Sustainable Materials and Technologies 44 (2025) e01410

Contents lists available at ScienceDirect

Sustainable Materials and Technologies

journal homepage: www.elsevier.com/locate/susmat

Beyond a second life: Mechanical recyclability of woven fabrics containing recycled wool

M.J. Glasper [a,*], G. Picerno [b], M. Tausif [a], S.J. Russell [a]

[a] Leeds Institute of Textiles & Colour (LITAC), School of Design, University of Leeds, LS2 9JT, Leeds, UK
[b] Manteco SpA, Via della Viaccia 19, 59013 Montemurlo, Italy

A R T I C L E I N F O

Keywords:
Wool
Textile
Mechanical recycling
Circularity
Post-consumer waste
MWool®

A B S T R A C T

Woven fabrics containing high proportions of post-consumer and/or post-industrial wool are manufactured for certain types of clothing, e.g. suiting, but their suitability for further mechanical recycling in a closed loop is not widely understood. Therefore, representative, industrially manufactured woven fabrics containing mechanically recycled post-consumer wool waste (2 % - 55 %), and post-industrial/process wool waste (6 % - 84 %) produced by the MWool® process were systematically studied, to determine levels of fibre breakage during textile processing and prospects for further recycling. The initial mean fibre length in woven wool fabrics was negatively correlated to the percentage retained mean fibre length after mechanical recycling, to a greater extent than in wool knitwear. In addition to fibre breakage in mechanical recycling, finishing of woven fabrics containing recycled wool to enhance fabric aesthetics and performance, using fulling, brushing, raising and calendering processes also lead to fibre breakage. Due to the relatively short fibre lengths in the woven fabrics, subsequent recycling leads to breakage, but to a lesser extent (average retained fibre length of 84 %) than for recycled knitted fabrics (average retained fibre length of 72 %), even though the absolute mean fibre length of the woven fabrics is shorter than for knitted fabrics. However, woven fabrics containing MWool® recycled wool still have potential to be recycled at least once more as part of a closed loop system, before fibre breakage would necessitate diversion to other end-uses or waste streams. Innovative finishing methods that limit frictional forces on the fabric surface (instead of brushing or raising) are needed to preserve fibre length and improve the recyclability of woven fabrics containing recycled wool.

1. Introduction

Mechanical recycling of used wool clothing, or 'rags' into new fabrics suitable for clothing is an established industry operating in Europe for over two hundred years [1]. Based on the pioneering work of Benjamin Law in Batley, West Yorkshire, UK, separate processing routes were developed for shoddy, composed mainly of post-consumer wool knitwear and low twist yarns, and mungo from "harder" (i.e. higher density) fabrics such as woven tailors' offcuts [2,3]. While wool's closed loop recycling history is well documented, open-loop applications such as nonwoven mattress components and insulation have become industrially important to valorise wool waste, together with emerging applications in fibre-reinforced composites, architecture, waste water treatment, organic nitrogen fertiliser, regenerated keratin proteins, and others [4] and sources therein.

In today's wool recycling industry, waste wool is reclaimed from different sources. The principal waste streams are post-industrial, or process waste (e.g. yarn or cutting waste) and post-consumer (e.g. discarded clothing) [1]. Wool waste is recycled via wet or dry processes, depending on the fabric structure [5], to control fibre breakage during recycling. During mechanical recycling, fibres are frictionally restrained and subjected to tension within the fabric structure and by the feed rollers of the machine, while bending forces are applied as fibres interact with toothed or pinned rollers. This results in a degree of fibre breakage, with potential for morphological damage depending on the specific process configurations and settings. Similar conditions apply in opening and carding processes prior to staple yarn production [6,7].

Recycled wool is an important feedstock for the woollen yarn production system, and the making of new fabrics as part of fibre-to-fibre, closed loop recycling. To improve compatibility with woollen yarn

* Corresponding author.
E-mail addresses: M.J.Glasper@leeds.ac.uk (M.J. Glasper), giuseppe.picerno@manteco.com (G. Picerno), M.Tausif@leeds.ac.uk (M. Tausif), S.J.Russell@leeds.ac.uk (S.J. Russell).

https://doi.org/10.1016/j.susmat.2025.e01410
Received 4 February 2025; Received in revised form 10 April 2025; Accepted 23 April 2025
Available online 25 April 2025
2214-9937/

production, as well as to meet final product performance specifications, post-industrial and post-consumer recycled wool is often, but not always, blended in different proportions (%), together with either virgin wool, or man-made fibres, prior to woollen yarn spinning (see Fig. 1). Depending on circumstances, wool also has potential to be recycled more than once [8].

The growing importance of the wool recycling industry is reflected by recent regulatory pressure and industry developments. The EU Strategy for Sustainable and Circular Textiles prioritises fibre-to-fibre closed-loop recycling, and will require all textile products sold in the EU to be made from recyclable materials by 2030 [9]. Elsewhere, industry-led initiatives and tools are defining preferred fibre materials, where recycled content is likely to provide a competitive advantage [10,11]. These tools have been embraced by many in the industry to help inform material sourcing decisions, and work is ongoing to refine and identify potential areas for improvement, especially for the assessment of natural fibres [12,13].

From a full-life-cycle assessment (LCA) perspective, the ability to recycle in a closed loop, based on mechanical recycling, also provides opportunities to reduce the overall environmental impacts of wool products. Increasing demands on textile producers to implement circular economies, and the need to accurately assess environmental impacts, 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. This is necessary to address misleading environmental impact comparisons for different fibres based on farm/factory-to-gate analyses, rather than finished products as the functional unit [13]. Furthermore, for some wool types including merino, there is potential to recycle wool fabrics in a closed loop multiple times before diverting to open-loop processes [8], potentially decreasing the overall carbon footprint [5]. Depending on how a final garment is used and maintained, Wiedemann et al. demonstrated that a wool blend sweater containing recycled fibre could reduce impacts by 66–90 % relative to a virgin pure wool sweater [14].

