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Challenges and Limitations in Recycling of Post-Consumer Cotton Denim Waste into New Textiles

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ABSTRACT

This study investigates the feasibility of recycling post-consumer cotton denim waste into new yarns by examining the effects of recycled fibers percentage, twist level, and spinning methods (ring vs. rotor) on the yarn and fabric quality. Recycled cotton fibers, blended with chemically recycled polyester in 3 different ratios, and 12 samples were developed, which then knitted into single jersey fabrics. Fiber yield and waste generation during the yarn production were critically monitored to check the effectiveness of recycling process. Results indicate that increasing recycled content by more than 10% significantly degrades the yarn strength, elongation, and fabric durability due to the fiber shortening from prior use. Mechanical recycling yielded only 45–50% usable fiber, with higher waste percentages in yarn production leading to greater processing losses. The resulting developed knitted fabrics exhibited poor pilling resistance (Grade 1) compared to virgin cotton blends (Grade 4). Statistical analysis confirmed that the percentage of recycled fibers critically impacts yarn tenacity and breaking force. Post-consumer textile recycling holds promise for circular fashion, but current mechanical methods face limitations in producing high-quality yarns. This research raises important questions about the feasibility of large-scale post-consumer textile recycling in achieving sustainability goals while maintaining quality of final product.

摘要

本研究通过考察回收纤维百分比、捻度和纺纱方法 (环锭与转杯)对纱线和织物质量的影响，研究了将消费后的棉牛仔布废料回收成新纱线的可行性. 开发了再生棉纤维，以3种不同的比例与化学再生聚酯混纺，以及12个样品，然后编织成单面针织面料. 对纱线生产过程中的纤维产量和废物产生进行了严格监测，以检查回收过程的有效性. 结果表明，由于之前使用的纤维缩短，将回收含量增加10%以上会显著降低纱线强度、伸长率和织物耐久性. 机械回收仅产生45-50%的可用纤维，纱线生产中的浪费率更高，导致加工损失更大. 与原棉混纺 (4级)相比，由此开发的针织物表现出较差的抗起球性 (1级). 统计分析证实，再生纤维的百分比对纱线韧性和断裂力有关键影响. 消费后纺织品回收有望实现循环时尚，但目前的机械方法在生产高质量纱线方面存在局限性. 这项研究提出了关于大规模消费后纺织品回收在实现可持续发展目标的同时保持最终产品质量的可行性的重要问题.

KEYWORD

Circular economy; cotton fibers; cellulose; post-consumer textile; recycling; sustainability

关键词

循环经济; 棉纤维; 纤维素; 消费后纺织品; 回收; 可持续发展

Introduction

The environmental impact of cotton production, including water usage and pesticide application, has led to growing concerns about the sustainability of cotton farming. Cotton cultivation requires an estimated 10,000 Liters of water to produce just one kilogram of fiber, which includes both natural rainfall and irrigation water (Zhang et al. 2023; Mikucioniene et al. 2024). According to the World Wildlife Fund approximately 3% of global freshwater use is attributed to cotton production WWF (2022). The extensive use of chemical fertilizers and pesticides in cotton farming leads to soil and water pollution, affecting both aquatic life and terrestrial organisms (Gonçalves et al. 2024; Radhakrishnan 2017). According to the Food and Agriculture Organization (FAO),

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approximately 80% of cotton production is dedicated to apparel, 15% to home furnishings, and the remaining 5% to non-woven applications such as filters and padding.

The apparel industry generates significant amounts of textile waste, primarily from post-consumer garments, contributing to environmental pollution, and cotton textiles play a crucial role in it (Rahman, Siddiqua, and Cherian 2022). Textiles, especially those made from fibers like polyester and cotton, contribute significantly to waste, with the global fashion industry alone accounting for 92 million tons of textile waste annually (Broega, Jordão, and Martins 2017). Textile waste, often disposed of in landfills, remains a significant environmental issue. The decomposition of fibers in landfills can take years, during which synthetic fibers release microplastics into the environment (Periyasamy and Tehrani-Bagha 2022). Recycling textiles can offer an essential solution to mitigate these environmental challenges. The recycling of post-consumer waste textiles has gained attention due to growing concerns over textile waste, environmental pollution, and the depletion of natural resources. This process involves the regeneration of discarded textiles into new fibers, yarns, and fabrics (Pensupa 2019).

Recycling of cotton textiles, particularly post-consumer waste, involves two main approaches: mechanical recycling and chemical recycling. Mechanical recycling entails the disintegration of cotton fabrics to recover the fiber, which is then spun into a yarn. The process involves shredding, carding, and spinning to convert the waste into a usable form. Chemical recycling, on the other hand, breaks down the cotton fibers into their base component, i.e., cellulose, which can then be reprocessed into new fibers and yarns. Chemical recycling has the potential to yield higher-quality fibers by addressing the degradation that occurs during mechanical recycling (Baloyi et al. 2024; Dissanayake and Weerasinghe 2021).

The mechanical recycling of cotton results in the shortening of fiber length, which affects the strength and quality of the resulting yarn (Guru et al. 2025). This reduction in fiber length often leads to the formation of weaker yarns, which may not perform as well as virgin cotton yarns (Baloyi et al. 2024). The shorter fiber length and the presence of contaminants or impurities in recycled cotton can lead to a reduction in overall yarn quality, affecting the texture and performance of the fabric (Stanescu 2021). Research indicates that yarns of recycled cotton generally have lower tensile strength and elongation compared to virgin cotton yarns (Yuksekkaya et al. 2016). A study by Aypar and Oner (2024) found that recycled cotton yarns exhibited a 30–40% reduction in tensile strength compared to their virgin counterparts. This reduction in strength can limit the application of recycled cotton yarns in products that require high durability, such as heavy-duty textiles or outdoor fabrics (Aypar and Oner 2024). Combining recycled cotton with virgin cotton or synthetic fibers has been shown to enhance the overall properties of recycled yarns, such as their tensile strength and durability (Mominul Motin et al. 2024). The physical appearance of recycled cotton yarns differs from that of virgin cotton yarns due to the presence of impurities, such as dye residues, synthetic fibers, and other contaminants (Liu et al. 2020).

Despite the growing importance of textile recycling, there is still a significant gap in understanding of how specific factors, such as the waste percentage, twist level, and spinning methods (ring or rotor), affect the quality, performance, and efficiency of recycled yarns, particularly those derived from post-consumer waste. The aim of this study is to address this gap by investigating how varying these processing parameters impacts the mechanical properties of the yarn and fabric, including strength, elongation, and durability. Used denim clothes were collected from the market and shredded into recycled fibers. From these, 12 different yarn variants were developed using a combination of chemically recycled polyester fibers and mechanically recycled cotton fibers. The yarn samples were created by varying percentage of the recycled fibers, yarn twist level and spinning technique, and their properties were compared to those of 100% virgin cotton and 100% virgin polyester yarns. This approach aims to assess the impact of these variables on the quality and performance of the recycled yarns. This study also analyses the efficiency of the recycling process, focusing on yield of fiber received after shredding and waste generation during the spinning stages, including blow room and carding.

After comparing the results, this research raises an important question whether such recycling of post-consumer garments into new yarns is a feasible and effective method to produce high-quality, sustainable textile products. Since the fibers of post-consumer garments degrade over time, primarily due to wear, washing, and environmental factors such as sunlight, sweat (Hossain et al. 2024). These factors cause the cotton fibers to break down, weakening their structural integrity and making them less suitable for reuse in high-quality yarn production. Contaminants such as dyes, oils, and chemicals from previous use of garments further degrade the quality of the fiber and cause further drawbacks and challenges in the recycling process (Abbas-Abadi et al. 2025). Moreover, the processing of post-consumer waste into new products involves water and energy costs, additional water and air pollution, so if the life cycle of such a new product is very short, questions arise about the efficiency of this process.

Materials and methods:

Waste collection and shredding

The materials used in this study include post-consumer denim, which is made up of approximately 97–98% cotton and 2–3% elastomeric yarn. These discarded denim garments, such as jeans and jackets, were collected from the local market and thoroughly washed to remove dirt, oils, and other contaminants. After washing, all non-fabric components, such as buttons, zippers, and rivets, were manually removed to ensure that only the fabric remained for further processing. The cleaned denim was then sent to a shredding machine, where it was transformed into small, manageable pieces. These shredded denim pieces were prepared for bleaching, a crucial step to remove any residual dyes and achieve a uniform, clean appearance. The bleaching process was carried out by soaking the shredded denim in a bleaching solution consisting of sodium hypochlorite (NaOCl), diluted to a concentration of 3%. The fabric was soaked for 2 hours at a room temperature (24°C approx.). After the bleaching process, the denim was thoroughly rinsed with water to remove excess bleach, and then neutralized using sodium bisulfite ($NaHSO_3$). Finally, the denim was washed again and dried, resulting in cleaner, lighter fabric pieces ready for further processing (Figure 1).

