



# Closed loop mechanical recyclability of post-consumer waste wool fabrics based on fibre length retention

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## 1. Introduction

Sustainable development of the textile industry relies heavily on transitioning to circular economies, where constituent fibre materials in post-consumer products are not wasted and remain in longer-term circulation. Post-consumer wool clothing has been mechanically recycled as part of a closed-loop industrial manufacturing system since the early 1800s traditionally using woollen spinning to produce yarns suitable for clothing fabrics (Russell et al., 2016). Open end (rotor) spinning of recycled wool is also used for yarn production, particularly to produce yarns for lower quality fabrics, and substantial quantities of recycled post-consumer wool is consumed by the nonwovens industry to produce industrial, non-clothing products as well (open loop).

Although virgin wool represents only about 1% of today's global fibre consumption, a relatively high proportion (ca. 6%, compared to other fibres) equating to about 70,000 tonnes is recycled (International Wool Textile Organisation, 2022; Textile Exchange, 2022). Such closed loop mechanical recycling of post-consumer waste, along with best-practice care and utilisation of resulting fabrics by the consumer, means it is possible to significantly prolong the active lifespan of wool fibre, reducing overall cradle-to-grave environmental impacts (Wiedemann et al., 2022). Not accounting for specific textile products at the end-of-life that are recycled, and assuming only one additional use cycle before disposal, can lead to misleading conclusions about the full life cycle environmental impacts of fibres such as wool (Bach et al., 2018; Sandin and Peters, 2018).

Traditionally, in wool recycling fibre is reclaimed from both pre-consumer/post-industrial (fibre, yarn, fabric, and garment production waste) and post-consumer (discarded clothing) sources (Russell et al., 2016). The wool waste is sorted by colour, fibre content, fabric construction (woven or knitted) and by yarn construction. Following sorting, the wool waste is mechanically processed, i.e. 'pulled' into loose recycled fibre suitable to produce yarns for apparel or interior fabrics (Hawley, 2006). Where colour sorting of the waste is performed, new

fabrics for clothing can be produced that do not require stock or piece dyeing.

For recycled wool to be suitable for woollen yarn production as part of a closed-loop recycling system, care must be taken to minimise deterioration in fibre properties such as mean fibre length and fibre tensile properties during the pulling process (Russell et al., 2016). In mechanical recycling of knitted or woven fabrics, frictionally restrained fibres are subjected to tension and bending forces due to the action of toothed or pinned rollers to achieve fibre-fibre opening, which usually leads to a degree of fibre breakage with potential for morphological damage. Similar conditions apply in opening and carding processes prior to yarn production (Gharehaghaji and Johnson, 1995; Hearle et al., 1998).

It is common to blend recycled wool from different sources (pre- and post-consumer), with virgin wool, or man-made fibres to compensate for any fibre physical property deficits resulting from recycling processes, and to meet the strict performance specifications of new fabrics.

As with other forms of textile recycling, commercial practice and know-how between different wool recyclers in terms of process configurations and machine settings varies, leading to differences in the properties of the resulting fibre, as well as environmental impacts. The M Wool® production process developed by Manteco (Italy), is an example of an industrially established, wool mechanical recycling operation that processes pre- and post-consumer wool waste, to enable high quality woollen yarn manufacture, as part of a closed loop system. Commercially, woollen yarns produced with recycled fibre from the M Wool® process contain high proportions of post-consumer recycled wool (up to 85%), and the yarns are woven into new fabrics meeting the quantitative performance requirements of international brands and retailers. By enabling waste wool to be recycled in this way, M Wool® is reported to reduce the carbon footprint of wool fibre to 0.1–0.9 kg CO<sub>2</sub> eq. from 10 to 103 kg CO<sub>2</sub> eq. for generic virgin wool (Bianco et al., 2022).

Practically, the feasibility of spinning woollen yarns containing

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recycled wool suitable for making new clothing fabrics, requires a retained mean fibre length of at least ca. 20 mm (Manteco, Personal Communication, n.d.; Textile Exchange, 2021), coupled with a minimal reduction in wool fibre tensile strength (Russell et al., 2016). Maintenance of such key fibre properties is therefore fundamental to maintaining the economic value of recycled fibre. The basic association between a material's economic value, before and after recycling based on differences between virgin and recycled properties, as well as the cost of recycling has led to the introduction of recyclability indices (R) such as those proposed by Villalba et al. (2002). Metals such as copper, which possess properties after recycling equivalent to the virgin material, achieve very high R values of  $\approx 1$ , because of the availability of cost-effective recycling processes, and properties after recycling that are comparable to the virgin material. In contrast, R values for polymeric materials such as textile fibres are normally substantially lower, due to relatively high recycling costs versus virgin fibre prices, and differences in the material properties before and after recycling (Villalba et al., 2002). Previous studies on the development of recycling indices have focused on the price of materials and the economic viability of recycling processes (Russell et al., 2010; Villalba et al., 2004; Ward et al., 2013). Based on typical fibre compositions found in post-consumer clothing donations in the UK, it has been estimated that to be economically viable, a minimum target R-value of 0.32 is required (Ward et al., 2013). In other work, the Recyclability Potential Index (RPI) for textile fibres incorporates economic and environmental factors, including the impacts of virgin fibre production and disposal, versus recycling (Muthu et al., 2012). However, previous approaches have not specifically considered the effects of mechanical recycling on the retained length of recycled fibres, which affects their economic value, or the additional complexity that some wool fibre types are potentially more recyclable than others.

One of the most challenging aspects of setting up and optimising modern mechanical recycling processes to minimise wool fibre breakage, and therefore promote the fibre's economic value, is taking account of the fibre's natural variability, as well as variations in the yarn and fabric structure of post-consumer clothing. This study presents the first quantitative analysis of how initial fibre length in industrially representative wool and cashmere post-consumer, waste fabrics prior to recycling, influences retained fibre length as well as fibre tensile strength after recycling in the MWOol® production process. Based on the experimental data for retained fibre properties, a new recyclability

index is also introduced, enabling estimates to be made about the longer-term mechanical recyclability of wool and cashmere fibres.

## 2. Materials & methods


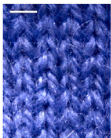
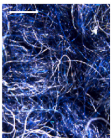

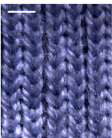

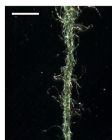
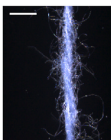
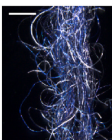
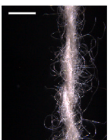
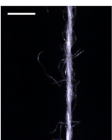
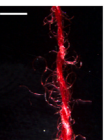
### 2.1. Sample wool fabrics

Six different post-consumer waste garments were supplied by one of Europe's largest wool recycling companies (Manteco, Italy), as summarised in Table 1. The garments denoted S1–S6, were representative of those mechanically recycled by Manteco in their MWOol® production process, and all comprised weft knitted fabric constructions with either woollen or worsted constituent yarns. In all samples, the basic fibre compositions were homogeneous, i.e. either 100% wool, or 100% cashmere, exclusive of trims. While not specified on the fibre content label, S4–S6 were found to have mean fibre diameters of  $\leq 22.5 \mu\text{m}$ , such that they are likely to comprise merino wool (Scobie et al., 2015). Such post-consumer fabrics for recycling are globally sourced via an established supply chain, involving waste collection and pre-sorting, a second sorting step, and then mechanical recycling to reclaim fibres for production of new yarns and fabrics in Italy. The source of the waste garments and details of the material flows have been previously described (Bianco et al., 2022).

