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Cost-performance evaluation of socks developed from post-consumer denim waste and recycled polyester

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Abstract

Post-consumer denim waste is a major cotton-rich waste stream, but its use in durable textile products remains challenging because mechanical recycling shortens and damages fibers. This study developed half-terry socks from recycled denim cotton blended with recycled polyester and compared them with virgin polyester/cotton control socks. Twelve variants of recycled yarns were produced using three recycled polyester/recycled cotton ratios: 90/10, 80/20, and 70/30, through ring and rotor spinning at two twist levels. The socks were evaluated for structural properties, comfort-related performance, durability and production cost. The recycled socks were successfully produced with comparable structural properties to the control and generally showed higher air permeability, indicating better breathability. Moisture management was mainly controlled by sock region, following the order leg>upper foot>terry sole, with the terry sole acting mainly as an absorbent and cushioning zone. Cost analysis showed that recycled socks were cheaper, costing 0.149 to 0.152 €/pair, compared with 0.160 €/pair for the virgin control. However, durability is the main limitation: all recycled socks showed pilling grade 1, while the control showed grade 3, and abrasion loss increased with recycled cotton content. Recycled denim-based socks demonstrated comparable structural properties, improved breathability, lower estimated production cost, slightly higher air permeability, and circular material benefits; however, poor pilling resistance and greater abrasion loss remain key barriers to commercial adoption, highlighting the need for further improvements in recycled yarn quality and surface durability.

Keywords Circularity · Cost analysis · Post-consumer textile waste · Recycled denim · Sustainability · Waste materials

Introduction

The growing volume of textile waste and the increasing pressure to reduce the environmental burden of the apparel sector have made textile recycling an urgent research priority[1]. In Europe alone, textile consumption reached 19 kg per person in 2022, rising from 17 kg per person in 2019, while EU Member States generated about 6.94 million tons of textile waste in 2022, equivalent to 16 kg per person[2]. Earlier European Environment Agency reported that roughly 16 kg of textile waste generated per person in 2020, only 4.4 kg was separately

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collected for reuse and recycling, while 11.6 kg ended up in mixed household waste[3]. The same reporting indicates that 82% of the textile waste came from post-consumer sources, confirming that used garments, rather than factory leftovers, form the largest part of the problem[4]. The environmental significance of this issue goes beyond solid waste alone. According to UNEP, the fashion and textiles sector accounts for 2–8% of global greenhouse gas emissions, consumes about 215 trillion liters of water annually, equal to roughly 86 million Olympic-sized swimming pools, and contributes around 9% of microplastic pollution reaching the oceans each year[5]. UNEP also notes that approximately 15,000 chemicals are used in textile manufacturing processes[6]. Together, these data highlight that improving textile circularity is not only a waste-management objective, but also a climate, water, chemical, and resource-efficiency priority.

Despite the strong sustainability promise of recycling, the value of recycled textiles cannot be judged only by the amount of waste diverted from landfill or incineration. A critical concern is whether recycled materials can be converted into products with sufficient quality, durability, and service life[6]. This concern is especially relevant for post-consumer recycling, because the fibers in used garments have already been exposed to manufacturing, dyeing, repeated laundering, wear, and mechanical damage before they are recovered[7]. As a result, post-consumer fibers are shorter, weaker, and more irregular than virgin fibers. In that sense, circularity is not achieved simply by recycling more material; it also depends on whether the recycled product remains functionally credible in use.

Among the different textile waste streams, post-consumer denim garments are particularly relevant[8]. Denim is widely consumed, heavily discarded, and largely cotton-based, making it an attractive source of reusable cellulose-rich fiber[9]. At the same time, denim waste is more difficult to recycle than pre-consumer cotton waste because it often contains dyes, finishes, worn regions, contamination, and in some cases blended elastane or synthetic components[10]. Mechanical shredding, which remains one of the most accessible and industrially relevant recovery methods, further shortens the recovered fibers and increases short-fiber content and irregularity[11]. The challenge is not just whether recycled denim fibers can be re-spun, but whether they can support the development of durable and comfortable textile products.

Hosiery represents a particularly demanding but meaningful product category for this kind of evaluation[12]. Socks are not simple knitted articles; they are next-to-skin products that must perform under repeated compression, friction, bending, perspiration, and localized stress during wear[13]. Previous research on socks clearly shows that fabric structure plays a major role in comfort behavior[14]. Also, it is well-known that air and water vapor permeability of knits strongly depend on fibers and yarns properties[15]. Tomljenović et al. reported that socks made from modal and micro-modal yarns showed better comfort properties, generally better pilling resistance, and, after pretreatment, abrasion resistance comparable to cotton socks[16]. Summaries of recycled-cotton knitted-fabric research report that the inclusion of recycled cotton tends to decrease air permeability, increase thermal resistance, and reduce tensile performance, largely because recycled yarn systems are often bulkier, hairier, and less uniform than those produced from virgin fibers[17]. Necef et al. notes that recycled and eco-friendly cotton decreased air permeability while increasing clothing insulation and thermal resistance in knitted fabrics[18]. Spinning technique affected durability, with ring-spun yarns showing relatively higher bursting strength, while rotor-spun structures showed about 25% poorer pilling performance[19].

Recycled fiber systems, especially those based on post-consumer cotton-rich waste, may lead to lower mechanical performance because the recovered fibers are shorter and more damaged[20]. This also negatively affects bursting strength, abrasion resistance, elongation, and long-term durability. A more meaningful question is whether the losses in strength remain within an acceptable functional range and whether structural design can compensate enough to preserve user comfort and serviceability. This is where the half terry construction becomes especially relevant: it offers selective cushioning and thickness without making the entire sock excessively heavy or rigid[21].

Most prior studies have focused on pre-consumer textile waste, have been limited to yarn or fabric development, or have investigated socks made from alternative virgin or regenerated fibers rather than recycled cotton obtained from post-consumer denim waste. Consequently, the practical feasibility of using post-consumer denim waste into hosiery products, particularly with respect to performance and durability, remains largely unexplored.

To address this gap, the present study focuses on the development and performance evaluation of half-terry socks produced from yarns containing post-consumer denim-derived recycled cotton blended with recycled polyester. In the earlier phase of this research, post-consumer denim waste was mechanically recycled and blended with chemically recycled polyester to produce 12/1 Ne yarns at various recycled polyester/recycled cotton blend ratios[22].In the current stage of the study, the recycled yarns were converted into half-terry socks and compared with socks produced from virgin polyester/cotton yarns, enabling evaluation of the effects of recycled fiber content and yarn characteristics on end-product performance. The evaluation covered key real-use properties, including abrasion resistance, pilling, air permeability, and moisture management. In addition, a cost analysis was performed by considering raw material cost, recycling/shredding cost, spinning cost, yarn consumption, auxiliary yarns, waste allowance, and knitting cost. Thus, the study does not only examine the technical possibility of producing socks from recycled fibers but also evaluates their practical viability. The main contribution is to determine whether recycled cotton/recycled polyester socks can offer a balanced compromise between cost reduction, comfort, durability, and circular textile production.

