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RESEARCH ARTICLE

Enabling Sustainability Through Ecodesign and Recyclability in the Textile Industry: Understanding Material Compositions of Denim

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Abstract

Transitioning the textile industry towards sustainability requires circular strategies like ecodesign and design for recycling, to reduce virgin resource usage and textile waste. However, to ensure functionality, affordability, and individual styles, garments are composed of a variety of different materials, from fiber blends to haberdashery and décor items, making the composition of post-consumer textile waste difficult to predict and recycle. This material complexity contributes to the global fiber-to-fiber recycling rate remaining below 1 %. This study examines the fiber composition of the product group denim trousers comparing fashion brands, jeans specialists and post-consumer products. While about 40 % of analyzed jeans are made solely of cotton and are generally a high-cellulose waste stream, many contain multiple fibers and highly variable elastic fiber contents, often unrelated to functional performance. Such blends significantly increase the technical difficulty and cost of recycling. Notably, fashion brands appear to use more pure cotton fabrics than jeans specialists, however offer also more loose fitting styles. These findings provide a basis and highlight the need for clear ecodesign guidelines and a strong extended producer responsibility to support a transition toward a circular textile economy. Accordingly, the study provides an example how the materiality and construction of products require re-consideration to move towards more sustainable product design.

Keywords Circularity · Circular Design · Ecodesign · Extended Producer Responsibility · Denim · Fibers · Garments · Post-Consumer Recycling · Textile Recycling

1. Introduction

The growing global population paired with the rising demand for affordable mass-produced fashion continues to drive the increasing fiber production, estimated to reach 169 million tons annually by 2030. Polyester and cotton fibers continue to dominate the market with a combined share of around 78 % (Textile Exchange, 2025). Despite the increasing awareness of sustainability challenges, rapid product turnover and low prices continue to fuel consumption, while the environmental impacts of textile production and waste remain substantial. Fiber-to-fiber (F2F) recycling represents a critical pathway toward circularity, yet makes up less than 1 % of the global fiber production annually (Textile Exchange, 2025). Economic barriers, particularly the higher cost of recycled fibers compared to virgin materials, as well as the highly heterogeneous nature of textile waste continue to inhibit large-scale implementation of textile recycling facilities.

Denim garments, especially jeans, are a highly interesting product group for recycling, due to their global popularity and historically high cotton content. Classic denim jeans are highly resource-intensive during

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production: cotton cultivation, indigo dyeing and finishing processes like washing and surface treatments contribute significantly to environmental impacts with high demands of water, chemicals and energy. Recent developments to improve the sustainability of jeans are e.g. synthetic indigo dyes, ozone and laser bleaching, enzyme finishing and the utilization of organic or recycled cotton fibers (Periyasamy & Periyasami, 2023). At the End-of-Life stage, recycling efforts can help to reduce the impact by reintroducing the fibers into the textile value chain. Currently, those efforts are hindered by complex fiber blends and insufficient material transparency. Elastic fibers like elastane are commonly added to jeans to improve fit and comfort, but are known to pose particular challenges during sorting and recycling. Due to the nature they are situated in the fabrics and the overall low content values, elastic fibers make automatic detection challenging (Cura et al., 2021). The absence of standardized guidelines for fiber blends further decreases the recycling efficiency and quality of recycled fibers. The role of elastic fibers as a recycling barrier has been widely established. This study aims to extend current knowledge by linking the presence of elastic fibers to the fit of a garment, providing a functional perspective on material use in denim.

Legal and policy frameworks to increase textile circularity and recyclability within the European Union like the Extended Producer Responsibility, eco-design requirements and the introduction of a Digital Product Passport to garments aim to improve traceability, transparency and to incentivize more recycling-friendly product design (EU Strategy for Sustainable and Circular Textiles, 2022). However, until such frameworks are implemented, a better understanding of the current material composition of garments remains essential to provide a scientific understanding of what is necessary and why. Furthermore, we expect that the discussion around microplastic may also result in limiting the usage of synthetic fibers in textile products in the future.

This study analyzed the fiber compositions of over 2900 pairs of jeans and examines the correlation between elastic fiber content and garment fit from fashion brands and jeans specialists. By identifying thresholds for elastic fiber content values that align with functional requirements, the findings provide evidence-based ecodesign recommendations to enhance recyclability, support automated sorting and contribute to the transition toward a circular textile economy.

2. Post-consumer Jeans: Material composition and recycling

This section outlines the characteristics of the product group jeans, focusing on material composition and their implications for recycling at the End-of-Life. Special focus is placed on the elastic fibers found in jeans, as they pose to be one of the greatest sorting and recycling inhibitors.

2.1. Product Group Jeans

Jeans are a popular clothing item and the most popular type of pants, broadly established and beloved by all gender identities and age groups (CivicScience, 2023; Paul, 2015). An estimated 3.27 billion pairs of jeans were produced in 2025 (Fibre2Fashion, 2022a), made from an estimated 4.5 billion meters of denim fabric (Fibre2Fashion, 2022b). Germany imported around 182 million pairs of jeans in the year 2024 (Federal Statistical Office of Germany, 2025a), equaling around 2.3 billion Euro (Federal Statistical Office of Germany, 2025b). In Germany most people are wearing jeans by the fast fashion brand H&M, followed by Levi’s jeans (Kantar, 2024).

Jeans are available in a wide variety of different styles and fits. Generally speaking, the fit can be grouped in four main categories: (1) Skinny, (2) Tight, (3) Regular and (4) Loose, though there are many styles blurring the lines of those categories. In a 2021 survey conducted in the U.S, India, Mexico, China and several European countries, most women said they prefer the Regular (37 %) and Straight fit (33 %), which in this study are combined to “Regular”. The Skinny fit reached 31 % and the Slim fit (in this study “Tight”) 34 % popularity, followed by the Relaxed fit (in this study “Loose”) with 27 % popularity (Cotton Incorporated Lifestyle Monitor, 2022). As a fashion item, the cut of jeans is also subject to trends. In recent years, a looser cut has been more popular, whereas e.g. in the 2010s, very tight styles were trending (Florester, 2025). The height of the waistband is also subject to strong trend fluctuations. This is supported by data from Levi’s, depicting the most searched for jeans styles in 2022. The “Mom Jeans”, a style with a high waistline and wider leg that we sorted into the Regular fit category, was searched over 8 million times on google, followed by “Baggy Jeans”, that we placed into the Loose fit category, with 5.4 million searches. In the 18 countries they analyzed, Skinny or Tight jeans were not once among the top searched jeans styles. (Levi's, 2023)

Historically, jeans were produced as heavy-duty work pants and thus made from heavy cotton (CO) twill fabrics woven with indigo dyed warp and undyed weft yarns to achieve the iconic blue denim look (Paul, 2015). With the rise of fast fashion, shorter lifecycles and pricing-pressure, some of the cotton content in the weft yarns of denim fabrics has been replaced with polyester fibers, mainly to reduce cost (Patra & Pattanayak, 2015). With jeans becoming more fashionable and less of a workwear item, the blending with elastic fibers, usually in the weft of the fabric, became necessary to make close-fitting styles more comfortable (Patra & Pattanayak, 2015). Cotton still remains the most popular fiber for denim production, used as a mono-material or in various blends together with other natural or synthetic fibers (Paul, 2015), resulting in a large variety of differently composed blends.

Aside from the predominantly cotton denim fabric used in the production of jeans, other materials are present on the garment, either to increase functionality or to individualize the piece. Typical materials and components on jeans are the seams made from polyester threads, cotton pocket-lining, a waistband lining to increase stability often from polyester, leather or fake leather patches with the brands logo as well as haberdashery items like metal buttons, rivets and zippers. Other fashionable items and prints can be present as well, there are no limits to design choices.

