THE EFFECT OF GARMENT CUTTING ON FIBER LENGTH RETENTION IN WOOL-BLEND OFFCUTS WITH RESPECT TO THEIR FUTURE USE IN RECYCLED YARN PRODUCTION

BASHO, MEGI*; CHAVOSHI, AVA AND CEBULLA, HOLGER

TU Chemnitz, Faculty of Mechanical Engineering, Professorship of Textile Technology, Reichenhainer Str. 70, 09126, Chemnitz, Germany

ABSTRACT

The growing demand for sustainable textile production highlights the importance for effective recycling of pre-consumer textile waste, particularly wool and wool blends. Production highlights the importance of recycling pre-consumer textile waste to minimize the environmental impact. While many studies focus on fiber recycling, few investigate the root cause of the fiber shortening during the cutting and shredding process. This study investigates how cutting fabric impacts fiber retention in recycled yarn production, focusing on three common knit patterns—Rib 1x1, Double Jersey, and Interlock. Using a 70% wool and 30% silk blend, the study identifies optimal cutting dimensions to minimize fiber loss during recycling. Experimental analyses of fabric samples (1–10 cm lengths) revealed that cuts of approximately 7 cm effectively preserved fiber lengths across all patterns, with confidence intervals demonstrating consistent retention. Image processing techniques further categorized leftover materials, enabling their allocation to specific spinning processes (short-staple, medium-staple, and long-staple). The findings contribute to optimizing recycling processes, improving fiber retention, advancing circular economy practices in textile production, and hold potential for practical implementation in automated recycling systems and enhanced yarn production workflows.

KEYWORDS

Textile Recycling, Pre-Consumer Waste, Wool, Wool Blends, Fiber Length Optimization, Rib, Interlock, Double Jersey.

INTRODUCTION

Fabrics, garments, and fibers are upcycled and recycled in a circular economy to maintain their high-quality value while reducing waste production; yet, around 53 million tons of fibers are generated globally each year in garment manufacturing via linear value chains. Raw materials such as crude oil and cellulose are used to create synthetic and cellulosic fabrics. 73% of global garment production is incinerated or discarded in landfills at the end of its life [1]. On a daily basis, a garbage truck full of textile waste is thrown around the world, consuming land, water, and fossil fuels and polluting the air, water, and soil [2]. When textiles are burned, chemicals and CO2 are produced [3]. The textile industry is one of the world's most important economic sectors, and it is growing in tandem with the worldwide population. Textile recycling reduces the necessity of new fibers in textile production, as well as the use of water and chemicals. Textile waste management is essential for lowering the environmental impact of the textile and garment industries [4]. Increasing textile waste clothing recycling aids in the transition to a circular economy by enabling a closed-loop circular textiles and fashion sector [1]. For this transition to be effective, parties in the (circular) value and supply chains have to engage and take act [1]. A system reform is necessary, with all players in the value chain contributing and cooperating [5]. The rate of change is determined by the quantity and quality of recycled textile waste fibers used in new fashion and interior textile production processes (Figure 1).

LITERATURE REVIEW

The current linear (take-make-dispose) economic model is increasingly unsustainable. Fortunately, circular economy concepts, which entail the continuous restoration and regeneration of value throughout a product's life cycle, are gaining traction in Europe. The circular economy model is defined by the three R's: reduce, reuse, and recycle, which are applied throughout the product's life cycle [6]. The circular economy is based on maximizing the use of available resources and generating renewable flows of materials and products [7]. Recent years have

* **Corresponding author:** Basho M., e-mail: *megi.basho@s2024.tu-chemnitz.de*

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Figure 1. Mechanical recycling of textile waste (authors own illustration).

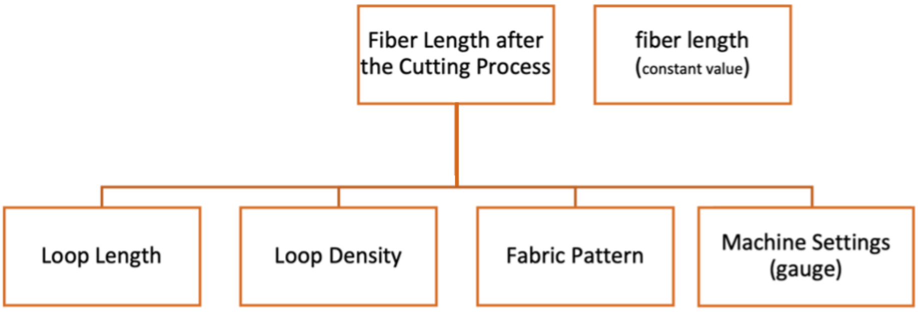


Figure 2. Illustration of the parameters that influence the fiber length after the cutting process (authors own illustration).

seen a surge in attempts to improve recycling efficiency in the textile industry. However, much of the focus has been on post-consumer waste, leaving a gap in understanding and addressing the difficulties of recycling pre-consumer waste, particularly wool and wool blends.