Materials and methods

Shredding

Post-consumer denim waste was used as the main source of recycled cotton fiber in this study. The discarded denim consisted of approximately 97–98% cotton and 2–3% elastomeric yarn. The fiber composition of the collected denim garments was verified from the manufacturer's composition label attached to each garment, and only garments containing approximately 97–98% cotton and 2–3% elastomeric fiber were selected for the study. Used denim jeans were collected from a local second-hand market and cleaned thoroughly to remove surface dirt, oils, and other contaminants. All non-textile components, including buttons, zippers, rivets, and labels, were removed manually before further processing. The cleaned denim fabric was then cut into smaller pieces and mechanically shredded to facilitate fiber recovery. To reduce the remaining indigo shade, the shredded denim was subjected to a bleaching treatment. The material was immersed in a 3% sodium hypochlorite (NaOCl) solution at a liquor ratio of 1:10 for 2 h and alkaline pH (10–11) at room temperature (approx. 24 °C). After bleaching, the material was rinsed thoroughly, neutralized with sodium bisulfite ($NaHSO_3$), washed again, and dried at 30–40 °C. NaOCl bleaching and $NaHSO_3$ neutralization can generate wastewater and contribute to fiber degradation. However, their specific effect was not evaluated separately in this study and is acknowledged as a limitation The pretreated denim waste was then converted from fabric form into reclaimed fiber using a GM600 recycling machine (Shandong New Haina Machinery, China). The recycling operation comprised four successive stages of tearing and cleaning. In each stage, pinned rollers mechanically opened the material, while sieving units removed dust, short fibers, and residual impurities. Repeated passage through the machine yielded progressively finer and cleaner recycled fibers suitable for spinning. The physical characteristics of the reclaimed denim fibers are presented in Table 1. Chemically recycled polyester fiber obtained from a local supplier was used as the second component for blending. The properties of the recycled polyester fiber are given in Table 2. A schematic representation of the yarn production route can be seen in Fig. 1.

Table 1 Properties of virgin and post-consumer recycled cotton fiber[22].

	Moisture content (%)	Micronair	Maturity ratio	Upper half mean length (mm)	Uniformity index (%)	Short fiber content	Fiber strength (g/tex)	Fiber elongation (%)
Virgin cotton fiber	8.1	4.36	0.85	26.92	81.4	13.4	29.1	7.7
Recycled cotton fiber	7.4	4.67	0.82	15.92	59.9	49.9	16.5	10.4

Table 2 Properties of recycled polyester fiber[22].

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

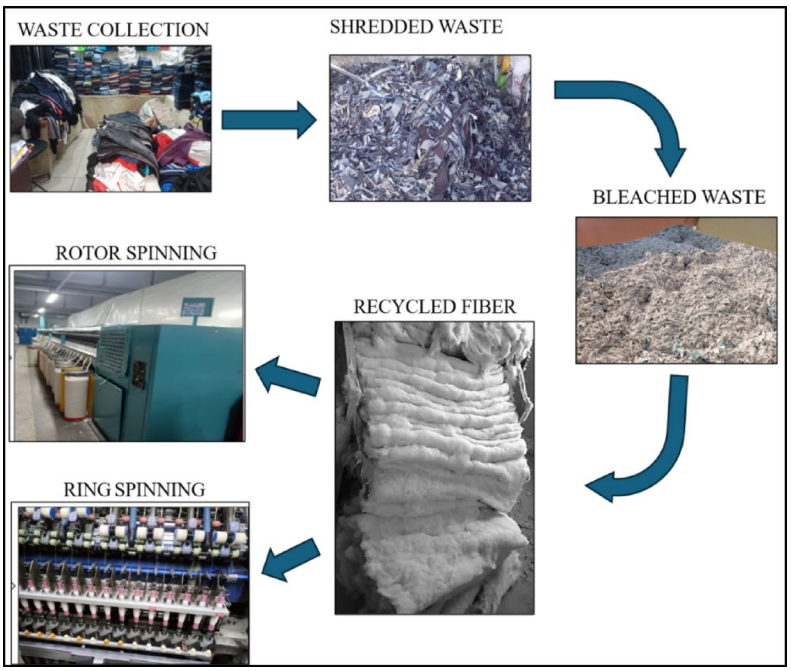


Fig. 1 Post-consumer denim waste recycling processes and spinning into yarn reproduced from[22]; photographs originally taken by the authors.

Yarn development

Reclaimed denim fibers and recycled polyester were blended to produce yarns of nominal count 12/s. Yarn manufacture was carried out through a conventional short-staple spinning sequence. Fiber opening and cleaning were first performed in the blow room using a Crosrol system (Crosrol Ltd., Halifax, UK). The opened fibers were then carded on a Rieter C70 carding machine (Rieter AG, Switzerland) to produce sliver. For ring spinning, the card slivers were processed through a simplex frame FL-100 (Toyota Industries, Japan) to produce roving, followed by spinning on an EJM-178 ring frame (Jingwei Textile Machinery, China). The spun yarns were finally wound on an Ex Qpro autoconer (Murata Machinery, Japan). For rotor spinning, the carded slivers were directly fed into a rotor spinning machine (Jingwei Textile Machinery, China; circa 1998), thereby eliminating the roving stage.

Three blend ratios were prepared, namely 90/10, 80/20, and 70/30 (ratio of recycled polyester/recycled cotton fibers). For each blend proportion, yarns were produced by both ring and rotor spinning systems. In addition, two levels of twist were selected, that is, 472 ± 20 m^{-1} and 512 ± 20 m^{-1}. A 12/s rotor-spun virgin polyester/cotton (70/30) yarn was also produced and used as the control sample. The virgin PC70:30 benchmark yarn was produced on the same rotor-spinning system using the same spinning parameters as the corresponding recycled rotor-spun yarns, allowing direct comparison under equivalent rotor-spinning conditions. However, because both cotton and polyester fiber origin differed between the recycled and virgin systems, the comparison does not isolate the independent effect of recycled denim cotton. In total, 13 yarn samples were included in the study, comprising 12 experimental yarns and one control yarn. The yarns were coded according to spinning method, waste content, and twist level. Properties of the developed yarns are summarized in Table 3. Detailed spinning-machine settings and yarn-development procedures have been reported in our previous study[22].

Table 3 Average physical properties of blended yarns developed from post-consumer cotton denim waste and recycled polyester[22].

Sample code	Linear density (tex)	Tenacity (cN/tex)	Breaking force (cN)	Elongation (%)	Lea strength (Lbs)	CLSP (Lb.Ne)
Ri10L	48.46	14.59	707.1	15.08	173.2	2110
Ri10N	46.22	18.77	867.4	16.13	236.0	3015
Ri20L	46.74	10.62	496.0	13.53	82.8	1046
Ri20N	44.65	14.79	660.4	14.79	160.0	2116
Ri30L	46.05	4.50	207.3	8.76	38.1	489
Ri30N	50.59	9.58	484.4	13.42	82.5	963
Ro10L	50.47	12.48	630.1	15.24	196.0	2293
Ro10N	49.86	14.40	717.9	11.25	212.0	2511
Ro20L	48.73	11.68	569.4	14.53	174.5	2115
Ro20N	48.61	13.39	650.7	11.24	208.5	2533
Ro30L	51.61	10.15	523.7	14.24	169.5	1939
Ro30N	48.77	12.88	628.1	10.85	182.5	2210
PC70:30	48.46	17.13	830.0	8.30	130.0	1584

Ri ring-spun, *Ro* rotor-spun yarns, *10, 20, 30* percentage of denim waste in the yarn, *L and N* represents, accordingly, lower and higher twist level, *CLSP* count lea strength product.