2.2. Elastane and Elastomultiester Fibers

Elastic fibers are generally used in small quantities to improve the comfort of close-fitting garments. Their elastic properties allow the fabrics to better mold against the body and also enhance flexibility during movement while at the same time preserving the dimensional stability of the garment. Elastic fibers are usually applied in values up to 20 % in garments (Mather, 2015), though for day to day fashion, it is generally more around the 5 % mark (Boschmeier et al., 2023). For woven fabrics, elastic fibers are usually used as the core of yarns, either covered, core-twisted or core-spun (Thiel et al., 2025) and applied in weft direction during weaving. Encasing the elastic filaments with other fibers helps protecting them from external influences like UV-rays and abrasion and prevents pre-tension during manufacturing (Patra & Pattanayak, 2015).

There are several elastic fibers available, the most popular being Elastane (EL). EL fibers are made from at least 85 % segmented polyurethane (BISFA, 2017) and are widely applied for their high elastic recovery (Mather, 2015). They have a high elasticity and elongation at break of 400-650 % (Senthilkumar, 2011). Elastane fibers can also reduce the shrinkage of cotton fibers during laundering and increase the bursting strength of fabrics (Azim, 2014). It is worth mentioning, that an increasing EL content can result in higher microfiber shedding, both of the EL fibers as well as other blend components (Rathinamoorthy et al., 2023), probably due to increased friction between the fibers during stretching.

Elastomultiester (EME) fibers are not as widely applied and established as EL fibers, though they are gaining in popularity. EME fibers are bicomponent polyester fibers, meaning two different ester macromolecules, usually polyethylene terephthalate (PET, 2GT) and polytrimethylene terephthalate (PTT, 3GT)-based polyesters, are arranged side by side to form one EME fiber (BISFA, 2017). During a heat-treatment, the two polyester components within the fiber shrink at different rates, giving the fiber a permanent helical crimp, which is responsible for the elastic properties (Rijavec & Bukošek, 2009). EME can only be stretched to 1.5 times its original length, compared to EL which can be stretched 3.0 times its original length, both can recover rapidly to their initial length (BISFA, 2017). EME fibers provide less elasticity and recovery, but ensures higher dimensional stability over longer periods of use (Rahim et al., 2023).

EL and EME fibers are often used together in dual-core yarns. At high-stress zones like knee and elbow areas, garments are prone to lose their dimensional stability over time, also known as bagging. Elastane can prolong the stability, though paired with EME, the dimensional stability will improve even more. Rahim et al. (2023) tested the yarn properties of a single-core CO/EL yarn with a dual-core CO/EL/EME yarn. The dual-core yarn had overall better results than the classic single-core yarn, especially the tenacity and elongation improved, resulting in lower deformation, while still maintaining high elasticity. A blend utilizing both EL and EME fibers in denim production thus seems very promising for producing high quality and long-living jeans with tighter fits but might complicate recycling efforts further.

2.3. Textile Recycling Pathways for Jeans

Textile recycling is one of the key pillars of the circular economy. In the textile industry, it is aiming to revert unusable textiles from waste back to valuable secondary resources. Despite the availability of different recycling technologies, F2F recycling remains limited, accounting for only estimated 0.6 % of the global fiber production (Textile Exchange, 2025). A major barrier is the lack of reliable information on material composition, which is essential for high-quality textile recycling (Arun et al., 2025). As this information is often unavailable at the End-of-Life, initiatives like the Digital Product Passport seek to improve transparency. Until such systems are widely implemented, the analysis of the material composition of existing products remains necessary to implement realistic sorting strategies and formulate based ecodesign guidelines.

Before recycling, the textile waste needs to be sorted. Current systems prioritize reuse, as defined in the EU Waste Framework (Directive 2008/98/EC), while material-based sorting for F2F recycling is not widely applied. Technologies like Near-Infrared (NIR) spectroscopy enable automated fiber identification by measuring material-specific spectra (Manley, 2014). However, there are certain limitations, especially with fiber blends, low fiber content values and coatings (Cura et al., 2021). Elastic fibers are known to be particularly challenging for this technology, as they are often imbedded in the core of yarns and usually only present in small quantities. Combining NIR with Artificial Intelligence (AI)-supported image recognition can improve prediction accuracy and reduce contamination in recycling systems (Arun et al., 2025). Adding product group specific ecodesign guidelines into the mix could further enhance accuracy during sorting.

For denim jeans, which are predominantly made from CO fibers, recycling pathways for cellulosic fibers are most relevant. As mentioned before, aside from fiber blends, there are other materials and items present on jeans, especially condensed around the hip area. Rivets, buttons and zippers, paired with a stabilized waistband and thick overlapping seams result in a compact material fusion, which is difficult to disassemble. This leads to the top part of jeans often being removed completely before recycling to reduce the number of contaminants, leaving only the legs, which usually have a lower contamination level. Small amounts of heavier or magnetic contaminants can usually also be removed in the running recycling process by weight or magnetism units.

Mechanical recycling remains the most established process. Garments are cut and shredded until their fibers are disentangled (Ribul et al., 2021). Contaminants like metal parts can be partially removed during this process, though pre-removal is advised. Colorants and finishes remain in the fibers, unless removed by prior pre-treatment steps. This process with high mechanical stress shortens the fibers and reduces tensile strength, resulting in the recovered fibers being of lower quality and requiring blending with virgin fibers for further usage in yarn production (Ribul et al., 2021; Wang & Salmon, 2022). Thus, mechanical recycled fibers are often downcycled into insolation or fleece (Pensupa, 2020). High elastic fiber contents or heavily coated fabrics can disrupt machinery and reduce output-quality and should be avoided. The process remains the most economical and widely applied option for recycling cotton.

Solvent-based processes, also known as polymer recycling technologies, offer higher material quality output from cellulosic textiles. Selective solvents dissolve the fibers to their cellulose polymers, enabling recovery and regeneration into man-made cellulosic fibers such as Viscose (CV) and Lyocell (CLY) (Pensupa, 2020; Ribul et al., 2021). This process can handle cellulose-rich blends, as other fibers remain as is and can be separated by filtration (Sun et al., 2021). The utilized solvents can be reused in closed systems, the polymer recovery rates depend on fabric material composition and process conditions. However, polymer quality must be sufficiently high in the textile input, as cellulose cannot be infinitely recycled and will show reduced degree of polymerization (DP) and tensile strength with each recycling cycle (Wang & Salmon, 2022). Ultimately, solvent-based recycling cannot be done in a closed loop, due to degrading polymer quality, though it allows us to keep the fibers in use for longer. While solvent-based recycling produces higher-quality fibers than mechanical processes, its application for post-consumer textiles is still limited mainly due to high levels of foreign fibers and contaminants, thus recycling plants are still largely on pilot scale.

Thermo-mechanical recycling as well as biological and chemical monomer recycling technologies are not as relevant for the recycling of jeans as they can either not process cellulose-based fibers at all or cannot regain cellulose based fibers for textile application in sufficient qualities. For synthetic fibers, those processes are viable, though jeans are predominantly produced from cotton fibers and thus do not offer an economically viable input.

Across all technologies, lower contamination levels and greater material homogeneity improve recycling efficiency and output quality (Andini et al., 2024). Therefore, material-based sorting and clear ecodesign guidelines are crucial facilitators for scaling F2F recycling and improving circularity in the textile industry.