### 2.2. Mechanical recycling processes and methods

Terms to describe pulling processes in mechanical textile recycling include shredding, fraying and garnetting, among others, depending on the configuration of specific processes and local traditions. Mechanical pulling of all fabric samples S1–S6 was performed by Manteco®, Italy. Traditionally, industrial-scale mechanical wool recycling involves sequential processes to extract the fibre, which can involve dry and wet processing. Wet state mechanical recycling of wool fabrics is a unique process developed specifically to minimise fibre breakage especially in the case of worsted woven fabrics. Herein, the specific process steps used in the MWOol® production process to pull the waste clothing relied entirely on dry processes. To enable precise tracking of the effects of mechanical recycling in this experimental work, it was necessary to process single, rather than mixed waste clothing feedstocks and therefore, lab-scale equipment in Manteco's Circular Lab was used, which

**Table 1**  
Industrially sourced post-consumer knitwear fabric samples.

Sample	S1	S2	S3	S4	S5	S6
<b>Garment</b>	Shetland cardigan	Cashmere cardigan	Aran jumper	Zip-up cardigan	Jumper	Cardigan
<b>Fibre Content</b>	100% Lambswool	100% Cashmere	100% Pure New Wool	100% Pure New Wool	100% Pure New Wool	100% Pure New Wool
<b>Fabric Type</b>	Weft knit, single jersey	Weft knit, single jersey	Weft knit with cables	Weft knit, single jersey	Weft knit, 2 x 2 rib	Weft knit, single jersey
<b>Weight, g/m<sup>2</sup></b>	201	207	668	242	242	183
<b>Stitch density, stitches/cm<sup>2</sup></b>	54	42	3	20	130	72
<b>Yarn type</b>	Single, Woollen	2-ply, Woollen	6-ply, Woollen	2-ply, Woollen	2-ply, Worsted	2-ply, Worsted
<b>Fibre diameter, <math>\mu\text{m}</math></b>	25.9	19.7	38.9	22.5	19.9	20.5
<b>Fabric<sup>a</sup></b>						
<b>Yarn<sup>a</sup></b>						

<sup>a</sup> Scale bar = 2 mm.

replicated the large-scale commercial M Wool® production process (Fig. 1).

Before recycling, each garment was cut in half lengthwise down the centre line of the body. Half of the garment was mechanically recycled (after removal of trims and sewing thread), and half kept intact. In Fig. 1, garments for recycling were cut into approximately 15 x 30–50 cm strips and fed on a conveyor to a pair of nipped feed rollers. While held by the feed rollers, the action of the pinned opening roller is to extract yarns and fibre from the arriving fabric, essentially causing it to disintegrate by fraying apart. Important settings governing the degree of fibre opening, such as the feed roller-to-opening roller distance (approximately 35 mm), the relative feed and opening roller surface speeds, and the pin density remained fixed throughout the experiments. Within the process, fibres from the pinned roller were centrifugally directed to a suctioned condenser roller, that removes particulate material (dust) and collects a layer of pulled fibre for continuous delivery to the collection box.

To compare results from the lab-scale and full-scale commercial M Wool® process (Fig. 2), a sample of processed knitwear was taken from full-scale production, and the differences in retained fibre length were measured and compared to the combined values of the processed S1–S6 samples. Comparable results between industrial and lab-scale processing would then suggest that any changes observed in the laboratory samples because of the recycling process are representative of what would be expected in larger-scale industrial production.

### 2.3. Fibre sampling

To determine the mean fibre length and fibre length distributions, fibres were sampled prior to, and after recycling according to the recommendations in BS EN 12751:1999, sections 4.3 and 3.3, respectively. For the knitted fabrics, four yarns were sampled from consecutive courses, and equal numbers of fibres were sampled along the length of

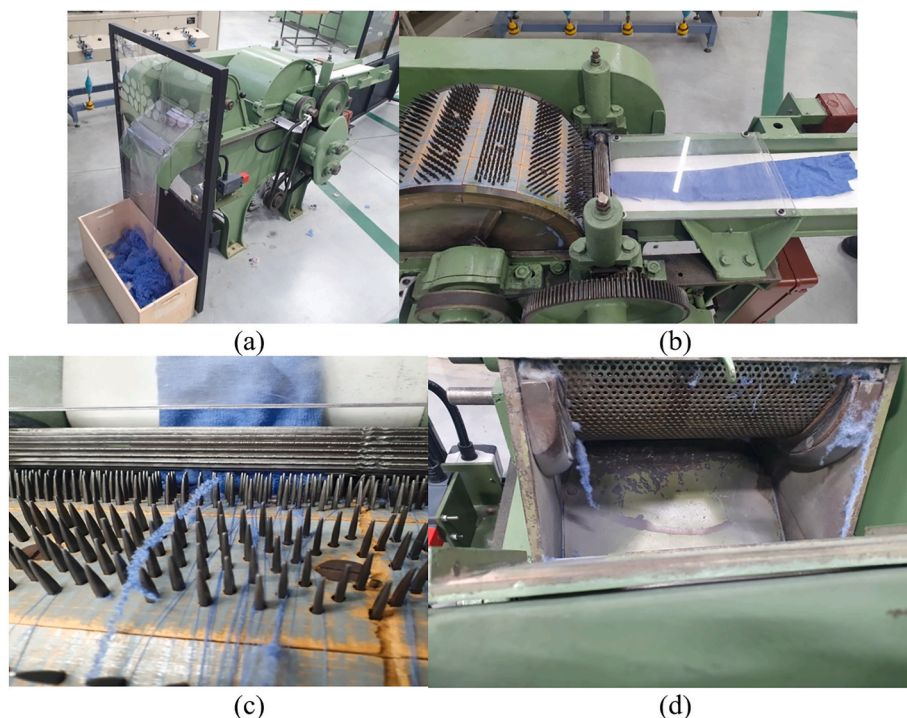
each yarn. The recycled fibre was sampled from five different zones, with the blending and halving performed manually.

