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Mechanical recycling and industrial reintegration of post-industrial stretch textile waste

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ABSTRACT

Elastane-containing textiles represent a challenging post-industrial textile waste stream for mechanical recycling because residual elastomeric filaments may contribute to fibre entanglement, persistent yarn fragments and heterogeneous fibre assemblies. This study screened mechanical recycling routes for a post-industrial textile waste composed of 68 wt% polyester, 29 wt% viscose and 3 wt% elastane, and then assessed industrial reintegration of selected fibre fraction. Among the evaluated configurations in a single laboratory trial, an alternating shredding–carding–shredding–carding (SCSC) sequence with TechSpin CT2 met the predefined visual-opening criterion provided the highest mean fibre length among the SCSC conditions (17.6 mm; SD 4.81 mm) The selected route yielded approximately 68% useable fibrous material. The recovered fibres were incorporated at 47.5 wt% ring-spun yarn with a tenacity of 16.5 cN/tex. Relative to the available virgin-yarn reference, tenacity was approximately 25% lower and mass irregularity and imperfections were higher. The yarn was nevertheless converted into four woven fabric variants under industrial conditions, demonstrating manufacturability within the tested route rather than equivalence to a virgin-fibre system. A screening-level gate-to-gate hotspot assessment of the laboratory fibre recovery stage estimated 4.1–4.3 kg CO_2-eq per kg of useable recycled fibre. This estimate is not a full life cycle assessment and is not suitable for direct comparison with virgin fibres. These findings establish a proof of technical reintegration for this specific waste stream, but the absence of independently replicated recycling trials, an elastane free control and an equivalent virgin fabric, limits causal and comparative interpretation.

1. Introduction

The transition towards circular textile production requires recovery routes that can return waste fibres to manufacturing while retaining sufficient processability (Baloyi et al., 2024; Candido, 2021; Biyada and Urbonavičius, 2025; Fonseca et al., 2023; Chamorro-Mera et al., 2023). Post-industrial waste is generally cleaner, more homogeneous and easier to trace than post-consumer waste, but blended stretch fabrics remain difficult to reprocess and are often downcycled, incinerated or landfilled (Baloyi et al., 2024; Biyada and Urbonavičius, 2025; Román-Collado et al., 2023; Solis et al., 2024; Butturi et al., 2025; Ellen McArthur Foundation A New, 2017; Farhana et al., 2022; Wojnowska-Baryła et al., 2024; European Commission A New Circular, 2020; Wojnowska-Baryła et al., 2022; Yao et al., 2025). Their performance depends on combinations of polyester, cotton or regenerated cellulosic fibres with a small elastane fraction, commonly below 10 wt% (Senthilkumar and Rathinamoorthy, 2023). During mechanical opening, residual elastomeric filaments may contribute to fibre entanglement, persistent yarn fragments and heterogeneous fibre bundles (Baloyi et al., 2024; Biyada and Urbonavičius, 2025; Yao et al., 2025; De Lima et al., 2025; Ghosh et al., 2025; Azevedo et al., 2025; Islam et al., 2025). These mechanisms can impair fibre control during drafting and increase yarn irregularity and imperfections. In the present waste stream, however, the contribution of elastane cannot be separated from blend

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composition, fabric construction, finishing history or mechanical processing because an otherwise equivalent elastane free control was unavailable.

Mechanical recycling is an established route for recovering fibres for yarns, nonwovens and other products (Baloyi et al., 2024; Candido, 2021; Wojnowska-Baryła et al., 2022; Yao et al., 2025; Karmakar et al., 2025). Its main limitations include fibre shortening, reduced cohesion, lower spinnability, increased yarn irregularity and lower yarn strength (Baloyi et al., 2024; Wojnowska-Baryła et al., 2022; Yao et al., 2025; Karmakar et al., 2025). For blended fabrics, the practical challenge is to open the textile structure sufficiently to reduce residual yarn fragments without excessive fibre damage. This balance must be assessed at the level of downstream manufacturing, because a fibre fraction that appears long after opening may still contain incompletely separated bundles. Product design also affects subsequent repair, disassembly and recovery; eco-design choices therefore remain relevant after technical fibre recovery (Fonseca et al., 2023; Chamorro-Mera et al., 2023; European Commission A New Circular, 2020; Rahee and Sarker, 2024).

Environmental evidence is also needed to identify burdens within a recycling route, but limited laboratory inventories must be distinguished from comparative life cycle assessments. Previous studies have addressed recycled-yarn production, textile-waste processing and circular product development (Brás et al., 2026; Habib et al., 2024a; Hamzi et al., 2025), yet evidence linking the mechanical opening of real, low elastane PES/CV/EA post-industrial waste to industrial ring spinning and weaving remains limited. This study addresses that gap by linking four stages: laboratory route screening; industrial production of a ring-spun yarn and woven fabrics; a screening-level, gate-to-gate hotspot assessment of the fibre recovery stage; and product-level proof-of-concept development. The specific contribution is an experimentally documented reintegration pathway for a 68/29/3 wt% PES/CV/EA waste stream, with explicit reporting of yield, fibre length distribution, yarn quality and the limitations of the unreplicated screening design. The study tests whether a route selected for fibre opening and preservation can provide material suitable for industrial manufacture; it does not statistically optimize the recycling process or isolate the effect of elastane.

2. Materials and methods

2.1. Materials and textile waste

The post-industrial PES/CV/EA stretch textile waste used in this study was supplied by Riopele -Têxteis S.A. and consisted of a white woven stretch fabric representative of industrial production residues. The material was composed of 68 wt% polyester (PES), 29 wt% viscose (CV), and 3 wt% elastane (EA). Throughout this manuscript, this material is referred to as post-industrial PES/CV/EA stretch textile waste. Prior to mechanical recycling, the fabric was optionally pre-treated with commercial softeners to reduce static build-up and improve fibre opening during shredding. Prior to mechanical recycling, the fabric was optionally pre-treated with commercial softeners to reduce static build-up and improve fibre opening during shredding. Three softeners were evaluated: Pantoctal CT-40 (Dilube, Barcelona, Spain), TechSpin CT2 (Achitex Minerva S.p.A., Vaiano Cremasco, Italy), and Eterol 100 (Cisme, Milano, Italy). For the preliminary washing resistance test of the PLA-based composite button prototypes, a ECE Non-Phosphate detergent (Entreprises Ltd, Thongsbridge, UK) was used.

2.2. Mechanical recycling process

Mechanical defibration of the textile waste was carried out using a Laboratory Shredding Machine 337S (Mesdan S.p.A., Puegnago del Garda, Italy), equipped with a conveyor belt, a main drum, upper rollers, and an air suction system for fibre collection. Conveyor belt speed, main drum speed, upper roller speed, and air suction intensity were independently adjustable. As the laboratory equipment comprises a single defibration module, the industrial opening process was simulated through repeated passages. The processing trials were designed as a route-screening study to examine the balance between fibre opening and fibre preservation, since increasing mechanical intensity may improve material liberation promoting fibre shortening (Brás et al., 2026). The screened factors were main drum speed, upper roller speed, air suction intensity, number of shredding passages, and the application of softener pre-treatments. Commercial softeners were diluted in water to 0.5% (v/v) and sprayed onto the waste before shredding.

In a second screening stage, an alternating shredding–carding–shredding–carding (SCSC) sequence was introduced to promote fibre disentanglement and alignment before further mechanical opening. Carding was carried out using a Cosmatex © Linea Campioni HL 500 (Benna, BI, Italy). Each condition comprised one 150 g laboratory trial. Fibre length distributions were measured as described in Section 2.3.4, and apparent opening was assessed qualitatively from visible residual yarn fragments and fibre entanglement. Selection followed a sequential rule defined from the available observations: (i) exclude conditions that remained insufficiently opened for reliable individual fibre measurement; (ii) prefer the SCSC conditions, which showed fewer visible residual fragments than repeated shredding; and (iii) among the SCSC conditions, select the condition with the highest mean fibre length while considering distribution width. On this basis, Sample 10 was selected because it met the visual-opening criterion and had the highest mean fibre length among Samples 7-10 (17.6 mm; SD 4.81 mm). The approximately 68% useable fibre recovery and industrial processability reported later characterize the selected route but were not used as retrospective scores. Because conditions were not independently replicated and visual opening was not quantified, the study is a route-screening exercise rather than statistical process optimization.