Fiber length is an important parameter in the recycling of wool and wool blends since it influences the quality and performance of the recovered yarn. Previous study has shown that longer fiber lengths result in stronger, more durable yarns that are more suited for recycling. Wiedemann et al. [8] and Wanassi et al. [9] discovered that precise cutting lengths can optimize fiber length during the shredding process, hence improving the quality of recovered yarn. Despite these findings, additional research is needed to improve fiber length and other key factors in recycling pre-consumer wool waste. This study seeks to close this gap by investigating factors influencing fiber length, such as sorting methods, textile orientation prior to cutting, surface design, and binding techniques, in order to establish new standards for closed-loop recycling of wool and wool blends via optimal cutting lengths and key elements in the cutting and shredding processes, as shown in Figure 2.

MATERIALS AND METHODS

Yarn and fabric production

The yarn used in this study consisted from a 70 % wool and 30 % silk fiber blend, with a linear density of Nm 44/1, 543 twists per meter, and an original fiber length of 76.2 mm, according to the producer, where the wool and silk fibers were cut in order to have the same length. Wool fibers had a diameter of 19.5 µm (merino wool), whilst silk fibers had a diameter of 12.3 µm (mulberry silk), ensuring blend-ability. The yarn went to a microscope examination, for distinguishing the wool and silk fibers within yarn, where a Leica Digital Stereomicroscope model M205 was used to acquire digital images from fiber and fabric samples (Figures 3 and 4). Furthermore, three knit patterns were produced from the same yarn blend with the same parameters: rib 1x1, double jersey, and interlock. The primary aim was to determine which knitting pattern, in combination with specific cutting lengths, would yield the highest fiber retention during the recycling process.

End use characteristics and testing

Several fabric properties were examined to assess recycling suitability, several parameters were examined, such as: loop density, loop length, square mass (weight) [g/m^2], etc. (Table 1). These parameters are important because they determine fabric weight, length, and dimensional stability, which all have an impact on the fabric's performance in various applications. To ensure consistency in the experiments, the fabrics were knit on a machine with the same gauge, loop length, yarn type, and yarn count. The mechanical qualities and performance of knitted textiles are heavily influenced by loop density, which is assessed on both the front and back of the fabric. In addition, fiber length was also investigated as it is a significant aspect in the recycling process. Ten samples of raw yarn, each measuring 50 cm, were obtained to assess fiber length distribution using ISO 6989:1981 Method A [12], in which an investigation of 100 fibers per yarn was made. Yarn was untwisted and the fibers were carefully removed from the yarns to determine their respective length using a WIRA Instrumentation machine, specifically designed for precise single fiber length measurements. Furthermore, to assess the fiber length within the fabrics, samples from 1 cm to 10 cm per each fabric were collected, with every fabric sample unraveled back into yarn. For every fabric pattern—Rib 1x1, Double Jersey, and Interlock—10 samples of yarn were collected for each fabric length for loop length examination. This means that for each fabric length (from 1 cm to 10 cm), 10 separate yarn

Table 1. Knitted fabric parameters.

Samples	S1	S2	S3
Garment	T-Shirt	T-Shirt	T-Shirt
Fiber Content	70% merino wool/ 30 % mulberry silk	70% merino wool/ 30 % mulberry silk	70% merino wool/ 30 % mulberry silk
Fabric Type	Weft knit, Rib1x1	Weft knit, Double Jersey	Weft knit, Interlock
Areal Density [g/m^2]	218	214	221
Yarn Fineness [tex]	22.7	22.7	22.7
Loop Length [mm] (per 10 cm)	61.25	65.87	76.51