### 2.4. SEM imaging

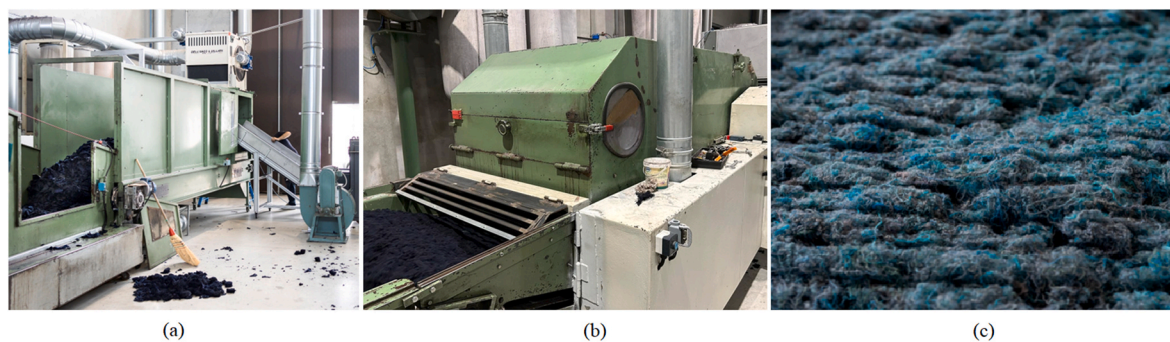
The effects of recycling on longitudinal fibre morphology were studied by scanning electron microscopy operating in secondary electron image (SEI) mode, at an accelerating voltage range of 5–8 kV. At least three separate images per sample were also taken of fibre ends at random to enable visual assessment of likely modes of fibre breakage.

### 2.5. Fibre length distribution measurements

Fibre length distribution measurements for each sample were obtained according to ISO 6989:1981 Method A, based on  $n = 100$  fibres per sample. Initial fibre length was determined by carefully extracting fibres from yarns in the fabrics prior to recycling. Measurements were made using a glass ruler with loupe (PEAK 1972-100) on white or black velvet board for contrast. Instead of smearing the glass plate with petroleum jelly, each fibre was sampled with tweezers, laid flat on the velvet surface, and the glass ruler placed over the top to measure. Preliminary fibre length measurements revealed most fibres sampled were  $>10$  mm in length, with a small proportion (approximately 5%) in the region of 5–10 mm, and the rest 0–5 mm, which is considered “dust” in the industrial process. Given the focus was on re-spinnable fibre lengths, this dust component of  $<10$  mm in length were not counted. Mean fibre lengths were calculated using individual fibre length measurements instead of the characteristic distribution mean value calculation outlined in section 8.2.1 of the test method. When using a bin size of 1, the characteristic mean values of every sample differed by exactly  $+0.5$  mm. Owing to this consistency across all samples, it was reasoned that the use of individual fibre length means for statistical analysis would not involve a significant change to the interpretation of results. Fibre length



**Fig. 1.** Lab-scale pulling process for mechanical recycling of wool and cashmere, showing: (a) Full machine with guards fitted (necessary for operation), consisting of feed conveyor, opening roller section, condenser roller section and collection box for the delivery of pulled fibre; (b) Feed and opening section of the machine with guards removed (necessary for cleaning when not in operation), showing feedstock on the conveyor and view of pinned opening roller; (c) Close up of static pinned roller after operation showing fibres held by pins on the roller surface, and (d) Suctioned rotating condenser roller for removal of airborne particulate material, and collection of the pulled fibre prior to its delivery into the collection box.



**Fig. 2.** Industrial Scale M Wool® Production Process showing (a) Industrial pulling process; (b) Opener with produced fibres on conveyor and (c) Close up of pulled wool fibre.

distribution measurements and statistical analyses were carried out with Origin 2023b software.

### 2.6. Fibre tensile testing

Fibres were sampled from each group of length-measured samples and tested according to BS EN ISO 5079:2020, based on  $n = 25$  fibres per sample. Measurements were made using a 20 mm gauge length and 20 mm/min rate of extension. Pretension for each sample (before and after recycling) was calculated using the average diameter of the specimens and the density of non-medullated wool (Merrick and Scobie, 1997). Pretension values for the fibres taken from each sample were as follows: S1 = 6 mN, S2 = 4 mN, S3 = 15 mN, S4 = 5 mN, and S5-6 = 4 mN. The fibres were adhered to a test carrier card, but due to their delicate nature and natural crimp, pretension was not applied at the fibre mounting stage. As a result, the true gauge length was recalculated for each specimen as 20 mm plus the crosshead distance travelled before the specified pretension was achieved. Representative averaged tensile curves were created by selecting two tests from each sample, one closest to the mean stress at break, and the other closest to mean strain at break. The representative average curve of both the virgin and recycled conditions were then graphed together for comparison.

## 3. Results & discussion

### 3.1. Fibre morphology

Fig. 3 reveals the basic effects of mechanical recycling on wool and cashmere fibres. Only subtle changes in fibre surface morphology resulting from mechanical recycling in the M Wool® production process were observed. Evidence of fibre breakage was present consistent with previously reported effects of tensile and bending mechanical forces during the fibre opening process (Gharehaghaji and Johnson, 1995; Hearle et al., 1998). Using reference photos from these texts, particulate debris accumulated on fibre surfaces, and an instance of scale lifting (see for example, Fig. 3, S5 Longitudinal, Recycled) were also identified. Note that fibre end damage was also present prior to recycling, most likely due to fibre-metal friction during production, particularly in the carding process, which is an integral part of woollen and worsted yarn production (Fig. 3, S5 Fibre End, Initial). Abrasion damage, potentially accumulated during garment use, prior to its disposal was also identified in samples before recycling (Fig. 3, S1-4 and S6 Fibre End, Initial). It is important to mention that SEM imaging gave a qualitative overview of the fibre surface morphology and fibre ends.

### 3.2. Retention of fibre length following mechanical recycling

Table 2 and Fig. 4 report the mean fibre length results for each sample, and their accompanying fibre length distributions. Mean fibre length retention after mechanical recycling varied markedly between

samples, with sample S3 producing the lowest mean fibre length retention value (36.0%), compared to samples S5, S6, which produced intermediate values (63.1–70%), and samples S1, S2 and S4, which retained 80.8–98.0% of their initial values.

With reference to Fig. 4, remarkably similar fibre length distributions, as well as mean lengths were obtained for samples S1, S2 and S4 before and after recycling, whereas for other samples, notably samples S3 and S5, there were large shifts in fibre length distributions. Structural differences between samples in terms of fabric density would be expected to affect fibre frictional resistance and therefore the forces on fibres during the pulling process, which could partly account for variations in fibre breakage. S3 and S5 are also not single jersey constructions, which may be an additional contributing factor. The shoddy and mungo wool recycling systems, which traditionally emerged over two centuries ago, recognised that longer retained fibre lengths could be obtained by pulling low density post-consumer knitted, rather than woven fabrics because of differences in the propensity for fibre breakage (Fry, 1925). Note however that following recycling, samples S3 and S4 were at opposite ends of the spectrum in terms of their retained fibre lengths (36% vs. 98%, Table 2), despite having the two lowest knitted stitch densities among the six samples, as well as comparable yarn structures (woollen). The correlation between fibre length retention and fabric density is poor ( $r = 0.01415$ ) but if S3 is excluded as an outlier, there is a strong relationship of reduced fibre length retention as fabric density increases ( $r = -0.93662$ ), which is to be expected. S3 could be considered an outlier due to it being quite different from the other tested samples in respect to its basis weight, stitch density, number of yarn plies, and mean fibre diameter.