2.3. Fibre characterization

2.3.1. ATR-FTIR

Fourier transform infrared spectroscopy (FTIR) coupled with an attenuated total reflectance (ATR) accessory was used to evaluate the chemical composition of the treated fibres. The analyses were performed using an IRAffinity S1 spectrometer (Shimadzu, Kyoto, Japan), equipped with an ATR accessory. Spectra were collected over 45 scans in the spectral range 4000−400 cm^{-1}, with a resolution of 4 cm^{-1} in transmittance mode. For each processing condition, fibre bundles were collected and analyzed at three different locations to account for sample heterogeneity.

2.3.2. TGA/DTG

Thermogravimetric analysis was used to assess the qualitative composition of the textile waste. The TGA/DTG analyses were performed using a STA7200RV Thermal Analysis System (Hitachi, Tokyo, Japan), in the range of 25–600 °C at 10 °C min^{-1}. The nitrogen flow rate was 200 mL min^{-1} and the initial sample mass ranged between 6.64 and 8.83 mg in alumina pans. Mass loss and derivative mass loss curves were recorded as a function of temperature.

2.3.3. SEM

Surface morphology of recycled fibres and cross-sections of the produced button prototypes were examined using a FlexSEM 1000 II scanning electron microscope (Hitachi, Tokyo, Japan). Samples were sputter-coated with gold for 90 s using a Quorum MiniQS sputter coater (Laughton, East Sussex, England). Images were acquired using secondary electrons at an accelerating voltage of 10 kV, with an acquisition time of 80 s.

2.3.4. Fibre length measurement and data analysis

Fibre length was manually determined by arranging individual fibres

on fibre combs and measuring them in ImageJ software, following ISO 6989:1981 (Textile Fibres). Approximately 800 fibres from each processed sample were measured to describe the within sample distribution. Mean fibre length and standard deviation were calculated in GraphPad Software (Boston, MA, USA). Each processing configuration was represented by one laboratory trial; individual fibres were therefore treated as subsamples, not independent process replicates. The results were interpreted descriptively and were not used to claim statistically significant differences between routes. AFIS measurements, fibre fineness and single fibre tensile testing were outside the study scope and should be included in future replicated work.

2.4. Industrial spinning and woven fabric production

The mechanically recycled fibres obtained under the selected processing conditions were blended with virgin PES/CV fibres to produce ring-spun yarns suitable for woven fabric applications. For industrial validation, the blend ratio selected was 52.5:47.5 (virgin fibre: mechanically recycled fibre). A preliminary industrial trial containing 40 wt% mechanically recycled fibre was successfully processed. Based on this result and on the available industrial blend formulation, the recycled fraction was subsequently increased to 47.5 wt% to provide a more demanding manufacturing demonstration. This was the highest recycled-fibre content evaluated in the present study and should not be interpreted as the maximum technically achievable incorporation level. Incorporation levels of 50 and 60 wt% were not investigated and remain subjects for future process development.

For yarn production, the fibre blends were processed on a carding machine (Trützschler TC 19i, Mönchengladbach, Germany) to obtain a homogeneous sliver with a linear density of 0.120 Ne. The carded sliver was then subjected to two drawing passages on Trützschler TD9 and TD10 draw frames (Mönchengladbach, Germany) to improve fibre parallelization, blend homogeneity and linear density control. The drawn sliver was subsequently converted into roving on a roving frame (Marzoli FT1D, Palazzolo sull'Oglio, Italy), where twist and draft were applied. The process parameters were set at 1.2 twists per inch (TPI) and a draft of 6.7, resulting in a roving with a linear density of 0.80 Ne. Ring spinning was then carried out on a ring spinning machine (Rieter G5/1D, Winterthur, Switzerland) using a draft of 30 and a twist of 20 TPI to produce yarns with a linear density of 24 Ne. The yarns were subsequently wound using a Murata winding machine (Takeda-Mukaishiro-cho, Fushimi-ku, Kyoto, Japan) to obtain packages suitable for subsequent processes.

The recycled yarns were then rewound on an SSM DP1-D rewinding

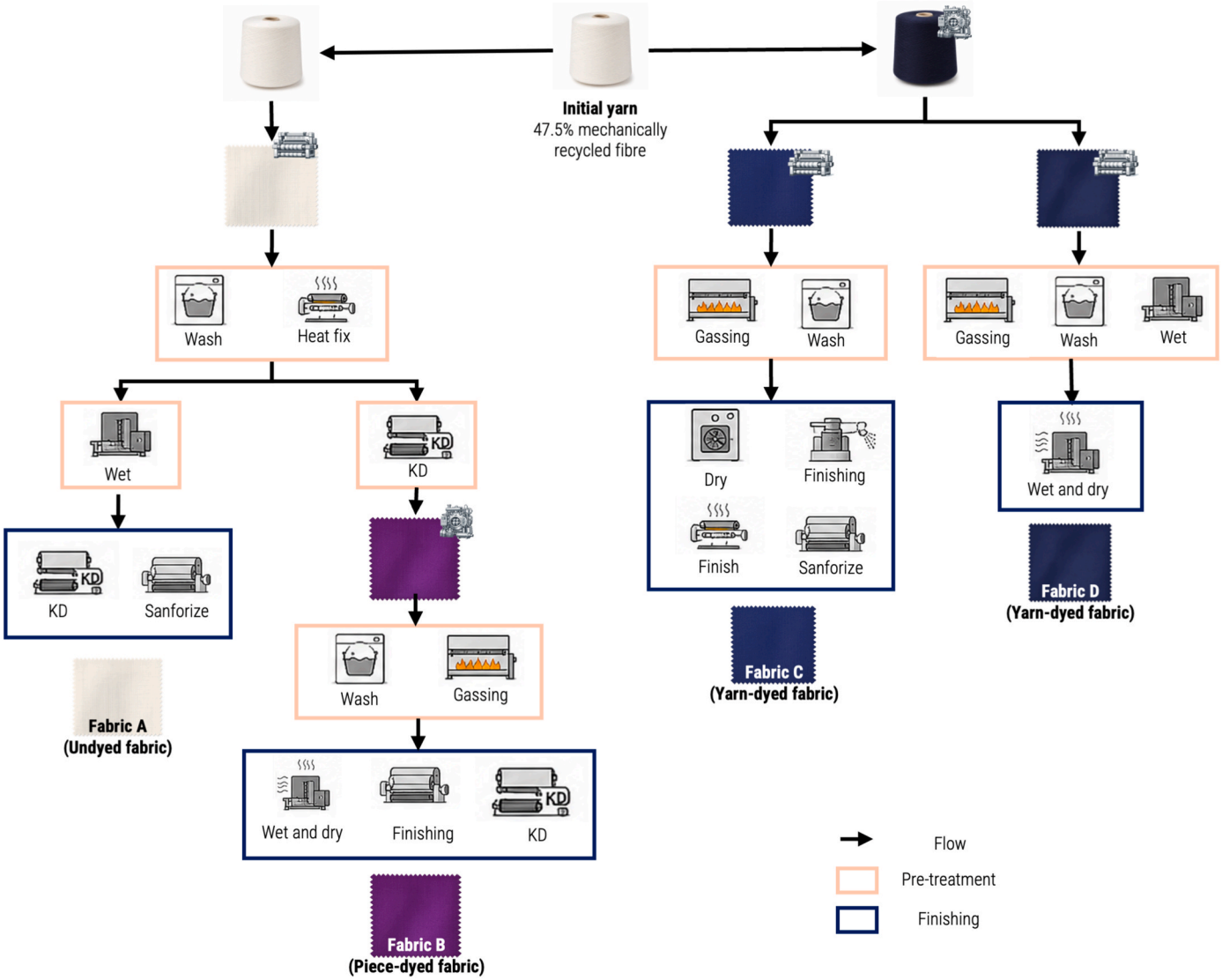


Fig. 1. Schematic representation of the preparation, dyeing, and finishing routes applied to fabrics produced from yarn containing 47.5 wt% mechanically recycled fibre.

machine and subsequently twisted on a twister (Saurer VTS-08-0-S, Arbon, Switzerland) to improve yarn strength. A twist of 17 TPI in the S direction was applied, resulting in a plied yarn with a linear density of 24/2 Ne. For woven fabric production, both warp and weft yarns were prepared. The warp yarns were wound on a sectional warping machine (Suzuki model, Gunma-ken, Kiryu-shi, Aioi-cho, Japan), after which the fabrics were woven on a rapier weaving machine (Dornier, Lindau, Germany). The resulting yarns were converted into four woven fabric variants that differed in weave construction, thread density, coloration route and finishing sequence. These variants were used to demonstrate the manufacturability of the recycled-yarn system under different industrial fabric-production conditions. Because construction and finishing varied simultaneously, the individual effects of these factors could not be isolated experimentally.