Practically, for closed loop recycling of wool to be possible, a sufficient fibre length of 20 mm [15] or 30 mm [16] must be retained to ensure the fibre is compatible with subsequent yarn production [16,17], which means minimising fibre breakage during mechanical recycling [1]. Retained fibre length therefore affects the economic value of the recycled fibre and this association between material properties, economic value, and the viability of recycling, has led to the development of recyclability indices (R) for different materials, including textiles, which are commonly defined as the ratio of economic value (£/kg) before and after recycling [18–20]. The Recyclability Potential Index (RPI), which is the sum of the environmental and economic gain indices for textile fibres, examines the impacts of virgin fibre production and disposal versus recycling [21].

A previous study of 100 % post-consumer wool knitwear introduced a Recycling Index to estimate wool fibre recyclability (and multi-recyclability) based on the retained fibre length after mechanical recycling, rather than economic and environmental factors [8], but it is not known if this can be extended to recycling of woven fabrics. The bulk density of woven apparel fabrics is usually higher than for knitted fabrics (in these studies, 0.24 vs. 0.17 g/cm^3 respectively), and in the manufacture of fabrics containing recycled wool, the fibre inputs come from several sources (see Fig. 1). Additionally, it is common to employ fabric finishing processes that consolidate the woven structure, e.g. fulling (to improve dimensional and mechanical properties), and raising or brushing (to frictionally raise fibres on the surface and improve aesthetics). These factors may affect the closed loop recyclability of woven fabrics containing recycled wool and therefore need to be further considered.

Accordingly, the aim was to determine the recyclability of industrially representative woven fabrics containing blends of post-industrial process waste, post-consumer recycled wool waste and virgin wool. As is common in the industrial-scale manufacture of fabrics of this type, some samples also contained a small proportion of polyamide (PA) fibres in the blend. Source fabrics suitable for use in suiting were manufactured by Manteco (Italy), one of Europe's largest recycled wool fabric producers and owners of the MWool® brand for recycled wool fibre content. In these woven suiting fabrics, the effects of woollen yarn and fabric manufacturing on mean fibre length and tensile properties was measured prior to and following mechanical recycling, to explore the influences on fibre properties. Potential for recycling more than once, as part of a closed loop process was then considered based on a modified recycling index.

2. Materials & methods

2.1. Wool fabrics

Woven wool suiting fabrics comprising blends of post-industrial and post-consumer recycled wool were supplied by Manteco, Italy, as summarised in Table 1. These fabrics were chosen for this study, as they are manufactured using the post-consumer recycled fibre investigated in the previous knitwear study as one of their fibre inputs [8]. The fabrics denoted F1 to F3, are representative of those typically produced by Manteco in their industrial fabric production process, and all comprised woven fabrics made of woollen yarns. Samples of the woollen warp and weft yarns used to make each fabric were also supplied, as well as the input fibre feedstocks: recycled knitwear and woven (post-consumer)

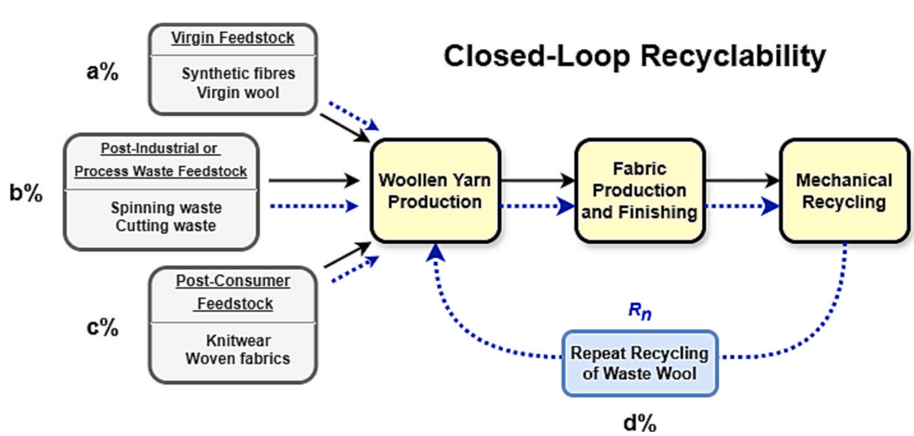
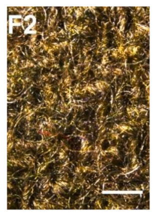


Fig. 1. Blending Strategy for Closed-Loop Recycling of Wool. The black arrows represent the first manufacturing process with typical fibre inputs available (a, b, c). The blue arrows represent repeated closed-loop recycling steps (R_n), where virgin and recycled feedstocks are blended with waste wool in different (a, b, c, and d) proportions (%) to manufacture new fabrics with recycled fibre content.

Table 1
Industrially sourced woven fabric samples with recycled wool content.

Sample	F1	F2	F2B	F3
Fabric description	Double cloth with PA binding yarn	Double cloth with PA binding yarn and one brushed face		Single layer cloth
Feedstock fibre composition (%)	73 % post-industrial recycled wool 25 % virgin PA 2 % post-consumer recycled wool	55 % post-consumer recycled wool 23 % virgin PA 16 % virgin wool 6 % post-industrial recycled wool		84 % post-industrial recycled wool 16 % virgin wool
Fabric structure	2 × 2 right-hand twill face and back	2 × 2 right-hand twill face and back		2 × 2 right-hand twill
Dyeing method	Blend of coloured Recype® recycled fibre	Blend of coloured Recype® recycled fibre		Blend of coloured Recype® recycled fibre
Fabric finishing	Fulling, Raising, Calendering	Fulling, Raising, Calendering	Fulling, Brushing, Raising, Calendering	Fulling, Brushing, Raising, Calendering
Weight (g/m^2)	378	385		237
Density, yarns/cm^2 (warp x weft)	22 (11 × 11)	23 (12 × 11)		30 (15 × 15)
Fabric*				

* Scale bar = 2 mm.

feedstocks, woollen spinning and cutting waste (post-industrial and process waste), virgin wool and PA fibre. The colour of each fabric was produced via the Recype® fibre blending process, which is achieved by sorting wool waste by colour, recycling the sorted batches, and blending the resulting fibre to achieve the desired shade [22]. In this way, the need for yarn or piece dyeing, and the resources required for dyeing, are eliminated. Owing to the sampling of test materials from large-scale commercial operations, it was not possible to receive greige or desized, unfinished fabric for analysis.