Socks development

Experimental half-terry socks were produced on a Lonati GL 544 (Lonati S.p.A., Italy) sock knitting machine with 12E gauge, 120 needles, and a 4-inch cylinder diameter. Half-terry refers to a sock structure in which terry loops are formed only on the lower foot or sole portion, while the upper foot remains plain knitted. A double-covered elastomeric yarn consisting of 140 den Lycra and 70/24/1 nylon was used in the leg part with a Lycra-to-nylon ratio of 19:81, leg part in the sock has not a true rib knitted structure; rather, it was a false rib structure produced by inserting elastomeric yarn on alternate wales. The alternate-wale elastomeric yarn caused localized contraction and created a rib-like surface appearance with open pathways between adjacent wales. A single-covered elastomeric yarn was used as the plating yarn in the whole socks, consisting of 20 den Lycra and 75/36/1 polyester, with a Lycra-to-polyester ratio of 7.5:92.5. The sock was produced as a crew-length article (Fig. 2). First the cuff is knitted, then the leg part, then the heel, and then the machine starts knitting the foot part. In the foot area, terry is formed only on the lower part of the sock. The main parts involved in terry formation are the feed-finger, needle, terry lever, sinker, stitch cam, and cylinder. The feed finger supplies the yarn, the needle catches and knits it, the terry lever controls sinker movement, the sinker forms the terry loop, and the cylinder together with the stitch cams maintains the knitting sequence. In the knitting process, the yarn passes through the feed finger to the needle, the needle catches the yarn and starts moving downward, and then the terry lever actuates the sinker. In the terry setting, the sinker projects further and retains more extra yarn before stitch completion. As a result, the loop formed on the inside of the sock becomes longer and thicker than that formed in half-terry. Thereafter, the needle continues its downward movement and completes the stitch, while the long terry loop remains on the inner side of the sock. The coding of the sock samples was derived from the yarn codes. All sock variants were produced within the same experimental production series; independent production-batch replication was not performed.

Waste collection process and yield estimation

This process was carried out to calculate the production price of recycled cotton socks and to compare it with socks produced from virgin cotton. For this purpose, the material yield and fiber loss at each processing stage were recorded, starting from fabric shredding to yarn development. The main objective was to determine how much usable fiber could be recovered from post-consumer denim waste and how much material was lost during processing, as these losses directly affect the final cost of recycled yarn and sock production. The fiber yield

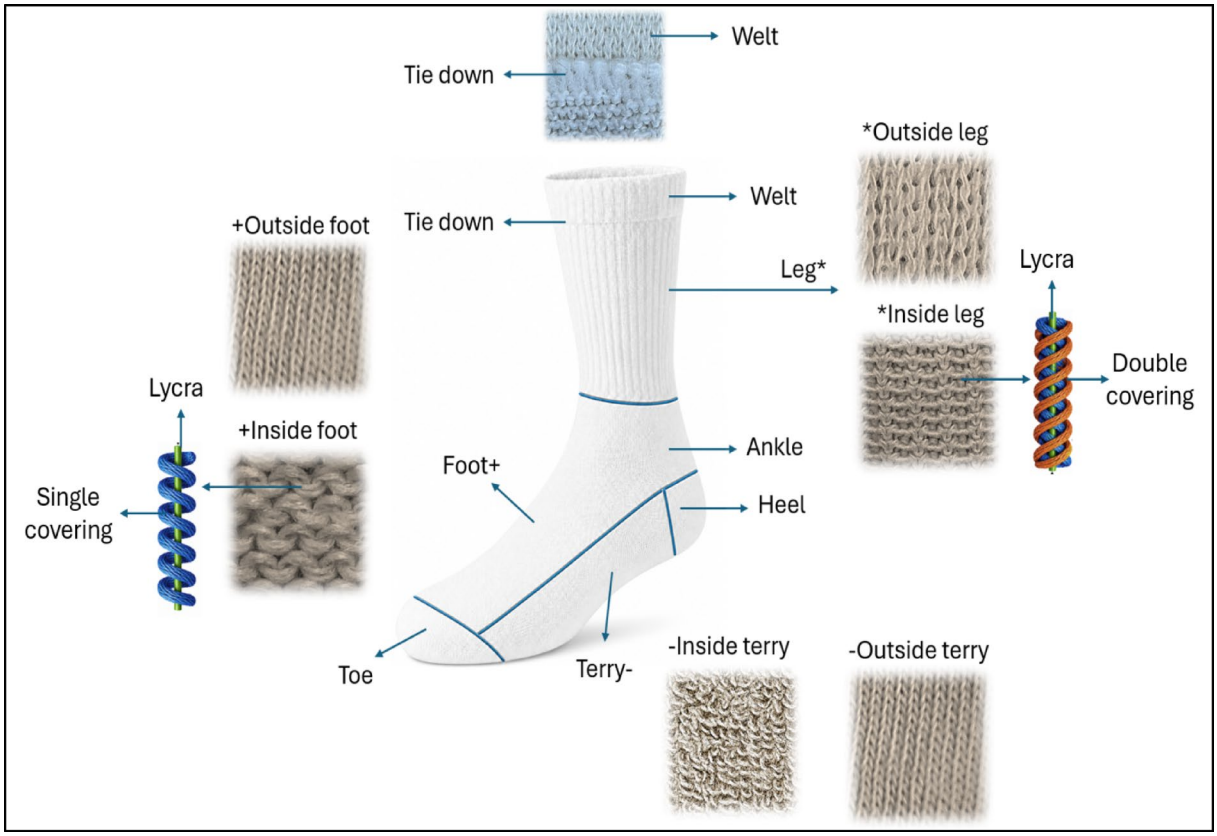


Fig. 2 Structural layout of the half terry crew sock, showing the main sock regions and corresponding knitted structures, including the tie-down, leg, upper foot plain knit, heel, toe, and inner \terry sole, *Leg portion has a rib like structure called as rib imitation, foot+has plain structure, and terry- has terry structure inside of socks, Photograph and figure developed by the authors.

Table 4 Weight loss during blow room and carding processes for recycled and virgin cotton blends.

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

obtained from post-consumer denim recycling was found to be substantially lower, approximately 45–50% by weight, compared with the 80–95% yield commonly reported for pre-consumer textile waste in the available literature[23]. This lower yield is mainly due to the degradation of post-consumer materials over time due to repeated washing, contamination, finishing treatments, fiber damage, and additional processing difficulties during recycling[24]. In addition to overall fiber recovery, the weight loss during the combine blow room and carding stages was measured for different recycled waste blends (Table 4). Waste fibers generated during these stages were collected and analyzed using the dissolution method to determine the actual cotton and polyester content lost during processing[22]. This provided a more accurate understanding of fiber loss according to composition and helped estimate the real material cost involved in recycled yarn production.

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

$$Fiber\ Yield\ (\%) = (Weight\ of\ fibers\ obtained / Weight\ of\ raw\ material) * 100 \quad (1)$$

Characterization

The fabricated socks were evaluated for structural, comfort-related, and surface performance properties. Structural characterization included mass per sock, density of courses per centimeter (CPC), and wales per centimeter (WPC). Comfort-related behavior was studied through air permeability and overall moisture management capacity (OMMC). Air permeability was measured to evaluate the ease with which air could pass through the sock structure, while OMMC was used to assess the ability of the sock structure to absorb and transport liquid moisture. Surface durability was examined by pilling and abrasion resistance tests in order to assess the tendency of the socks to develop pills and to resist wear during use. Before testing, all specimens were conditioned under the standard atmosphere for textile testing at 20 ± 2 °C and 65 ± 2% relative humidity in accordance with ISO 139. Samples for each characterization were taken from comparable regions of the socks in order to minimize variations caused by differences in local fabric geometry. For each property, at least three measurements were taken, and the average value was used for analysis. These measurements were technical replicates from the developed sock samples rather than independently replicated production batches; therefore, the results are presented using descriptive statistics. The corresponding test methods and standards for OMMC, air permeability, pilling, abrasion, CPC, and WPC are presented in Table 5.