3. Methodology

To get a broad overview of the product group jeans, we analyzed jeans from six popular brands as well as post-consumer (PostC) data collected by students at the University of Applied Sciences HTW Berlin, Germany. The students were studying Garment Technology in the seventh semester and were tasked with documenting the material compositions of the jeans they owned. The recorded garments are not post-consumer waste yet as they are still in use, but they allow us to gain insights in the composition of PostC jeans nevertheless. The brands selected were clustered in two groups: Jeans Specialists (JS) and Fashion Brands (FB). The three JS and FB selected were the top-selling brands in their respective categories (Statista, 2025a, 2025b). The JS and FB data was collected in May and December in 2025 to present spring/summer and autumn/winter seasons, from the German versions of each brand's online shop, as the authors are based in Germany. Despite the data origin being Germany, the authors do not expect drastic changes compared to other European countries due to overlapping European markets, laws and restrictions, the data should thus be able to reflect the European market. Table 1 shows the applied filters and number of documented pieces from each brand. To better visualize the results, we will combine brands and time of sample into three groups: JS, FB, and PostC. During the analysis, we further divided the JS and FB samples by time of data collection. In this paper we did not make this distinction unless mentioned otherwise. As seen in the Table 1, some data sets were cleared from the analysis as they were incomplete. This number was largest for the PostC sample, as consumers had either removed the labels or the labels became illegible due to laundering. Other reasons include incomplete information in the online shops and incomplete documentation. This resulted in a total sample size of 2952 jeans. The data collected in this study is included in the supplementary materials. The JS and FB datasets were constructed using a purposive sampling approach to capture variability across brands, price segments, and product characteristics, while the post-consumer sample reflects a convenience sample based on garment availability during data collection. Thus, compared to the FB and JS samples, the PostC sample is smaller and is not intending to be statistically representative, but rather to illustrate how increasing brand diversity can lead to greater variability in material composition, thereby reducing predictability in the absence of ecodesign guidelines.

Table 1. Search criteria and no. of results for analyzed jeans

Origin		Date	Filter	No. of Total Results	Adjusted no. of results
JS	Levi's	26th May 2025	Clothing – Women – Jeans	365	364
		15th Dec 2025		314	312
	Wrangler	28th May 2025	Women – Clothing – Jeans	79	
		21st Dec 2025		58	57
	Lee	28th May 2025	Women – Clothing – Jeans	93	
		22nd Dec 2025		82	81
FB	Zara	27th May 2025	Women – Jeans	415	
		18th Dec 2025		405	
	H&M	27th May 2025	Women – Clothing – Jeans + Brand: H&M	427	425
		16th Dec 2025		488	487
	Uniqlo	29th May 2025	Women – Pants – Jeans	60	
		22nd Dec 2025		68	
PostC		1st Oct 2025	Wardrobe study	125	106
Total				**2979**	**2952**

In this study, we focused solely on the material composition of the fabric, other recycling inhibitors like haberdashery items, coloring or coatings were not taken into account. It is important to note that the sewing thread and care labels are usually PET. Accordingly, the material stream for recycling will always carry PET contamination in small quantities that either needs to be removed or tolerated. The fiber composition was analyzed in relation to the fit of the garment, with a special focus on elastic fibers. As we analyzed a large sample size, we were unable to confirm the material compositions provided by the brands through chemical testing. For the sake of this study the provided data is assumed to be correct, even though studies like Wilting & Van Duijn (2020) suggest that up to 41 % of material data might be false. Furthermore, the Textile Labeling Act (Regulation (EU) No 1007/2011), allows certain tolerances in the declaration of fiber content. We acknowledge the possibility potential discrepancies arising from legally permitted labeling tolerances.

For each garment, we documented (a) the fiber composition provided on the care label or online shop, (b) the fit of the garment. Figure 1 provides the guideline for classifying the shape of the jeans, distinguishing between four fits: (1) Tight, (2) Skinny, (3) Regular, (4) Loose. This guide does not include all available styles, the classification thus was made by our allocation. The students collecting the PostC data were thoroughly briefed on how to classify the fit beforehand.

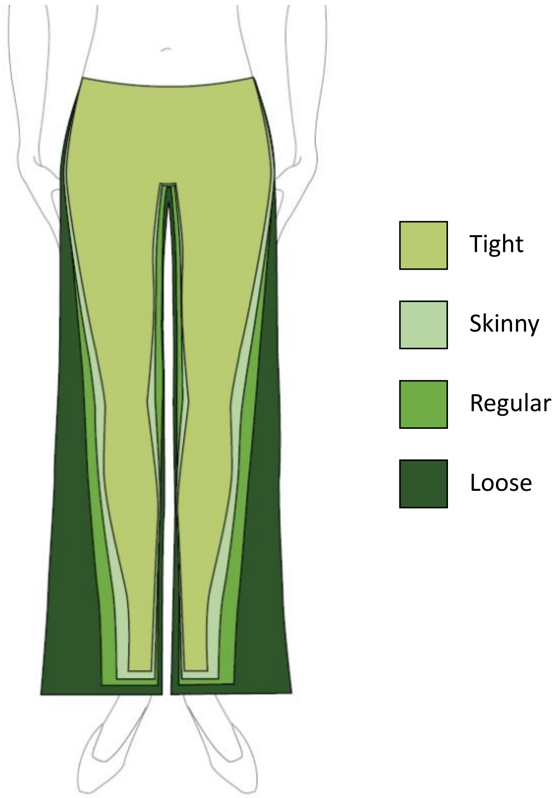


Figure 1. Schematic overview of the different fit categories of jeans

Analyzing the material composition in relation to the fit of jeans allows us an overview of typical blends utilized as well as the typical elastic fiber content values based on the fit of the garment. Connecting fit, fiber composition and content value of elastic fibers allows us to find out the specific requirements of the garments to formulate specific ecodesign guidelines and reducing the number of recycling inhibitors. This will help predicting the material composition of garments during automated sorting processes, allowing us to create more homogenous material streams tailored to the requirements of the different recycling technologies.

4. Results

The analyzed sample size spans 2952 jeans total, distributed over three categories: (1) JS with n=986, (2) FB with n=1860, (3) PostC with n=106. As shown in Figure 2, 42 % of all analyzed jeans were produced from a single fiber type, the remaining 58 % were made from fiber blends with up to five fibers. Over half of FB jeans were made from mono materials, for JS jeans it was only 23 % and for PostC around 44 %. In JS, fiber blends with three or four different fiber types were more often utilized (49 %). 2- and 3-Fiber blends were used a similar amount in the total sample with 27 % and 26 % respectively. Blends with five fibers were a rarity, only used for n=10 jeans total. The majority of mono-fiber jeans were made from CO with a total of n=1235 pairs of jeans. The only other mono-material documented was Polyester (PET) with n=1.