Waste recycling

Fabric to fiber recycling process was done using the machine GM600, Shandong New Haina Machinery, China. In the first step, the waste fabric was introduced into the machine through the feeding system. It then enters the first set of tearing and sieving rollers, where the tearing rollers equipped with sharp pins mechanically tear the fabric apart, breaking it into smaller pieces and loosening the fibers.

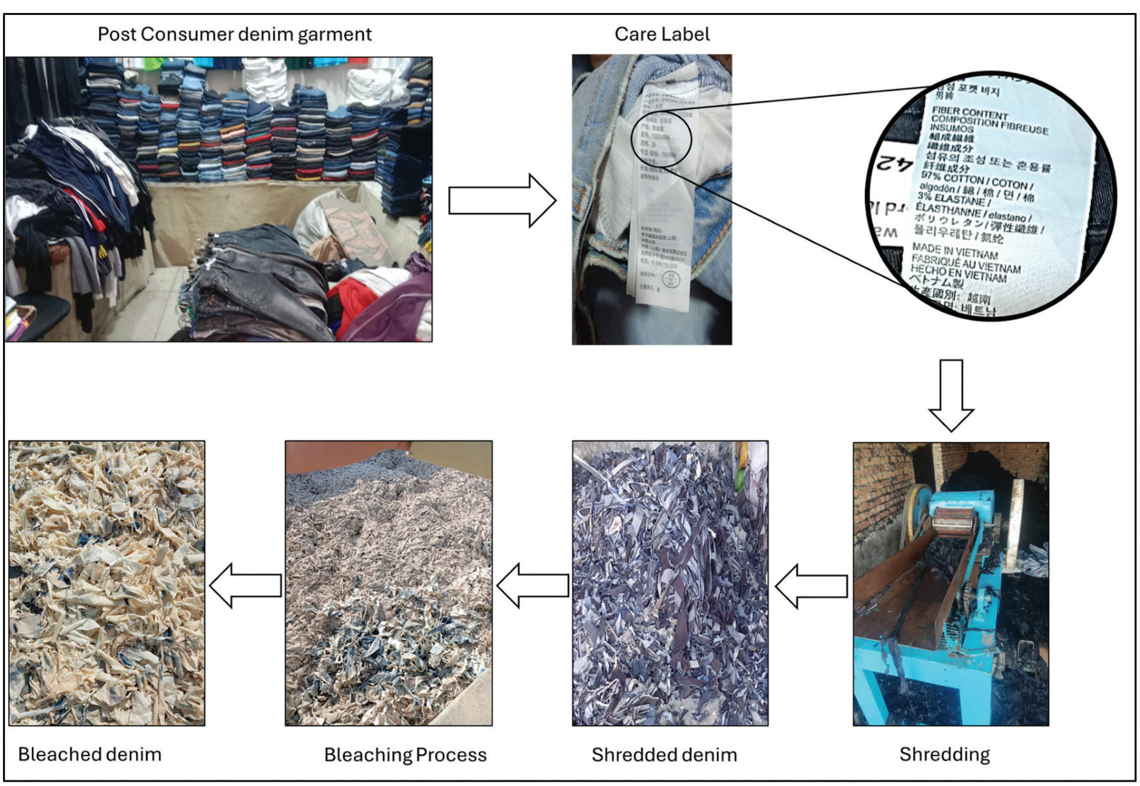

Figure 1. Post consumer denim waste collection, sorting and shredding.

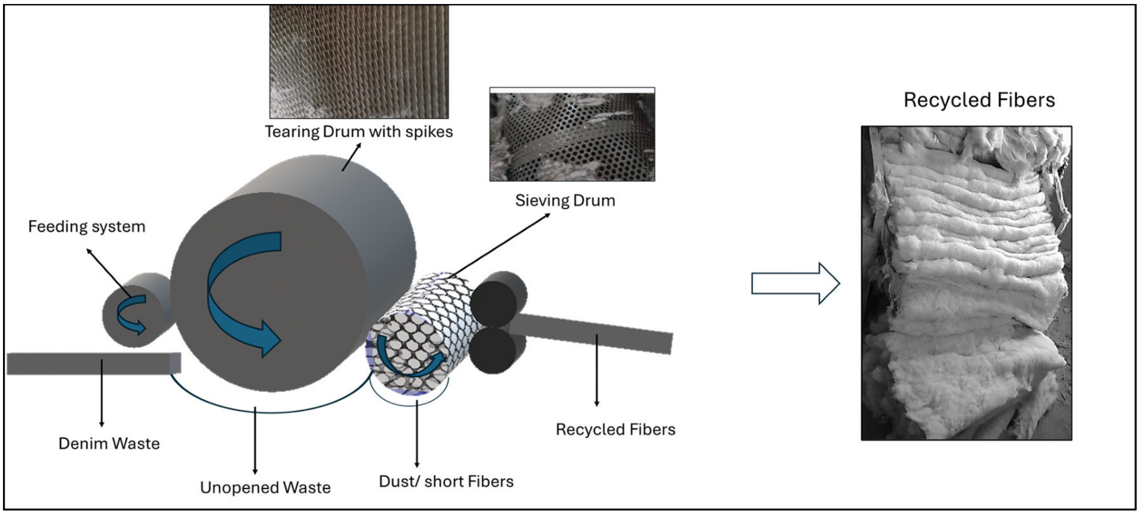

Figure 2. Recycling process of post-consumer denim waste after bleaching.

Table 1. Properties of virgin cotton and recycled fiber from post-consumer denim waste.

	MSt (%) (Moisture Content)	Mic (Micronair)	Mat (Maturity Ratio)	UHML (mm) (Upper Half Mean Length)	UI (%) (Uniformity Index	SF (Short Fiber Content)	Str (g/tex) (Fiber Strength)	Elg (%) (Elongation)
Virgin cotton fiber	8.1	4.36	0.85	26.92	81.4	13.4	29.1	7.7
Recycled waste fiber	7.4	4.67	0.82	15.92	59.9	49.9	16.5	10.4

Table 2. Abbreviations, full forms, and meanings for cotton fiber testing parameters.

Abbreviation	Full Form	Meaning
MSt (%)	Moisture Content (%)	The percentage of water in the fiber sample.
Mic	Micronaire	A measure of fiber fineness and maturity. Not actual diameter, but air permeability of a compressed cotton sample.
Mat	Maturity Ratio	Indicates the degree of cell wall development. Higher maturity = stronger fiber
UHML (mm)	Upper Half Mean Length	The average length (in mm) of the longest 50% of fibers. More accurate than average length.
UI (%)	Uniformity Index (%)	Calculated as (UHML/Mean Length) × 100. Higher = more uniform fiber length.
SF	Short Fiber Content (%)	Percentage of fibers less than 12.7 mm. Lower SF is better—reduces yarn breakage and improves spinning.
Str (g/tex)	Fiber Strength	Strength measured in grams per tex (force per unit linear density). Higher = stronger fibers.
Elg (%)	Elongation (%)	How much the fiber can stretch before breaking. Indicates flexibility and processing behaviour.

Simultaneously, the sieving rollers, with a mesh sheet, sift the material, allowing smaller particles like dust and short fibers to pass through, while the larger pieces are retained for further processing.

The second step follows a similar process where the fabric moves to the second set of tearing and sieving rollers. The tearing rollers continue to break down the fibers, refining the material further and separating any remaining large clumps. The sieving rollers once again filter out fine particles, ensuring that only the larger, more manageable fibers remain. In the third step, the fabric enters the third set of tearing and sieving rollers. The tearing action becomes more intense, breaking the fibers into smaller, finer pieces. The sieving rollers filter out even smaller particles, leaving behind more refined fibers. After this, the fabric moves to the fourth set of tearing and sieving rollers, where the fibers are broken down to an even finer state, and the sieving action becomes more precise, removing the smallest particles and impurities. With each successive step, the tearing and sieving rollers work together to refine the material, progressively reducing the fabric size and ensuring that only high-quality, larger reclaimed fibers remain. By the final step, the material is thoroughly processed, with most of the unwanted fine particles and impurities removed, resulting in a cleaner, more uniform fiber product Figure 2. Properties of received fibers are presented in Table 1. Description of these properties is given in Table 2.

Table 3. Properties of recycled polyester fiber.

	Cut length (mm)	Denier	Breaking Load (cN)	Tenacity (g/d)	Elongation (%)	Moisture (%)
RC Polyester	38	1.2	8	6.5	21	0.4

Table 4. Design of experiment of the research.