Cost analysis of recycled and control socks

A cost analysis was carried out to compare the economic feasibility of socks produced from recycled cotton/recycled polyester blends with the control socks produced from virgin cotton/virgin polyester. Only the Ri10L sock was unraveled for yarn consumption analysis because all samples were knitted using the same machine settings, sock design, and yarn feeding arrangement. Thus, the consumption of main yarn, double-covered yarn, and single-covered yarn were expected to remain comparable across samples. Since the experimental variables were mainly blend ratio, spinning method, and twist level rather than sock construction, the average yarn consumption from three Ri10L socks was used as a representative value for the cost calculation of all samples. The analysis included the cost of raw materials, recycling of denim waste, spinning, yarn consumption during sock production, yarn waste allowance, double-covered yarn, single-covered yarn, and knitting cost. Finishing and packaging costs were not included in the calculation. In addition, a 1.5% yarn waste allowance was added (a standard practice) to each yarn component to account for yarn loss during knitting (Table 6). All costs were calculated in euros for the samples developed. However, these costs should be considered approximate, as these market prices may vary depending on industrial conditions, raw material availability, processing costs, energy prices, supplier rates, and other market-related factors. The cost inputs were based on quotations and prevailing industrial rates obtained from local suppliers and production facilities during the study period. All cost inputs were based on prevailing industrial and supplier rates during the study period. The waste denim cost (€0.093/kg) represents the acquisition cost of post-consumer denim, while the recycling cost (€0.108/kg) includes cleaning, bleaching,

Table 5 Characterization methods and standards used for testing sock performance.

Characteristic	Standard	Units
Wales and courses density	EN 14971:2006	cm^{-1}
Fabric thickness	EN ISO 5084:1996	mm
Pilling	ASTM D4970	Pilling grade
Air permeability	ASTM D737	$dm^3/(m^2\ s)$
Abrasion resistance	ASTM D4966	Weight loss (%)
Overall moisture management capacity	AATCC 195–2011	–

Table 6 Input cost parameters used for economic analysis of recycled and virgin sock production.

Parameter	Unit	Value in EUR
Post-consumer waste denim acquisition cost, C_{waste}	€/kg	0.093
Complete denim recycling cost, $C_{recycling}$	€/kg	0.108
Denim shredding/recycling yield, $Y_{recycling}$	%	50
Recycled polyester cost, C_{RP}	€/kg	0.618
Virgin cotton cost	€/kg	1.39
Virgin polyester cost	€/kg	0.803
Ring spinning cost	€/lb	0.185
Rotor spinning cost	€/lb	0.154
Double-covered yarn cost	€/kg	3.829
Single-covered yarn cost	€/kg	5.867
Complete sock knitting cost, $C_{knitting}$	€/pair	0.037
Main yarn consumption	g/piece	14
Double-covered yarn consumption	g/piece	4
Single-covered yarn consumption	g/piece	4.5
Yarn waste allowance	%	1.5

neutralization, washing, drying, and mechanical shredding/opening. Spinning and auxiliary-yarn costs were based on industrial processing and supplier rates. The sock knitting cost (€0.037/pair) represents the complete knitting charge, including labor, machine depreciation, energy consumption, and routine production overhead; finishing and packaging were excluded.

Calculation of recycled cotton cost

The effective recycled cotton cost was calculated by considering the cost of waste denim, mechanical recycling/shredding cost, and the fiber recovery yield. Since the denim recycling yield was approximately 50%, the effective recycled cotton cost was calculated as:

$$C_{RC} = \frac{C_{waste} + C_{recycling}}{Y_{recycling}} = 0.401\ €/kg \tag{2}$$

where C_{RC} is the effective recycled cotton cost, C_{waste} is the waste denim cost, $C_{recycling}$ is the recycling/shredding cost, and $Y_{recycling}$ is the denim fiber recovery yield.

Therefore, the effective cost of recycled cotton recovered from post-consumer denim waste was taken as 0.401 €/kg.

Spinning cost conversion

The spinning cost was provided in €/lb and was converted into €/kg using the following conversion factor, 1 kg = 2.2046 lb.

Therefore:

$$C_{ring} = 0.185 \times 2.2046 = 0.408\ €/kg$$
$$C_{rotor} = 0.154 \times 2.2046 = 0.340\ €/kg$$

Yarn blend cost calculation

The recycled yarns were developed using three recycled polyester/recycled cotton blend ratios: 90/10, 80/20, and 70/30. The blend cost was calculated using:

$$C_{blend} = (P_{RP} \times C_{RP}) + (P_{RC} \times C_{RC}) \tag{3}$$

where P_{RP} and P_{RC} are the fractions of recycled polyester and recycled cotton in the blend, respectively, and C_{RP} and C_{RC} are their costs per kilogram.

For the 90/10 recycled polyester/recycled cotton blend: $C_{90/10} = 0.596$ €/kg

For the 80/20 recycled polyester/recycled cotton blend: $C_{80/20} = 0.574$ €/kg

For the 70/30 recycled polyester/recycled cotton blend: $C_{70/30} = 0.553$ €/kg

For the virgin polyester/cotton control sample: $C_{control} = 0.979$ €/kg

Yield calculation during blow room and carding

The material loss during blow room and carding was included in the cost calculation because this loss increases the amount of fiber required to produce usable carded material for spinning. The yield values used in the calculation are shown in Table 4.

Like, for the 30% recycled cotton blend: $Y = \left(\frac{75.60}{85.50}\right) \times 100 = 88.42\%$

The blend cost was corrected using the blow room and carding yield, and the spinning cost was then added separately:

$$C_{yarn} = \frac{C_{blend}}{Y} + C_{spinning} \tag{4}$$

where (Y) is expressed as a decimal.

For the rotor-spun 70/30 recycled polyester/recycled cotton blend: $C_{yarn} = 0.966$ €/kg.

Yarn consumption and waste allowance

The yarn consumption values were measured per sock piece (Table 7). Therefore, the values were doubled to calculate the consumption per pair. A 1.5% waste allowance was then added to each yarn component.

$$C_{Costed\ consumption} = C_{\text{Actual consumption}} \times 1.015 \tag{5}$$

For the main yarn: $C_{Costed\ consumption} = 0.02842$ kg

For the double-covered yarn: $C_{Costed\ consumption} = 0.00812$ kg

For the plating yarn: $C_{Costed\ consumption} = 0.00914$ kg

Sock cost calculation

The cost of the main yarn per pair was calculated as:

$$C_{main} = C_{yarn} \times C_{Costed\ consumption} \tag{6}$$

The double-covered yarn cost: $C_{double} = 0.031$ €/pair.

The plating yarn cost: $C_{plating} = 0.054$ €/pair.

The total sock cost per pair was calculated as:

Table 7 Yarn consumption per sock piece and pair, including 1.5% waste allowance.

Yarn component	Consumption per piece (g)	Consumption per pair, $C_{Actual\ consumption}$ (g)	Consumption after 1.5% waste (g/pair)	Costed consumption, $C_{Costed\ consumption}$ (kg/pair)
Main yarn	14	28	28.42	0.02842
Double-covered yarn	4	8	8.12	0.00812
Single-covered yarn	4.5	9	9.14	0.00914

$$C_{sock} = C_{main} + C_{double} + C_{plating} + C_{knitting} \quad (7)$$

For the rotor-spun 70/30 recycled polyester/recycled cotton sample:

$$C_{main} = 0.027 \text{ €/pair}$$
$$C_{sock} = 0.149 \text{ €/pair}$$

Results and discussion

Structural properties of sock samples

The structural properties of the developed socks were evaluated in terms of wale per centimeter, courses per centimeter, fabric thickness at different sock regions, and weight of sock. These parameters are important because they directly influence comfort, cushioning, air permeability, abrasion resistance, and overall sock performance. Since the sock has different structural zones, the upper foot, leg, and terry sole were evaluated separately for thickness and for wales and courses these are same for all parts, that is why mentioned only once (Table 8).