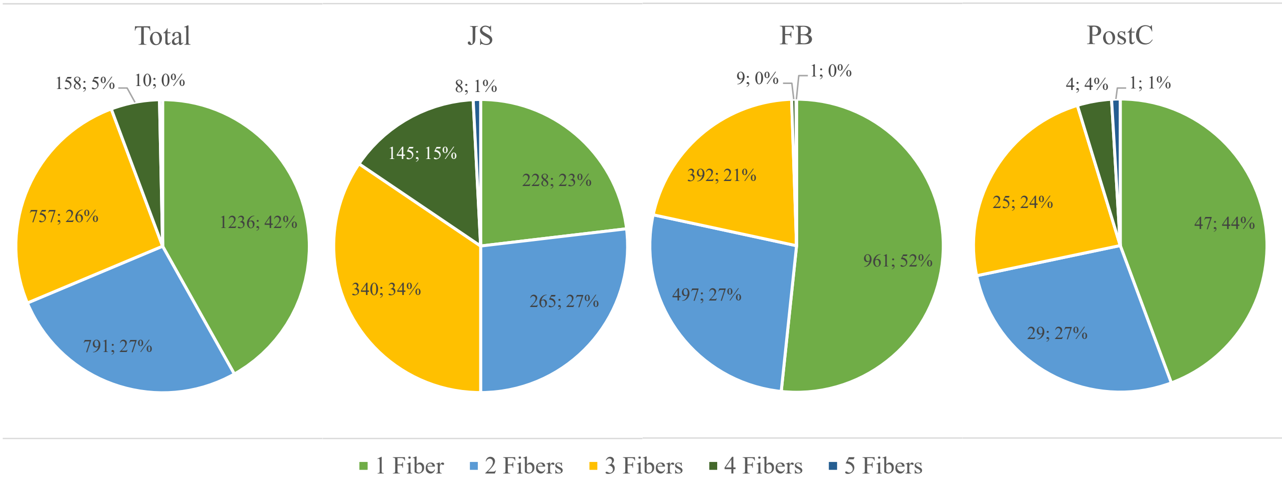


Figure 2. Distribution of no. of used fibers utilized for jeans found in JS, FB and PostC garments in pcs and %

To gain an overview of the fibers utilized in the production of jeans, we analyzed the number of times the fibers were present in the sample. This includes mono-material garments as well as blends, counting each fiber separately. CO is the most utilized mono-fiber, but as shown in Figure 3, CO also dominates in blends, resulting in a total of 99 %jeans (n=2929) to contain CO fibers. Second in popularity is EL, present in 49 % of the garments (n=1435). PET fibers are on third place, present in 21 % of jeans (n=632). Next to CO, the most utilized cellulosic fiber is CLY with 11 % (n=311), which is more than the remaining cellulosic fibers combined (Linen (LI), Jute (JU), CV, Modal (CMD); 6 %, n=189). The results do not indicate a clear relationship between fiber price and market segment. Higher-priced fibers like JU or LI were not disproportionately represented in JS jeans, while lower-priced fibers such as PET were not predominantly used in FB products. This suggests similar fiber usage patterns across segments. Furthermore, no significant differences in material composition were observed between summer (JS May, FB May) and winter samples (JS Dec, FB Dec).

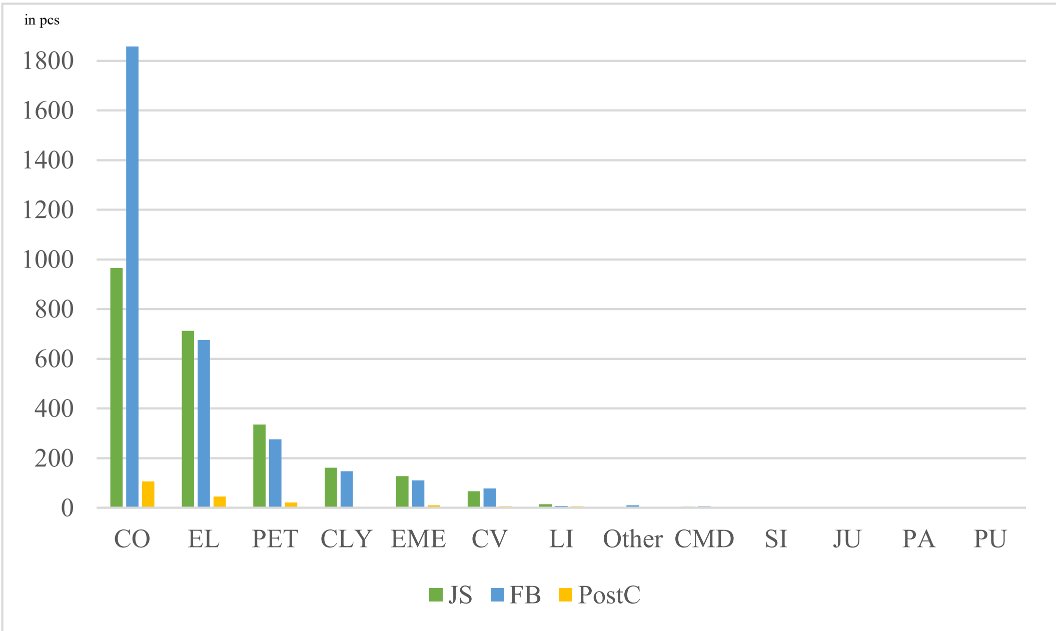


Figure 3. Number of times each fiber was utilized for jeans in JS, FB and PostC garments in pcs.

Since around 58 % of all jeans were made from fiber blends, we took a closer look at the material compositions. With n=791, 2-Fiber blends have the biggest share with 27 % of the whole sample. To better understand the overall composition of the blends, we first grouped the fibers into main categories. As seen in Figure 4, CO blended with either EL or EME fibers made up most of the analyzed 2-Fiber blends with 68 % of garments made from 2-Fiber blends (n=540). The second largest group were different cellulosic fibers blended together, resulting in 28 % of 2-Fiber blend jeans (n=218). Polycotton blends were not as present, with only n=19 and lastly other blends with n=14. Figure 4 only shows the main fiber groups used in the blends. For a full list of the specific blends, please refer to the supplementary material.

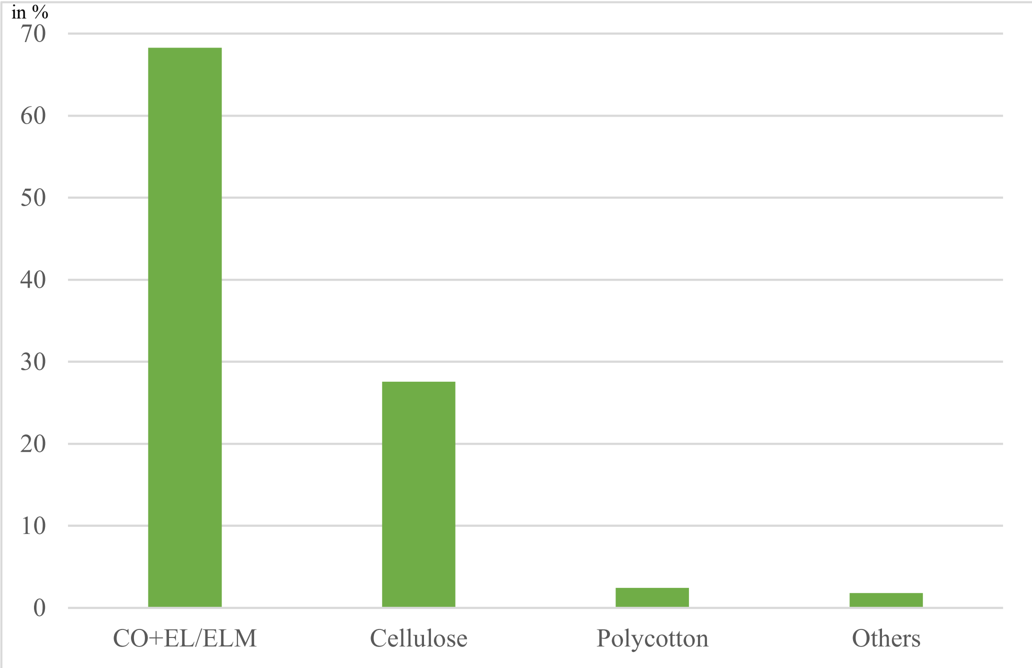


Figure 4. Most utilized 2-Fiber blends for jeans found in JS, FB and PostC garments in %

In total, we recorded 70 different 2-Fiber blends. 29 of them were only utilized once, 14 blends twice. Figure 5 showcases the most popular blends. Due to the large number of blends, we only included blends that have been recorded at least seven times in the diagram. Blends with a high cotton content were most popular. In general, most blends present in the diagram were made from up to 100 % cellulosic fibers, blended with low values of EL or EME. Some blends were used over multiple samples and have been marked accordingly (see Figure 5). The two most popular blends were used in all five samples (JS March, JS December, FB March, FB December and PostC) with 17 % of all analyzed jeans (n=516).