2.2. Mechanical recycling processes and methods

Mechanical recycling of each fabric sample in Table 1 was undertaken in an industrial setting by Manteco, Italy, using a lab-scale version of their MWool® production process, the details of which have been described previously [8]. To verify the comparability of results from the lab-scale and full-scale commercial MWool® process (Fig. 2), a sample of recycled fibre was taken from full-scale production, and differences in retained fibre length were measured and compared to the F1-F3 recycled samples.

2.3. Fibre sampling

For mean fibre length and fibre length distribution determinations, fibres were sampled from the initial feedstocks, yarns, fabrics, and mechanically recycled outputs according to the recommendations in BS EN 12751:1999. Fibres were selected from the beginning, middle, and end of each provided yarn sample. When sampling fibres from the woven fabrics, care was taken to extract equal numbers from both the warp and weft yarns, and from the face and back of the double-cloth fabrics. Five sampling zones were chosen to obtain the feedstock and recycled fibre samples, with the blending and halving performed manually.

2.4. 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. Details of this procedure have been described previously [8]. Fibre length distribution measurements and statistical analyses were carried out with Origin 2024b software.

To approximate pre-spun fibre blends comprising the input feedstocks, 100 fibres from each sample were measured, and weighted fibre length averages were obtained based on the percentage fibre composition (see Table 1) and considering the number of PA versus wool fibres per n = 100 sample (see Section 3.2) for the wool/PA blends. The mean fibre length of virgin wool was estimated using the overall average of virgin fibre lengths from previous work [8], and the knitted cutting waste mean fibre length was assumed to be equivalent to recycled post-consumer knitwear as they are similar structures, and mechanically recycled using the same process.

2.5. Fibre tensile testing

Fibres were sampled from the yarn, fabric, and recycled length-measured samples for F1 and F3, and tested according to BS EN ISO 5079:2020, based on $n = 25$ fibres per sample. Owing to similarities between F1 and F2 regarding fabric weight, construction, density, and overall fibre content, F2 was not included in the tensile strength evaluations. 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 [23] and PA [24]. The average diameter of each specimen was determined by measuring the diameter at five locations along the length of the fibre and calculating the mean of those values. Fibre cross-sections for all specimens were assumed to be circular. Pretension values for the fibres taken from each sample were as follows: F1 (wool) = 6 mN, F1 (PA) = 3 mN, and F3 (wool) = 6 mN. The fibres were adhered to a test carrier card, but due to the natural crimp of wool fibres, 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 engineering stress-strain 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. These tests were selected due to variability in the tensile responses, with a small number of specimens exhibiting high stress but low strain, and vice versa. Unless a test failed to run properly, specimens were not excluded from the results so that a realistic understanding of the fibre properties could be achieved. Creating a mean tensile curve across all

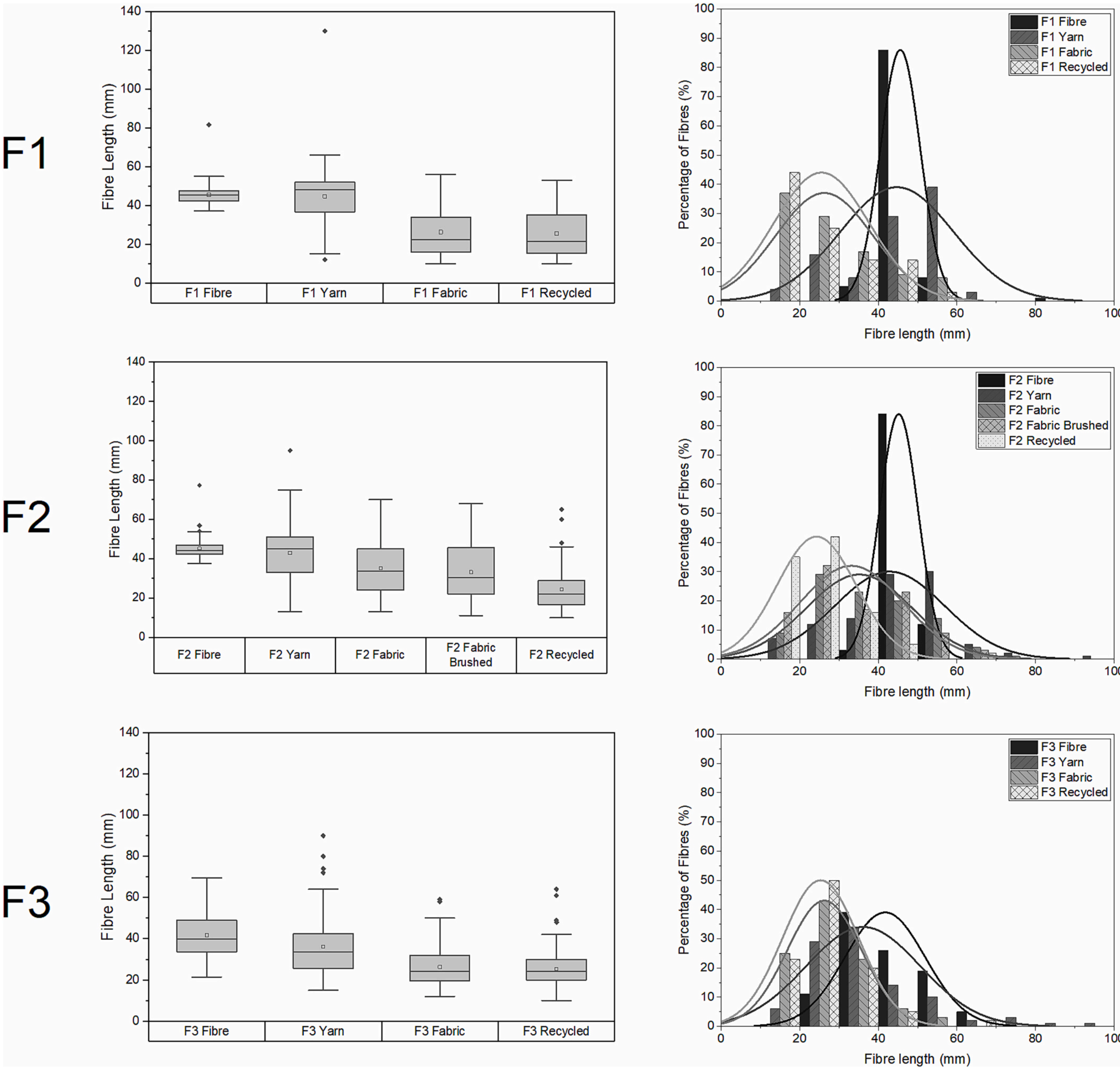


Fig. 2. Changes in the Mean Fibre Lengths and Fibre Length Distributions at the Fibre, Yarn, Fabric, and Recycled Manufacturing Stages for Woven Fabrics containing Recycled Wool.

shared ranges of strain resulted in a very short curve that was not representative of the group, and so the two specimens closest to the mean stress and strain were chosen. The representative average curves of the yarn, fabric, and recycled samples were then graphed together for comparison.