All recycled cotton/recycled polyester blended yarns were successfully knitted into socks, indicating that the recycled yarns had sufficient processability for sock production. The wale density of the recycled samples ranged from 5.0 to 5.5 cm^{-1}, while the course density ranged from 6.0 to 6.5 cm^{-1}. The wale CV% remained low, ranging from 0.00 to 5.97%, while the course CV% ranged from 0.00 to 4.68%. These values indicate acceptable structural consistency among the knitted samples. The virgin polyester/cotton control sample showed a wale density of 5.5 cm^{-1} and the highest course density of 7.0 cm^{-1}. This suggests that the control sock had a slightly more compact knitted structure than the recycled socks. The higher course density in the control sample can be related to the better yarn regularity and dimensional stability of virgin fibers compared with recycled cotton fibres. Clear differences were observed among the different sock regions. The upper foot thickness of the recycled socks ranged from 3.02 to 3.10 mm, while the leg thickness ranged from 2.75 to 2.90 mm. The terry sole showed the highest thickness values, ranging from 6.00 to 6.30 mm. Because the terry sole contains pile loops on the inner surface, which increase bulk, cushioning, and fabric thickness. In comparison, the upper foot and leg regions were thinner.

The mass values of socks were round figured before adding, the mass of a single sock varied from 23.0 to 25.5 g for the recycled samples, while the virgin polyester/cotton control sample showed the highest mass of 28.0 g. The mass CV% of the recycled socks ranged from 1.82 to 5.83%. Higher CV% values were observed for Ri30L, Ri30N, Ro30L, and Ro30N, indicating slightly greater mass variation in the socks produced with 30% recycled cotton content.

The results show that the virgin polyester/cotton control sample showed slightly higher compactness and mass, and the recycled socks-maintained wale density, course density, thickness, and mass within a practical and consistent range. The slightly lower compactness of the recycled socks can positively impact air permeability and comfort, but it can also influence durability-related properties such as pilling and abrasion resistance.

Abrasion resistance

Abrasion resistance was evaluated on the lower foot part of the sock, where terry loops were formed on the inner side. This region was selected because it is the main contact area during use and is exposed to repeated rubbing against the foot and shoe insole. Since the outer structure of the socks was kept the same, the abrasion test was focused only on the terry foot region to assess the effect of yarn composition, spinning system, and twist level on wear resistance. The test was conducted up to 50,000 abrasion cycles (maximum requirement for work and

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Table 8 Structural properties of recycled and virgin sock samples.

Specimen code	Structural parameters (cm^{-1})				Fabric thickness (mm)						Mass (g)	
	Wale	Wale CV%	Course	Course CV%	Upper foot	Upper foot CV%	Leg	Leg CV%	Terry sole	Terry sole CV%	Single sock	Single sock CV%
Ri10L	5	5.59	6	4.68	3.04	3.33	2.85	3.57	6.3	3.17	23.5	2.13
Ri10N	5	5.97	6.5	4.56	3.09	3.23	2.82	2.08	6.2	4.84	24	3.33
Ri20L	5	5.59	6	0	3.05	4.98	2.9	4.08	6.2	5.69	23	2.61
Ri20N	5	5.59	6.5	4.68	3.06	3.77	2.8	4.08	6.15	3.23	25.5	2.75
Ri30L	5	5.59	6	4.68	3.03	1.95	2.88	3.57	6.23	5.63	25	4.8
Ri30N	5.5	5.97	6.5	4.68	3.02	3.33	2.78	2.08	6.15	5.69	23	5.22
Ro10L	5	0	6.5	4.68	3.1	3.23	2.9	3.45	6.19	3.23	22	1.82
Ro10N	5.5	5.59	6.5	0	3.09	4.98	2.75	3.57	6	3.33	23	3.04
Ro20L	5	5.41	6.5	4.68	3.02	3.33	2.83	4.08	6.1	4.92	25	3.2
Ro20N	5	5.59	6.5	4.68	3.1	3.77	2.8	4.08	6.19	4.84	25.5	1.96
Ro30L	5	0	6.5	4.68	3.06	1.95	2.78	3.57	6.2	3.23	24	5.83
Ro30N	5.5	0	6.5	4.68	3.08	3.23	2.9	3.45	6.1	4.92	24	5
PC70:30	5.5	5.09	7	4.33	3.15	3.13	2.92	2.08	6.3	5.55	28	2.86

Sample size ($n = 3$).

special professional socks), and the percentage weight reduction was used as an indicator of material loss. A lower percentage reduction indicates better abrasion resistance (Fig. 3).

The abrasion results show that the control sample (virgin polyester/cotton, PC70:30) exhibited the lowest weight reduction of 4.23% after 50,000 cycles, indicating the highest abrasion resistance among all samples. This is due to the higher fiber length and strength, and more uniform yarn structure of the virgin fiber blend. Virgin cotton fibers retain better integrity than mechanically recycled cotton fibers, while virgin polyester also contributes to improved wear resistance due to its strength and resilience. Among the recycled samples, abrasion weight reduction increased with increasing recycled cotton content. The 10% recycled cotton blends showed lower weight loss than the 20% and 30% blends. For example, the ring-spun higher-twist sample Ri10N showed only 4.60% weight reduction, which was very close to the virgin control sample. In contrast, the samples with 30% of recycled cotton showed considerably higher weight loss, with values of 10.40–10.69% for ring-spun yarns and 11.27–12.29% for rotor-spun yarns. This indicates that increasing the proportion of mechanically recycled denim cotton fibers reduced abrasion resistance. The lower abrasion resistance of higher recycled cotton blends is related to the physical properties of the recycled cotton fibers. The shorter fibers are less effectively bound within the yarn structure and can be more easily removed from the fabric surface during rubbing.

The spinning system also influenced abrasion performance. Ring-spun samples showed better abrasion resistance than rotor-spun samples at the same recycled cotton content, particularly for the 10% and 30% blends. Ri10N showed 4.60% weight reduction, while Ro10N showed 6.83%. Similarly, Ri30N showed 10.69%, whereas Ro30N showed 12.29%. Ring spun yarns provided better fiber integration and yarn cohesion, which reduced fiber removal during abrasion. Rotor-spun yarns, although economically favorable, contain a more wrapper-like structure and less fiber parallelization, which can contribute to higher surface fiber loss during rubbing. In the 10% and 20% recycled cotton ring-spun samples, higher twist improved abrasion resistance compared with the lower twist. However, at 30% recycled cotton content, the improvement was not observed. This can be due to the higher proportion of short and damaged recycled cotton fibers limited the beneficial effect of twist. For rotor-spun samples, the effect of twist was less consistent. The 10% recycled cotton rotor sample showed improved abrasion resistance at normal twist, whereas the 20% and 30% rotor-spun samples showed slightly higher weight reduction at higher twist. This suggests that in rotor-spun yarns, abrasion performance was controlled not only by twist but also by yarn structure, fiber distribution, and the higher content of recycled cotton fibers.