Sample #	Yarn type	Recycled Polyester (%)	Post-consumer Cotton Waste %	Twist Level	Sample Code
1	Ring	90	10	Medium	Ri10MT
2	Ring	90	10	High	Ri10HT
3	Ring	80	20	Medium	Ri20MT
4	Ring	80	20	High	Ri20HT
5	Ring	70	30	Medium	Ri30MT
6	Ring	70	30	High	Ri30HT
7	Rotor	90	10	Medium	Ro10 MT
8	Rotor	90	10	High	Ro10 HT
9	Rotor	80	20	Medium	Ro20 MT
10	Rotor	80	20	High	Ro20 HT
11	Rotor	70	30	Medium	Ro30 MT
12	Rotor	70	30	High	Ro30 HT
Control sample	Rotor	70:30	100% Virgin polyester (P) and cotton (C) 70:30	Optimum for knitting	PC 70:30

Yarn development (ring & rotor)

In the next phase, the shredded denim fibers were blended with chemically recycled polyester (RC Polyester) to create different yarn samples. Recycled polyester was sourced from a local market and physical properties of it are given in Table 3. A total number of 12 samples of 12/s yarn were produced, with varying material ratios to determine their properties. The material ratios used were 90% recycled polyester and 10% recycled cotton, 80% recycled polyester and 20% recycled cotton, and 70% recycled polyester and 30% recycled cotton. The samples were developed using two different spinning techniques, ring spinning and rotor spinning and two twist levels were applied – for ring yarns (12.0 ± 0.5 TPI) and for rotor yarns (13.0 ± 0.5 TPI) called as medium and high twist. In Table 4, the design of experiment is presented. 12/s rotor polyester and cotton blend of 70:30 (virgin polyester and virgin cotton) yarn was used as a controlled sample. The sample codes represent yarns produced using ring (Ri) or rotor (Ro) spinning with 10%, 20%, or 30% post-consumer waste content, (MT) for medium twist and (HT) for high twist, i.e., Ri10HT abbreviates ring spun yarn with 10% post-consumer waste and high twist level.

The yarns were developed using a series of conventional textile spinning machines. The fiber processing began with mixing, opening and cleaning in the Blow Room using a Crosrol system (Crosrol Ltd., Halifax, United Kingdom). Carding was carried out on a Rieter C70 carding machine (Rieter AG, Winterthur, Switzerland) to individualize the fibers and form carded slivers. For ring-spun yarns, the carded slivers were processed through a simplex frame FL-100 (Toyota Industries Corporation, Kariya, Japan) to produce rovings which were then spun into yarns using a ring spinning machine EJM-178 (Jingwei Textile Machinery Co., Ltd., Zhengzhou, China). The yarns were finally wound using the autoconer Ex Qpro (Murata Machinery, Ltd., Kyoto, Japan). For open-end (rotor) spun yarns, the carded slivers were directly fed into a rotor spinning (Circa 1998, Jingwei Textile Machinery, Jiangsu, China) to produce yarns without the need for a roving stage Figure 3.

Waste collection process and yield estimation

From fabric shredding to yarn development, the output yield at each stage of the process has been carefully recorded to estimate the yield of recycled yarn. In addition to this, fiber waste generated during the blow room and carding processes has been collected for analysis. The waste fibers collected during this process were tested via dissolved method to determine the actual percentage of cotton or polyester fiber waste, giving a more accurate representation of the fiber content lost at each stage. By tracking both the yield and waste throughout the process, it gives a clearer understanding of the overall efficiency, and the fiber properties involved in recycled yarn production.

The fiber yield formula used to calculate the percentage of fiber obtained from a raw material after processing:

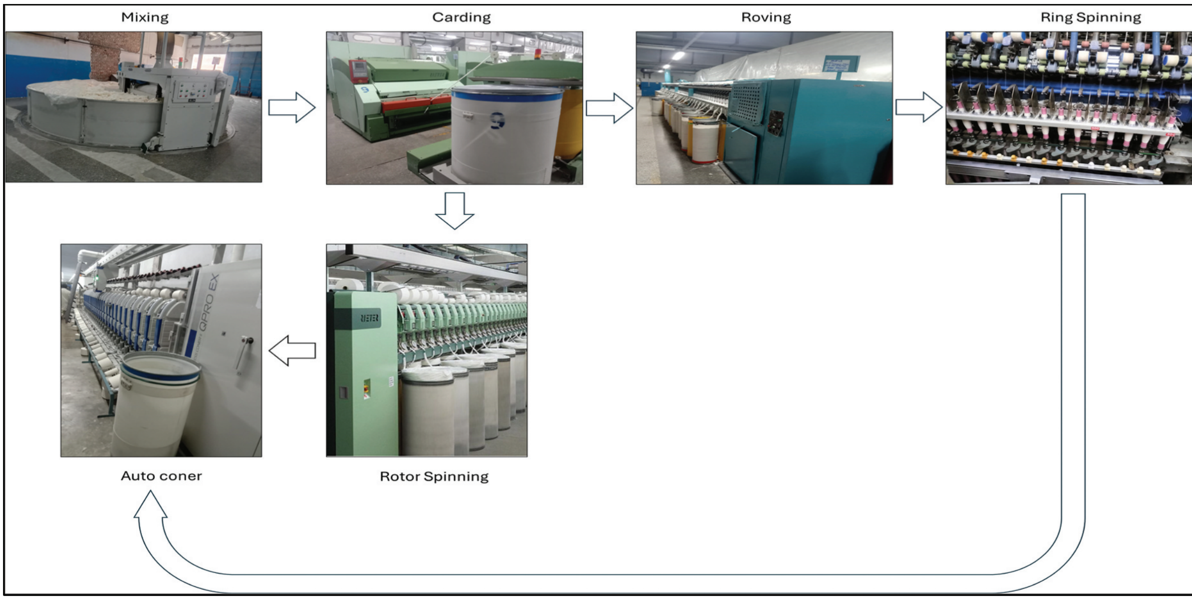

Figure 3. Spinning process of developed yarn.

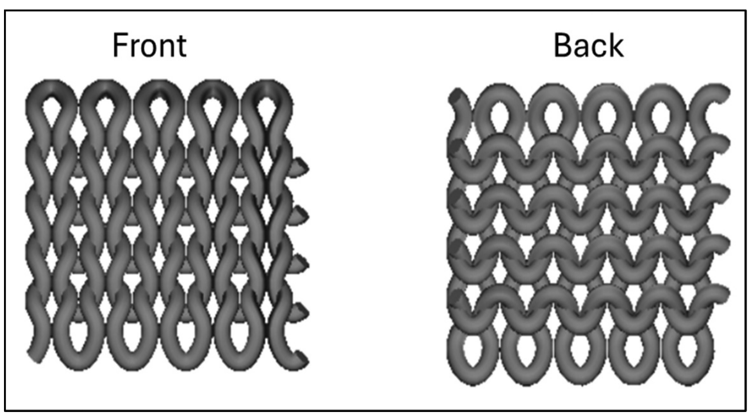

Figure 4. Illustration of single jersey fabric structure.

$$Fiber\ Yield(\%) = (Weight\ of\ fibers\ obtained/Weight\ of\ raw\ material) * 100$$

Development of knitted fabric

Figure 4 Single jersey fabric was produced on the Stoll CMS 530 HP, Germany, knitting machine having gauge of 14E. The stitch length (S.L) was maintained constant for all samples at approx. 2.9 mm, ensuring consistency in the fabric structure. Take down tension was also kept uniform throughout the knitting process. The fabric was knitted at a carriage speed of 0.5 m/s, with the constant yarn tension from the cones to the needles by machine's integrated tension control system.

Characterization:

Yarn and fabric testing

The fiber composition of each yarn sample was determined to quantify the ratio of cotton and polyester by weight. This analysis was performed according to the solubility test method described in ASTM D276. 70% sulfuric acid (H_2SO_4) was used to selectively dissolve the polyester component, while the cotton fibers remained intact. After dissolution, the undissolved cotton residue was carefully rinsed, dried, and weighed. The difference in mass before and after the treatment allowed for accurate calculation of the fiber content. The single yarn breaking strength (tenacity) and elongation were tested using a Tensilon RTG-1310 universal testing machine (Japan). Following ASTM D2256, yarns were stretched until it broke, and the force required for breakage was recorded as the tenacity. The Uster Tester 5 (Switzerland), was used to analyze the evenness, imperfections, and defects in the yarn. The wale density and course density were determined in accordance with ASTM D8007-1, providing insights into the fabric's structure and the distribution of loops. The Martindale Abrasion Tester (model 220 Abrasion Tester, Zurich, Switzerland) was used to evaluate pilling resistance according to ISO 12947–2 standard. Specimen of 140 mm diameter, rubbed against each other for 5000 cycles. The tester provided a detailed assessment of the fabric's durability and its resistance to pilling. The amount of pilling was compared visually against a given standard.