3. Results & discussion

3.1. Retention of fibre length following mechanical recycling

Table 2 and Fig. 2 report the mean fibre length results for each

Table 2
Summary of initial and residual fibre length results and mean fibre length retention before and after mechanical recycling for all fabrics.

	Mean Fibre Length [SD], mm				Mean Fibre Length Retention, %			
Sample	Fibre	Yarn	Fabric	Recycled	Fibre to Yarn	Yarn to Fabric	Fabric to Recycled	Overall (Fibre to Recycled)
F1	45.6 [5.1]	44.7 [14.5]	26.3 [12.4]	25.5 [12.2]	98.1	58.7*	97.3	56.0*
F2	45.2 [4.9]	42.9 [14.0]	35.1 [13.4]	24.3 [10.0]	94.9	81.9*	69.1*	53.7*
F2B			33.2 [13.1]			77.3*	73.2*	
F3	41.7 [10.2]	36.2 [14.5]	26.3 [9.5]	25.3 [9.7]	86.7*	72.7*	96.3	60.7*

* Significant difference, $p < 0.005$.

sample, and their accompanying fibre length distributions. For F1 and F2, both with PA content, no significant difference was observed in fibre length between the fibre and yarn stages (see Table 2 for *P*-values). As indicated in Section 3.2, though the proportion of PA in both fabrics is 23–25 % by weight, a greater number of PA fibres are present because of their lower linear density (nominally 3.3 dtex) compared to the wool fibres (8.4 dtex). This is highlighted when comparing the fibre length distributions for F1 and F2, where a large peak at 40–50 mm is observed, corresponding to the PA mean fibre length of 47.6 ± 5.5 mm. There is a significant difference in fibre length observed in F3 between the fibre and yarn stages, suggesting that the carding process impacts the recycled wool fibres more than the virgin PA.

Interestingly, for every sample there was a marked difference in measured fibre length between the yarn and fabric stages. This degree of difference is unexpected, and due to the unavailability of greige or unfinished fabrics, it is not possible to ascertain where exactly this reduction in fibre length occurred. It is likely to be influenced by the finishing steps routinely used in wool fabric production, particularly brushing or raising, that involve frictional forces applied to the fabric surface. For example raising, intended to modulate woven fabric softness and tactile properties by creating a fibrous pile or textured surface on the fabric, is achieved by passing the fabric over rotating abrasive clothed rollers [25]. This step is often followed by shearing, where raised fibres on the surface are cut to a uniform height.

Samples F2B and F3 both underwent an additional brushing stage to further consolidate the fabric structure, with the aim of enhancing abrasion resistance and physical durability. Owing to differences in fibre blends and fabric construction (double vs. single), the influence of brushing on fibre length between fabrics cannot be reliably compared. However, it is instructive to consider sample F2, where one side of the fabric was brushed, and the other was not. A small difference in the fibre length between the brushed and unbrushed sides of the fabric is evident, although the difference is not statistically significant ($p = 0.69$). Therefore, brushing is one of the potential contributors to fibre breakage, but the effects of other finishing steps need to be further explored.

Regarding the retained fibre length after the fabrics were mechanically recycled, samples F1 and F3, both with fabric fibre lengths of ca. 25 mm, were not significantly different, whereas sample F2, with a fabric fibre length of ca. 33–35 mm did show a significant difference. When the mean fibre length retention values are plotted as a function of the mean initial fibre length, a strong linear relationship is observed (Pearson correlation coefficient, $r = -1$). This was similarly observed in the recycling of post-consumer wool knitwear, however the rate of change is greater for woven fabrics with a slope of −3.22 versus −0.68 [8]. This increased rate of change could be due to the higher twist yarns used in woven fabrics, higher bulk density, and the consolidation of the fabric structure during fabric finishing, e.g. fulling. Note that all three samples achieved a mean recycled fibre length of 25.0 ± 0.64 mm, similar to the previously observed trend in recycled wool knitwear, though at a longer mean fibre length of 34.9 ± 8.6 mm [8]. As with wool knitwear, this trend towards a similar recycled mean fibre length between samples is likely due to machine settings, e.g. short fibre extraction or the distance between the feed rollers and the pinned roller, and requires further investigation.

Finally, when the mean recycled fibre length measurements of F1–3 are compared to a sample of recycled (shredded) fabric taken from full-scale production, the mean fibre lengths are not significantly different ($p > 0.05$, see Fig. 3). This demonstrates that the observed effects on fibres at the lab-scale are comparable to those in the full-scale industrial process.

3.2. Fibre tensile strength

Fibre tensile properties are important to produce serviceable yarns and fabrics, so it is important to understand how mechanical recycling affects these properties when woven suiting fabrics containing recycled wool undergo mechanical recycling. Previous investigations into 100 % wool knitwear showed insignificant changes in both the stress and strain of the fibres after mechanical recycling [8], but it is not known whether mechanical recycling of woven fabrics containing already recycled wool fibre leads to similar findings. In Tables 3 and 4 the separated and combined results for the wool and PA fibre components in sample F1 are reported.