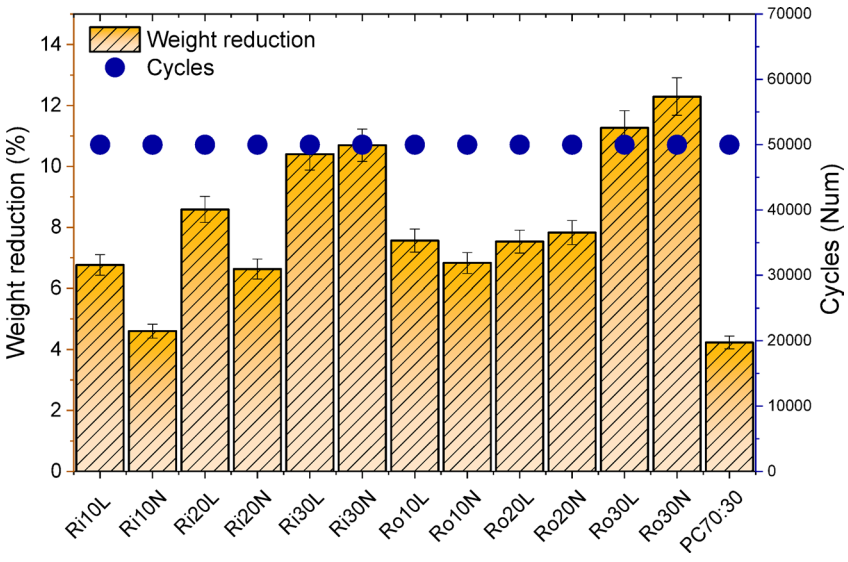


Fig. 3 Effect of recycled cotton content, spinning system, and twist level on abrasion resistance of the sock.

Pilling resistance

All recycled sock samples received a pilling grade of 1 indicating poor pilling resistance and severe surface pill formation. While the virgin polyester/cotton control sample showed a higher pilling grade of 3, indicating better surface appearance retention. The poor pilling performance of the recycled samples is attributed to the characteristics of the mechanically recycled denim cotton fibers. The recycled cotton fibers had a much higher short fiber content and lower fiber strength than virgin cotton. Short and damaged fibers are less firmly held within the yarn structure and can easily migrate to the fabric surface during rubbing. Once exposed on the surface, these fibers become entangled and form pills. This directly affected the pilling behavior of the socks. In knitted structures, especially socks, repeated friction occurs during wearing, washing, and contact with footwear. The presence of short, recycled cotton fibers increases fuzz formation and accelerates pill development. The similarity of pilling grades across all samples suggests that fiber quality had a stronger influence on pilling than local sock structure. The pilling results indicate that mechanically recycled cotton from post-consumer denim waste can be used for sock production, but its surface durability remains a major limitation (Table 9).

Air permeability

Air permeability was measured at three different regions of the sock: upper foot, leg, and terry sole (Fig. 4). These regions were selected because sock comfort is not controlled by one uniform structure. Instead, air flow depends strongly on the local fabric geometry: the structure is single (plain), double (fleece), or spatial (terry). The upper foot and leg regions mainly represent the outer/regular knitted structure, while the terry sole contains pile loops on the inner side of the sock. Therefore, the terry sole is structurally thicker and more compact, which restrict air passage compared with the upper foot and leg parts.

The air permeability results showed differences among the three sock regions, depending on the knitting pattern. For all samples, the leg region showed the highest air permeability, followed by the upper foot knitted in plain structure, while the terry sole showed the lowest air permeability. This trend shows that air permeability is strongly affected by the knitted structure. The leg part showed higher values, ranging from 802 to 1020 $dm^3/(m^2$ s), while the terry sole showed lower values, ranging from 390 to 470 $dm^3/(m^2$ s), due to the presence of terry loops on the inner side. The virgin polyester/cotton control sample, PC70:30, showed the lowest air permeability in all three regions, with values of 560 $dm^3/(m^2$ s) for the upper foot, 802 $dm^3/(m^2$ s) for the leg part, and 390 $dm^3/(m^2$ s) for the terry sole. The control sock had a comparatively more compact structure than the recycled samples. Because all socks were knitted using the same machine program and construction settings, the lower density and mass observed in several recycled variants represent the resulting structural response of the yarn systems rather than intentionally imposed construction differences. Therefore, the air-permeability differences are

Table 9 Pilling grades of recycled and virgin sock samples.

Sample code	Pilling grade
Ri10L	1
Ri10N	1
Ri20L	1
Ri20N	1
Ri30L	1
Ri30N	1
Ro10L	1
Ro10N	1
Ro20L	1
Ro20N	1
Ro30L	1
Ro30N	1
PC70:30	3

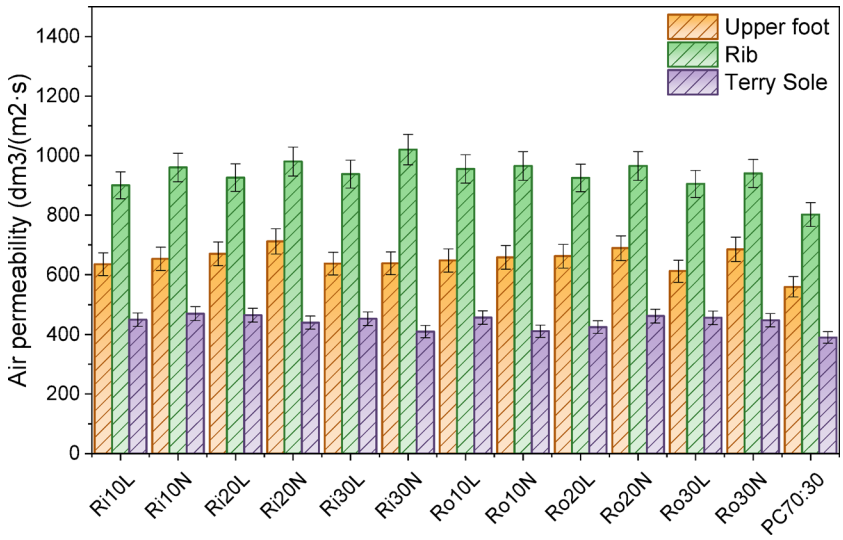


Fig. 4 Air permeability of upper foot, leg, and terry sole regions of recycled and virgin sock samples.

interpreted as a combined yarn-structure effect rather than an effect of recycled fiber content alone. Most recycled cotton/recycled polyester socks exhibited higher air permeability. This is due to the shorter and more irregular recycled cotton fibers, which influence yarn packing, fabric porosity, and loop formation. The effect of recycled cotton content was not completely linear. In some cases, increasing recycled cotton content increased air permeability, while in others it reduced. This variation can be explained by the combined effects of yarn irregularity, fiber length, twist level, and knitted loop formation & different amounts of fibers loss during knitting. Higher recycled cotton content increase yarn hairiness and fiber irregularity, which can either create more open spaces or block pores depending on the structure. Therefore, air permeability in socks is not determined only by fiber composition, but by the interaction between yarn properties and regional fabric geometry. The spinning method influenced air permeability, although the effect varied by sock region and also ring-spun and rotor-spun samples showed comparable values in several cases.

The recycled cotton/recycled polyester socks generally showed higher air permeability than the virgin polyester/cotton benchmark, reflecting the combined influence of yarn characteristics and the resulting sock structure. This is beneficial for sock comfort because higher air permeability can improve ventilation, reduce heat accumulation, and support moisture evaporation during wear. However, this must be seen in parallel with the lower wear resistance of socks made from recycled fibers. The slightly increased breathability cannot be unequivocally seen as an advantage. The lower permeability of the terry sole is expected and can be considered acceptable because the terry structure is designed to provide cushioning and comfort in the foot-contact area. Therefore, the sock structure creates a functional balance: the leg and upper foot regions allow higher air exchange, while the terry sole provides cushioning with comparatively lower air flow.