An indication of another important factor is provided by Fig. 4, which reveals a  $\sim 4x$  difference in the initial mean fibre length between samples S3 and S4 prior to recycling, suggesting that the mean fibre length in the fabric prior to recycling is also a major indicator of the retained length after recycling. Further evidence is provided by the results for Samples S1, S2 and S4, which had the lowest initial mean fibre lengths before recycling, but the largest percentage retained fibre lengths after recycling. Interestingly, when mean fibre length retention values are plotted as a function of the mean initial fibre length (Fig. 5), a linear relationship is observed ( $r = -0.9391$ ). When S3 is similarly excluded from the initial vs. retained fibre length correlation,  $r = -0.819$  which still indicates a strong relationship between those variables, even with the differences in fabric density, weight, or yarn ply. The percentage retained fibre length after recycling therefore appears to be heavily dependent on the initial mean fibre length, such that shorter wool types, e.g. merino, as opposed to longer cross-bred wools can be expected to be less sensitive to fibre breakage during mechanical recycling.

Similar sensitivity to fibre breakage as fibre length increases, is known to be present in mechanical pre-opening and carding processes, where fibres restrained within a feed roller nip are acted upon by pinned or toothed rollers (Scobie, 2019; Townend and Spiegel, 1946). Although

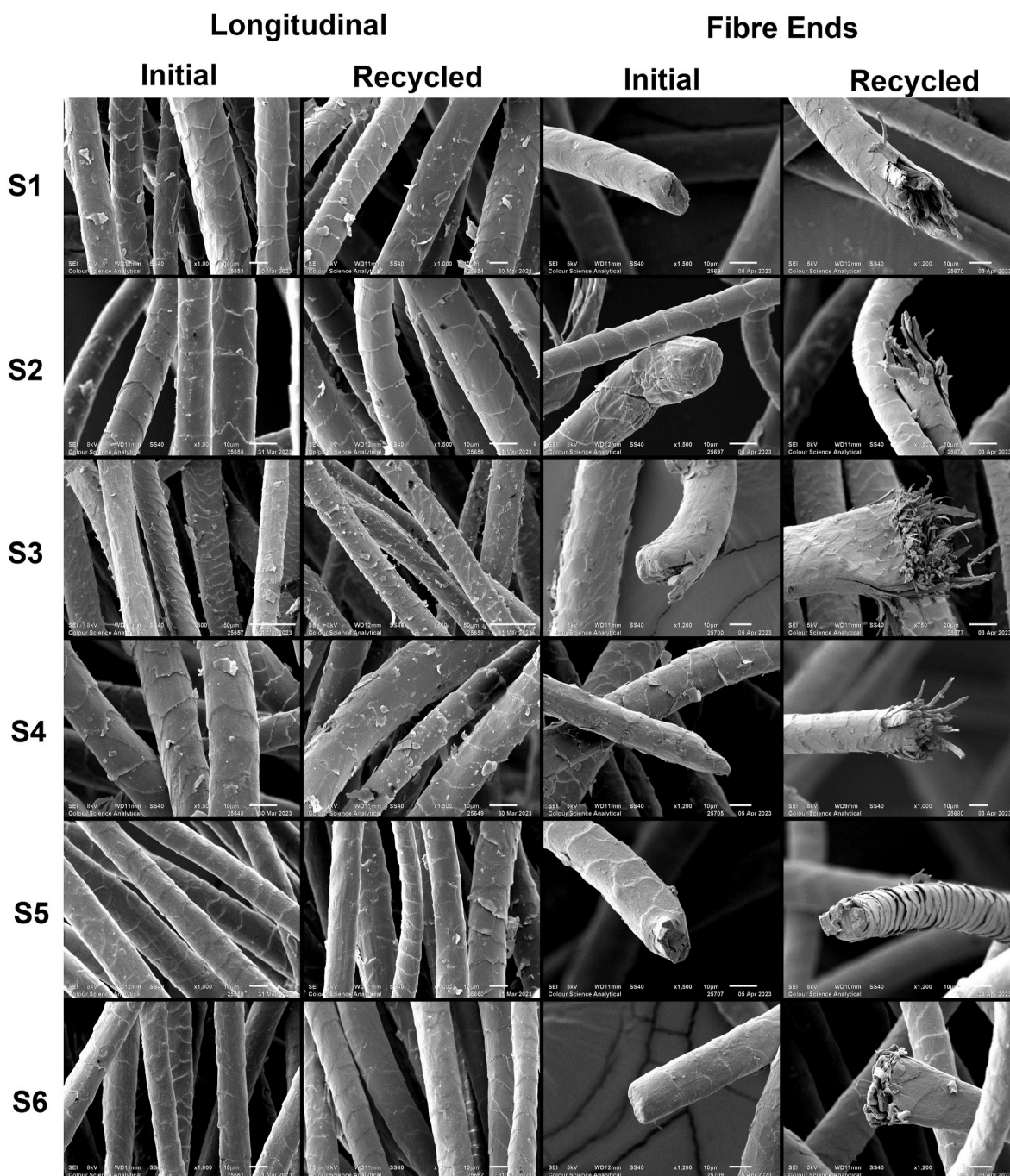


Fig. 3. SEM Micrographs of the Fibres in Samples (S1–S6) Before and After Recycling. All scale bars = 10 μm, except for S3 longitudinal images (50 μm) and S3 recycled end (20 μm).

**Table 2**  
Summary of initial and retained fibre length and mean fibre length retention before and after mechanical recycling for all samples (S1–S6).

Sample	Initial Mean Fibre Length, mm [SD]	Retained Mean Fibre Length, mm [SD]	Mean Length Retained (%)
S1	27.7 [9.5]	22.4 [8.3]	80.8 <sup>a</sup>
S2	40.7 [12.9]	35.1 [11.6]	86.3 <sup>a</sup>
S3	104.4 [34.4]	37.6 [15.1]	36.0 <sup>a</sup>
S4	31.1 [12.5]	30.5 [12.0]	98.0
S5	76.8 [23.6]	48.5 [25.6]	63.1 <sup>a</sup>
S6	50.4 [16.6]	35.3 [15.6]	70.0 <sup>a</sup>

<sup>a</sup> Significant difference, *df* = 99, *p* < 0.005.

these processes are not identical in their configuration, the basic scenario of a nipped roller fibre feed interacting with a toothed or pinned opening roller is not dissimilar to what is integral to wool fibre mechanical recycling systems. As in pre-opening and carding, the specific design of recycling equipment, roller speeds and gauge settings, tooth density, throughput, and other process details are likely to influence the degree of fibre breakage, and therefore mean fibre length retention after recycling, and so is open to a certain degree of control by a skilled textile engineer by optimising the recycling process parameters.