The woven fabrics were subsequently subjected to industrial preparation, dyeing and finishing routes to generate variants with distinct color, surface and handle characteristics for garment development (Fig. 1). During the preparation stage, the woven fabrics were washed at 80 °C using a pad steam system (Benninger, Fabrikstrasse, Switzerland). Thereafter, the fabrics were dried on a stenter frame (Monforts, Mönchengladbach, Germany) for 10 min at 120 °C. To stabilize the fabrics, a thermal setting treatment was also applied at 190 °C for 50 s, regardless of the presence of elastane. The fabrics were also subjected to a singeing process to remove the surface hairiness generated during the preparation process. This singeing treatment was applied to both sides of the woven fabrics at a speed of 120 m/min on an Osthoff machine (Lusamatex, Portugal). The fabrics were dyed using two different approaches: yarn dyeing and fabric dyeing. For yarn dyeing, a dye bath containing reactive and disperse dyes was prepared at a bath ratio of 1:6, and the process was carried out in a Thies iCone autoclave (Thies, Germany). Fabric dyeing was carried out in a Jet Thies machine (Thies, Germany) using a bath ratio of 1:12 with disperse and reactive dyes. Fabric finishing consisted of applying 20 g/L of polyurethane resin and 5 g/L of a silicon-based softener on the stenter frame (Monforts, Germany). In addition, the sanforisation process was carried out on a Sanfor machine (Monforts, Germany) with a compression setting of 4 mm and a processing speed of 20 m/min. KD finishing was carried out using industrial equipment supplied by Biela Shrunk (Italy). It is an industrial finishing treatment used to improve dimensional stability, fabric compactness and surface appearance after dyeing and finishing.

2.5. Yarn and woven fabric characterization

Linear density of the produced yarns was determined using an Uster Autosorter 4 (Uster, Switzerland), whereas yarn evenness was analyzed using the Uster Tester 4 (Uster, Switzerland). Subsequently, the mechanical properties and twist of the yarns were determined using an Uster TensoRapid 3 (Uster, Switzerland) and an Uster Zweigle D302 (Uster, Switzerland). For each yarn formulation, 150 measurements were obtained from 5 different bobbins. The results are reported as mean values together with the corresponding standard deviation. Industrial validation culminated in the manufacture of four woven fabric variants that were subsequently characterized according to the methods described below. Dimensional stability during washing was evaluated using a Wascator (James Heal, United Kingdom) according to ISO 6330:2021 (Textiles, 2021). Dry-heat dimensional stability was evaluated according to ISO 9866-2:1991 (Textiles, 1991) using a fusing machine (Meyer, Germany). A German Hoffman press (Hoffman Iberia, Portugal) was used to evaluate fabric behavior under hot pressing conditions, using the parameters described in DIN 53894-2:2018 (Testing of Textiles, 2018). The physical analysis of the fabrics included determination of width according to EN 1773:1999 (Textiles, 1999), threads and picks per inch according to ISO 7211-2:2024 (Textiles, 2024), and mass per unit area according to ISO 3801:1977 (Textiles, 1977). Regarding the mechanical properties of the woven fabrics, the tests were carried out using an Instron dynamometer, through which elasticity was determined according to EN 14704-1:2005 (Determination of the Elasticity of, 2005), tensile strength according to ISO 13934-1:2013 (Textiles, 2013), tear strength, according to ISO 13937-3:2000 (Textiles, 2000a), elongation, according to ISO 13934-1:2013 (Textiles, 2013), and seam slippage according to ISO 13936-1:2004 (Textiles, 2000b). Pilling and abrasion resistance were also evaluated using the Martindale method according to ISO 12945-2:2020 and ISO 12947-2/M&S P19 (Textiles, 2020).

2.6. Eco-design and prototype development

2.6.1. Sustainable product development

The eco-design approach was defined to evaluate how fabrics containing 47.5 wt% mechanically recycled fibre could be translated into garment concepts while limiting additional material complexity. The fabrics used in the collection were based on a polyester-viscose-elastane (PES/CV/EA) system incorporating 47.5 wt% mechanically recycled fibre. The recycled fraction originated from a post-industrial PES/CV/EA stretch textile waste composed of 68 wt% polyester (PES), 29 wt% viscose (CV), and 3 wt% elastane (EA), representative of industrial stretch fabrics widely used in apparel. Given the technical constraints associated with elastane-containing blends, particular attention was paid to process compatibility and to design choices intended to facilitate future end-of-life processing. The eco-design strategy adopted in this work was aligned with the principles of the EU Ecodesign for Sustainable Products Regulation (ESPR) and considered material transparency, traceability and compatibility with future circular material flows (European Commission A New Circular, 2020).

Design and pattern development were carried out using Adobe Illustrator to support iterative prototyping prior to physical sampling and thereby reduce material waste during development. Garment structures were intentionally simplified to minimize construction complexity and avoid unnecessary multi-material assemblies that could hinder end-of-life processing and recycling. Because the base fabric was already a PES/CV/EA blend, the eco-design strategy focused on avoiding additional material heterogeneity at garment level. Mixed-component linings, composite interlinings, and difficult-to-remove accessories were avoided wherever possible. Seams, labels, fastenings, and trims were selected or designed to improve compatibility with mechanical recycling and, where feasible, to facilitate easier removal at end of life. Where the use of additional components was unavoidable, design-for-disassembly principles were considered during garment development by favoring simple constructions and components that could be more readily separated. The collection was conceived as a versatile and gender-inclusive ensemble with different garment typologies, colors, and fabric constructions, to assess whether fabrics produced from yarn containing 47.5 wt% mechanically recycled fibre could be translated into functional apparel products designed according to eco-design principles. The eco-design approach adopted in this work was intentionally qualitative and aimed to demonstrate the practical application of selected eco-design and design-for-recycling principles during garment development. Quantitative eco-design metrics, such as recyclability scores, material circularity indicators or design-for-disassembly indices, were beyond the scope of the present study but constitute an important direction for future research.