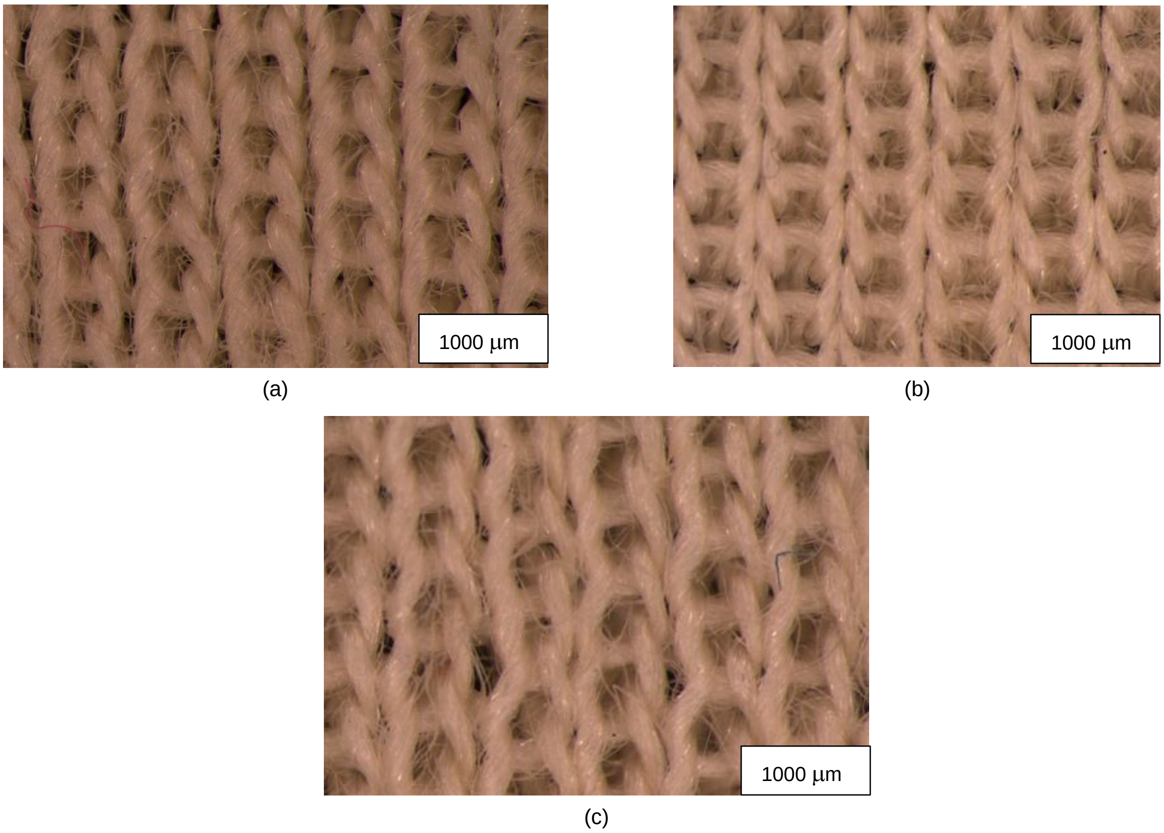
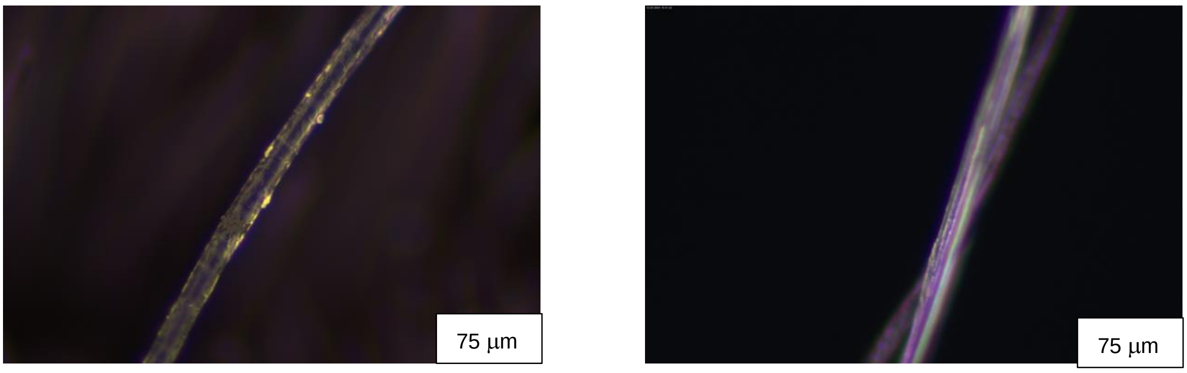


Figure 3. Microscopic images of three knitted patterns: (a) rib1x1, (b) double jersey, (c) interlock with a scale of 1000 µm.



(a) (b)

Figure 4. Fiber identifying on microscope with a scale of 75 µm: (a) wool fiber, (b) silk fiber.

Table 2. Loop density of 3 types of knitted fabrics [cm^{-1}].

	Wale			Course		
	MEAN [mm]	**STD [mm]**	**CV [%]**	**MEAN [mm]**	**STD [mm]**	**CV [%]**
Rib 1x1	10.7	0.67	5.1	9.8	0.42	4.3
Double Jersey	13.2	0.63	4.8	10.2	0.42	4.1
Interlock	13.6	0.52	3.8	13	0.67	5.1

samples were carefully unraveled and tested for fiber length with the same ISO 6989:1981 method [12]. This detailed process allowed for a precise evaluation of how cutting affects the fibers within the fabric structure.

