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Design–sorting mismatch limits circularity in fast-fashion garments

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ABSTRACT

Automated textile sorting is increasingly promoted as a key enabler of fibre-to-fibre recycling, yet its effectiveness depends on whether garments are designed in ways that current near-infrared (NIR)-based systems can identify and route. This study uses retailer product data from H&M and Uniqlo in the United Kingdom and Australia to assess garment-level design compatibility with NIR-based automated textile sorting. We develop a rule-based framework that translates documented sorting constraints into measurable indicators of recognition scope, blend complexity, low-share components, black-colour proxy for optical risk, and surface–hidden material mismatch. Across 47,522 colour-specific garment variants, 50.3% violated at least one baseline sorting-relevant rule, with a sensitivity range of 45.0–64.0%. The largest barriers were unsupported recognition scope (36.4%), more-than-two-fibre blends (20.0%), and minor-component detectability (17.3%), followed by the black-colour proxy for optical risk (13.7%) and surface–hidden mismatch (8.2%). These findings highlight design-for-sorting, reliable component-level product information, and continued development of sorting capabilities as complementary prerequisites for scalable textile circularity.

1. Introduction

The transition toward more circular textile systems has become an increasingly important policy and industrial priority across major textile markets. In the European Union, the EU Strategy for Sustainable and Circular Textiles and the revised Waste Framework Directive have reinforced the role of textile reuse, recycling, and separate collection in the circular economy (European Commission, 2022a, 2025). Similar signals are emerging elsewhere. In North America, California's Responsible Textile Recovery Act of 2024 established the first textile extended producer responsibility framework of its kind in the United States (California Legislature, 2024). In China, national policy targets call for a relatively complete waste-textile recycling system by 2025, including a 25% recycling rate and 2 million tons of recycled fibre output annually (State Council of the People's Republic of China, 2022). Together, these developments show that textile sorting is becoming a strategic condition for circularity rather than a marginal downstream activity.

Among the many barriers to textile circularity, collection and sorting are two closely linked bottlenecks. The scale of the challenge remains substantial. In 2022, each person in the EU consumed on average approximately 19 kg of clothing, footwear, and household textiles, while EU Member States generated approximately 16 kg of textile waste per person. Of the waste generated, about 4.6 kg per person was separately collected, whereas approximately 11.1 kg per person entered mixed household waste. These figures demonstrate a substantial separate-collection gap. At the same time, the European Environment Agency cautions that sorting and recycling capacities must also expand as separate collection increases; otherwise, additional collected textiles may still be incinerated, landfilled, or exported (European Environment Agency, 2024, 2025). In the United States, the EPA estimates that 17 million tons of textiles were generated in 2018, representing 5.8% of total municipal solid waste, while only 14.7% were recycled (US EPA, 2026). In China, official sources reported roughly 22 million tons of textile waste in 2020, of which only about one-fifth was recycled (State Council of the People's Republic of China, 2022). Together, these examples show that scaling textile circularity requires both effective separate collection and sufficient sorting capacity and material resolution to route collected textiles into reuse and fibre-to-fibre recycling pathways.

As separate collection expands, larger volumes of heterogeneous textiles must be routed into reuse, recycling, and disposal pathways. Sorting should therefore be understood not merely as an intermediate logistics step, but as a core process that conditions whether collected

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textiles can enter higher-value circular pathways. Current manual sorting remains labour-intensive, costly, and difficult to scale when waste streams are heterogeneous in fibre composition, colour, structure, and condition. Automated textile sorting (ATS) technologies, especially systems based on near-infrared (NIR) spectroscopy, are therefore increasingly promoted as one of the most promising routes toward industrial-scale material recovery. This is no longer only a conceptual prospect: the SIPTex facility in Malmö, Sweden, has been described as the world's first industrial-scale automated textile sorting plant, using NIR/VIS to sort textile waste by fibre type and colour with a reported capacity of 24,000 t per year (European Commission, 2022b), while broader initiatives such as T-REX (T-REX Project, 2026) and Sorting for Circularity Europe (Fashion for Good, 2022) are actively building the business case, infrastructure logic, and value-chain coordination needed to scale automated sorting as a feedstock-preparation step for fibre-to-fibre recycling.