2.6.2. PLA-based composite button prototypes

Textile residues collected as carding waste during fibre preparation, consisting mainly of short fibres unsuitable for further spinning, were selected for composite production by thermal compression moulding. A commercial polylactic acid grade, Ingeo™ Biopolymer 4032D, manufactured by NatureWorks LLC (Minnetonka, MN, USA) and supplied in powder form by Kai Parthy (Germany), was used as the polymer matrix. The grade was selected because of its thermoplastic processability and bio-based origin. Composite preparation involved three stages (Fig. 2): (a) preparation of PLA films, (b) assembly and consolidation of the

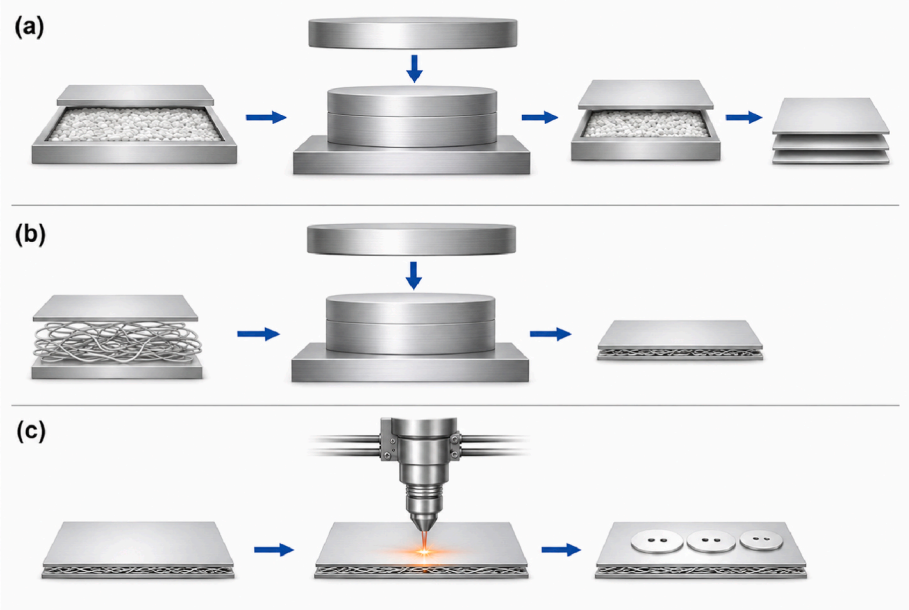


Fig. 2. Schematic representation of the preparation of PLA-based composite button prototypes: (a) PLA film production by compression moulding; (b) composite assembly and consolidation by thermal compression moulding; and (c) laser cutting of the consolidated sandwich composite for button prototype fabrication.

sandwich composite, and (c) laser cutting. First, PLA films were produced by compression moulding using a LabEcon 300 hydraulic hot press (Fontijne Presses, Rotterdam, The Netherlands) equipped with heated plates and a metallic mould. For each film, 15 g of PLA were distributed within the 10 × 10 cm mould and hot-pressed at 170 °C for 2 min under a compressive force of 60 kN. Second, the sandwich composite was prepared by placing one PLA film at the bottom of the mould, followed by a homogeneous and randomly oriented textile fibre layer (5 g), and a second PLA film. The assembly was closed with a counter-mould and consolidated at 170 °C for 3 min under 20 kN. Third, the consolidated sandwich composite was cut using a CO_2 laser machine with an M2 controller (PT 4060, 50 W, Nexform, Portugal) to produce button prototypes (Fig. 2c). The cutting layout was designed in Adobe Illustrator and imported into K40 Whisperer to control the cutting operation. Cutting was performed in a single pass at 50% power and 20 mm.s^{-1}.

2.6.3. *Washing resistance test of button prototypes*

A preliminary washing resistance test was conducted to assess the short-term stability of the composite button prototypes under controlled aqueous laundering conditions. Five specimens were initially placed in a Washtec-P laboratory washing fastness tester (Roaches, West Yorkshire, United Kingdom). The washing protocol consisted of five consecutive cycles at 40 °C for 30 min, with one specimen removed after each cycle for analysis. Thus, each specimen was exposed to a different number of washing cycles, and only one specimen completed all five cycles. The test was performed to provide an initial evaluation of the resistance of the composite structures to repeated aqueous washing exposure. After each cycle, the removed specimen was dried at room temperature and examined for visible changes in morphology, dimensional stability, surface degradation, cracking, delamination, and loss of structural integrity. The results were interpreted as an initial functional screening rather than as a full validation of end-use durability or industrial performance.

3. Results and discussion

3.1. *Textile waste characterization*

The post-industrial PES/CV/EA stretch textile waste was first characterized by ATR-FTIR, TGA/DTG and SEM to assess its qualitative composition and the morphological features relevant to mechanical recycling. The ATR- FTIR spectrum (Fig. 3a) showed features consistent with a polyester-rich blend containing regenerated cellulose. The carbonyl band at 1708 cm^{-1} and bands associated with aromatic terephthalate structures at 1504, 1237, 1089 and 721 cm^{-1}, confirmed the predominance of polyester in the waste stream. The broad O-H absorption centred at 3320 cm^{-1} and the band at 891 cm^{-1} were consistent with cellulose containing fibres, confirming the presence of cellulose within the blend and supporting the nominal viscose composition (Bashir et al., 2011; Dong et al., 2020; Liu et al., 2020; Trejo-Carbajal et al., 2022; Ding et al., 2022; Hu et al., 2020; Mecozzi and Nisini, 2019; Djebara et al., 2012; Pardini and Amalvy, 2008; Senoz et al., 2012; Yuan et al., 2015; Lee et al., 2021; Akbarpour et al., 2019; Puszka, 2018). Elastane could not be resolved unequivocally because of its low content (approximately 3 wt%) and overlap between urethane-related bands and the dominant polyester and viscose absorptions.

The TGA and DTG curves (Fig. 3b) were consistent with the thermal degradation behavior expected for the main polyester and viscose components of the waste stream. The first major degradation event, occurring between approximately 200 and 360 °C with a maximum degradation rate at 341 °C, was assigned to the decomposition of the viscose fraction, while the second major event between 380 and 505 °C, with a DTG maximum at approximately 433 °C, was attributed to polyester degradation (Dong et al., 2020; Trejo-Carbajal et al., 2022; Mecozzi and Nisini, 2019; Alongi et al., 2015). No distinct degradation event could be assigned to elastane under the conditions used. This does not exclude its presence but indicates that its low content and overlapping degradation range prevent a reliable thermal assignment in the blend. The residual mass of approximately 18% at 600 °C may be associated with char formation from the cellulosic fraction and thermally stable aromatic residues from polyester. Therefore, the TGA/DTG results support the presence of the major PES and CV components, while elastane identification requires complementary evidence, particularly the nominal formulation of the waste stream and the morphological observations obtained by SEM.

Scanning electron microscopy (SEM) was used to examine the morphology of the post-industrial PES/CV/EA stretch textile waste and to distinguish the fibre components based on morphological features