Knitting machine

The knitted fabric samples were produced in a circular double bed knitting machine, namely a Terrot type RH 216-1. This machine features an E20 gauge, allowing it to make efficient and high-quality fabrics. The machine was set up to knit three fabrics (Rib1x1, Double Jersey, and Interlock) with the same yarn blend. This continuous yarn specification ensures that the three fabric samples are comparable, allowing for precise study and comparison of their end-of-use qualities. The main factor that influences the rows and the columns of the fabric is the machine gauge, that played a key role in determining the structure and density of the rows and columns in each knitted fabric, influencing the overall fabric characteristics, with the yarn evenly distributed in the whole fabric (length, width etc.).

Fiber length measurement

Fiber lengths were measured using a WIRA Instrumentation machine (manufactured in Italy), specifically designed for precise single fiber length measurements. The assessment began by measuring fiber lengths from ten raw yarn samples, each 50 cm long, to establish a baseline for fiber length distribution prior to recycling. Fibers were subsequently extracted from the leftover fabric, which had been precisely cut into samples of varying lengths, ranging from 1 cm to 10 cm. This step aimed to thoroughly assess how the cutting process affected fiber length. For each fabric sample, 100 individual fibers were carefully analyzed [12].

RESULTS AND DISCUSSION

Loop density

The loop density data (Table 2) provide valuable insight on the structural properties of the knitted fabrics investigated in this pre-consumer waste recycling research.

Analysis found that the Rib 1x1 sample designation had a wale density of 10.7 loops per centimeter and a course density of 9.8 loops per centimeter, implying a balanced and consistent distribution of loops throughout the fabric. The loop density for the Double Jersey pattern was determined to be 13.2 loops per centimeter in the wale direction and 10.2 loops per centimeter in the course direction. When compared to Rib 1x1 and Interlock, Double Jersey's loop density resides between the two, providing a good combination of density and flexibility. The tension used in Double Jersey is higher than in Rib 1x1, leading to a denser wale structure, but the course direction remains relatively less dense due to the fabric's inherent elasticity and double-layered construction. In comparison, the Interlock sample designation had a higher loop density, with 13.6 loops per centimeter in the wale direction and 13 loops per centimeter in the course direction, indicating a denser and tighter knit fabric construction.

Fiber length distribution in raw yarn length

The yarn producer's data sheet reported an initial fiber length of 76.2 mm for both wool and silk fibers. To assess the actual fiber length distribution, ten raw yarn samples, each 50 cm in length, were analyzed using the aforementioned ISO method, which involves examining 100 fibers per sample. The yarn was carefully untwisted, and individual fibers were extracted for precise measurement. Cross-verification of the results revealed a minimum fiber length of 72.8 mm, a maximum of 74.2 mm, and an average of 73.4 mm, with a standard deviation of 0.47 mm and a coefficient of variation of 0.64 %. These findings, illustrated in Figure 5, provide a more accurate understanding of the actual fiber length, which is a critical parameter for evaluating recycling efficiency.

Distribution of fiber length and yarn length (loop length) in cut fabrics

To determine the influence of different cutting lengths on the fiber length, the fabrics were cut in samples from 1 cm till 10 cm in course direction. Afterwards the loops of the fabric pieces are unraveled. The loop length for 10 cm on each of the knitted fabrics is shown in Table 1. The analysis focuses on the course direction (width) because the loops that define the structure of weft knitted fabrics are aligned in this direction (Figure 6).

The loop length (LL) of 10 cm fabric samples for the three knitted patterns shows significant variation in both average loop length and consistency. The Interlock design has the longest mean loop length (76.51 cm), indicating a higher yarn need per unit length than the other patterns.

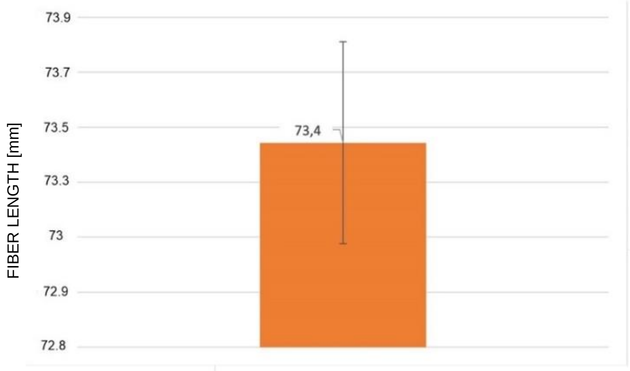


Figure 5. Mean [mm], standard deviation [mm], and coefficient of variation [%] of fiber length in ten raw yarn samples.