Lastly, the specific flexural rigidity ( $R_f$ ) was calculated for all fibres (Hearle and Morton, 2008), which ranged from 0.14 to 0.18 mN mm<sup>2</sup>/tex<sup>2</sup>. There were no significant differences in  $R_f$  between the samples, except for the two extreme values S2 ( $R_f$  = 0.18) and S3 ( $R_f$  =

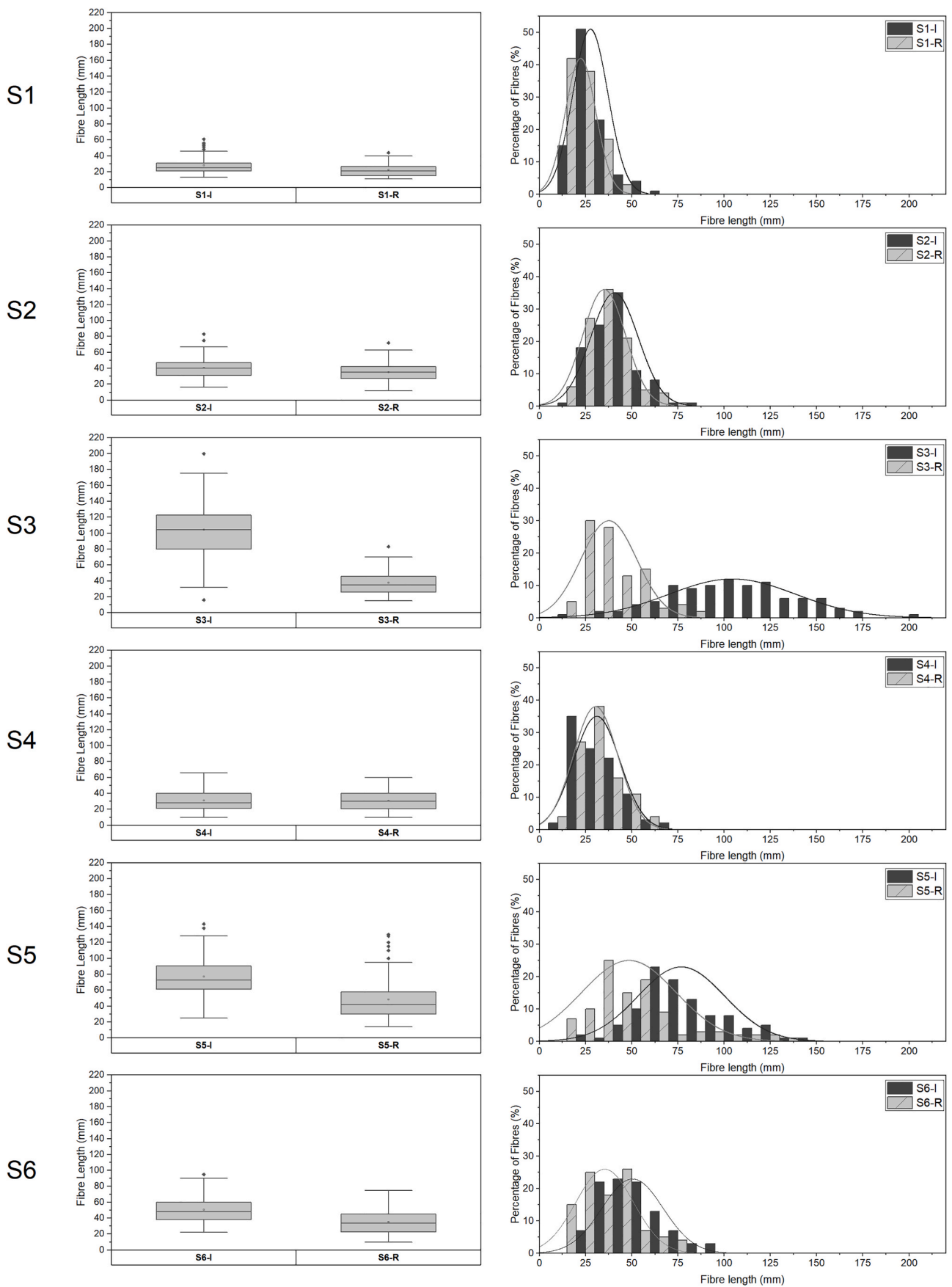


Fig. 4. Shift in Mean Fibre Length and Fibre Length Distribution following Mechanical Recycling for All Samples (S1-S6). I = initial; R = recycled.

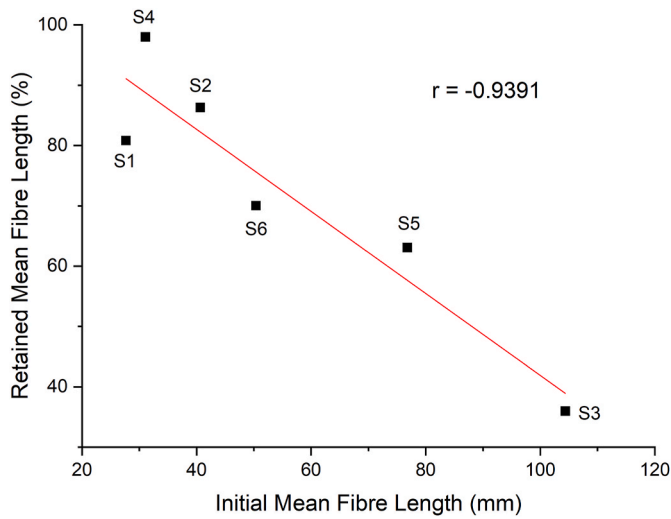


Fig. 5. Retained Mean Fibre Length after Recycling versus the Initial Mean Fibre Length in the Fabric prior to Recycling. Linear relation,  $y = 109.87 - 0.68x$

0.14), which represent the fibres of finest and coarsest fibre diameters, respectively.

It is also instructive to observe the reduced dispersion within fibre length distributions for the recycled samples, as compared to the distributions before recycling (Figs. 4 and 6). Notwithstanding the removal of retained fibre lengths <10 mm in the measurements, a narrower range of fibre lengths was evident after recycling ( $34.9 \pm 8.6$  mm) versus the range prior to recycling ( $55.2 \pm 29.9$  mm). Interestingly, the approximate gauge setting distance between the nipped feed rollers and the pinned roller in these experiments was 35 mm, which is very close to the overall mean retained fibre length for all samples. Thus, instead of a consistent proportionate reduction in fibre length after recycling, the fibre lengths trend towards a similar retained value, which is still above the minimum length threshold for compatibility with the woollen yarn spinning process. In practice, this will be dependent on the careful selection of machine settings and optimisation of the operating conditions used in the M Wool® process. Further investigations are needed to determine whether the feed-to-pinned roller distance is directly correlated to the mean retained fibre length of processed materials.

Finally, when the combined retained fibre length measurements of

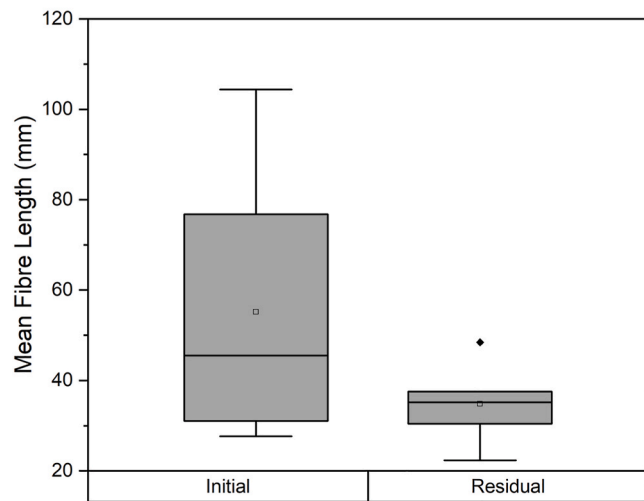


Fig. 6. Initial and retained mean fibre lengths for all mechanically recycled samples (S1–S6).