Overall moisture management capacity (OMMC)

Similarly, the moisture management behaviour of the socks was evaluated in three different regions: terry sole, plain upper foot, and leg. These regions were tested separately because socks do not have a uniform structure, and each region plays a different role during wear. The lower foot or sole region is one of the main areas where sweat is generated and accumulated because it remains in direct contact with the foot and shoe insole. Therefore, the terry sole is designed with terry loops on the inner side to improve cushioning and absorb perspiration from the foot surface (Table 10).

The results showed that the terry sole region had the lowest OMMC values, ranging from approximately 0.03 to 0.06. In this region, the bottom wetting time was recorded as >120 s, while the bottom absorption rate and

Table 10 Moisture management properties and OMMC values of terry sole, upper foot, and leg regions of recycled and virgin sock samples.

Sample code	Sock region	Test time (s)	Wetting time top (s)	Wetting time bottom (s)	Absorption rate top (%/s)	Absorption rate bottom (%/s)	Spreading speed top (mm/s)	Spreading speed bottom (mm/s)	OMMC
Ri10L	Terry Sole	120	12.35	>120	190	0	0.95	0	0.04
	Upper foot		16.25	82	105	11	0.65	0.06	0.26
	Leg		9.36	58	145	22	1.15	0.12	0.34
Ri10N	Terry Sole	120	13.52	>120	172	0	0.87	0	0.03
	Upper foot		17.42	87	95	9	0.58	0.05	0.25
	Leg		10.53	63	135	19	1.07	0.1	0.32
Ri20L	Terry Sole	120	11.38	>120	202	0	0.99	0	0.05
	Upper foot		15.28	79	112	13	0.69	0.06	0.27
	Leg		8.38	55	155	24	1.19	0.13	0.35
Ri20N	Terry Sole	120	12.55	>120	184	0	0.91	0	0.037
	Upper foot		16.45	84	102	11	0.62	0.05	0.26
	Leg		9.55	60	142	21	1.11	0.11	0.33
Ri30L	Terry Sole	120	10.4	>120	213	0	1.03	0	0.05
	Upper foot		14.3	76	118	15	0.73	0.07	0.28
	Leg		7.41	52	165	26	1.23	0.14	0.36
Ri30N	Terry Sole	120	11.57	>120	195	0	0.95	0	0.04
	Upper foot		15.47	81	108	13	0.65	0.06	0.27
	Leg		8.58	57	150	23	1.15	0.12	0.34
Ro10L	Terry Sole	120	11.7	>120	198	0	1.01	0	0.04
	Upper foot		15.6	79	115	13	0.71	0.07	0.27
	Leg		8.71	55	158	24	1.21	0.13	0.35
Ro10N	Terry Sole	120	12.87	>120	178	0	0.93	0	0.03
	Upper foot		16.77	84	104	10	0.63	0.05	0.26
	Leg		9.88	60	140	21	1.13	0.12	0.33
Ro20L	Terry Sole	120	10.72	>120	208	0	1.05	0	0.05
	Upper foot		14.62	76	122	15	0.75	0.07	0.28
	Leg		7.74	52	162	26	1.25	0.14	0.36
Ro20N	Terry Sole	120	11.9	>120	190	0	0.97	0	0.04
	Upper foot		15.8	81	110	12	0.67	0.06	0.27
	Leg		8.9	57	145	23	1.17	0.12	0.34
Ro30L	Terry Sole	120	9.75	>120	218	0	1.09	0	0.06
	Upper foot		13.65	73	130	17	0.79	0.08	0.29
	Leg		6.76	49	172	28	1.29	0.14	0.37
Ro30N	Terry Sole	120	10.92	>120	200	0	1.01	0	0.05
	Upper foot		14.82	78	118	15	0.71	0.07	0.28
	Leg		7.93	54	158	25	1.21	0.13	0.35
PC70:30	Terry Sole	120	9.1	>120	220	0	1.08	0	0.06
	Upper foot		11.7	64	135	18	0.78	0.08	0.28
	Leg		7.54	46	175	29	1.24	0.14	0.36

bottom spreading speed were 0 for all samples. This indicates that moisture was mainly absorbed and retained by the inner terry loops rather than rapidly transferred through the entire fabric thickness. The terry-loop structure increases the absorbent surface area and helps hold sweat and also restricts through-thickness moisture transfer and reduces the overall OMMC value. The upper foot region showed moderate moisture management performance, with OMMC values ranging from about 0.25 to 0.29. The plain upper foot structure is thinner and more open than the terry sole, allowing better liquid movement from the inner to the outer fabric surface. This region can therefore support moisture evaporation and improve breathability during wear. Among the recycled samples, higher OMMC values were observed in samples with higher recycled cotton content, such as Ro30L, which showed an OMMC of 0.29. Although this behavior supports sweat absorption and cushioning, limited

through-thickness moisture transfer may lead to moisture retention and possible dampness during prolonged wear.

The leg region showed the highest OMMC values, ranging from approximately 0.32 to 0.37. The leg part had shorter wetting times, higher absorption rates, and faster spreading speeds than the terry sole and plain upper foot regions. The highest OMMC value was observed for Ro30L at 0.37, followed closely by the virgin control PC70:30 at 0.36. It gives highest moisture management performance among the tested sock regions. Because it has relatively open and extensible structure. The leg part in the sock was not a true rib knitted structure; rather, it was a false rib structure produced by inserting elastomeric yarn on alternate wales. The alternate-wale elastomeric yarn caused localized contraction and created a rib-like surface appearance with open pathways between adjacent wales[21]. These structural channels improved liquid spreading and moisture transfer compared with the thicker terry sole and the more compact upper foot region. The OMMC results followed the trend, Leg>Upper foot>Terry sole. This trend shows that moisture management was controlled more strongly by fabric structure than by fiber composition alone. Therefore, the developed recycled cotton/recycled polyester socks can provide acceptable moisture management, especially in the leg and upper foot regions, while the terry sole mainly functions as an absorbent and cushioning zone.

Cost-performance and sustainability trade-off

All yarn consumption and cost values were first measured and calculated on a single-sock basis and were then multiplied by two to express the final production cost as cost per pair in Table 11. This conversion was made because socks are commercially produced, sold, and compared as pairs rather than as individual pieces. The difference between recycled and virgin fibers sock cost was moderated by the fixed costs of double-covered yarn, single-covered yarn, and knitting (Fig. 5). These components were the same for all samples and contributed a large part of the total cost. Therefore, although the effective yarn costs of the control group sock were much higher, the final price difference per pair decreased when all sock components were included.

From Table 11, the estimated production cost of socks made from recycled cotton/recycled polyester blends ranged from 0.149 to 0.152 €/pair, while the virgin polyester/cotton control sample showed a higher cost of 0.160 €/pair. The lowest cost was obtained for the rotor-spun 70/30 recycled polyester/recycled cotton samples, Ro30L and Ro30N, with an estimated cost of 0.15 €/pair. The lower cost of recycled socks was mainly due to the lower raw material cost of recycled fibers. The effective recycled cotton cost after shredding and recycling was 0.40 €/

Table 11 Estimated production cost per pair of socks produced from recycled polyester/recycled cotton blends and virgin polyester/cotton control yarns.