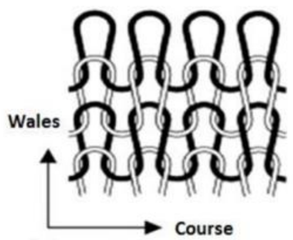


Figure 6. Course and wale direction [13]

Double Jersey, with an average loop length of 65.87 cm, is slightly longer than Rib 1x1, but much shorter than Interlock. The Rib 1x1 pattern has the least mean loop length of 61.25 cm and is the most yarn-efficient for this fabric sample size. For the fiber length distribution in cut fabric length were analyzed three knit patterns: Rib 1x1, Double Jersey, and Interlock. Fiber lengths were measured across fabric sample lengths of 1–10 cm for each pattern, following ISO 6989:1981 Method A. The experimental setup included 100 fiber measurements per sample, with ten yarn samples unraveled per fabric length. The analysis incorporated 95% confidence intervals (CIs) to quantify variability and precision in fiber retention (Figure 7).

The analysis of the Rib 1x1 pattern showed fiber lengths ranging from 44.8 mm to 74 mm within the yarn. It was found that cutting the fabric into lengths greater than 6 cm - ideally between 7 cm and 10 cm -helped retain fiber lengths close to 73.4 mm to 74 mm. This better fiber retention in Rib 1x1 can be attributed to the lower yarn tension during knitting, allowing the fibers to preserve more of their original length. For the Interlock pattern, fiber lengths varied from 46.6 mm to 74 mm, with the optimal cutting length identified between 5 cm and 10 cm. The higher yarn tension used in this pattern resulted in a tighter knit, which caused a slightly greater reduction in fiber length during recycling compared to Rib 1x1. However, despite this reduction, the denser structure of Interlock provided sufficient strength in the recycled fibers. External influences, such as environmental conditions and temperature shifts, may also influence the variability exhibited at the 4 cm length, affecting the fabric's structure. Humidity and temperature changes are known to affect the mechanical properties of textiles, such as fiber tension and elasticity, potentially worsening the effects of loop density and yarn tension when cutting.

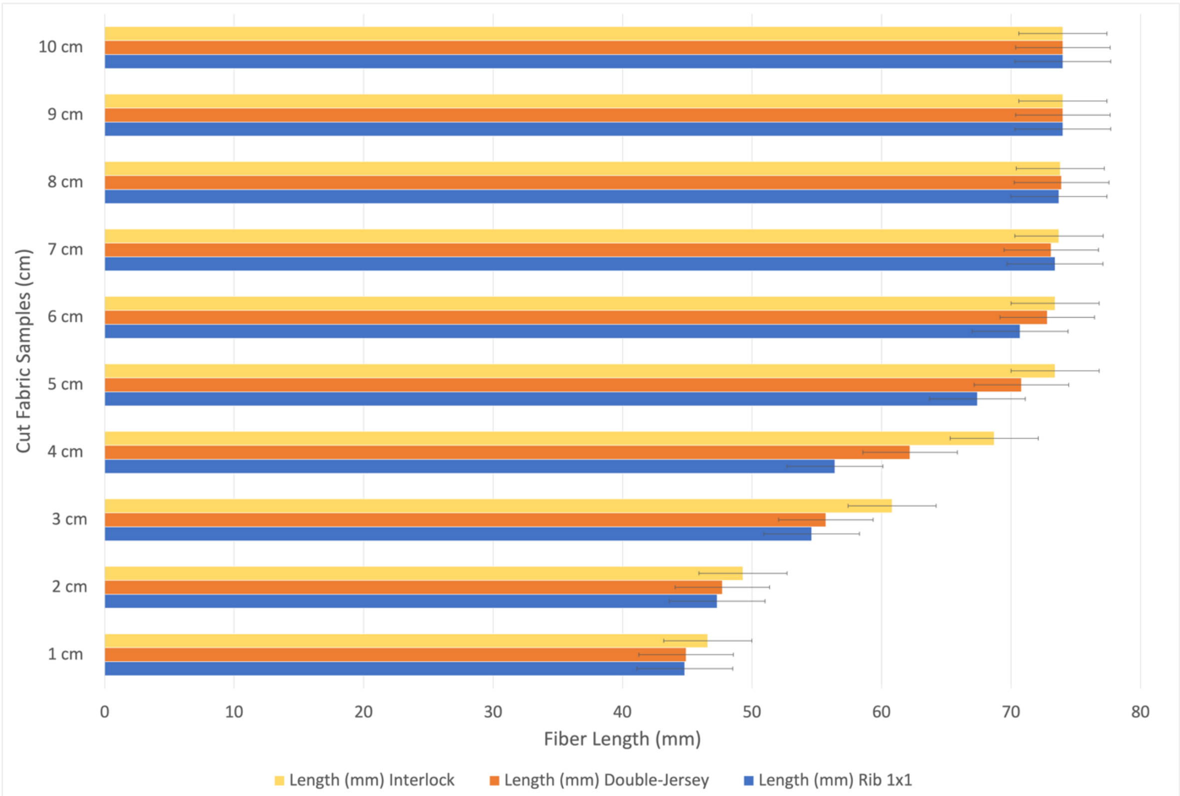


Figure 7. Fiber length of wool-silk blends from cut pre-consumer-waste fabrics (Rib 1x1, Double Jersey, and Interlock).