Microscopic analysis

Microscopic analysis was conducted on the recycled fiber, developed yarns, and knitted fabric to assess their structural characteristics using Delta Optical Smart 5MP Pro Digital Microscope & Nikon ECLIPSE E200. For the recycled fiber, the analysis can reveal the presence of shorter, finer fibers and potential fiber damage due to the recycling process. This can affect the overall strength and integrity of the fibers. In the developed yarn, microscopic examination focused on the alignment, twist, and uniformity of the fibers, highlighting the efficiency of the spinning process in incorporating recycled fibers. The knitted fabric was analyzed to examine the loop formation, interloping of yarns, and fabric structure, which are critical factors influencing the fabric's elasticity, durability, and overall texture.

Results and discussion

Recycling and yarn formation yield

The substantially lower fiber yield (45–50%) by weight is observed in post-consumer denim recycling, compared to the 80–95% yield typically achieved with pre-consumer textile waste as quoted in available literature due to the fundamental differences in material degradation over time and processing challenges (Sari, Uzumcu, and Ozsahin 2024). Post-consumer cotton garments undergo significant mechanical and chemical degradation during its service life, including repeated laundering, abrasion, and exposure to environmental stresses, which collectively degrade cellulose and ultimately reduce fiber length and tensile strength (Arun et al. 2025). This degradation is exacerbated during mechanical recycling, where additional fiber breakage occurs during opening process. While pre-consumer waste, consisting of clean unused leftover garments, production offcuts, etc., retains near-original fiber properties, enabling higher recovery rates (Ütebay, Çelik, and Çay 2019).

The recycling of post-consumer garments generates higher neps and trash content during carding, to produce spinnable fibers (Lu et al. 2023). Table 5 Results of the spinning process until the carding stage revealed how different percentages of recycled denim waste fiber (blended with recycled polyester) influence weight loss compared to virgin cotton. The data demonstrates that as the recycled denim waste fiber content increases, the processing waste also rises. For 10% denim waste, the blow room input was 83.65 kg, with a 6.45% weight loss, leaving 78.25 kg after carding. At 20% denim waste, the input was 85.45 kg, but the weight loss increased to 10%, resulting in 76.96 kg after carding. With 30% denim waste, the loss was even

Table 5. Input and output weight of blow room to carding.

Sample type	Process	Weight (kg)	Weight loss (%)
10% waste	Blow room (input)	83.65	6.45
	Carding (output)	78.25	
20% waste	Blow room (input)	85.45	10
	Carding (output)	76.96	
30% waste	Blow room (input)	85.5	11.58
	Carding (output)	75.6	
Virgin cotton (PC 70:30)	Blow room (input)	86.2	3.2
	Carding (output)	83.44	

higher (11.58%), reducing the output to 75.6 kg. While virgin cotton exhibited the lowest weight loss (3.2%), with an input of 86.2 kg and an output of 83.44 kg. This trend suggests that higher recycled fiber content leads to greater fiber loss, likely due to shorter and weaker fibers in post-consumer waste, which are more susceptible to removal during processing. Virgin cotton, with its longer and stronger fibers, experiences less waste (Utebay, Celik, and Cay 2023).

Recycling of post-consumer waste can reduce environmental impact, but higher waste percentages in the new products manufacturing may compromise processing efficiency. These findings underscore the technical and economic challenges of scaling of post-consumer textile recycling.

Comparison of fiber properties (virgin vs recycled)

The comparison of virgin cotton fiber and recycled cotton fiber derived from post-consumer denim waste highlights significant differences in fiber properties that directly impact their performance in textile applications. Figure 5 Micronaire values (Table 2) of virgin cotton (4.36) and recycled cotton (4.67) indicate that recycled cotton fibers are coarser, with a higher micronaire value signaling less maturity and a thicker structure (Liu and Hinchliffe 2025). Microscopic analysis of these fibers also shares that the diameter of recycled cotton is higher than of virgin cotton fiber's diameter (Figure 6). This results from the degradation of fibers during the recycling process, where mechanical forces break down the fiber structure. The lower maturity value in recycled cotton (0.82) compared to virgin cotton (0.85) further supports this, indicating that the fibers have undergone structural damage during the recycling process. A key difference between the two fiber types is in the high mean length (HML) value, where virgin cotton fibers were significantly longer (26.92 mm) compared to recycled cotton fibers (15.92 mm). Longer fibers give better spinning performance and yield stronger and more uniform yarns (Long et al. 2010). The grinding and carding actions involved in the mechanical recycling of post-consumer waste break longer fibers into shorter segments, which results in a higher short fiber content (49.9% in recycled cotton compared to 13.4% in virgin cotton).

The uniformity index (UI) highlighted the difference in fiber consistency, with virgin cotton showing the higher UI (81.4%) than recycled cotton (59.9%). The UI measures the consistency of fiber length, and recycled cotton fibers are more variable in length due to the mechanical shearing forces that break them down into irregular lengths during recycling (Sasi et al. 2024). The strength of virgin cotton fibers

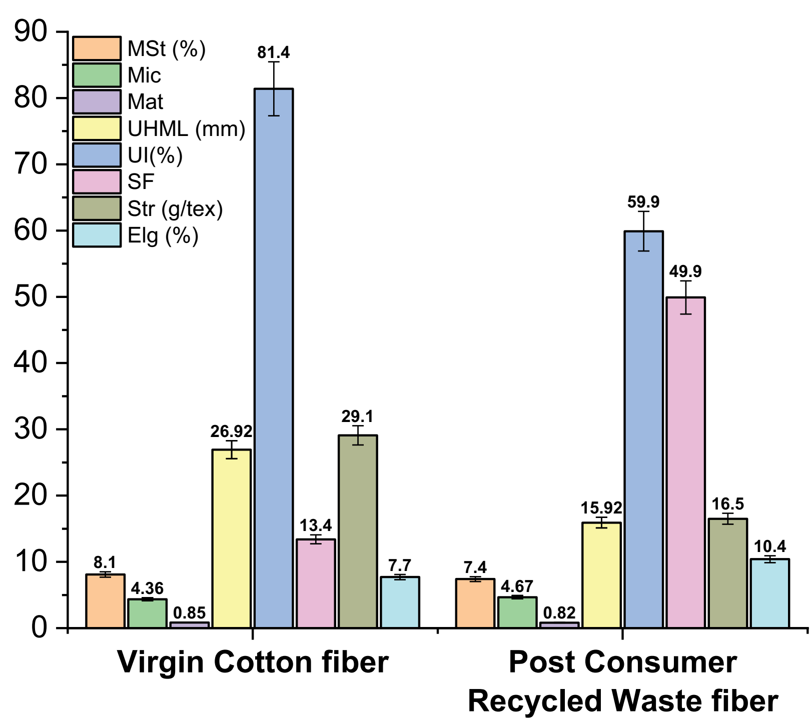

Figure 5. Comparison of physical properties of post-consumer denim waste recycled and virgin cotton fibers.

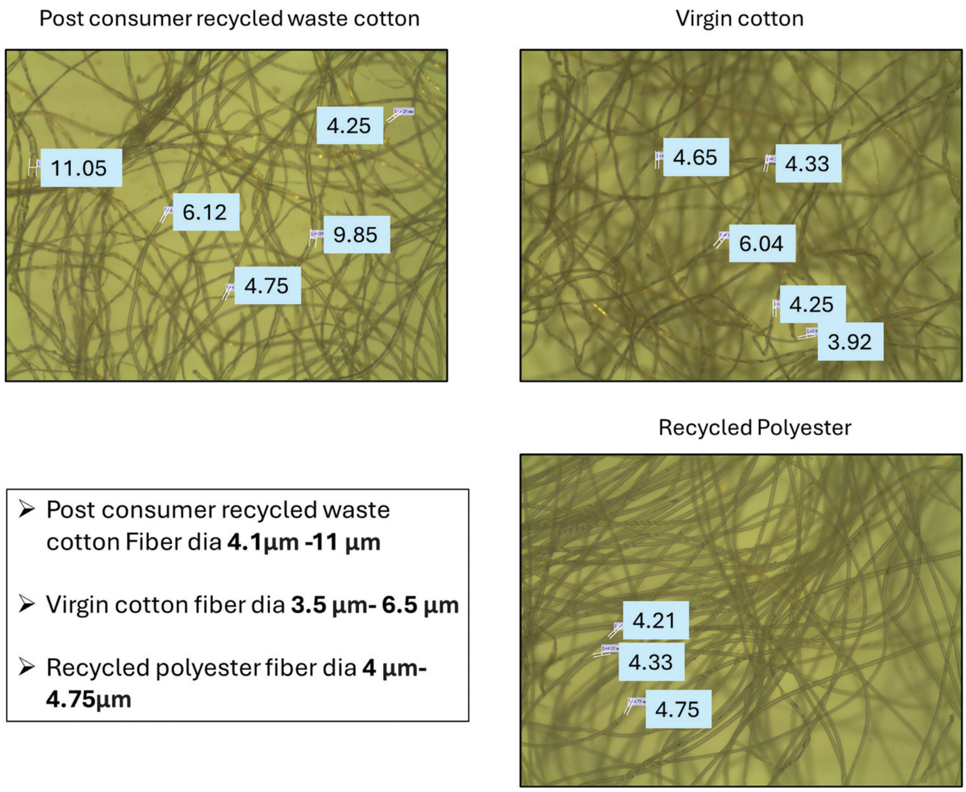

Figure 6. Microscopic analysis of post-consumer recycled and virgin cotton fiber and chemically recycled polyester fibers.

is 29.1 g/tex, compared to 16.5 g/tex for recycled post-consumer cotton fibers. The lower properties of post-consumer waste fibers, specifically the reduction in strength, length, and uniformity, is due to the repeated use of garments during its life-cycle. These garments undergo multiple cycles of wear and washing, which causes fiber shortening, abrasion, and a reduction in fiber strength. When these garments are recycled, the fibers are subjected to mechanical forces that break them down further, leaving behind fibers that are shorter, weaker, and less uniform compared to their virgin counterparts (Yousef et al. 2020). While this process reduces waste and promotes sustainability, it causes irreversible damage to the fiber structure, which in turn leads to a shorter life cycle for products made from recycled fibers (Abtew, Atalie, and Dejene 2025).