S1–S6 ( $n = 600$ ) are compared to a sample taken from full-scale production ( $n = 100$ ), the mean fibre lengths of  $34.9 \pm 17.5$  and  $36.1 \pm 16.8$  mm, respectively, are not significantly different ( $p > 0.05$ , see Fig. 7). This shows that the effects on the fibres observed at the lab-scale are directly comparable to the full-scale industrial process.

### 3.3. Fibre tensile strength

Given the importance of fibre mechanical properties in yarn and fabric manufacturing systems, as well as in determining fabric properties and performance, it is important to understand how mechanical wool recycling affects fibre tensile properties, particularly stress at break. Across all samples (S1–S6), mechanical recycling was found to have very little effect on retained fibre tensile strength, with fibre stress at break retention values of >92% compared to initial values before recycling (Table 3). For S1 and S2, there is a statistically insignificant increase in fibre tensile stress, potentially due to a small, (but statistically insignificant) decrease in mean fibre diameter after recycling (S1-R = 23.8  $\mu$ m, S2-R = 19.56  $\mu$ m), resulting in higher calculated stress values. During the mechanical recycling process, fibres will undergo mechanical deformations and tensile extension within the elastic limit of the material, such that a small reduction in fibre breaking strain could be anticipated. Previous studies have observed that after a wool fibre has undergone tension, microdefects present in the fibre can act as propagation sites for future tensile failure (Gharehaghaji et al., 1999). Although the percentage mean fibre breaking strain retention was slightly lower (retention of >83%) for all samples compared to stress at break (Table 4), such a small deficit would not be expected to compromise textile processing in subsequent yarn and fabric production.

The stress-strain curve behaviour of the wool fibres in each fabric sample, before initially (I) and after recycling (recycled-R) are reported in Fig. 8. The S3 stress-strain curves are especially characteristic of observed wool tensile behaviour, with an initial Hookean region up to 2% extension, a yield region from 2 to 30%, a post-yield section with a higher slope after that, finally breaking at around 40% extension (Hearle and Morton, 2008). The low-modulus yield section and the higher-modulus post-yield section corresponds to the transition from the  $\alpha$ -to  $\beta$ -conformation states of the keratin protein microfibrils within the fibre, where complete elastic recovery is possible at extensions  $\leq 30\%$ , and near-complete at extensions beyond that (Hearle, 2000). The representative tensile curves for each sample before and after recycling

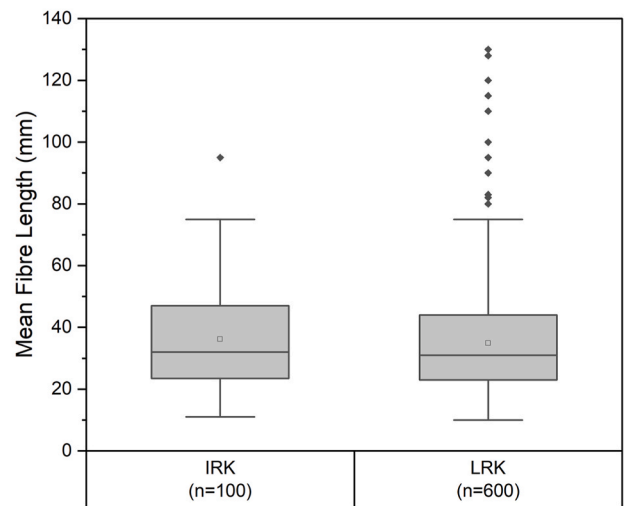


Fig. 7. Comparison of the Mean Retained Fibre Lengths of Industrially Recycled Knitwear (IRK) sample and Lab-Recycled Knitwear (LRK) sample.

**Table 3**  
Summary of Fibre Tensile Stress at Break (before and after mechanical recycling).

Sample	Initial Mean Fibre Stress at Break, MPa [SD]	Recycled Mean Fibre Stress at Break, MPa [SD]	Mean Fibre Stress at Break Retained (%)
S1	97.9 [40.2]	103.0 [28.5]	105.1
S2	102.3 [31.4]	117.4 [34.3]	114.8
S3	155.7 [37.9]	153.6 [49.9]	98.6
S4	116.4 [42.2]	112.8 [39.1]	97.9
S5	127.7 [35.2]	124.0 [32.4]	97.1
S6	114.9 [25.5]	105.7 [39.5]	92.0

All samples not significantly different before and after recycling,  $df = 24$ ,  $p > 0.05$ .

**Table 4**  
Summary of Fibre Strain at Break (before and after mechanical recycling).

Sample	Initial Mean Fibre Strain at Break [SD]	Recycled Mean Fibre Strain at Break [SD]	Mean Fibre Breaking Strain Retained (%)
S1	0.08 [0.10]	0.08 [0.08]	98.4
S2	0.11 [0.09]	0.17 [0.12]	148.2
S3	0.31 [0.11]	0.28 [0.12]	90.7
S4	0.18 [0.13]	0.15 [0.12]	83.2
S5	0.29 [0.13]	0.27 [0.12]	93.7
S6	0.19 [0.12]	0.18 [0.12]	98.5

All samples not significantly different before and after recycling,  $df = 24$ ,  $p > 0.05$ .

closely overlap throughout, showing no substantial differences in the tensile behaviour resulting from the M Wool® process. These characteristics of wool contribute to the minor differences seen in the reported mean tensile properties, i.e. breaking stress and strain (Tables 2 and 3).

### 3.4. Implications for wool fibre recyclability

Given the excellent retention of key wool fibre properties after mechanical recycling for samples such as S1, S2 and S4, in respect of fibre length and fibre tensile properties, the results have further implications in terms of the potential multi-recyclability of different wool and hair fibres.

Based on the machine settings used in the M Wool® process, larger percent retained fibre lengths were found to be achievable when mechanically recycling fabrics containing wool fibres with relatively short mean fibre lengths (e.g. Sample S4) and hair fibres (Sample S2), such that multiple recycling cycles may be feasible, before the minimum threshold fibre length for woollen yarn spinning is reached.

Such fibres are also among the most economically valuable virgin materials, i.e., merino with mean fibre diameters of ~14.5–24.5  $\mu\text{m}$  (Scobie et al., 2015), compared to much coarser cross-bred wools. Therefore, an important added value of such wools and hair fibres could be the potential to be recycled more than once.

Practically, closed loop mechanical recyclability depends on achieving a satisfactory fibre yield (difference between input and output production by weight) in the recycling process, as well as the retention of key physical and dimensional fibre properties such as maximum fibre length retention (Russell et al., 2010). An industrially acceptable yield is ~98%, representing the amount by weight of useable fibre that is retained after the recycling process; the remaining 2% is extracted as dust (Manteco, Personal Communication, n.d.). Based on two parameters, (i) the production yield of fibres in the recycling process (%), and (ii) fibre length retention (%), i.e.  $(L_i - L_r)/L_i \times 100\%$ , a simple Recyclability Index ( $R$ ) can be proposed (Eq. (1)). Herein, based on an industrially acceptable recycling yield of 0.98,  $L_i$  and  $L_r$  are the initial and retained mean fibre lengths (mm), respectively. Given that no major changes in fibre tensile properties after recycling were observed, most

likely because of the intrinsic extensibility and elasticity of wool and cashmere fibres (Hearle, 2000), fibre tensile strength retention was not included in the Recyclability Index.

$$R = 0.98 * \frac{L_r}{L_i} \quad (\text{Eq.1})$$

The calculated recyclability indices (R-values) for all samples (S1–S6) are given in Table 5 to provide a quantitative value for fibre recyclability, based on one recycling cycle.