In Tables 3 and 4, sample F1 shows no significant differences (see tables for *P*-values) in fibre stress at break between the yarn, fabric, or recycled stages, though it should be noted that the (in)significance of the differences for the PA fibre were borderline from yarn to fabric ($p = 0.051$) and from fabric to recycled ($p = 0.079$). There is, however, a significant decrease in strain at break from yarn to fabric, with further decreases after recycling, though not significant at that stage. This contributes to an overall 58.2 % decrease in strain at break for the PA fibres, while there is no significant impact on the wool fibres. The difference in the PA results account for the overall significant decrease in strain at break for the combined values of wool and PA, especially given the number of PA fibre specimens relative to wool in the sample. It is possible that the tensile and frictional forces the fibres were exposed to during finishing and recycling slightly increased the stiffness of the PA fibres, however more investigation is needed to determine the exact cause. In Fig. 4, the wool and PA fibre stress-strain curves of the fabric and recycled samples are noticeably different from fibres in the yarn, with a steeper initial modulus and higher stress at break. The mean

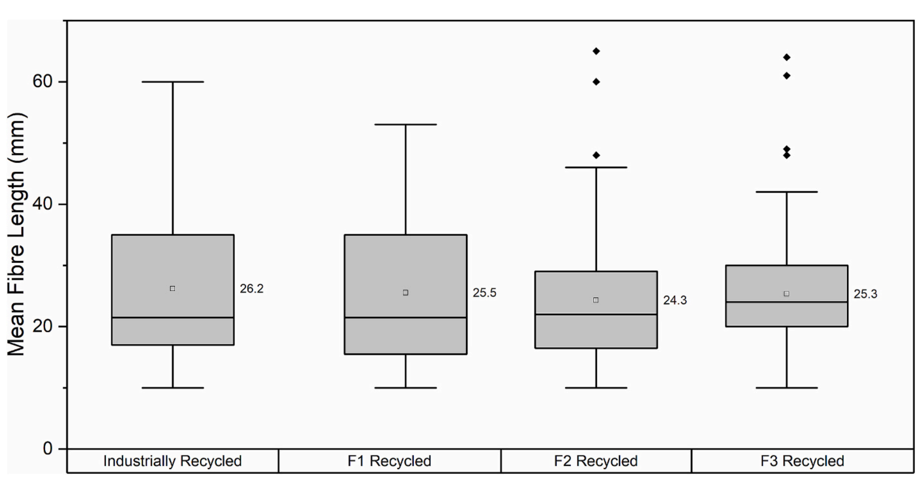


Fig. 3. Comparison of the Mean Recycled Fibre Lengths of Industrially Recycled Woven Wool Fabrics (left) and Lab-Recycled Woven Fabric Samples (F1-F3).

Table 3
Summary of fibre tensile stress at break results for samples F1 and F3 after each stage of production.

Sample	Fibre Type	Mean Fibre Engineering Stress at Break [SD], MPa			Mean Fibre Engineering Stress at Break Retained, %		
		Yarn	Fabric	Recycled	Yarn to Fabric	Fabric to Recycled	Overall (Yarn to Recycled)
F1	Wool	109.1[a] [47.2]	139.2[b] [39.6]	121.5[b] [26.6]	128	87.2	111
	PA	329.3[c] [82.9]	400.4[d] [84.4]	335.1[c] [101.4]	122	83.7	102
	Combined	267.6 [124.9]	337.7 [136.5]	281.7 [129.2]	126	83.4	105
F3	Wool	140.9 [39.2]	105.7 [25.2]	114.6 [32.6]	75.0*	108	81.3*

[a] n = 7.
[b] n = 6.
[c] n = 18.
[d] n = 19.
* Significant difference, $p < 0.05$.

Table 4
Summary of fibre strain at break for samples F1 and F3 after each stage of production.

Sample	Fibre Type	Mean Fibre Engineering Strain at Break [SD]			Mean Fibre Engineering Strain at Break Retained, %		
		Yarn	Fabric	Recycled	Yarn to Fabric	Fabric to Recycled	Overall (Yarn to Recycled)
F1	Wool	0.22[a] [0.12]	0.32[b] [0.15]	0.24[b] [0.18]	142	77.2	110
	PA	0.45[c] [0.13]	0.34[d] [0.12]	0.26[c] [0.08]	74.8*	77.8	58.2*
	Combined	0.39 [0.16]	0.33 [0.13]	0.26 [0.11]	85.9	77.6	66.7*
F3	Wool	0.26 [0.12]	0.16 [0.13]	0.17 [0.14]	64.4*	102	65.7

[a] n = 7.
[b] n = 6.
[c] n = 18.
[d] n = 19.
* Significant difference, $p < 0.05$.

diameter of the PA fibres decreased with each manufacturing step, though not significantly, from 24.2 μm (yarn) to 21.7 μm (fabric) to 20.5 μm (recycled), which is suggestive of fibre extension beyond the yield point and a drawing effect.

A significant decrease in both the fibre tensile stress and strain from yarn to fabric was observed for Sample F3, though for strain $p = 0.048$, which is why the overall difference is not significant, and there was no change from the fabric to the recycled stages. While no significant differences in fibre tensile behaviour were detected when mechanically recycling post-consumer wool knitwear [8], the lower twist yarns and lower density of knitted fabrics (compared to mechanically finished woven fabrics studied herein) likely contributed. Sample F3, while made of 100 % wool, is a woven structure with high twist yarns (compared to those typically found in wool knitwear), and predominantly comprised recycled wool (84 %). While wool fibre is remarkably elastic, even beyond the yield point [26], reduced elastic recovery may be expected with each extension imposed by repeated mechanical processing, which would affect the stress-strain response [27]. The tensile and frictional forces applied during the recycling process would be expected to lead to fibre breakage, however the largest contributor to both fibre shortening and reduced tensile strength occurred between the yarn and finished fabric stages. Whether this is due to the greater proportion of recycled content in the fabric, or the potential for the single layer construction to be less resilient to applied forces in finishing, requires further investigation.