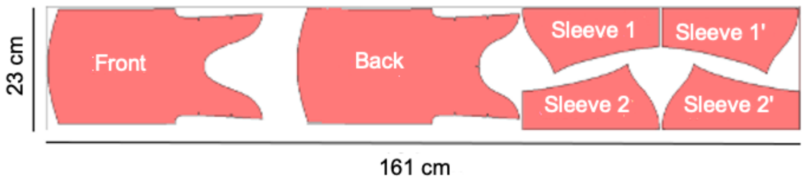


Figure 8. Basic T-Shirt Cutting Pattern (authors own illustration).

Double Jersey pattern offered additional insights into recycling efficiency. Fiber lengths in Double Jersey samples ranged from 44.9 mm to 74 mm, and the best cutting length for recycling was determined to be between 6 cm and 10 cm. While this range is similar to the Rib 1x1 and Interlock patterns, Double Jersey's looser structure resulted in slightly shorter average fiber lengths, which could influence the strength and quality of the recycled yarn. The higher tension applied in the wale direction during Double Jersey knitting created a more compact fiber arrangement, leading to a slight reduction in fiber length. However, by maintaining a cutting length between 6 cm and 10 cm, the resulting fiber lengths remained close to the original 72.8 mm to 74 mm. The diagram displays the fiber lengths for three knit patterns—Rib 1x1, Double-Jersey, and Interlock — across different fabric sample lengths, with 95% confidence intervals (CI) given to show measurement variability. The error bars show the confidence intervals, which provide information on the precision of fiber length retention. Rib 1x1 has the lowest fiber retention, especially in shorter fabric samples, and exhibits greater variability, as indicated by bigger error bars. With a CV of 14.20% and a CI of 5.33 mm, Rib 1x1 has the most variability of the three knit patterns, indicating less consistency in fiber length preservation after recycling. The coefficient of variation (CV) for Interlock is 12.66 %, showing moderate variability, and the CI (5.04 mm) is quite narrow, indicating a consistent and stable fiber retention mechanism. Double-Jersey has similar tendencies but has slightly shorter fibers than Interlock, with more apparent variability. The CV for Double-Jersey is 13.50 %, indicating slightly more variability than Interlock, while its CI (5.20 mm) indicates significantly less precision.

An important observation is that, as shown in Figure 7, after a fabric length of 7 cm, the fiber lengths in the cut samples became identical. This suggests that the cutting dimensions - whether 7x7 cm, 10x10 cm, or even 15x15 cm - have little effect on fiber length retention beyond 7 cm. The fibers in these samples reflect their true length, and this consistency can only be ensured through careful examination of the fabric pattern.

Impact of cutting size and pattern type

In this sub-chapter, fiber lengths within the leftover fabric from pre-consumer wool-silk waste were analyzed. During this investigation, it was found that this waste varies significantly in both shape and size. This prompted the question of how to determine optimal cutting dimensions before recycling to maximize fiber retention. To explore this, a commonly used garment-cutting pattern of a T-Shirt studied, identifying different fabric lengths in the leftover material.

Figure 8 presents a template a T-Shirt cutting pattern, commonly used by garment producers and designers, illustrating the cutting procedure and highlighting areas of leftover fabric. These leftover pieces, whose size and shape are key to fiber retention during recycling, play a crucial role in determining the fiber length outcome. In this case study, the knitted fabric measured 161 cm in length and 23 cm in width, although due to the tubular production on a circular double-bed knitting machine, the actual fabric width would be 46 cm if cut open.

The pink area represents the fabric used for garment production, while the white area shows the leftover pre-consumer waste. The fabric used for two garments is 161 cm, yielding an efficiency of 73 %. The main objective is optimization of the recycling process through the minimization of the fiber length reduction during the process, therefore to reduce the amount of the fiber waste.

Image analysis

Image processing techniques were employed to automate the measurement of fiber lengths in the white area of the fabric pattern depicted in Figure 8, enhancing process efficiency and reducing measurement errors associated with manual methods. The script, developed in Python using OpenCV, Numpy, and scikit-image libraries, first converts the original image to grayscale and then applies the Otsu threshold method to convert it to binary format [14, 15]. To ensure accurate detection, a single-pixel white padding is added around the fabric parts to prevent border interference. Subsequently, two sets of functions are utilized to identify and store the length and location of textile parts in each column of the image. The pixel-based results are then converted to millimeters using metadata from the original image (Figure 8), then the program rounded the lengths to mm. The outcomes ranged from 1 mm to 239 mm. It means each fiber is flagged with red, light blue, blue, and green, based on its detected length. In a further step, to visually represent this division, the fibers are shown with their represented tag-colors in Figure 9(a), 9(b) and 9(c).