This analysis can be extended to consider multi-recyclability, i.e., the potential for a fabric to be recycled more than once, based on the projected fibre length retention after each successive recycling cycle. A crude estimate can be made if the linear relation between initial and recycled mean fibre length observed in Fig. 5, is assumed to hold for further recycling passes, and the observed differences in fibre strength retention are also maintained. Of course, beyond the first recycling cycle, potential changes to production yield or fibre properties must also be considered due to the production steps involved in making a new fabric from the recycled fibres (e.g. fibre opening, carding, spinning, fabric production, dyeing and finishing). This is represented by the variable  $M$ , which will vary depending on the selection of processes and settings used to reprocess the fibre after the first cycle of recycling. For the purposes of this preliminary analysis, values of  $M$  were not experimentally available and so the value was defined as  $M = 1$ . The recycled mean fibre length ( $L_r$ ) can therefore be estimated after the second recycling cycle, ( $L_{r2}$ ) and subsequent cycles ( $L_{rn}$ ), where  $n$  = the cycle number, as shown in Equation (2).

$$L_{rn} = M * L_{r(n-1)} * (109.87 - 0.68 * L_{r(n-1)}) / 100 \quad (\text{Eq.2})$$

$$R_n = 0.98 * \frac{L_{rn}}{L_i} * \left(1 - \frac{L_{rn}}{20}\right) \quad (\text{Eq.3})$$

It is then possible to estimate the theoretical maximum number of cycles each fabric sample could be mechanically recycled before the minimum spinnable fibre length for wool fibres of 20 mm is reached (Manteco, Personal Communication, n.d.; Textile Exchange, 2021), and the predicted R-value at that cycle can be calculated (Equation (3)).

This new R-value calculation builds on Equation (2) by including the difference between the predicted fibre length and the minimum spinnable fibre length of 20 mm. Once the predicted mean fibre length is < 20 mm, the R-value becomes less than, or equal to zero. The differences in R-value between the samples decreases slightly with each successive cycle, because a lower proportion of the initial mean fibre length is retained each time (see Appendix/supplemental information). Once a sample has passed the threshold of  $R = 0$ , the fibre would no longer be compatible with woollen spinning, but may still be processable using an open loop recycling stream e.g., nonwoven fabric manufacture.

Using this basic approach, if the composition, structure and properties of the fabric to be recycled in each successive cycle of recycling was the same as the first (i.e. knitted fabric into knitted fabric), a theoretical maximum number of up to about six recycling passes could be possible for wool and cashmere fabrics, before the threshold required to ensure compatibility with woollen yarn spinning is reached (Fig. 9).

However, as reflected by the  $M$  variable, the actual number of times the fibre can practically be recycled depends heavily on subsequent fabric manufacturing decisions after the first recycling cycle. For example, it is generally more common for mechanically recycled wool fibres obtained from knitwear, such as those produced by the M Wool® process to be converted into relatively high twist woollen yarns for weaving, rather than for knitting again into new fabrics. Such woven fabrics also undergo mechanical finishing, including brushing to consolidate their structure, with a view to promoting abrasion resistance and physical durability for use in clothing. Naturally, when pulling such woven fabrics as part of a second round of recycling, the propensity for fibre breakage is greater than pulling the original waste knitwear. Fig. 9 therefore, represents the theoretical best-case-scenario, with actual

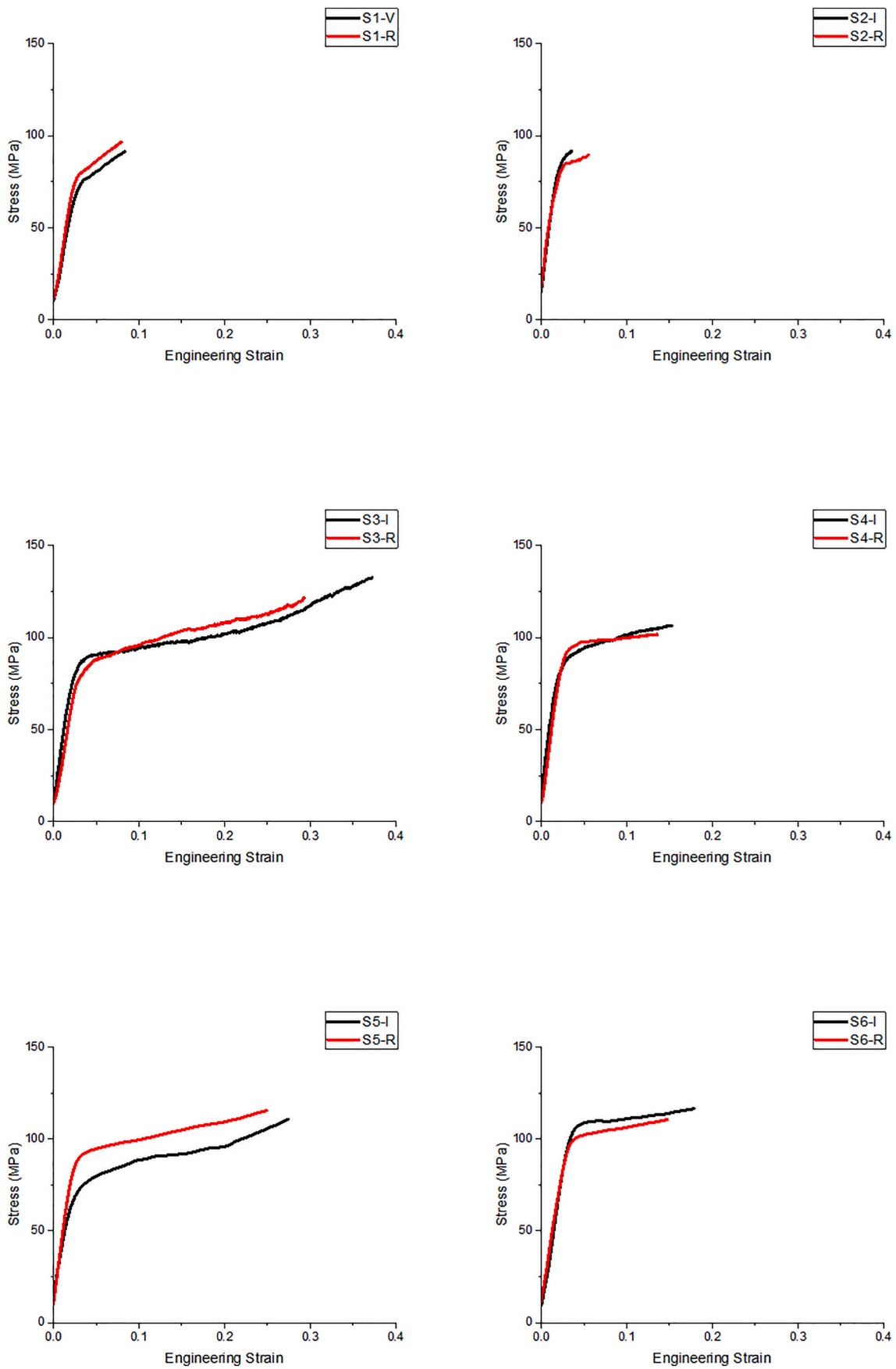


Fig. 8. Representative Tensile Stress-Strain Curves for Fibres in Fabrics prior to Mechanical Recycling (black) and after Mechanical Recycling (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