3.3. Additional closed-loop recycling potential

When investigating the mechanical recyclability of post-consumer wool knitwear, no significant change in fibre tensile properties was observed in the process [8] and so was omitted from the recyclability index used to determine potential for recycling more than once (R_K, Eq. (1)). However, when recycling woven fabrics containing recycled wool, differences in fibre tensile properties were observed between manufacturing stages, and so this is accounted for in Eq. (2) (R_W). In these equations, 0.98 is the recycling efficiency as reported by the manufacturer [15], L_r is the recycled mean fibre length, and L_f is the fabric fibre length. In Eq. (2), σ_r and σ_f are the mean stress at break for recycled and fabric fibres respectively, and ε_r and ε_f are the mean strain at break for recycled and fabric fibres. The R-Index is calculated for the mechanical recycling process only, as shown in Table 5. While tensile tests were not performed on the F2 samples, the fabric weight, construction, density, and overall fibre content is similar to sample F1 and the fibre tensile results are assumed to be the same for the purposes of this analysis.

$$R_K = 0.98 * \frac{L_r}{L_f} \quad (1)$$

$$R_W = 0.98 * \frac{L_r}{L_f} * \frac{\sigma_r}{\sigma_f} * \frac{\varepsilon_r}{\varepsilon_f} \quad (2)$$

If, however, the entire production process is considered, including the production efficiency (fibre yield), fibre length changes, and fibre tensile property changes from the beginning, i.e. from the input fibre stage onwards, the R-Index better reflects the industrial system. Accordingly, in Eq. (3) (R_M), the remanufacturing production efficiency value of 0.69 is included to account for average fibre mass loss by multiplying the proportions of fibre retained during the carding (90 %), spinning (91 %), warping/weaving (93 %), and finishing (90 %) steps [15]. L_f is replaced with L_i for the initial fibre length before spinning into yarns, and σ_f and ε_f (fabric) are replaced with σ_y and ε_y (yarn). Here, it is assumed that fibre tensile properties from the fibre to yarn stages remain unchanged.

$$R_M = 0.69 * 0.98 * \frac{L_r}{L_i} * \frac{\sigma_r}{\sigma_y} * \frac{\varepsilon_r}{\varepsilon_y} \quad (3)$$

Interestingly, while woven wool fabrics are largely thought to be more difficult to mechanically recycle than knitted fabrics because of their dense construction, and the likelihood of fibre breakage, the spread of recycling-only R_W values for F1–3 (0.62–1.04) largely overlap with the R_K values for S1–6 (0.35–0.96) from the previous recycled knitwear study [8], even with the added tensile variables. While comparable R_M

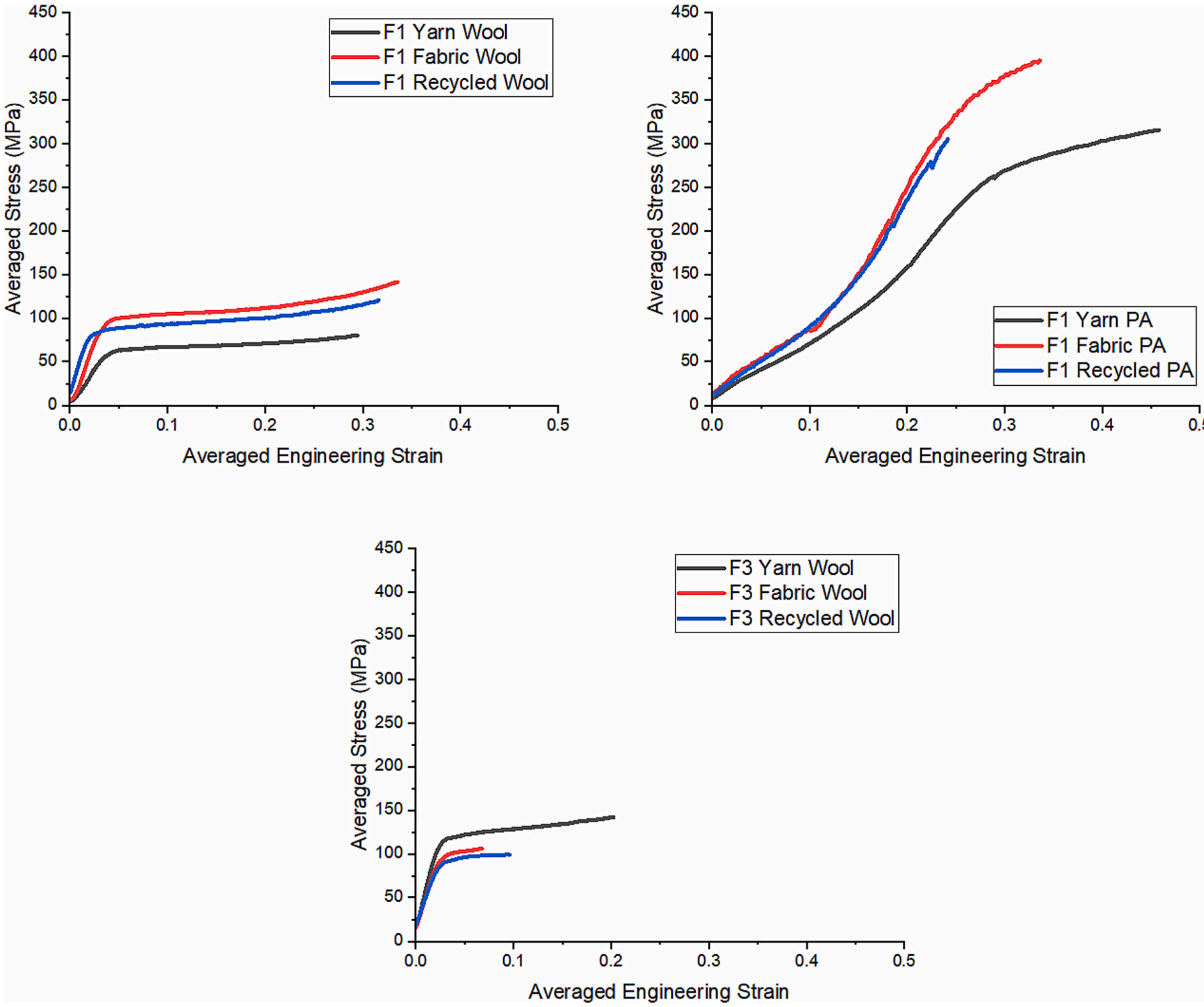


Fig. 4. Representative Tensile Stress-Strain Curves for Fibres at Different Stages of Production: Yarn (black), Fabric (red) and Recycled (blue). F1 is the top row (wool left, PA right), F3 is the bottom (100 % wool).

Table 5
Recyclability index (R) values for woven wool fabric containing recycled wool fibre, after mechanical recycling.

Sample	R_W: Recycling of the Woven Fabric (Eq. (2))	R_M: Recycling Plus Remanufacture (Eq. (3))
F1	0.62	0.42
F2	0.77	0.53
F3	1.04	0.72

data is not available for post-consumer knitwear materials, it is logical to expect the R_M value to be somewhat higher for knitted fabrics because the finishing treatment will differ from those involved herein for woven fabrics.