To overcome these limitations, research into improving recycling technologies and fiber regeneration processes is necessary. Innovations in chemical recycling methods, which can preserve fiber strength and structure better than mechanical methods, can help to improve the quality of recycled cotton, enabling it to be used in a wider range of high-quality textile applications.

Physical properties of yarns

From Table 6 experimental data reveals significant challenges in producing high-quality yarns from post-consumer waste as the recycled content increases beyond 10%. Incorporating 10% recycled fibers (Ri10HT) yields yarn has competitive tenacity (17.63 cN/tex) and breaking force (867.4 cN) values, which come close to those of virgin cotton yarns. Increasing the waste content to 20% and 30% leads to decline of severe mechanical properties which questions the viability of high recycled percentages. At 30% waste (Ri30MT), tenacity falls to just 4.21 cN/tex – a 76% reduction compared to the 10% variant, highlighting the impracticality of high waste ratios for performance driven garment applications. This sudden decline is based on multiple factors related to fiber damage during recycling, including shortened staple length (from ~26 mm in virgin cotton to ~15 mm in 30% recycled content), reduced fiber tensile strength (up to 30% weaker than virgin fibers) and increased short fiber content (rising from 13.4% to 49.9%), which critically undermine yarn strength and spinning efficiency Fig. 5 (Arafat

Table 6. Physical properties of yarns developed from post-consumer denim waste.

Sample Code	Linear density (tex)	Tenacity (cN/tex)	Breaking force (cN)	Elongation (%)	Lea strength (Lbs)	CLSP (Lbs)	Twist (TPM)
Ri10MT	48.46	14.37	707.1	15.08	173.25	2110	407
Ri10HT	46.22	17.63	867.4	16.13	236	2874	445
Ri20MT	46.74	10.08	496	13.53	82.75	1056	421
Ri20HT	44.65	13.42	660.4	14.79	160	2020	448
Ri30MT	46.05	4.21	207.3	8.76	38.05	503	420
Ri30HT	50.59	9.84	484.4	13.42	82.5	1057	446
Ro10 MT	50.47	12.8	630.1	15.24	196	2287	475
Ro10 HT	49.86	13.31	654.9	11.25	212	2480	510
Ro20 MT	48.73	11.57	569.4	14.53	174.5	2066	506
Ro20 HT	48.61	14.44	710.7	11.24	208.5	2524	587
Ro30 MT	51.61	10.64	523.7	14.24	169.5	2059	492
Ro30 HT	48.77	12.76	628.1	10.85	182.5	2087	529
PC 70:30	48.46	20.3	630	8.3	130	1560	492

Table 7. Coefficient of variation of physical properties of yarns developed from post-consumer denim waste.

Sample Code	Linear density CV%	Tenacity CV%	Breaking force CV%	Elongation CV%	Lea strength CV%	CLSP CV%	Twist CV%
Ri10MT	1.08	4.04	4.2	2.3	2.9	2.4	0.88
Ri10HT	0.79	1.19	1.6	2.5	2.7	2.1	0.9
Ri20MT	0.85	2.21	2.5	4.9	5	4.8	0.2
Ri20HT	0.42	0.99	0.8	3.5	3.1	3.9	0.6
Ri30MT	1.46	7.03	6.26	5	4.6	4.9	0.7
Ri30HT	0.43	5.81	5.1	3.6	3.2	3.9	0.39
Ro10MT	0.88	1.03	0.9	2.1	2.9	2.3	0.42
Ro10HT	0.27	0.68	0.7	2.7	2.6	2.5	1.08
Ro20MT	0.27	3.56	3.9	4.7	4.9	4.8	0.79
Ro20HT	0.53	0.72	0.8	3.8	3.6	3.3	0.85
Ro30MT	0.39	0.45	0.6	4.9	4.6	4.7	0.42
Ro30HT	0.39	0.44	0.7	3.4	3.2	3.4	1.2
PC70:30	0.42	0.72	2.5	2.4	2.9	2.7	0.43

and Uddin 2022). Table 7 demonstrates that variation of measured values did not exceed 10% (in majority cases did not exceed 5%), and the presented differences of yarns characteristics depending on the blend ratio and twist level are significant.

The performance degradation follows a clear pattern: each 10% increase in waste content results in approximately 7–9% reduction in tenacity and 5–7% decrease in breaking force. This almost linear relationship suggests the negative effects of fiber shorter length, making higher waste percentages progressively more problematic. The CLSP (Count-Lea Strength Product), an important industry metric for yarn quality, shows even more sensitivity to waste content, decreasing by 10–12% for each 10% waste increment. Ri10HT achieves an excellent CLSP of 2874, while Ri30HT manages only 1057, i.e., a 63% reduction that would be unacceptable for most commercial applications. Rotor-spun yarns (Ro series) exhibit better tolerance for moderate waste levels, with Ro20HT achieving 14.44 cN/tex tenacity even surpassing its 10% counterpart. This unexpected result is attributed to rotor spinning's ability to better incorporate short fibers through its unique core-sheath structure. But this anomaly does not extend to 30% waste (Ro30HT: 12.76 cN/tex), confirming that excessive recycled content universally degrades yarn integrity beyond what any spinning technology can compensate for. Comparatively, the polyester-cotton blend (PC70:30) outperforms recycled variants in tenacity (20.3 cN/tex) due to polyester's inherent strength (Figure 7). The results clearly demonstrate the interplay between spinning method, waste content, and twist level in determining yarn properties. Yarns made from ring spinning tend to outperform those made by rotor spinning, especially in terms of strength-related properties like tenacity, breaking force, and lea strength. Increasing post-consumer waste content, while providing an eco-friendly alternative, negatively impacts yarn quality, leading to reduced strength. The incorporation of high twists in yarns can partially mitigate the negative effects of waste content, but not to the extent observed in the less waste percentage yarns.

The pursuit of greater waste utilization, without considering the fundamental limitations, risks producing poor-quality textiles, which could undermine the circular economy goals of creating products that fail prematurely or need to be replaced more frequently. Future efforts must prioritize quality-preserving methods over arbitrary waste quotas to ensure that recycled textiles can truly replace virgin materials in the market. As recycling technologies improve, these thresholds may increase, but current evidence suggests

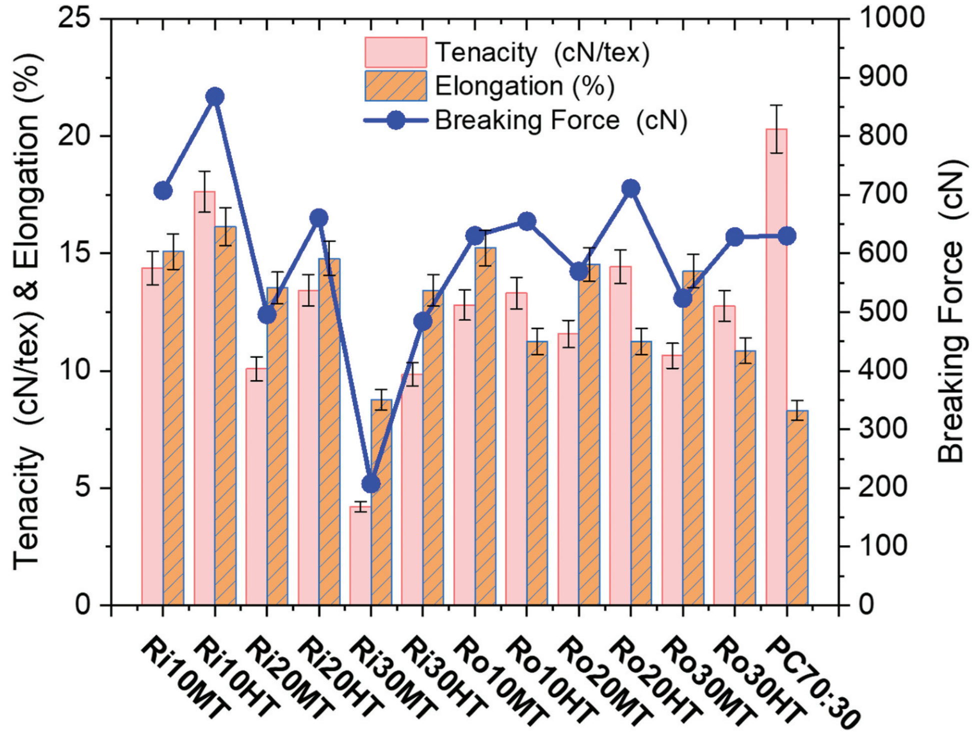

Figure 7. Comparison of mechanical properties of developed yarns.