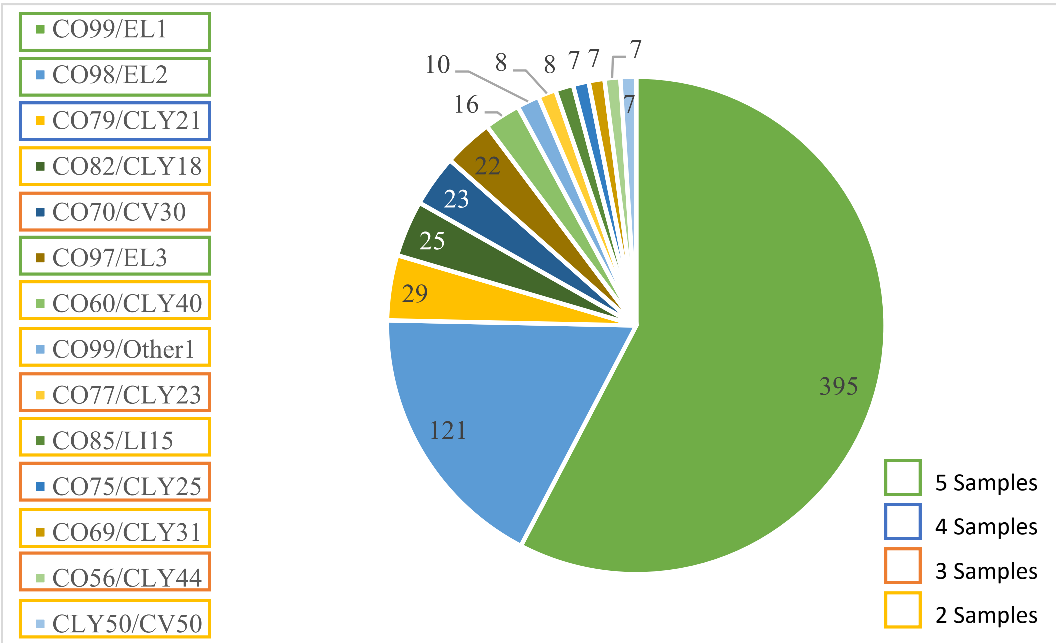


Figure 5. Most popular 2-Fiber blends for jeans in pcs

Complementary to the 2-Fiber blends shown above, we also analyzed the 3-Fiber blends. As seen in Figure 6, we identified five main blend types. The most popular blend are cellulosic fibers blended with PET and either EL or EME with 72 % of all jeans made from 3-Fiber blends (n=541), followed by CO blended with EL and EME blends with 18 % (n=135). The remaining three blend categories were used between n=10 and n=52. Again, Figure 6 only shows the main fiber groups used in the blends. For a full list of the specific blends, please refer to the supplementary material.

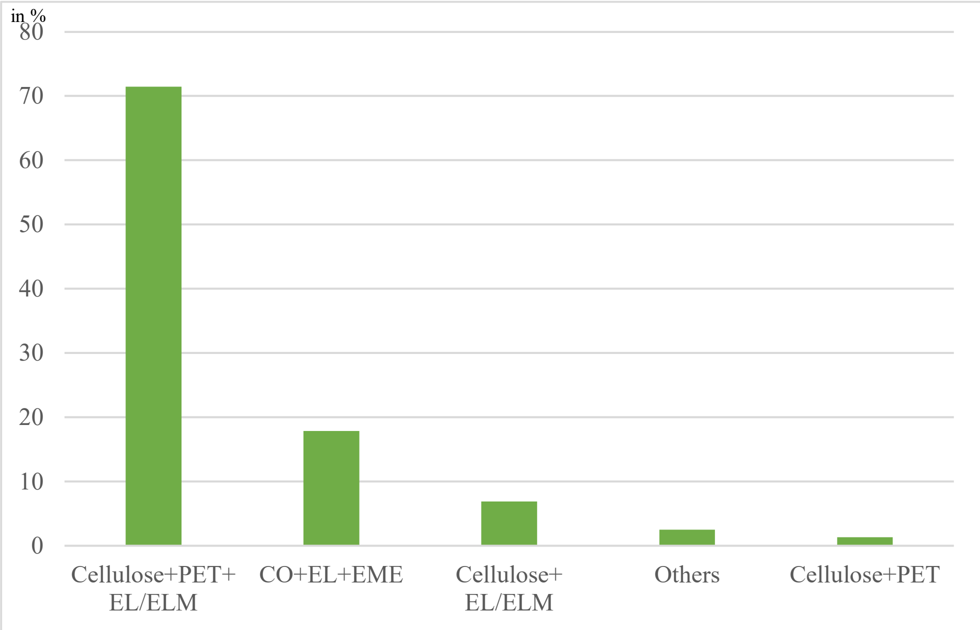


Figure 6. Most utilized 3-Fiber blends for jeans found in JS, FB and PostC garments in %

In total, we recorded 93 different 3-Fiber blends. 25 of them were only utilized once, 11 blends twice. Figure 7 showcases the most popular 3-Fiber blends. Due to the large number of blends, we only included blends that have been recorded at least 12 times in the diagram. The most utilized blend has a high cotton content paired with PET and EL with 8 % of garments made from 3-Fiber blends (n=59), followed by a blend of 97 % CO with 3 % elastic fibers with 7 % (n=54). As seen with the 2-Fiber blends, high cellulose content, most often in the form of CO fibers, is dominating the blend compositions, most often combined with elastic fibers and PET. Some blends were used over multiple samples and have been marked accordingly (see Figure 7).

