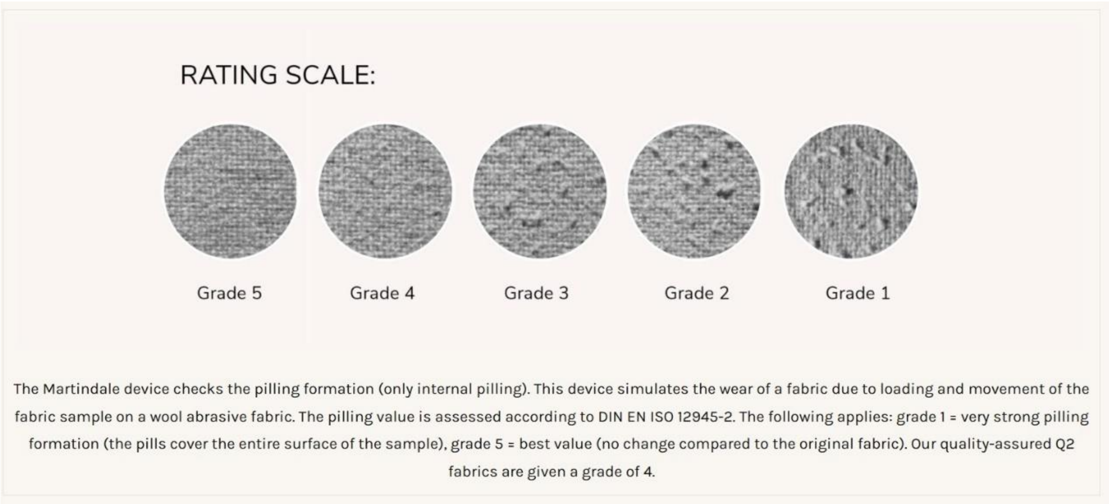
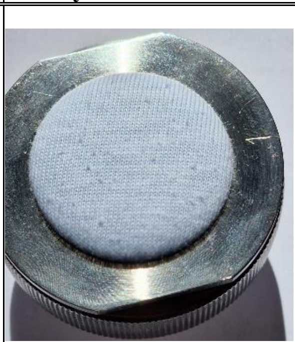
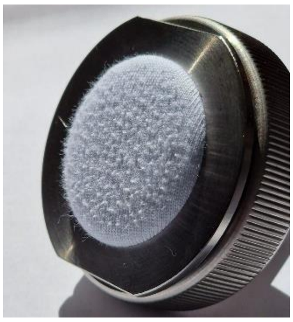


Figure 3. The pilling 5-point rating scale [16]

Table 8

Pilling test results and assessment

125 cycles **Conventional cotton**	**125 cycles** **Recycled cotton blend**	**500 cycles** **Conventional cotton**	**500 cycles** **Recycled cotton blend**
 Grade 4	 Grade 5	 Grade 2	 Grade 3

The Martindale pilling test revealed a marked difference in fabric performance between the two T-shirts. The 100% cotton T-shirt developed visible pilling after approximately 125 rub cycles, reaching a pilling grade of 3 out of 5 at 500 cycles. In contrast, the T-shirt containing 30% recycled cotton maintained a higher grade (4–5) over the same testing period, indicating slower pilling formation. These results suggest that the recycled cotton blend possesses superior durability, which is expected to extend the effective lifespan of the garment under normal consumer use. The implications of these findings are significant for environmental performance. Because the functional unit in the LCA was defined as “one T-shirt worn until the end of its usable life,” a longer-lasting garment reduces the per-use environmental impact. The pilling test provides empirical evidence that supports modeling assumptions regarding lifespan differences between virgin and recycled fiber garments.

4. CONCLUSIONS

The combined results demonstrate that the recycled cotton blend T-shirt is a more sustainable option from both environmental and consumer perspectives. The improved pilling resistance suggests that consumers may retain the garment longer, reducing the frequency of replacement and associated environmental impacts. These findings align with previous studies indicating that lifespan is a critical determinant of the overall sustainability of textiles. The study also illustrates the need to couple LCA modeling with experimental assessments to capture real-world performance. While recycled cotton may sometimes raise concerns regarding fiber strength or processing complexity, in this case, it contributed to both environmental and functional benefits. Future work could expand the analysis to include additional durability metrics and washing frequency variations.

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