that 10–15% of recycled waste fibers represents the practical limit for most commercial applications without significant quality compromises

Material ratio calculation (actual vs calculated)

Figure 8 shows that the increased short fiber content (SF: 49.9%) and decreased fiber length (UHML: 15.92 mm) in the recycled cotton waste directly explain the discrepancies in the composition of the yarn blends. These shortened fibers exhibit poor spinnability, leading to disproportionate waste generation. Analysis of waste collected from blow room and carding process shows dominance of cotton 90% in blow room and carding waste streams from this recycled yarn production. The fundamental length disparity between the mechanically recycled cotton (15.92 mm) and chemically recycled polyester (38 mm length) creates an inherent imbalance in fiber retention rates. Post-consumer cotton fibers due to their shorter length were more susceptible to removal during opening and carding processes (Raiskio et al. 2025). While chemically recycled polyester retains better integration into the yarn structure. Consequently, to compensate for this processing loss and achieve the target blend ratios, additional recycled cotton waste fibers are added, which ultimately skews the yarn composition to a higher actual cotton percentage than calculated.

Structure and properties of knitted fabric

Analysis of developed knitted fabrics shows significant variations in properties based on the yarn composition and spinning technology. Rotor-spun fabrics (Ro series) consistently demonstrated higher area density values (184–233 g/m^2) compared to the ring-spun fabrics (161–192 g/m^2) Figure 9. This 15–20% difference in fabric weight stems from the bulkier structure of rotor yarns Figure 10, which enhances fabric coverage and density due to their characteristic fiber arrangement. The open-end spinning process creates less compact yarns that form heavier fabrics at identical stitch lengths, as the looser structure allows for better fiber packing in the knitted construction. Stitch density parameters such as wale density and course density (WPC/CPC) remained relatively stable across samples (7–7.5 cm^{-1} WPC, 12–17 cm^{-1} CPC) due to the same machine gauge (14E) and consistent stitch length (2.8 – 2.9 mm). However, rotor-spun fabrics show higher

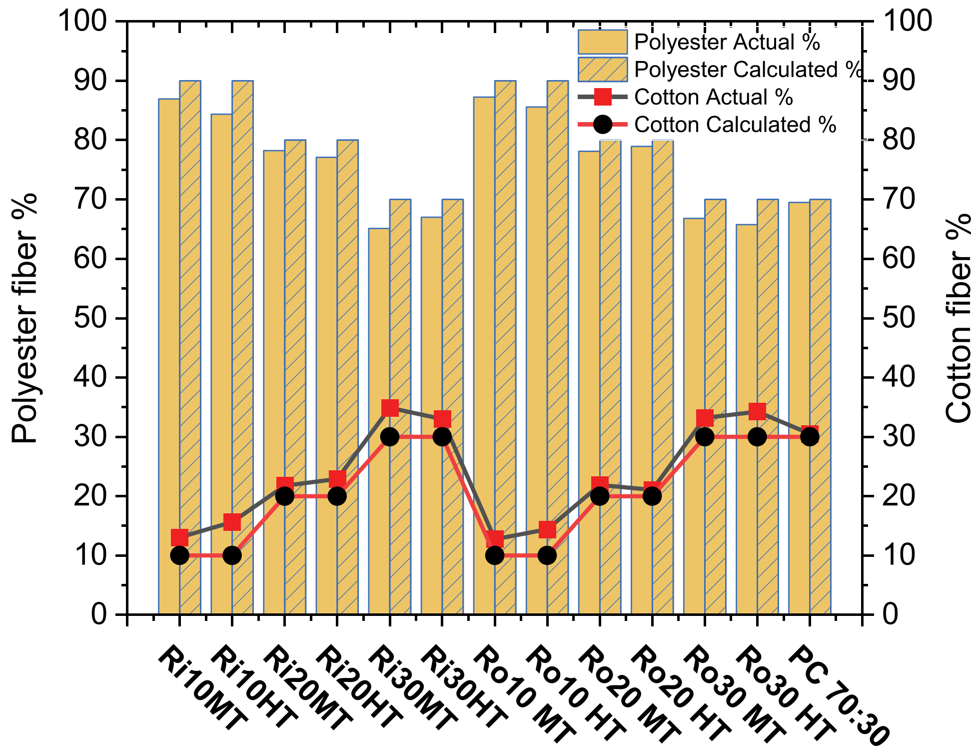

Figure 8. Comparison of material composition in percentages: actual and calculated.

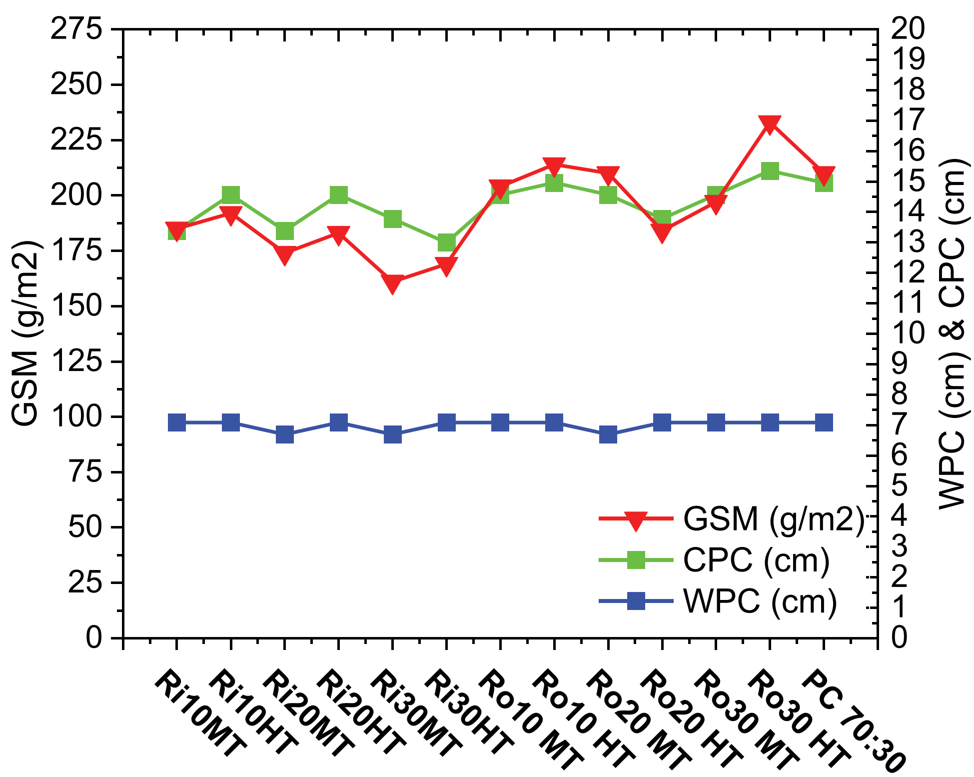

Figure 9. Comparison of area density (GSM) and stitch density (wale density WPC and course density CPC) of fabrics knitted from recycled cotton/polyester yarns.

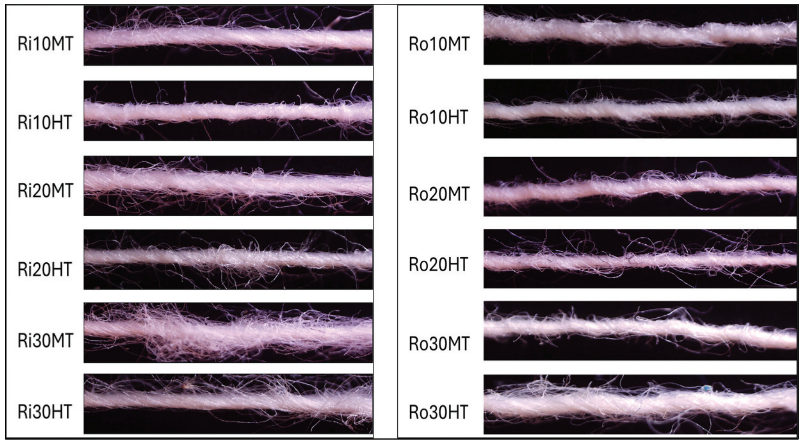

Figure 10. Microscopic analysis of developed yarns.