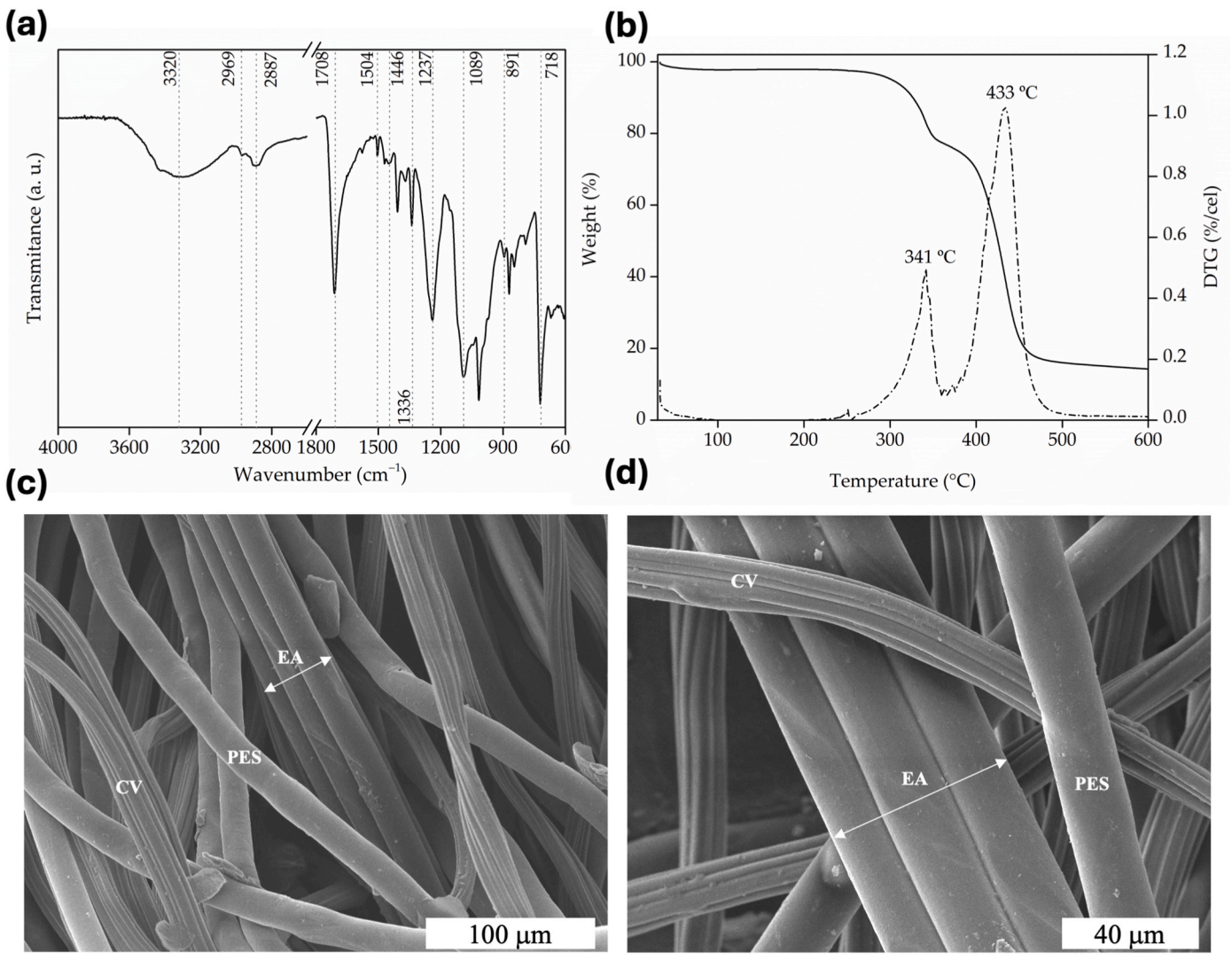


Fig. 3. Characterization of the post-industrial PES/CV/EA stretch textile waste before mechanical recycling: (a) ATR-FTIR spectrum, (b) TGA-DTG curves and (c, d) SEM micrographs showing the overall fibre morphology and the highly entangled network composed of polyester (PES), viscose (CV) and elastane (EA) fibres.

(Fig. 3c and d). The micrographs reveal a highly entangled fibrous structure composed of fibres with distinct morphologies. Polyester fibres exhibit a smooth and regular cylindrical surface, with diameters between 15.26 and 20.89 µm, typical of melt-spun synthetic filaments. In contrast, viscose fibres show a more irregular surface with characteristic longitudinal grooves, and diameters between 14.93 and 21.67 µm, consistent with regenerated cellulosic fibres produced by wet spinning. Thicker and smoother filaments, attributed to elastane, with diameters between 43.8 and 56.86 µm, can also be observed within the structure, supporting the presence of an elastomeric component in the blend as a minor fraction. The combined ATR-FTIR, TGA/DTG and SEM analyses confirmed that the waste stream was a polyester-rich blend in which elastane, although present as a minor mass fraction, remained structurally embedded within a highly entangled fibrous network. This morphology is relevant for mechanical recycling because elastomeric filaments can contribute to yarn cohesion and hinder complete fibre individualization during defibration.

3.2. Screening of mechanical recycling conditions: fibre opening versus fibre shortening

3.2.1. Screening strategy and processing matrix

The post-industrial PES/CV/EA stretch textile waste was subjected to mechanical defibration under controlled laboratory conditions using the Mesdan 337S shredding unit. The feed speed (0.5 m min^{-1}) and the main drum rotational speed (980 rpm) were kept constant throughout the initial screening trials, while the upper roller speed (15 and 30 rpm) and the air suction speed (2000 and 4000 rpm) were varied to evaluate their influence on fibre opening efficiency and fibre length preservation. The complete set of mechanical and pre-treatment conditions investigated is summarized in Table 1.

In the first screening phase, eight consecutive shredding passages (8-S) left visible yarn fragments in the processed material. Increasing shredding exposure alone was therefore insufficient to obtain the apparent opening required for individual-fibre processing. Upper-roller and air-suction speeds were varied because they affect transport and mechanical action, while Pantoctal CT-40, Eterol 100 and TechSpin CT2 were screened at 0.5% (v/v) to reduce friction and static accumulation. Softener application under repeated-shredding conditions did not remove the visible residual fragments. The second phase consequently combined shredding with intermediate carding (SCSC), and the conditions were compared using the decision rule described in Section 2.2.

3.2.2. Fibre length distributions and selection of the processing route

Approximately 800 fibres per measurable condition were used to describe fibre length distributions. Samples 1 and 2 remained insuffi-

Table 1
Processing conditions and fibre length distribution obtained after mechanical defibration of post-industrial PES/CV/EA stretch textile waste.

Sample	Upper drum speed (rpm)	Air suction speed (rpm)	Passages	Pre-treatment	Fibre length (mm)	
					$\bar{x}$	SD
1	15	2000	8-S		-	-
2	15	4000			-	-
3	30	2000			18.5	8.02
4				Pantoctal CT-40	19.3	7.60
5			4-S		18.1	8.21
6				Pantoctal CT-40	21.8	8.94
7			SCSC		12.3	3.55
8				Pantoctal CT-40	13.7	4.09
9				Eterol™ 100	12.5	4.62
10				TechSpin CT2	17.6	4.81

S = shredding passage, C = carding step, SCSC = alternating shredding–carding–shredding–carding sequence.

ciently opened for reliable measurement of individual fibres and were excluded from this analysis. The resulting mean fibre length ($\bar{x}$) and standard deviation (SD) are presented in Table 1. Under eight shredding passages at an upper-roller speed of 30 rpm and air suction of 2000 rpm, Sample 3 had a mean fibre length of 18.5 mm (SD 8.02 mm). Its broad distribution, together with visible residual fragments, indicates that high mean length alone did not identify a suitable opening condition. Fig. 4 illustrates this distinction: Sample 1 retained a compact, heterogeneous structure, whereas Sample 10 appeared more open and homogeneous. The image comparison is qualitative and does not provide a numerical opening index.

Under otherwise identical eight-pass conditions, Pantoctal CT-40 increased mean fibre length from 18.5 mm (SD 8.02 mm; Sample 3) to 19.3 mm (SD 7.60 mm; Sample 4), but visible partially opened yarn fragments remained. With four shredding passages, Sample 5 had a mean of 18.1 mm (SD 8.21 mm), and Pantoctal CT-40 produced 21.8 mm (SD 8.94 mm) in Sample 6. Thus, the largest mean obtained by repeated shredding coincided with the widest distribution and incomplete apparent opening; it cannot be interpreted as superior fibre preservation independently of bundle separation.

The SCSC conditions produced lower mean lengths but narrower distributions and fewer visible residual yarn fragments than the repeated-shredding conditions. Sample 7, without softener, had a mean of 12.3 mm (SD 3.55 mm). With softener, means ranged from 12.5 mm for Eterol 100 (Sample 9) to 17.6 mm for TechSpin CT2 (Sample 10), with SD values of 4.09-4.81 mm. The observations therefore show a trade-off between apparent opening and fibre length. Elastane is one plausible contributor to persistent cohesion in this blend, but its independent effect cannot be determined from these trials.

Sample 10 was selected by applying the sequential criteria stated in Section 2.2. Samples 1 and 2 failed the measurability criterion, and Samples 3-6 retained more visible yarn fragments under repeated shredding. All four SCSC conditions improved apparent opening; among them, Sample 10 had the highest mean fibre length (17.6 mm) with a distribution width (SD 4.81 mm) narrower than those of the measurable repeated-shredding samples (SD 7.60-8.94 mm). Selection was therefore based on an observable eligibility criterion followed by quantitative comparison within the eligible SCSC group. No numerical score was assigned to the qualitative visual observations, and no inferential comparison is claimed because each route was tested once. The 68% useable fibre recovery and subsequent spinning and weaving results validate the selected material only within this single route demonstration.