Next, an estimate of retained fibre length was made, if the recycled fibre from the woven fabric was to be converted into woven fabric again, and then mechanically recycled again. To predict the "re-recycled" fibre length, L_r was plotted as a function of L_i to calculate a new linear relationship ($r = -0.90$) representing fibre length retention across all manufacturing steps from the input fibre to after mechanical recycling. Accordingly, Eq. (4) accounts for the M variable that was used in the knitwear analysis to represent fibre length loss in fabric remanufacture, and L_{rn} is the predicted fibre length after the nth number of recycling and remanufacturing cycles.

Finally, the R-Index R_{Mn} is calculated for these repeated mechanical recycling and remanufacturing cycles, with a minimum spinnable fibre length parameter (for woollen spinning) of 20 mm (Eq. (5)). This parameter was also applied in the knitwear analysis and so avoids artificial increases in the calculated values due to proportional increases in retained fibre length as the pre-recycling lengths become shorter.

$$L_{rn} = L_{r(n-1)}*\left(128.59 - 1.63*L_{r(n-1)}\right)/100 \quad (4)$$

$$R_{Mn} = 0.69*0.98*\frac{L_{rn}}{L_i}*\frac{\sigma_r}{\sigma_y}*\frac{\varepsilon_r}{\varepsilon_y}* - \left(1 - \frac{L_{rn}}{20}\right) \quad (5)$$

Fig. 5 shows that if no additional recycled or virgin fibres are added as part of the remanufacturing process to supplement the MWool® recycled fibre, each batch of mechanically recycled fibre from the woven fabrics could be recycled at least one more time, before the fibre length is too short to be compatible with the woollen yarn production system and must therefore be diverted to other end-uses or waste streams. Note however, that blending with fibre from virgin, post-consumer, post-industrial, and process waste feedstocks would usually occur in industrial settings, (see Fig. 1) with the potential to extend the usable life of the wool recyclate even further.

4. Conclusions

The challenge of mechanically recycling woven apparel fabrics that already contain recycled wool, is different from recycling post-consumer wool knitwear, because they have a denser fabric structure, contain

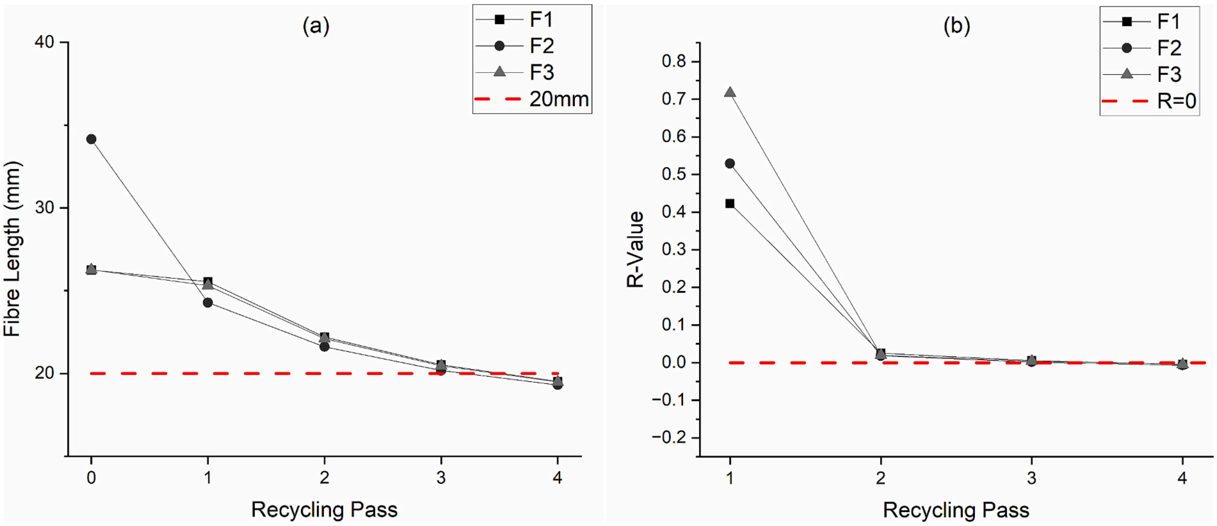


Fig. 5. (a) Measured mean fibre lengths at L_f (0) and L_r (1), with the predicted mean fibre lengths (L_{rn}) for each additional cycle up to four (assuming the same manufacturing process for each cycle). The minimum spinnable fibre length of 20 mm is indicated with a red dashed line. (b) The calculated (R_M) and predicted (R_{Mn}) R-values after each recycling cycle are shown. $R = 0$ is indicated with a red dashed line.

higher twist yarns and undergo different finishing processes, which means fibre breakage is more likely. When processing recycled wool fibre into new woollen yarns and woven apparel fabrics, substantial fibre breakage occurs, especially during fabric finishing, e.g. brushing and raising. The reduction in mean fibre length at this stage can even exceed the fibre breakage observed after mechanical recycling. Despite the obvious construction differences between knitted and woven fabrics made of wool, the recycling-only R-Indices are comparable for both, suggesting that the trend towards a similar recycled mean fibre length is likely due to recycling machine settings. Owing to the observed breakage of recycled fibres during woven fabric finishing (e.g. due to brushing and raising), and the increased consolidation (e.g. due to fulling), the potential for multi-recyclability is lower for woven wool fabrics than for wool knitwear. However, for wool fabrics that already contain mechanically recycled MWool® fibre, there is potential for at least one additional closed-loop cycle before it is necessary to divert the recyclate to other end-uses or waste streams. These findings demonstrate the potential for fabric finishing processes, e.g. fulling, brushing or raising and calendering to modulate residual fibre length after mechanical recycling, and highlight the importance of careful selection of process sequences and settings to extend the recyclability of wool fibres.

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. **S.J. Russell:** Writing – original draft, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors report financial support was provided by Manteco SpA.

Acknowledgements

The authors wish to thank Dr. Jianguo Qu at the University of Leeds for assistance with fibre tensile testing and fibre length measurements. Thanks are also due to Manteco SpA, Via della Viaccia, 19, 59013 Montemurlo, Italy for financially supporting this study. SJR gratefully acknowledges the support of Back to Baselines in Circular Fashion and Textiles, part of the Network Plus Circular Fashion and Textile Programme, funded by the Natural Environment Research Council under grant no. NE/Y004043/1.