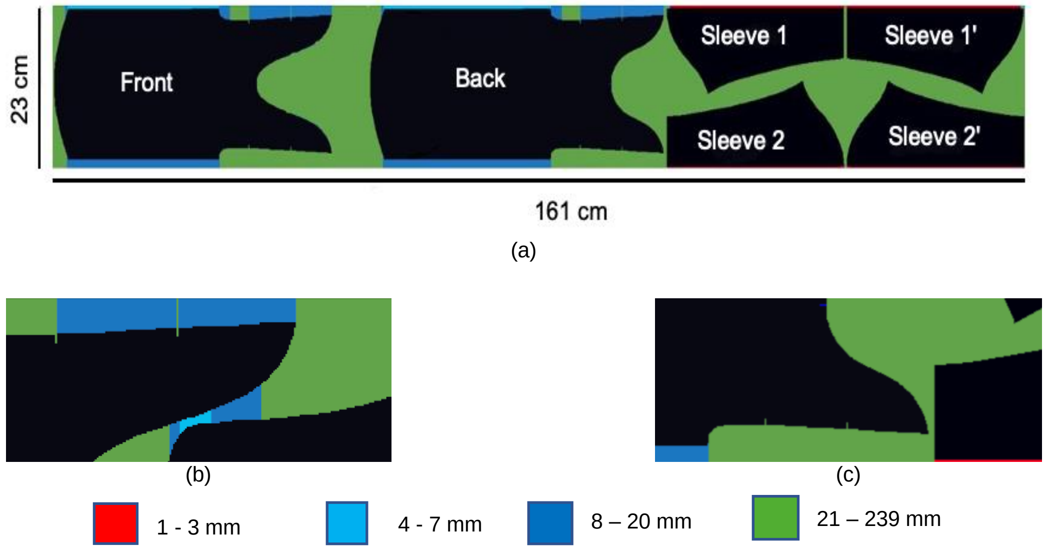


Figure 9. (a) Cutting Pattern colored in accordance with the length of the detected fibers after the cutting process; (b) and (c) magnified view of fiber length distribution in the cutting pattern after the cutting process (authors own illustration).

Table 3. Fabric length [mm] from the leftover material in the cutting pattern; conversion and categorization to fiber length [mm] with programming language.

Categories	Fabric Length [mm]	Fiber Length [mm]
	1 3	4.5 13.4
	4 5 6 7	17.8 22.4 26.8 31.3
	8 9 10-15 16-20	35.8 40.3 45.3 46.8
	21-25 26-30 31-35 36-40 41-45 46-50 51-55 56-60 61-65 66-70 71-239	51.2 55.0 59.4 62.0 65.4 67.3 69.7 70.4 71.6 72.9 74.0

The fabric lengths resulted from this analysis, then were multiplied from the program with the average values from the Figure 7. The fiber length for very short fabric pieces, such as a 1 mm leftover, is predicted to be 4.5 mm. This proportionate association persists throughout the dataset, indicating a progressive rise in fiber length as fabric length increases. As fabric lengths increase, this pattern remains visible. For example, fabric leftovers of 10-15 mm equate to a fiber length of 45.3 mm, while those measuring 16-20 mm correspond to a slightly longer fiber length of 46.8 mm. This slow increase implies a direct but non-linear relationship between fabric length and fiber length, implying that as fabric length grows, the converted fiber length reaches a limit. This plateau effect is evident in bigger fabric lengths, as fiber length reaches approximately 74 mm for fabric remnants ranging from 71 to 239 mm, implying that the conversion rate stabilizes after a certain fabric length.

Table 3 indicates that the conversion from fabric to fiber length is not purely linear, with diminishing rewards as length increases. This data is critical for evaluating fiber recovery efficiency in textile recycling, especially when planning for fiber reuse in new yarn manufacturing, where fiber length uniformity can influence yarn quality and textile performance. To visualize the outcome, the different fiber lengths are flagged with different colors (red for 1 mm to 3 mm, light blue for 4 mm to 7 mm, dark blue for 8 mm to 20 mm, and green for 21 mm to 239 mm). This categorization not only helps identify fiber lengths but also aligns each length range with an adequate recycling process, improving sorting accuracy for spinning applications. These insights allow manufacturers to optimize cutting techniques to minimize the generation of less valuable shorter lengths and maximize the retention of high-contributing ranges. This analysis serves as a foundation for directing specific fabric lengths toward appropriate spinning methods (e.g., short-staple, medium-staple, or long-staple), further enhancing the recycling process. By identifying and focusing on the most impactful categories, this approach aids in optimizing textile waste recovery and contributes to sustainable practices in circular textile production.