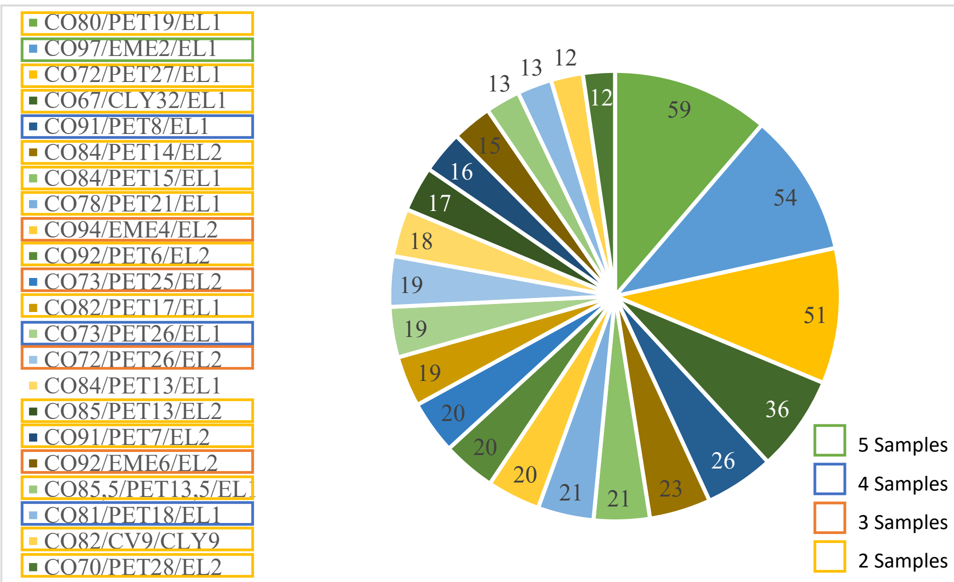
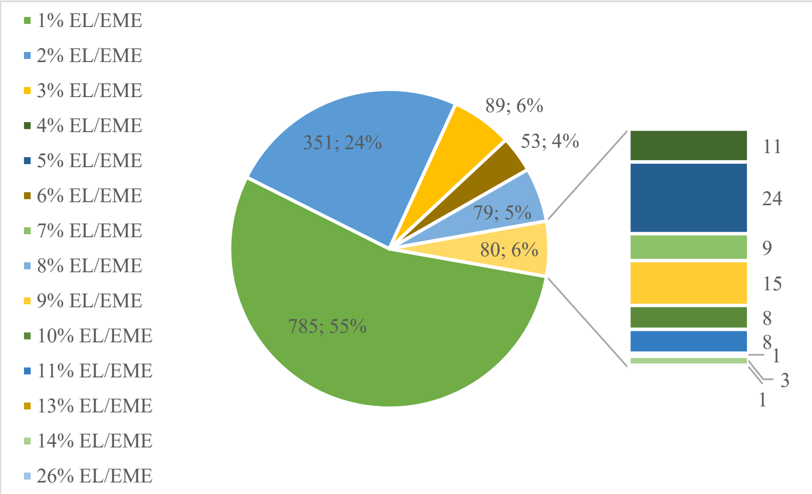


Figure 7. Most popular 3-Fiber blends for jeans in pcs

For 4- and 5-Fiber blends, we identified three main blend compositions: Cellulose with elastic fibers (66 %), PET with Cellulose and elastic fibers (33 %) and others (1 %). For a full list of the specific blends, please refer to the supplementary material. The most popular blend CO85/CLY7/EME6/EL2 has been utilized n=58 and used in two of the five samples (JS May and JS Dec).

Since elastic fibers are the second most used fiber group documented and are also considered a major recycling inhibitor, we paid particular attention on the content values present. Elastic fibers were present in a total of 49 % of jeans (n=1437), with values reaching from 1 to 26 %. Figure 8 gives an overview of the recorded values. The most utilized value is 1 % elastic fiber content with a total of 55 % of jeans containing elastic fibers (n=785), followed by 2 % elastic content with 24 % (n=351). The remaining values are used significantly less, from n=1 to n=89. Most values remain ≤5 % elastic fiber content (88 %, n=1260), elastic fiber content values of ≥10 % are less common with n=21.



EL and ELM in %	Total in pcs	% of Garments w/ EL/ELM	% of all Garments
0%	1515		51.3
1%	785	54.6	26.6
2%	351	24.4	11.9
3%	89	6.2	3.0
4%	11	0.8	0.4
5%	24	1.7	0.8
6%	53	3.7	1.8
7%	9	0.6	0.3
8%	79	5.5	2.7
9%	15	1.0	0.5
10%	8	0.6	0.3
11%	8	0.6	0.3
13%	1	0.1	0.0
14%	3	0.2	0.1
26%	1	0.1	0.0

Figure 8. Most used elastic fiber content values in blends for jeans in pcs and %.

As the silhouette is expected to be closely linked to the content value of elastic fibers, we analyzed the fit of the garments next. Figure 9 highlights the four different fits documented. The most popular fit is Loose with 45 % of jeans in the whole sample. Especially FB and PostC jeans are dominated by the Loose fit with 56 % (n=1038) and 63 % (n=67) respectively. Jeans offered by JS are predominantly Tight with 37 % (n=365) and Regular fitting with 27 % (n=264). Looking at the whole sample size, wider fits like Regular and Loose cuts are the most popular with around 71 % (n=2089) combined.

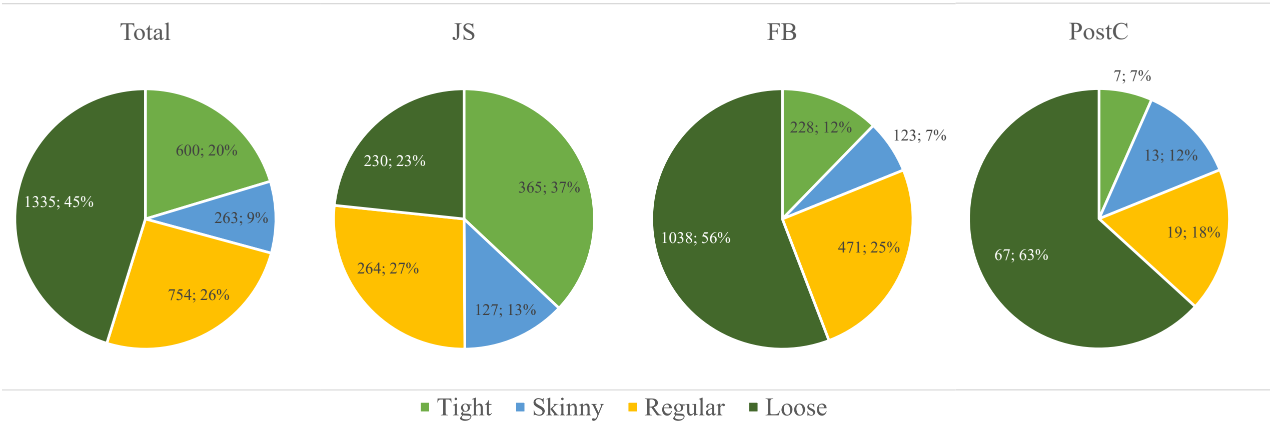


Figure 9. Distribution of the Fit of the jeans in JS, FB and PostC garments in pcs and %

Figure 10 illustrates the correlation between the garment fit and presence of elastic fibers. Especially Regular and Loose fits do not require elastane fibers, resulting in n=361 and n=1094 jeans without elastic fibers respectively. Most jeans with a Tight fit have an elastic fiber content of 1 or 2 % with n=266 and n=157 respectively. Regular jeans are also documented with 1 % (n=256) and 2 % (n=84) elastic fiber content. Tight jeans reached an elastic fiber content up to 26 % (n=1), with the most used values of 1 % (n=266) and 2 % (n=157). Skinny fits reached fiber values up to 13 % (n=1), most popular is a value of 1 % (n=100). Tight and Skinny fits were also documented to have 0 % elastic fiber content, though the number of jeans was rather low with n=55 and n=5 respectively. The analysis shows a skewed distribution toward low elastic fiber contents across all fits.