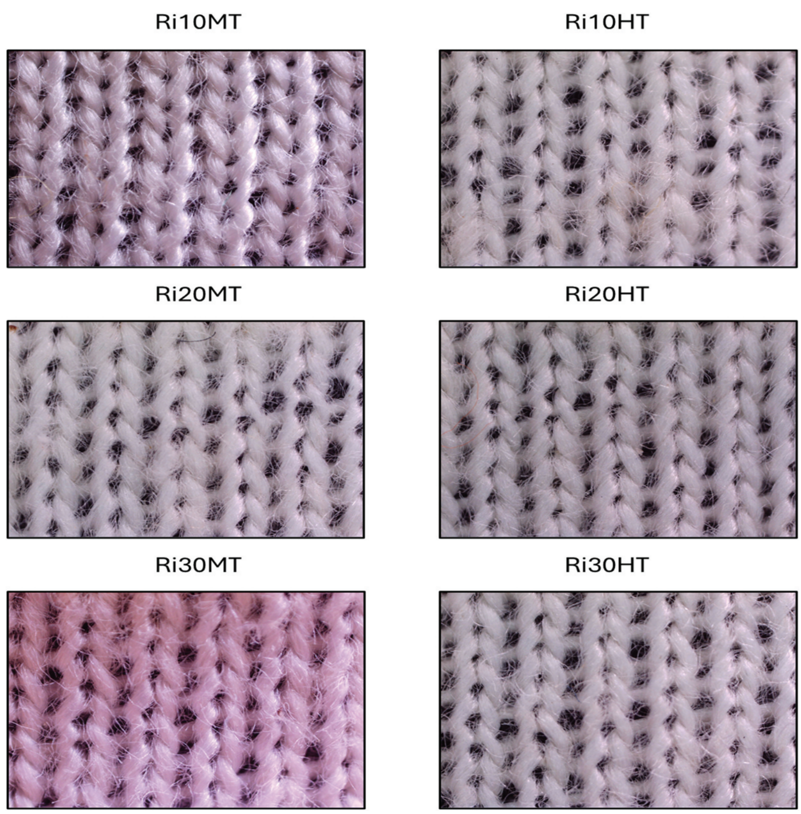

Figure 11. Developed fabrics from ring spun yarns.

CPC (14–17 cm^{-1}) compared to ring-spun samples, particularly at higher waste levels where Ri30HT shows 12 cm^{-1} CPC and makes fabrics denser Figures 11, 12. This stability reflects the inherent advantage of rotor spinning in producing more uniform yarns from variable fiber inputs.

Twist level emerged as another critical factor influencing fabric characteristics. High-twist yarns (HT) in both spinning systems influenced heavier fabrics, with Ri10HT weighing 192 g/m^2 compared to 185 g/m^2 for its medium-twist counterpart. This effect was even more pronounced in rotor-spun samples, where Ro10HT reached 214 g/m^2 versus 204 g/m^2 for Ro10MT. The increased twist improves yarn compactness and fiber packing efficiency. From Table 8 Coefficient of variation (CV%) indicate a very low level of variability (less than 1%).

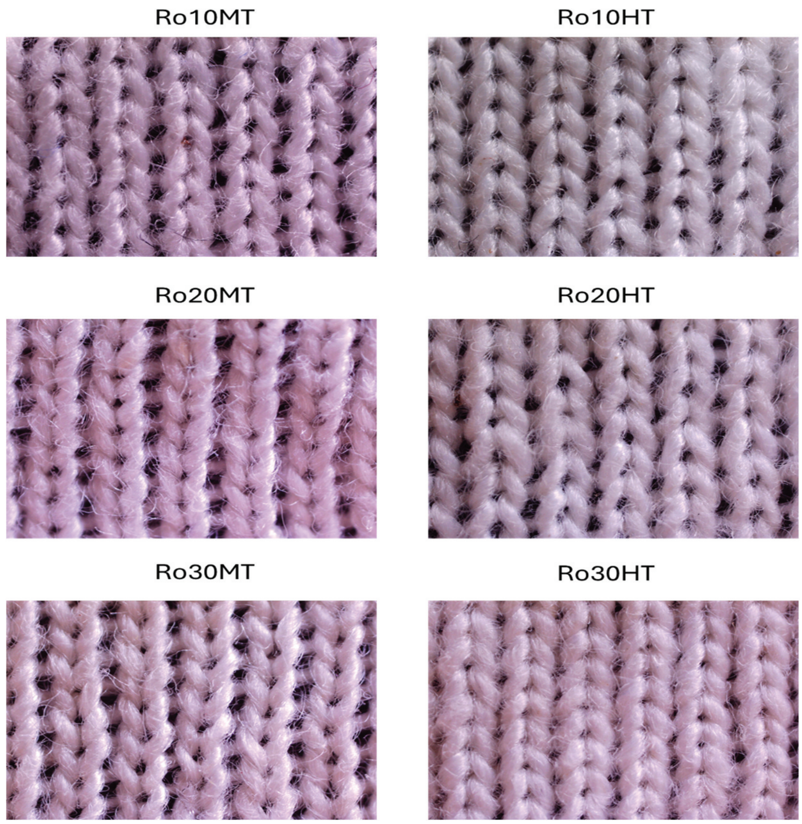

Figure 12. Developed fabrics from rotor spun yarns.

Table 8. Coefficient of variation of physical properties of fabric.

Sample Code	WPC CV%	CPC CV%	GSM CV%
Ri10MT	0.43	0.53	0.82
Ri10HT	0.54	0.63	0.91
Ri20MT	0.29	0.46	0.73
Ri20HT	0.58	0.55	0.88
Ri30MT	0.36	0.52	0.64
Ri30HT	0.49	0.42	0.71
Ro10MT	0.32	0.51	0.92
Ro10HT	0.46	0.59	0.99
Ro20MT	0.23	0.35	0.78
Ro20HT	0.51	0.43	0.62
Ro30MT	0.38	0.49	0.91
Ro30HT	0.63	0.53	1
PC70:30	0.52	0.61	0.79

The impact of recycled fibers content followed important trends. Fabrics incorporating 30% recycled denim waste (Ri30/Ro30 series) showed the lowest GSM values, with Ri30MT at just 161 g/m^2. This decrease was due to the short fiber length and increased short fiber content in yarns with higher waste content, which affects both yarn integrity and fabric formation. The samples with 30% of post-consumer denim waste fibers exhibited greater variability in courses per cm values, particularly in ring-spun constructions, indicating challenges in maintaining consistent stitch density with recycled fibers (Gedilu et al. 2022).

Pilling test

The pilling test results demonstrate a significant difference between fabrics knitted from recycled post-consumer denim yarns and the virgin polyester-cotton (PC 70:30) benchmark. All samples of recycled yarns showed poor pilling resistance (Grade 1), while the PC 70:30 blend exhibited superior performance

(Grade 4). This difference is due to the fundamental differences in fiber properties resulting from the recycling processes (Anas et al. 2023). The inferior pilling resistance of recycled fabrics is attributed to multiple factors related to mechanical recycling damage. The shorter length and high content of short fibers create weak fiber cohesion, making them more likely to loosen from the yarn structure during abrasion (Asanovic et al. 2022; Busiliene, Lekeckas, and Urbelis 2011). Both ring-spun and rotor-spun recycled yarns exhibited this vulnerability, indicating the fundamental limitations of using recycled cotton fibers. Excellent pilling resistance (Grade 4) of PC 70:30 blend results from the properties of its constituent fibers. Fabrics with Grade 1 pilling resistance will typically show visible surface roughness within just 1–5 washing and wearing cycles, significantly impacting their aesthetic appeal and perceived quality (Busiliene, Lekeckas, and Urbelis 2011). Due to this rapid degradation, fabrics made from recycled fibers can only be used in products where the surface appearance is less important, such as inner lining materials or certain technical products.

Statistical analysis (ANOVA method)

To evaluate the influence of twist level, waste percentage, and spinning method on yarn properties, both main effect and interaction plots were analyzed alongside statistical significance (p-values). A main effect plot gives the average effect of each factor independently, while an interaction plot shows whether the effect of one factor depends on the level of another, indicated by non-parallel or intersecting lines.

From the main effects plots Figure 13(a-d), it is evident that higher twist level and lower waste percentage improved tenacity (Figure 13a), breaking force (Figure 13b), and lea strength (Figure 13d), whereas the influence on elongation was less pronounced (Figure 13c). Ring-spun yarns showed comparatively lower strength values than rotor-spun yarns, except in the case of elongation, where ring yarns exhibited slightly higher mean values. These trends were supported by p-values, where waste percentage significantly affected tenacity ($p = .041$), breaking force ($p = .041$), and lea strength ($p = .029$). The spinning method had a significant effect only on lea strength ($p = .018$), while its effect on other properties was statistically insignificant ($p > .4$). Twist level had near-significant effects on tenacity and breaking force ($p = .059$), but no significant effect on elongation ($p = .66$) Table 9.