Categorization of the leftover fabric waste

The classification of residual fabric lengths was meticulously determined by evaluating the remaining fabric fragments, as shown in Figures 9(a), 9(b), and 9(c), and converted to fiber lengths as shown in Table 3. These fragments, often discarded as waste, are further categorized in different spinning processes according to their length and are illustrated in Figure 10.

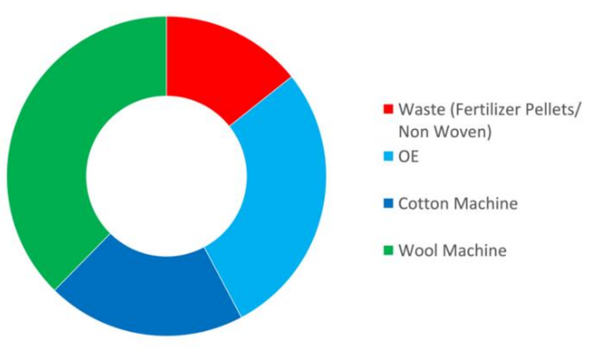


Figure 10. Classification of pre-consumer-waste prior to cutting process [%].

The next step in the recycling process is the spinning process where the fibers are processed by different spinning processes. The long staple fibers can again process in a long staple spinning machinery for wool (green fibers > 50 mm). This is the largest portion with 37.6 % of the fabric.

The fibers with middle fiber length can be processed in the so-called Cotton spinning process (dark blue: from fibers between 35.8 mm to 46.8 mm). Additionally, 20.1 % of the fabric is categorized for processing with cotton spinning machinery. This category requires moderately longer fibers, making it suitable for re-spinning into new yarns. The shorter fibers can be processed in the Open-End spinning process (light blue: from 17.8 mm to 31.3 mm), with a 27.9 % of the fabric is suitable for this spinning process. The OE spinning system is particularly efficient for shorter fibers, making it an ideal choice for this category of residual fabric.

And the rest 14.3 % (from 4.5 mm to 13.4 mm) is too short for dry spinning process. This waste we still can use for non-woven processes or for fertilizer pellets. This classification system optimizes the recycling process by ensuring each type of residual fabric is directed to the most appropriate reprocessing method, maximizing efficiency and sustainability.

Future research

Future research should expand on these findings by looking at a wider range of fabric designs, such as Single Jersey and other core knit structures, in order to gain a more complete understanding of fiber length and retention across diverse patterns. Incorporating these additional patterns would allow for a more comprehensive investigation of the basic knit structures, increasing our understanding of how different knit types effect fiber retention and waste management outcomes.

The following crucial step is to apply these insights directly to cutting machine procedures. This would entail applying the optimal cutting lengths and techniques discovered in this work to actual applications, allowing for the optimization of cutting machine settings for different fabric types and patterns. Researchers can improve the efficiency and precision of fiber recovery by refining the cutting process, ensuring that the maximum feasible fiber length is kept throughout recycling. Furthermore, this study will focus on optimizing the shredding process that occurs after cutting. An efficient shredding process would be designed to manage the various fabric lengths and thicknesses discovered during cutting, ensuring that fibers remain as intact as possible, improving the quality of recovered fibers and lowering waste. Fine-tuning the shredding parameters to meet the individual needs of various knit patterns could considerably increase the production and quality of reusable fibers. By implementing automated technologies, such as advanced fiber measurement and sorting systems, recycling facilities could significantly increase efficiency, reducing labor costs and minimizing resource usage. Exploring automation's potential to streamline the recycling process and decrease material loss would contribute to a more sustainable approach to textile waste management.

CONCLUSIONS

This study emphasizes the importance of fabric designs and cutting lengths in maximizing fiber retention when recycling wool and wool-silk mixes, where these findings suggest that cutting fabric into 7 cm lengths efficiently reduces fiber loss, especially in the Interlock design, which had the maximum fiber retention due to its dense loop structure. This method kept fiber lengths near to the original length, demonstrating that targeted cutting tactics and fabric design are critical in minimizing fiber damage throughout the recycling process. Statistical evaluations, including confidence intervals and coefficients of variation, show that Interlock's compact structure is more consistent in fiber retention than Rib 1x1 and Double Jersey, which have higher variability in fiber length preservation. These findings highlight the importance for employing appropriate fabric structures and cutting procedures to improve the quality of recycled yarn, establishing wool-silk blends as a valuable, sustainable resource in closed-loop textile production systems. The study's classification of fiber lengths for certain spinning processes (e.g., Open-End, Cotton, and Wool) demonstrates how targeted recycling procedures can enhance resource efficiency by diverting waste to appropriate reprocessing technologies. Advancing these developments will help to create more environmentally friendly textile processes and a sustainable approach for managing textile waste.

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