**Table 5**  
Recyclability Index (R) values for Once-Recycled Fabric Samples.

Sample	Recyclability Index, R
S1	0.79
S2	0.85
S3	0.35
S4	0.96
S5	0.62
S6	0.69

results more likely falling in the range of 1–6 additional cycles of recycling, depending on the specific methods employed in fabric re-manufacture. This analysis can serve as a useful tool for manufacturers to identify where in their production processes they can make changes to enhance material circularity.

#### 4. Conclusions

Mechanical recycling of postconsumer knitwear does not necessarily damage wool or cashmere fibres to the extent that it becomes too short to spin into high quality yarns. This depends on the initial mean fibre length in the fabric to be recycled, which is not a constant, as well as process settings. In the M Wool® mechanical recycling process, the effect on wool fibre tensile properties is negligible, and the degree of fibre shortening when processing post-consumer wool knitwear is found to depend on the initial mean fibre length of the fabric to be recycled. Fabrics containing higher-value wool and hair fibres such as merino and cashmere (respectively), that typically possess lower mean fibre lengths than most cross-bred wools, can be expected to retain a greater proportion of their initial fibre length after mechanical recycling than longer fibre wools, at the same recycling process settings. Sufficient fibre length above the minimum threshold necessary for woollen spinning as part of a closed loop system, can therefore be retained even when the initial wool fibre length is relatively short and there is also potential for closed-loop multi-recyclability, provided fabrics are carefully designed and recycling and fabric manufacturing processes are appropriately adapted. The mean fibre length after mechanical recycling is influenced by the gauge setting distance between the feed rollers and the opening

roller of the mechanical recycling equipment. This highlights the importance of the specific design of recycling processes in preserving mean fibre length, as well as the careful selection of wool fabrics to be recycled.

While these results focus on mean fibre length and tensile property retention using closed-loop M Wool® process, they do not consider other tools such as blending postconsumer recycled wool with virgin wool, man-made or post-industrial recycled fibres, to further extend potential for recycling. Most clothing fabrics containing recycled wool are based on carefully engineered blend compositions. Quantifying the effects of additional fibre opening, carding, spinning, weaving or knitting, dyeing, and mechanical finishing processes on retained fibre length after additional cycles of recycling would also be instructive, enabling appropriate values of  $M$  to be obtained.

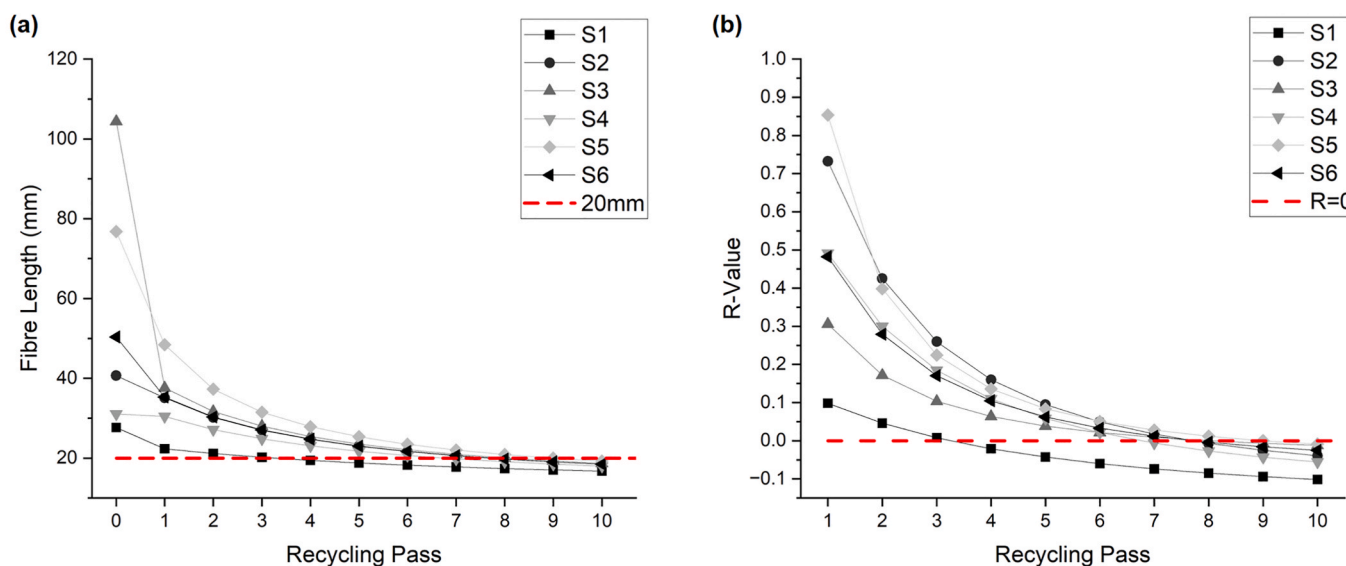
Increasing regulatory pressure in the fashion and textile industry is necessitating improved data and evidence gathering on the full life cycle of specific, rather than generalised categories of textile products, enabling meaningful calculation of real-world environmental impacts. Based on an evaluation of the existing industrially installed M Wool® process, postconsumer wool knitwear is not only mechanically recyclable as part of a closed loop process, but multi-recyclability is also implementable using the same recycling platform. This should be considered in all future life cycle assessments of postconsumer wool and cashmere knitwear products.

#### CRedit authorship contribution statement

**M.J. Glasper:** Writing – original draft, Methodology, Investigation, Formal analysis. **G. Picerno:** Writing – review & editing, Resources, Conceptualization. **M. Tausif:** Writing – review & editing, Formal analysis. **S.J. Russell:** Writing – original draft, Supervision, Methodology, Funding acquisition, Conceptualization.

#### Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: The authors report financial support was provided by Manteco SpA.



**Fig. 9.** (a) Measured mean fibre lengths at initial (0) and after the first recycling cycle, with the predicted mean fibre lengths for each additional cycle up to ten (assuming the same fabric composition, structure and properties before each successive recycling cycle). The minimum spinnable fibre length of 20 mm is indicated with a red dashed line. (b) The calculated (first cycle) and predicted R-values after each recycling cycle are shown.  $R = 0$  is indicated with a red dashed line. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

## Data availability

Data will be made available on request.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.clet.2024.100796>.

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