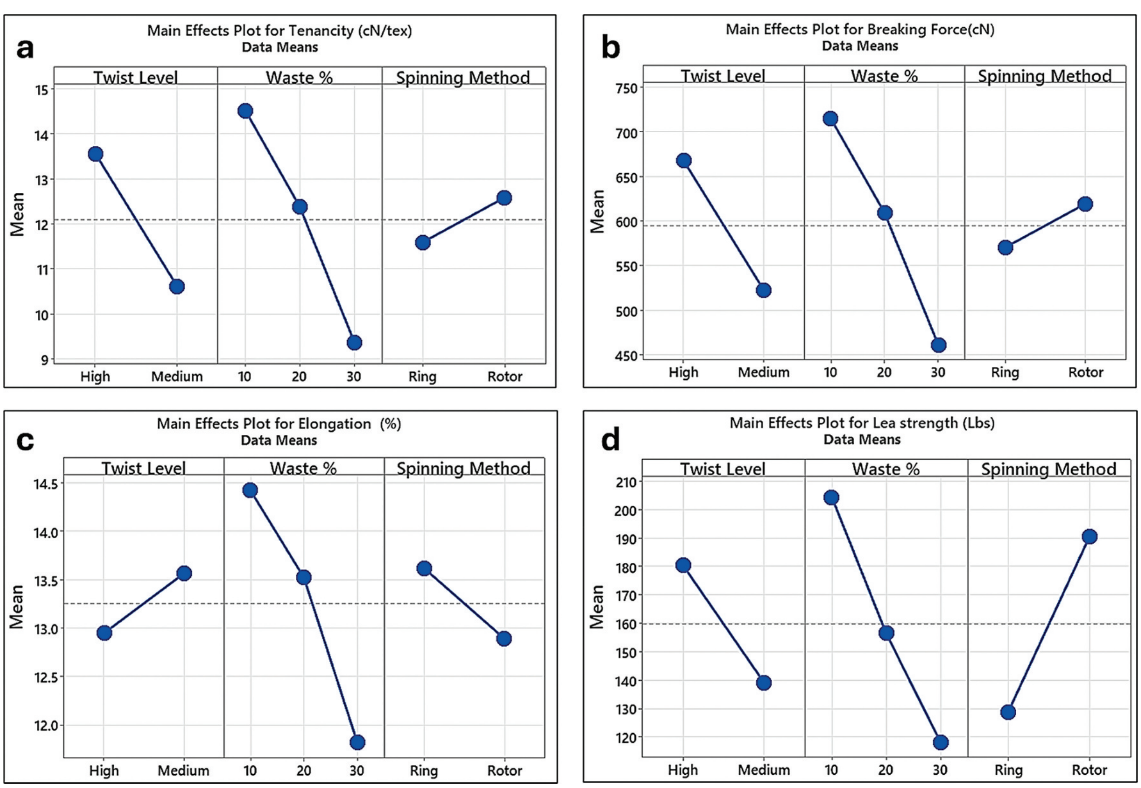

Figure 13. Main effect plots: a) tenancity, b) breaking force, c) elongation & d) Lea strength.

Table 9. P- values of different responses.

	Twist level (m^{-1})	Cottn waste percentage (%)	Spinning type
Tenacity (cN/tex)	0.059	0.041	0.473
Breaking force(cN)	0.059	0.041	0.472
Elongation (%)	0.66	0.332	0.605
Lea strength (Lbs)	0.08	0.029	0.018

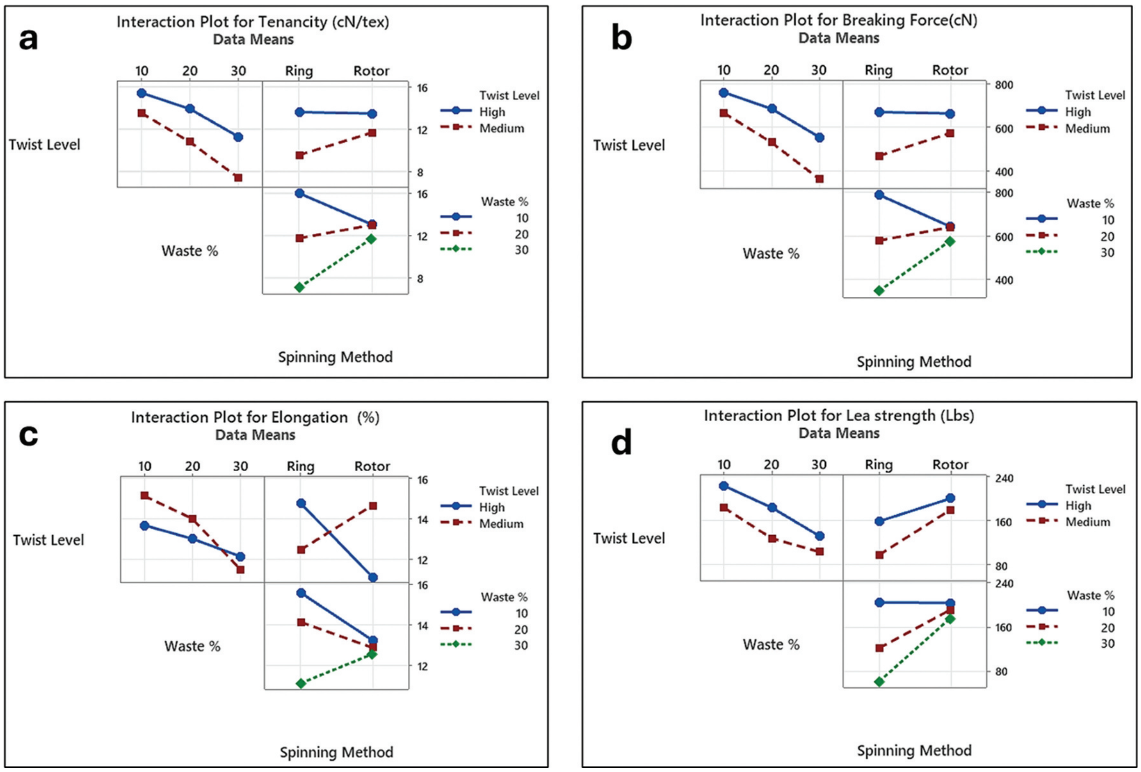

Figure 14. Interaction plots: a) tenancity, b) breaking force, c) elongation & d) Lea strength.

Interaction plots Fig. 14 highlighted combined effects. Non-parallel lines, particularly in tenacity and breaking force (Figure 14a,b), suggest strong interactions between twist level, spinning type, and recycled waste percentage. Rotor-spun yarns with high twist retained better tenacity even with higher recycled waste levels, unlike ring yarns. These observations suggests that not only the individual factors but also their interactions are critical in optimizing yarn properties when incorporating recycled content.

Conclusion:

This study critically evaluates the challenges and limitations associated with recycling post-consumer denim waste into viable textile products. While the circular economy framework advocates for textile recycling to reduce waste and resource depletion, but the practical limitations question the scalability and efficacy of current mechanical methods. Key findings highlight three critical barriers:

- Post-consumer cotton fibers suffer irreversible damage from wear, washing, and mechanical recycling, resulting in shorter lengths (15.92 mm vs. 26.92 mm for virgin cotton), reduced strength (16.5 g/tex vs. 29.1 g/tex), and higher short-fiber content (49.9% vs. 13.4%). These deficiencies directly compromise yarn tenacity, with 30% waste blends showing a 76% reduction in strength compared to 10% waste blends.
- Low fiber yield (45-50%) and elevated waste generation during processing, particularly at higher recycled content undermine the economic and environmental viability of mechanical recycling. The disproportionate loss of cotton fibers during carding further raises concerns about consistency and quality control.

- Even with optimization (e.g., high twist, rotor spinning), fabrics knitted from recycled fiber yarns exhibited inferior pilling resistance (Grade 1) and mechanical properties compared to virgin counterparts. This suggests their applicability to low-value products, potentially a downcycling loop rather than true circularity.

The data suggests that mechanical recycling alone is not sufficient to meet basic garment quality standards, emphasizing the need for hybrid approaches combining mechanical recycling with chemical or enzymatic processes to restore fiber integrity, also promoting the use of pre-consumer waste. Standardization of recycling thresholds is needed to balance waste diversion and product performance. While post-consumer textile recycling is in line with the principles of the circular economy, its current implementation risks replacing one environmental problem (waste accumulation) with another (low-quality, short-lived textiles). Future research must prioritize quality preserving technologies and systemic shifts in textile design to ensure recycling delivers genuine sustainability benefits.

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