3.3. *Industrial spinning demonstration and yarn quality*

Fibres from Sample 10 were used in the industrial spinning demonstration because that condition met the apparent-opening criterion and had the highest mean fibre length among the SCSC conditions. The blend contained 47.5 wt% mechanically recycled fibre, the highest fraction tested in this study; it is not a demonstrated maximum incorporation level (Table 2).

The 52.5:47.5 virgin: recycled fibre blend corresponded to a nominal composition of 62.9 wt% PES, 35.7 wt% CV and 1.4 wt% EA. Industrial spinning at the initially targeted Ne 30/1 was unstable, whereas Ne 24/1 could be processed with greater twist insertion. The recycled fibre yarn reached 16.5 cN/tex, approximately 25% below the available virgin-yarn reference, and showed substantially higher irregularity and imperfection counts (Table 3). Because the reference was not established as compositionally and operationally equivalent, this comparison is contextual and does not isolate the effect of recycled fibre incorporation. The recycled blend required lower processing speed and careful control, consistent with the effects of short fibres and heterogeneous fragments on drafting. It nevertheless yielded yarn that could be woven under the tested industrial conditions. Its CVm was 14.6%, with 1796 thin places/km, 4582 thick places/km and 6586 neps/km; these values are substantial quality limitations, not evidence of equivalence to conventional

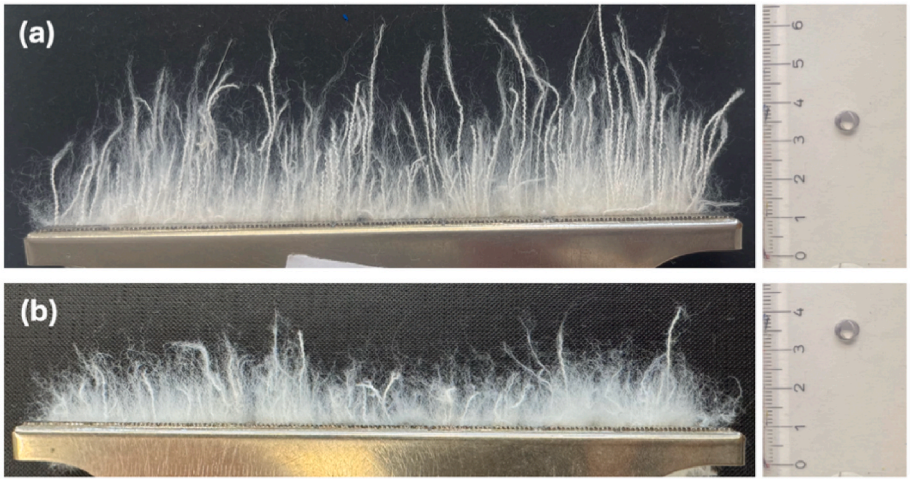


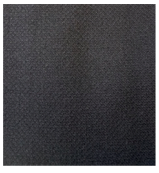
Fig. 4. Representative visual appearance of the fibrous web obtained after mechanical recycling under two selected processing conditions: (a) Sample 1 and (b) Sample 10. The images illustrate differences in fibre arrangement, protrusion, and apparent homogeneity after defibration.

Table 2
Mechanical and evenness properties of the virgin yarn reference and the yarn containing 47.5 wt% mechanically recycled PES/CV/EA fibre.

Sample	Count Ne	Tenacity cN/tex	CV Tenacity %	Irregularity Um, %	Thin places −50%/km	Thick places 50%/km	Neps 200%/km	Elongation %	CV Elongation %	Hairness S3	Breaking work cN.cm	Twist variation T/m
Control	24	21.8	11.8	11.3	14	30	40	11	11	3.3	2400	1500
52.5:47.5	23.4	16.5	14.6	24.5	1796	4582	6586	11.4	9.7	3.4	1960	1240

Values correspond to the second industrial spinning trial (52.5 wt% virgin fibres/47.5 wt% mechanically recycled fibres). Yarn properties were determined from 150 measurements collected from five bobbins per formulation.

Table 3
Coloration, finishing treatments and physical and mechanical properties of the four woven fabrics variants containing 47.5 wt% mechanically recycled fibre.

Recycled fibres fraction	47.5%			
Composition	62.9 wt% PES; 35.7 wt% CV and 1.4 wt% EA			
Denomination	**Fabric A**	**Fabric B**	**Fabric C**	**Fabric D**
Colouring route	Undyed fabric	Piece-dyed fabric	Yarn-dyed fabric	Yarn-dyed fabric
Singeing	Both sides	Both sides	Both sides	Face side only
Finishing treatment	Wash + Heat set + Wet + Sanforization + KD	Wash + Heat set + Wet + Finishing + KD	Wash + Dry + Finishing + Sanforization	Wash + Wet + Wet and Dry
Useable width	150 cm	143 cm	150 cm	143 cm
Weight	313 g/m^2 ± 5%	284 g/m^2 ± 5%	325 g/m^2 ± 5%	306 g/m^2 ± 5%
Abrasion	No breakdown at 19,000 cycles			
Tearing strength	Warp: 4.41 kgf Weft: 4.26 kgf	Warp: 6.09 kgf Weft: 5.72 kgf	Warp: 5.08 kgf Weft: 4.96 kgf	Warp: 7.41 kgf Weft: 7.2 kgf
Seam slippage	20 kgf			
Tensile strength	Warp: 91.9 kgf Weft: 100.7 kgf	Warp: 74.1 kgf Weft: 61.2 kgf	Warp: 70.5 kgf Weft: 72.7 kgf	Warp: 102.4 kgf Weft: 85.8 kgf
Pilling resistance	3.5 (2000 cycles)	1.5 (2000 cycles)	2 (2000 cycles)	2.5 (2000 cycles)
Elasticity	Warp: 21.5% Weft: 10.4%	Warp: 8.6% Weft: 18%	Warp: 20.2% Weft: 13.8%	Warp: 9% Weft: 15.7%
				

virgin yarn. Similar deterioration in strength and evenness with increasing mechanically recycled content has been reported for recycled cotton and process-waste yarns (Habib et al., 2024a; Hamzi et al., 2025). Habib et al. linked higher recycled-cotton content to greater irregularity and imperfections and lower strength and elongation, while the present study extends the manufacturing evidence to a mechanically recovered PES/CV/EA blend and subsequent weaving. Studies of purpose-designed hybrid and dual-core yarns further show that filament type, core configuration and insertion method affect yarn and fabric performance (Duru et al., 2024; Habib et al., 2024b, 2025). Those controlled architectures differ from the present residual elastane-containing staple-fibre mixture. Accordingly, the observed incomplete opening and yarn irregularity may reflect elastane, blend composition, fabric construction and mechanical history in combination; the absence of an elastane-free control precludes attribution to elastane alone.

3.4. Woven fabric performance: effect of construction and finishing on garment-relevant properties

Four woven fabric variants were produced from the same yarn system containing 47.5 wt% mechanically recycled fibre, but weave, thread density, mass per unit area, coloration and finishing varied simultaneously (Table 3). All variants were woven successfully, with useable widths of 141.5-150 cm and masses of 284-325 g/m^2. No breakdown occurred after 19,000 Martindale cycles. Tear strength ranged from 4.26 to 7.41 kgf, with Fabric D giving the highest values in both directions. These results document manufacturability and the range obtained across the four process combinations; they do not isolate the effects of construction, coloration or finishing and cannot be compared directly with an equivalent virgin fabric because none was produced.

Seam slippage resistance was 20 kgf for all variants. Tensile strength ranged from 70.5 to 102.4 kgf in the warp direction and from 61.2 to 100.7 kgf in the weft direction; Fabric D had the highest warp value and Fabric A the highest weft value. Pilling resistance ranged from grade 1.5 to 3.5 after 2000 cycles, and elasticity ranged from 8.6% to 21.5% in warp and from 10.4% to 18.0% in weft. These differences are consistent with the combined influence of architecture, density and finishing, but the experimental design does not support causal attribution to an individual factor. Likewise, the retained elastane fraction may have contributed to directional elasticity, but its independent contribution was not tested.