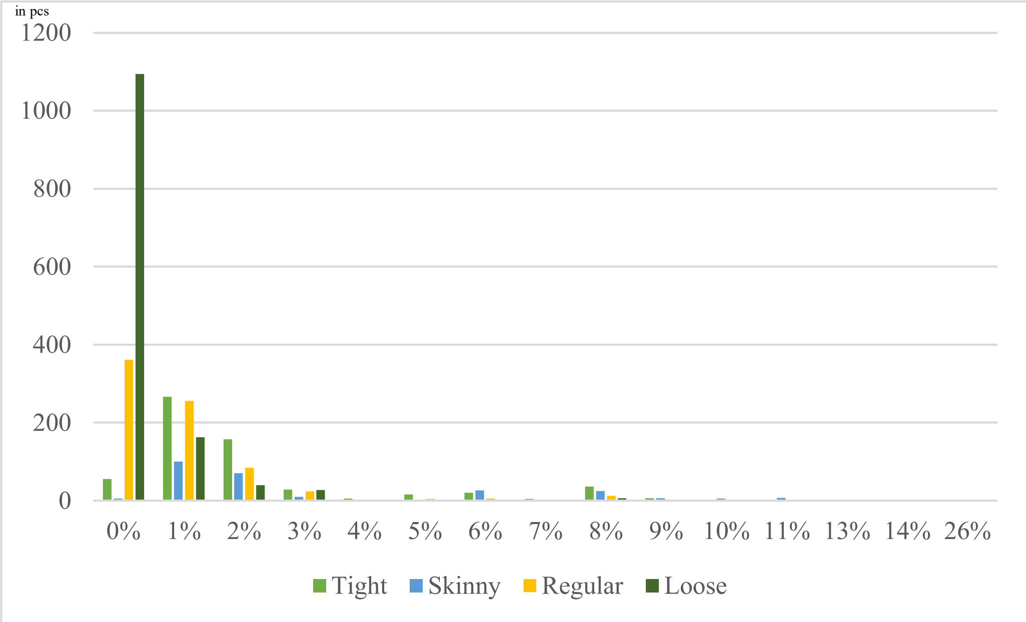


Figure 10. Elastane content values of all jeans paired with the fit in pcs

Up to this point, we looked at EL and EME combined as elastic fibers. The following Table 2 highlights the differences in usage. EL is often used on its own in a blend (n=1227) with values up to 7 %, while EME is often paired with EL (n=248) and rarely used on its own in a blend (n=1). EME is used less than EL, but often utilized with higher content values up to 26 %.

Table 2. Usage of Elastane and Elastomultiester for jeans in pcs

EL \ EME	0%	1%	2%	3%	4%	5%	6%	7%	8%	9%	10%	26%
0%												1
1%	784	1	58	2	5	3			4	1		
2%	390			14	41	8	79	5	2	6		
3%	31							5	7		1	
4%	10		2			1					3	
5%	5											
6%	6											
7%	1											

5. Discussion: From material heterogenity to recyclability-oriented ecodesign

Historically, jeans were produced from cotton fabric due to its durability and abrasion resistance. Accordingly, the high number of jeans containing cotton was expected. CO was present in 99 % of all jeans documented, in values of 22 % to 100 %. With 42 % (n=1235) mono-material Cotton jeans, denim remains a highly cellulose-rich waste stream, making it suitable for mechanical and solvent-based recycling. The high share of mono-material jeans (>50 %) in the FB sample further demonstrates that it is still possible to produce 100 % CO jeans despite the increased requirements of the consumers. This fraction represents the most suitable input for high-quality F2F recycling and could be expanded through targeted ecodesign measures. The near absence of mono-PET jeans (n=1) confirms denim's continued dependence on cellulosic fibers, emphasizing the relevance of cellulose-focused recycling pathways. However, 58 % (n=1716) fiber blends reveal a transition of the jeans from mono-material workwear to a multi-component fashion product. The resulting heterogeneity reduces material predictability and thus increasing sorting complexity, and complicating high-quality recycling. Despite this complexity, the challenge is not due to a lack of cellulose, but due to contamination and blend diversity.

Elastic fibers are the primary contaminant, present in almost 50 % of jeans, confirming elastic properties as a defining feature of contemporary denim jeans. The dominance of low content values of 1-2 % suggests that minimal input is sufficient for most elastic performance and may support the development of tolerance thresholds for cellulose recycling. Though, even low levels can reduce mechanical recycling quality, interfere with dissolution processes and compromise overall process stability (Choudhury et al., 2024). EL remains the dominant elastic fiber with 42 % (n=1227), typically used as the sole elastic fiber in blends in low percentages, whereas EME is often combined with EL (8 %, n=248), suggesting functional differentiation within stretch systems and combination for performance fine-tuning. Multi-elastic fiber systems further increase polymer incompatibility and sorting complexity. Detection is additionally hindered by the core-spun structure of elastic yarns and NIR sorting limitations for low-percentages as well as fibers not visible on the surface. Thus, recycling feasibility is not solely of chemical but also of technical nature.

The blend analysis confirms that stretch is the primary driver for fiber diversification. While recycling systems can tolerate certain contamination levels (e.g. ≥88 % cellulose as input for solvent-based cellulose recycling (Infinited Fiber, n.d.)), lower foreign fiber content improves economic viability. Especially in mechanical recycling, elastic fibers in the input can complicate the process, reducing e.g. fiber quality and processing stability (Islam et al., 2025). The extremely high blend diversity, 199 distinct blends of which many occurring only once (72 blends) or twice (30 blends), is suggesting experimental material choices that are not tailored to the needs of denim jeans specifically and demonstrates a lack of material standardization, significantly reducing sorting efficiency and scalability. Blends can remain recyclable if regulated through polymer compatibility and content thresholds. The more fibers are blended together, the higher the risk for introducing multi-polymer incompatibility during recycling. The low prevalence of polycotton blends (0,6 %, n=19) was unexpected, given polyester's common use in apparel for cost reduction and durability improvements. Most of the polycotton jeans (n=16) were from FB, confirming the utilization for price reduction.

PET was overall only present in 21 % of the sample in values from 2 % to 100 %. Especially PET values ≤5 % (n=24) seem questionable regarding their functional impact on improving garment properties. A possible explanation for the rather low number of PET is that denim fabrics already achieve sufficient mechanical performance through fabric construction, paired with potentially altered fabric behavior due to PET fibers during finishing processes (e.g. distressing) which may conflict with the aesthetic expectations of classic denim products. Lyocell fibers are the second most dominant cellulosic fiber with 10.5 % of the whole sample. In comparison, the remaining cellulosic fibers combined reached 6.4 %. CLY is regarded as the most suitable regenerated cellulose fiber for jeans production (Patra & Pattanayak, 2015) and is often blended with e.g. CO to reduce the cost. It is suitable to be recycled together with CO in solvent-based and mechanical processes, as it does not introduce incompatible polymers. Though as it is a regenerated fiber, the number of times it is suitable for recycling is less than for CO due to a lower DP. Since regenerated fibers can be produced from wood cellulose, CLY seems to be a good alternative to conventional cotton from an environmental standpoint and to viscose due to excellent fiber properties (Jiang et al., 2020).

The most common 3-Fiber blend combines cellulose with PET and elastic fibers (18 %, n=541), creating multi-polymer systems that are more difficult to recycle selectively. These blends are most likely performance-driven, to give more elasticity and durability to classic denim fabrics, but at the expense of recyclability, requiring thorough pre-sorting and pre-treatment steps to prevent quality losses in cellulose recovery and to keep the processes economically viable. Cotton blended with EL and EME could be counted as such as well, since EME is a bicomponent-polyester fiber, resulting in four different polymer types (Cellulose, Polyurethane from EL and PET+PTT from EME). PTT introduces a second polyester-type, though it should still be possible to recycle both polyesters within the same recycling system, as they share the same acid (Terephthalic acid) which is polymerized with different glycol components and thus should result in a mixture of three different monomers to be separated. Selective depolymerization technologies show potential for PET and PTT recovery (Luo et al., 2024), their applicability in mixed textile waste streams remains unverified. PET-cellulose blends are more compatible with certain solvent-based recycling systems, due to selective dissolution and potential recovery of both fiber components. While three or more fibers blended together seem to indicate further performance optimization opportunities, the complexity may exceed contamination tolerances and technical viability of recycling technologies. Increasing blend diversity also leads to increased pre-processing costs, enhancing the need for thorough sorting and contaminant removal before recycling. The functional necessity of such complex overengineered blends should thus be critically evaluated against their recycling implications. Recurrent blend patterns across samples furthermore suggest potential for standardization without compromising market diversity, design freedom or comfort.