Sample code	Blend cost (€/kg)	Effective yarn cost (€/kg)	Main yarn cost/pair (€)	Double-covered cost/pair (€)	Single-covered/plating cost/pair (€)	Knitting cost/pair (€)	Total sock cost/pair (€)
Ri10L	0.596	1.046	0.03	0.031	0.054	0.037	0.152
Ri10N	0.596	1.046	0.03				0.152
Ri20L	0.574	1.047	0.03				0.152
Ri20N	0.574	1.047	0.03				0.152
Ri30L	0.553	1.034	0.029				0.151
Ri30N	0.553	1.034	0.029				0.151
Ro10L	0.596	0.977	0.028				0.15
Ro10N	0.596	0.977	0.028				0.15
Ro20L	0.574	0.979	0.028				0.15
Ro20N	0.574	0.979	0.028				0.15
Ro30L	0.553	0.966	0.027				0.149
Ro30N	0.553	0.966	0.027				0.149
PC70:30	0.979	1.352	0.038				0.16

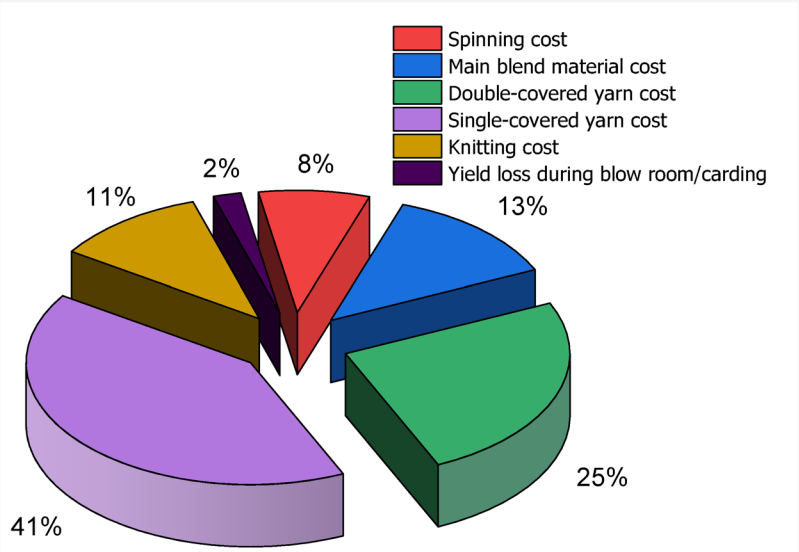


Fig. 5 Approximate percentage contribution of material, yield loss, spinning, covered yarns, and knitting costs to the final production cost recycled sock.

kg, which was considerably lower than the virgin cotton cost of 1.39 €/kg. Similarly, recycled polyester cost 0.62 €/kg, compared with 0.80 €/kg for virgin polyester. Therefore, replacing virgin fibers with recycled fibers reduced the blend cost. Among the recycled blends, the 90/10 recycled polyester/recycled cotton blend showed a slightly higher blend cost of 0.60 €/kg than the 70/30 blend, which showed a blend cost of 0.55 €/kg, because recycled polyester was more expensive than recycled cotton. Although the 70/30 blend had a lower blow room and carding yield, its higher recycled cotton content reduced the overall blend cost. As a result, the 70/30 recycled polyester/recycled cotton blend remained the most economical composition. The rotor-spun samples showed lower production cost than the ring-spun samples because rotor spinning cost was lower than ring spinning. The effective yarn cost of ring-spun recycled samples ranged from 1.03 to 1.05 €/kg, whereas the effective yarn cost of rotor-spun recycled samples ranged from 0.97 to 0.98 €/kg. Therefore, samples produced through rotor spinning showed lower effective yarn cost and lower final sock cost.

From a sustainability perspective, the use of post-consumer denim waste provides potential resource benefits by diverting textile waste from disposal and reducing dependence on virgin cotton and polyester. However, the environmental discussion presented here should be considered a preliminary assessment rather than a formal life cycle assessment (LCA). Published water-footprint values for virgin cotton and water-scarcity indicators for polyester are based on different functional units, system boundaries, geographical conditions, and impact-assessment methods; therefore, they are not directly compared quantitatively with the water consumed during the recycling process in this study.

The recycled route also involves environmental burdens. Post-consumer denim was bleached using 3% sodium hypochlorite, followed by rinsing, sodium bisulfite neutralization, washing, and drying. These processes consume water and chemicals and may generate wastewater containing residual oxidizing agents, salts, dissolved colorants, and fiber impurities. Based on the process liquor ratio, the estimated water consumption associated with these wet-processing stages was approximately 40 L/kg of denim waste, corresponding to approximately 0.68 L per pair for the 70/30 recycled sock. This value represents process-water use only and should not be interpreted as a water-scarcity impact. A complete environmental comparison between recycled and virgin socks would require a consistent LCA using the same functional unit, system boundary, inventory assumptions, and impact-assessment method.

The most important negative side is durability. All recycled socks showed a pilling grade of 1, while the virgin control showed grade 3, indicating better surface stability in the virgin socks. Abrasion resistance also decreased with increasing recycled cotton content: the virgin control showed only 4.23% weight reduction after 50,000 cycles, while higher recycled cotton samples showed greater material loss, reaching 12.29% for Ro30N means

the most economical and most circular sample is not the most durable. If recycled socks pill faster, lose appearance earlier and have a shorter service life, the real sustainability benefit decreases because the product needs to be replaced more frequently. Therefore, the recycled system is sustainable only if the product maintains acceptable service life and the recycling process is managed responsibly. The best approach can be to balance recycled content, singeing and anti-pilling or bio-polishing treatments.

Conclusion

This study demonstrates that post-consumer denim waste can be effectively transformed into recycled cotton fibers and successfully blended with recycled polyester to produce half-terry socks. The recycled socks exhibited satisfactory structural integrity and breathability performing comparably to the virgin polyester/cotton control samples in terms of comfort-related properties.

The cost analysis highlighted the viability of the recycled alternatives. Production costs ranged from €0.149 to €0.152 per pair, compared with €0.160 per pair for virgin control. The most cost-effective solution was the rotor-spun 70/30 recycled polyester/recycled cotton socks, benefiting from both the lower recycled fiber cost and lower rotor spinning cost. Despite these advantages, durability remains a significant challenge. The recycled socks showed substantially lower pilling resistance, achieving the pilling grade 1 compared to the grade 3 for the control socks, and higher abrasion loss, especially at 30% recycled cotton content. These findings indicate that higher recycled fibers content improves circularity and slightly reduces cost but reduces surface durability and service life. From a sustainability perspective, the recycled socks provide meaningful benefits by diverting post-consumer denim waste from disposal, reducing dependence on virgin cotton and polyester, but the sustainability of recycled socks should not be judged only by recycled content, but by whether the product can survive repeated use while the recycling process remains environmentally responsible. Overall, the results suggest that recycled cotton/recycled polyester socks can achieve a promising balance between circular material utilization, cost efficiency, breathability, and moisture management. Nevertheless, durability remains the primary barrier to broader market adoption. For applications requiring extended wear life and appearance retention, lower recycled cotton content or further optimization of fiber processing, yarn structure, and finishing treatments will be necessary to improve long-term performance while preserving the environmental advantages of recycled materials.

Author contributions Muhammad Sohaib Anas: Methodology, Investigation, Formal analysis, Writing - original draft. Inga Dabolina: Supervision, Validation, Writing - review and editing. Daiva Mikucioniene: Conceptualization, Supervision, Validation, Formal analysis, Writing - review and editing. All authors have read and agreed to the published version of the manuscript.

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Declarations

Competing interests The authors declare no competing interests.

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