The finishing routes also produced different surface appearance and handle. Fabric A remained undyed and underwent KD finishing and sanforization; Fabric B was piece dyed; and Fabrics C and D were yarn dyed with different finishing sequences. Singeing, resin, softener and sanforization can affect surface fibres, cohesion, handle and dimensional stability, but these mechanisms were not independently evaluated here. The fabric data therefore support only two conclusions: the recycled yarn was convertible into four woven variants under the tested industrial conditions, and those variants differed in garment-relevant properties. They do not establish recycled-versus-virgin fabric equivalence or identify a dominant construction or finishing variable.

3.5. Product-level eco-design demonstration using mechanically recycled PES/CV/EA fabrics

The garment concepts were developed to evaluate how fabrics produced from yarn containing 47.5% mechanically recycled fibre could be applied in product-level prototypes with different construction and finishing requirements (Fig. 5). This stage was conceived as a product-level design compatibility assessment, rather than as a commercial collection or a full garment durability validation.

The garment prototypes examined whether the four recycled fibre fabric variants could be incorporated into different product constructions (Fig. 5). Fabric A was used for an undyed coat, Fabric B for a dress and shorts, Fabric C for a vest, and Fabric D for a bolero. Material selection considered the measured fabric properties and the intended construction, while the designs avoided unnecessary mixed components and favoured simpler assemblies. This stage demonstrates prototype compatibility only. It did not quantify recyclability, circularity, consumer performance or long-term durability, and the observed fabric differences cannot be assigned to individual finishing variables.

3.6. Proof-of-concept valorization of non-spinnable residual fractions through PLA-based composite button prototypes

In addition to fibre-to-yarn recycling, non-spinnable residual fractions generated during carding were explored as secondary feedstocks for PLA-based composite button prototypes (Fig. 6a). The aim was not to fully validate a commercial accessory, but to assess whether these residual streams could be incorporated into a simple thermoplastic composite structure with sufficient integrity for preliminary handling and washing-resistance screening. The composites were prepared using polylactic acid (PLA) as the polymer matrix, selected for its thermoplastic processability and bio-based origin (Rajendran et al., 2024; Khouri et al., 2024; Tripathi et al., 2021). The composite was produced by thermal compression moulding and subsequently cut into button prototypes using CO_2 laser cutting. Morphological analysis of the button cross-sections (Fig. 6b-f) showed that the composite structures were generally cohesive and that the residual textile fractions were successfully incorporated into the PLA matrix, resulting in prototypes with a thickness of 2.60 mm. The cross-sectional images revealed a relatively compact outer region and a more heterogeneous internal structure, in which dispersed fibres, fibre rich domains, and voids could be observed. This heterogeneity suggests that, although consolidation was achieved,



Fig. 5. Garment concepts developed using woven fabrics produced from yarn containing 47.5 wt% mechanically recycled fibre, including a natural-tone coat, a fuchsia dress, a navy bolero, a navy vest and fuchsia shorts.

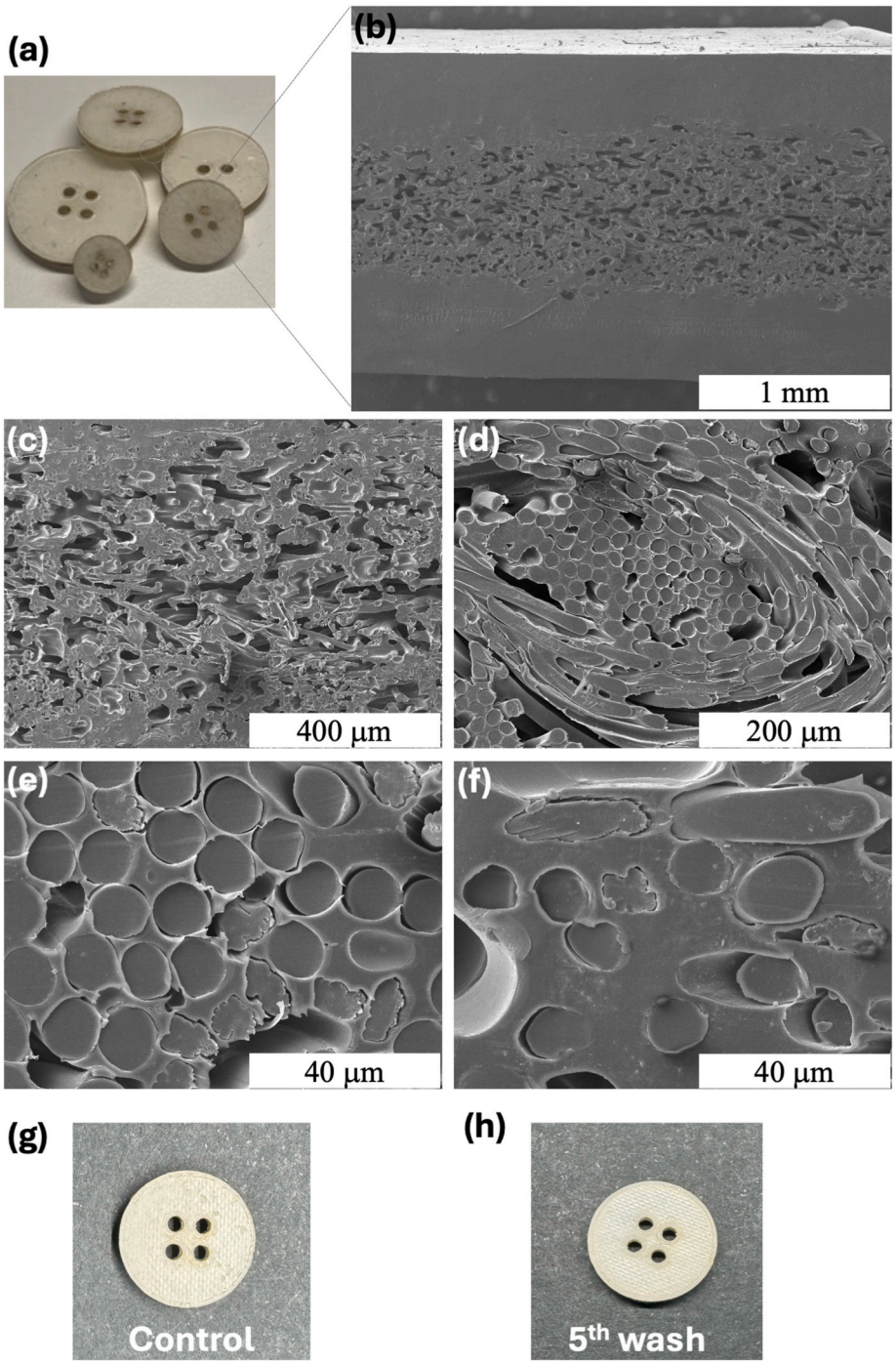


Fig. 6. Morphology of PLA-based composite button prototypes produced from residual textile fractions: (a) macroscopic appearance and SEM images of the cross-section showing the (b) button diameter and outer layers and (c-f) core morphology at different magnifications and preliminary washing resistance of PLA-based composite button prototypes (g) before and (h) after five consecutive washing cycles.

fibre distribution and matrix impregnation were not fully uniform throughout the thickness of the composite. Nevertheless, the overall structural continuity of the cross-section indicates that these residual fractions can be converted into cohesive PLA-based composite prototypes suitable for preliminary functional screening.

The preliminary washing observations (Fig. 6g and h) showed no visible changes in shape, surface appearance, cracking, delamination or loss of structural integrity after five washing cycles. These results indicate that non-spinnable residual fractions can be converted into cohesive PLA-based composite prototypes and may represent a secondary valorization route for residues generated during mechanical recycling. However, each exposure level was represented by only one specimen, and only one specimen completed all five cycles. Therefore, these observations constitute an exploratory visual screening and do not demonstrate laundering durability or accessory performance. The composite contained approximately 14.3 wt% textile residue and remained predominantly PLA by mass. Mechanical strength, impact resistance, button-attachment performance, dimensional variability, extended laundering and replicated durability testing are required before industrial, or circularity claims can be made.