The dominance of Loose fits confirms a broader market shift away from Tight and stretch-dependent silhouettes. JS shows a stronger percentage of Tight and Regular fits, suggesting segment-specific design strategies. With 71 % of garments categorized as Regular or Loose, most jeans do not structurally require elastic fibers. Historically, traditional jeans silhouettes were straight or relaxed fits made from rigid cotton fabrics, the high prevalence of wider fits suggests a partial return to constructions compatible with mono-material cotton. From a recycling perspective, this outlook is desirable as it will provide cellulose-rich waste streams with low elastic contamination, as utilizing elastic fibers in wider fits is not functionally justified. Loose and Regular fits frequently contain no elastic fibers (49 %, n=1455 combined of total sample), indicating that stretch is not structurally necessary for the majority of jeans. An exception might be jeans with a higher waistline, as a certain degree of stretchability might proof beneficial to cater to more body types without having to increase the size chart. As we did not analyze the placement of the waistband in this study, the wider fits containing elastic fibers might have this feature. Tight fits are primarily associated with 1–2% elastic fiber content, suggesting a functional threshold for body-conforming designs is possible. The presence of Tight and Skinny jeans without elastane (n=60) was unexpected, as even altered pattern construction shouldn't be able to increase stretchability enough that omitting elastic fibers can be possible while preserving comfort and functionality. Thus, labeling inaccuracy cannot be excluded, particularly in light of the 3% manufacturing tolerance permitted under the Textile Labeling Act (Regulation (EU) No 1007/2011). These findings support the development of fit-dependent, threshold-based ecodesign guidelines, linking fit categories to maximum elastane contents. Especially reducing elastic fibers in wider fits would not compromise functionality but would improve recyclability.

Overall, denim waste remains cellulose-rich but becomes increasingly heterogenous. The primary recycling barrier is not chemical incompatibility but blend variability and elastic fiber contamination. As certain blends already reoccur frequently and the market viability of mono-cotton and low-elastic fiber blends is demonstrated, the potential of blend standardization is high. Quantitative thresholds like maximum elastic fiber content, minimum cellulose share and fiber-count limitations in blends could significantly enhance recyclability while maintaining functionality and design freedom. Blend simplification thus improves overall sorting reliability, not only processing compatibility, especially if elastic thresholds are tied to the fit of a garment and can be analyzed with AI-supported image recognition. Rather than demanding strict mono-materiality, threshold-based ecodesign offers a pragmatic pathway towards improved recycling compatibility. Blend simplification, fit dependent elastic fiber limits and justification of each additional fiber, linked to Extended Producer Responsibility mechanisms like higher waste disposal fees through eco-modulation, can reduce contamination without compromising durability or aesthetic diversity. Circular denim must therefore balance functionality, longevity and material recovery potential. From a product development perspective, these findings highlight the need to harmonize consumer expectations, such as comfort, fit, and elasticity, with design-for-recycling principles and forthcoming European law. The results indicate that many performance requirements—particularly for Regular and Loose fits—can be achieved without or with only minimal elastic fiber content. For tighter fits, where elastic fibers are functionally justified, limiting their content to clearly defined thresholds may provide a compromise between wearability and recyclability. Overall, aligning material selection with actual functional requirements can reduce unnecessary material complexity without compromising consumer acceptance, thereby supporting the transition toward more circular denim products.

We therefore suggest to utilize mono-material cotton or blends utilizing high-quality cellulose fibers where functionally feasible. The usage of elastic fibers should be limited drastically in Loose and Regular fits, effectively introducing fit-dependent elastic fiber thresholds. Overengineered multi-polymer constructions should be avoided, the number of overall fibers blended together reduced to improve polymer compatibility. Furthermore, a 100 % cellulose content would reduce the risk of microfiber shedding significantly, leaving only the seams as a possible polluter. PET fibers should only be used in combination with EME as they can be both recycled together, blending of cellulose with PET and EL should be avoided due to enhanced polymer incompatibility. Recycling repercussions need to be considered during the design and material selection phase. Table 3 gives a brief overview of proposed ecodesign guidelines for jeans, specific blends and values need to be tested and implemented.

Table 3. Proposed fiber contents for jeans by fit

Fit	Proposed elastic fiber content	Proposed main fiber composition	Notes
Tight	Max. 5 %	Min. cellulose content of 80 %	
Skinny	Max. 2 %		
Regular	0 %	90 - 100 % cellulose	Exceptions for elastic fiber usage up to 2% can be made for high-waisted styles
Loose	0 %		

6. Conclusion

This study examined the material composition of jeans to assess their compatibility with F2F available recycling systems and provides a basis for a more streamlined fiber percentage combination to increase efficiency of sorting and recycling. Denim remains a cellulose-rich waste stream, with CO present in nearly all garments, though the increasing number of different fiber blends has transformed jeans into a heterogeneous waste stream. Approximately 60 % of the analyzed jeans were made from blends containing up to five different fiber types, with elastic fibers present in almost half of the sample. The findings demonstrate that the primary barrier to high-quality F2F recycling is material complexity and low-level contamination. 2-Fiber blends combining CO with low content values of elastic fibers dominate the market. However, even low elastic fiber contents can reduce recovery efficiency of the main fibers and challenge sorting technologies due to NIR limitations. The occurrence of more complex fiber blends further increases polymer incompatibility and may exceed technical tolerance thresholds of recycling technologies.

Beyond confirming elastic fibers as a critical barrier to recycling, this study advances the field by introducing a fit-based perspective on material composition. The fit analysis revealed elastic fiber usage beyond functional necessity, particularly in wider fits. This indicates significant reduction potential for elastic fibers without compromising functionality or comfort of the garments. The results therefor support the development of quantitative, fit-dependent fiber content thresholds for recyclability, including caps for elastic fiber contents, limitations on fiber count and minimum cellulose content for jeans. Rather than demanding strict mono-materiality, threshold-based ecodesign strategies may offer a more realistic pathway toward a circular textile economy. Simplification and standardization of blends could substantially improve sorting reliability, recycling efficiency as well as quality and economic scalability while preserving design diversity and garment longevity. Denim jeans are a valuable, cotton-rich waste stream suitable for circularity, if fit-specific material thresholds are implemented.

Further research should investigate trade-offs between durability and recyclability, validate technical tolerance limits under industrial conditions and explore how regulations such as the Extended Producer Responsibility can incentivize recyclability-oriented design and material decisions. Furthermore, contaminants like haberdashery items, colorants and coatings found on jeans have to be analyzed regarding their necessity and recyclability. By linking product design, material composition and End-of-Life constraints, this study contributes empirical evidence to support the transition toward more recyclable and system-compatible denim jeans.

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Data Availability Data can be found in Supplementary Material files.

Declarations

Competing Interests The authors declare no competing interests.

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Abbreviations

The following abbreviations are used in this manuscript:

Abbreviation	Name
AI	Artificial Intelligence
CO	Cotton
CLY	Lyocell
CMD	Modal
CV	Viscose
DP	Degree of Polymerization
EL	Elastane
EME	Elastomultiester
F2F	Fiber-to-Fiber
FB	Fashion Brand
JU	Jute
JS	Jeans Specialist
LI	Linen
NIR	Near Infrared
PA	Polyamide
PET	Polyester/ Polyethylene Terephthalate
PTT	Polytrimethylene Terephthalate
PostC	Post-Consumer
PU	Polyurethane
SI	Silk
TPA	Terephthalic acid