Data availability

Data will be made available on request.

References

[1] S. Russell, P. Swan, M. Trebowicz, A. Ireland, Review of wool recycling and reuse, in: Nat. Fibres Adv. Sci. Technol. Ind. Appl., Springer, 2016, pp. 415–428, https://doi.org/10.1007/978-94-017-7515-1_33.

[2] E.B. Fry, Textile by-products; Mungo, Shoddy &c, J. Text. Inst. Proc. 16 (1925) P60–P64, https://doi.org/10.1080/19447012508665448.

[3] N.C. Gee, The reclamation of wool fibres, J. Text. Inst. Proc. 41 (1950) P192–P201, https://doi.org/10.1080/19447015008664835.

[4] Y. Sun, B. Li, Y. Zhang, H. Dou, W. Fan, S. Wang, The progress and prospect for sustainable development of waste wool resources, Text. Res. J. 93 (2023) 468–485, https://doi.org/10.1177/00405175221098572.

[5] I. Bianco, R. Gerboni, G. Picerno, G.A. Blengini, Life cycle assessment (LCA) of MWool® recycled wool fibers, Resources 11 (2022) 41, https://doi.org/10.3390/resources11050041.

[6] A.A. Gharehaghaji, N.A.G. Johnson, Wool fibre microdamage caused by opening processes Part II: a study of the contact between opening elements and wool fibre in controlled extension, J. Text. Inst. 86 (1995) 402–414, https://doi.org/10.1080/00405009508658767.

[7] J.W.S. Hearle, B. Lomas, W.D. Cooke, Atlas of Fibre Fracture and Damage to Textiles, CRC Press, Boca Raton, 1998. Cambridge, England: Woodhead Pub. in association with Textile Institute.

[8] M.J. Glasper, G. Picerno, M. Tausif, S.J. Russell, Closed loop mechanical recyclability of post-consumer waste wool fabrics based on fibre length retention, Clean. Eng. Technol. 22 (2024) 100796, https://doi.org/10.1016/j.clet.2024.100796.

[9] European Commission, EU Strategy for Sustainable and Circular Textiles. https://environment.ec.europa.eu/strategy/textiles-strategy_en, 2022 (accessed September 23, 2022).

[10] Sustainable Apparel Coalition, Higg Materials Sustainability Index (MSI) Methodology. https://howtohigg.org/wp-content/uploads/2020/07/Higg-MSI-Methodology-July-31-2020.pdf, 2020 (accessed August 22, 2024).

[11] Textile Exchange, Materials Market Report. https://textileexchange.org/app/uploads/2024/09/Materials-Market-Report-2024.pdf, 2024.

[12] N. Palomo-Lovinski, Missed opportunities: fashion fabric sourcing professionals' use of the MSI in the Higg index, Fash. Pract. (2024) 1–18, https://doi.org/10.1080/17569370.2024.2312925.

[13] K.J. Watson, S.G. Wiedemann, Review of methodological choices in LCA-based textile and apparel rating tools: key issues and recommendations relating to assessment of fabrics made from natural fibre types, Sustainability 11 (2019) 3846, https://doi.org/10.3390/su11143846.

[14] S.G. Wiedemann, L. Biggs, S.J. Clarke, S.J. Russell, Reducing the environmental impacts of garments through industrially scalable closed-loop recycling: life cycle assessment of a recycled wool blend sweater, Sustainability 14 (2022) 1081, https://doi.org/10.3390/su14031081.

[15] Manteco, Personal Communication, 2025.
[16] D.A. Ross, G.A. Carnaby, J. Lappage, Woollen-yarn manufacture, Text. Prog. 15 (1986) 1–70, https://doi.org/10.1080/00405168608689000.
[17] V. Kadam, A. Singh, Woollen spinning technologies, in: Dev. Yarn Spinn. Technol., Elsevier, 2025, pp. 231–252, https://doi.org/10.1016/B978-0-443-13887-4.00011-9.
[18] S.J. Russell, N. Morley, M.J. Tipper, I. Drivas, G.D. Ward, Principles of the recovery and reuse of corporate clothing, Proc. Inst. Civ. Eng. Waste Resour. Manag. 163 (2010) 165–172, https://doi.org/10.1680/warm.2010.163.4.165.
[19] G. Villalba, M. Segarra, A.I. Fernández, J.M. Chimenos, F. Espiell, A proposal for quantifying the recyclability of materials, Resour. Conserv. Recycl. 37 (2002) 39–53, https://doi.org/10.1016/S0921-3449(02)00056-3.
[20] G.D. Ward, A.D. Hewitt, S.J. Russell, Fibre composition of donated post-consumer clothing in the UK, Proc. Inst. Civ. Eng. Waste Resour. Manag. 166 (2013) 29–37, https://doi.org/10.1680/warm.12.00014.
[21] S.S. Muthu, Y. Li, J.-Y. Hu, P.-Y. Mok, Recyclability potential index (RPI): the concept and quantification of RPI for textile fibres, Ecol. Indic. 18 (2012) 58–62, https://doi.org/10.1016/j.ecolind.2011.10.003.
[22] Manteco, Recype® | The Art of Creating Wool Colors with no Dyes or Chemicals, Manteco, 2025. https://manteco.com/recype/ (accessed April 1, 2025).
[23] N.C. Merrick, D.R. Scobie, Volume measurement of wool samples, Proc. N. Z. Soc. Anim. Prod. 57 (1997).
[24] AATCC Test Method 20A, Fiber Analysis: Quantitative, American Association of Textile Chemists and Colorists, Research Triangle Park, NC, 2014.
[25] C. Tomasino, Chemistry & Technology of Fabric Preparation & Finishing, College of Textiles, North Carolina State University, Department of Textile Engineering, Chemistry & Science, 1992.
[26] J.W.S. Hearle, A critical review of the structural mechanics of wool and hair fibres, Int. J. Biol. Macromol. 27 (2000) 123–138, https://doi.org/10.1016/S0141-8130(00)00116-1.
[27] R. Meredith, 12 — a comparison of the tensile elasticity of some textile Fibres, J. Text. Inst. Trans. 36 (1945) T147–T164, https://doi.org/10.1080/19447024508659711.