3.7. Screening-level gate-to-gate environmental assessment of the selected SCSC sequence

A screening-level gate-to-gate environmental assessment was performed to estimate the order of magnitude of the direct burdens associated with the laboratory-scale mechanical fibre-recovery stage (Fig. 7). The inventory used the general system-boundary principles of ISO 14044:2020 (Environmental Management, 2006), but the study was not a full ISO-compliant life cycle assessment. The reference flow was 1000 g of input waste, corresponding to approximately 680 g of useable recycled fibre at the measured aggregate yield. Results were normalized to 1 kg of useable recycled fibre. The boundary included electricity for shredding and carding and the softener applied before shredding. It excluded waste generation, collection, sorting, transport, spinning, weaving, garment manufacture, use and end of life. The results identify laboratory-stage hotspots only and do not support comparative claims about recycled fibres, virgin fibres, products or alternative recycling technologies. For a reference input of 1000 g, the selected trial yielded approximately 680 g of useable recycled fibre and an aggregate loss of approximately 320 g. Short fibres, dust, residual yarn fragments and other non-recoverable material were not weighed separately; the 68% value is therefore an overall useable-fibre yield, not a fraction-resolved mass balance. Scaled electricity demand for the SCSC sequence was 10.73 kWh per 680 g of useable fibre (3.39 kWh for shredding and 7.34 kWh for carding), equivalent to 15.8 kWh/kg useable fibre. With the stated electricity factor (Despacho n, 2008), the associated climate-change estimate was approximately 3.95 kg CO_2-eq/kg useable recycled fibre.

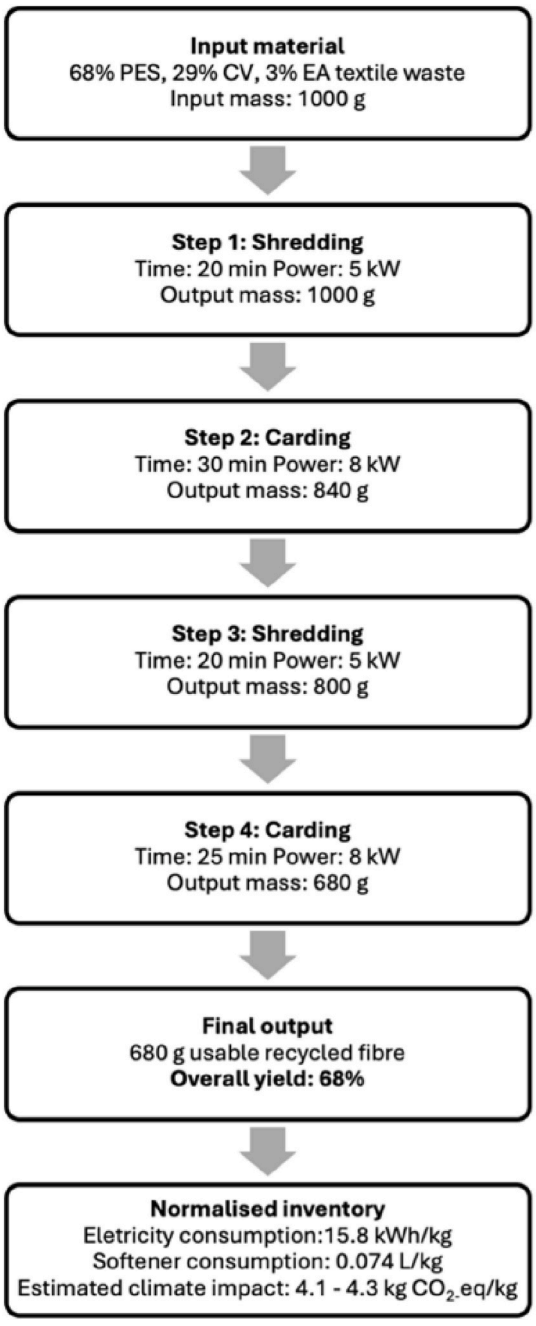


Fig. 7. System boundaries and inventory of the screening-level gate-to-gate environmental assessment of the selected SCSC mechanical recycling route, including material flows, processing conditions, overall yield and normalized environmental inventory.

The first shredding pass used 50 mL of non-ionic softener per 1000 g of input waste, equivalent to 0.074 L/kg useable recycled fibre. Applying the generic auxiliary-chemical factor of 2-4 kg CO_2-eq·L^{-1} (Sadhukhan et al., 2025), gave 0.15-0.30 kg CO_2-eq/kg useable fibre. The combined screening estimate for the selected laboratory route was therefore approximately 4.1-4.3 kg CO_2-eq/kg useable recycled fibre.

Published cradle-to-gate or other fibre-production estimates are not directly comparable with this gate-to-gate laboratory inventory because system boundaries, scale, allocation and energy mixes differ (Almeida et al., 2026; Gonzalez et al., 2023; Abagnato et al., 2024). They are therefore not used here as performance benchmarks. Within the stated boundary and assumptions, electricity accounted for most of the 4.1-4.3 kg CO_2-eq/kg estimate, and carding accounted for most of the measured electricity. Replicated industrial-scale inventories are needed before environmental comparisons or improvement claims can be made.

4. Conclusions

This study establishes a proof-of-technical-reintegration pathway for one post-industrial PES/CV/EA waste stream, linking laboratory mechanical opening to industrial ring spinning and weaving. Among the single-run configurations screened, the SCSC sequence with TechSpin CT2 met the apparent-opening criterion and gave the highest mean fibre length within the SCSC group (17.6 mm; SD 4.81 mm). The selected trial recovered approximately 68% useable fibre.

The recovered material was incorporated at 47.5 wt% into a 24 Ne ring-spun yarn with a tenacity of 16.5 cN/tex. Relative to the available virgin-yarn reference, tenacity was approximately 25% lower, and irregularity and imperfection counts were substantially higher, while hairiness S3 was similar (3.4 versus 3.3). The yarn nevertheless remained processable through industrial weaving. Four woven variants were produced, demonstrating manufacturability under the tested conditions rather than equivalence to a virgin-fibre fabric.

The screening-level, gate-to-gate assessment estimated 4.1-4.3 kg CO_2-eq/kg useable recycled fibre for the laboratory fibre recovery stage and identified electricity, particularly carding, as the principal hotspot. This value is not a life cycle assessment and cannot be compared directly with virgin-fibre production or alternative recycling routes. The garment and PLA-button prototypes provide qualitative demonstrations only.

The main limitations are the absence of independent recycling-route replicates, quantitative fibre-opening measurements, an elastane-free control, a fraction-resolved mass balance and an equivalent virgin fabric. Construction and finishing also varied simultaneously among fabric variants. These constraints prevent statistical optimization, causal attribution to elastane and direct recycled-versus-virgin fabric or environmental comparisons.

Future work should replicate the recycling routes, quantify fibre opening and individual mass-loss fractions, test an otherwise equivalent elastane free material, compare matched recycled and virgin fabrics, assess durability, and compile industrial-scale environmental

inventories. Within these limits, the study provides quantitative evidence that this specific 68/29/3 wt% PES/CV/EA post-industrial waste can be recovered and reintegrated into industrial yarn and woven-fabric manufacture.

CRediT authorship contribution statement

Ana Catarina Silva: Writing – original draft, Visualization, Supervision, Software, Investigation, Formal analysis, Conceptualization. **Duarte Brás:** Writing – original draft, Software, Methodology, Investigation, Data curation. **Tiago Azevedo:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Diego M. Chaves:** Writing – review & editing, Visualization, Methodology, Investigation. **Ângela Teles:** Writing – original draft, Data curation. **Albertina Reis:** Writing – review & editing, Resources. **Raúl Fangueiro:** Writing – review & editing, Resources, Project administration, Funding acquisition. **Diana P. Ferreira:** Writing – review & editing, Validation, Resources, Project administration, Funding acquisition, Conceptualization.

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Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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