However, current NIR-based ATS remains constrained by several well-documented technical limitations. Existing systems classify textiles against predefined spectral libraries, reference databases, or trained recognition classes rather than identifying unrestricted material compositions. These recognition libraries are not permanently fixed and can be expanded when representative calibration data and validated models become available. Current industrial documentation nevertheless illustrates the practical constraints faced today. Fibersort, a commercial NIR- and RGB-based textile-sorting system, reports six trained fibre types and notes that additional fibres can be added through further training. It also states that textiles containing three or more fibre types or atypical concentrations are harder to sort accurately and that its current sorting process focuses primarily on mono-material textiles (Valtech, 2026). Surface-related constraints, however, cannot be addressed through library expansion alone. Dark or carbon-black-rich textiles can suppress usable spectral signals, while coatings, laminates, and other finishes may mask the underlying fibre signature (Gorla et al., 2026). NIR-based sorting is also inherently surface-dominant: concealed linings, fillings, bonded layers, and coated substrates may therefore be absent from the measured signal or only partially represented. These constraints show that ATS capability depends both on evolving model coverage and on whether garment material architecture is compatible with what an optical surface scan can physically detect.

These technical constraints are closely linked to garment design. Research on textile circularity and recycling-system scaling increasingly emphasizes that the feasibility of fibre-to-fibre recycling depends not only on downstream technology, but also on the material anatomy of garments entering the system (Logan et al., 2025). Recent work analysing textile anatomy identifies fibre blends, linings, disruptors, and adornments as key determinants of route compatibility, while broader studies on closed-loop textile recycling stress that scaling textile-to-textile systems requires feedstock that is materially consistent, identifiable, and sufficiently aligned with downstream processes (Charnley et al., 2024). Fast fashion is a particularly relevant setting because its high-volume production, rapid assortment turnover, frequent consumption, and comparatively short use cycles accelerate material throughput into post-consumer systems (Niinimäki et al., 2020). However, the underlying design–sorting mechanisms are not unique to this market segment. This leaves a central research question for the present study: to what extent do garments in contemporary fast-fashion and mass-market product offerings exhibit design features that are poorly aligned with the practical capabilities of current NIR-based automated sorting?

To address this question, this study develops a rule-based framework that translates documented NIR sorting barriers into measurable garment-level indicators and applies it to a large retailer product dataset from H&M and Uniqlo. The analysis reports the share of offered colour-specific garment variants flagged by at least one sorting-relevant rule and the separate shares flagged by each of the five rule domains. These estimates describe the prevalence of disclosed characteristics in the sampled product offerings and should not be interpreted as sales-weighted prevalence, future waste-stream composition, or realised sorting-failure rates. By isolating design-related barriers from downstream factors such as product use, collection, contamination, and facility operation, the study identifies product-stage conditions that may constrain current NIR-based sorting.

2. Methodology

2.1. Study design and analytical framework

This study develops a garment-variant-level, rule-based assessment of compatibility with NIR-based automated textile sorting using retailer-disclosed product data. Fig. 1 illustrates how one retailer-disclosed garment record is normalized into rule inputs and evaluated against the baseline indicators. The unit of analysis is the colour-specific garment variant because colour and composition may differ across variants of the same nominal product and are directly relevant to the evaluated rules. The main outputs are the share of variants violating each rule and the share exhibiting at least one barrier. Additional robustness analyses are described in Section 2.5 and Supplementary Note S1.

2.2. Data preparation

The analysis was based on the harmonized garment-variant dataset archived by the authors (Li and Walther, 2026), derived from H&M and Uniqlo product pages in the United Kingdom and Australia. We summarize the data construction steps relevant to the present sorting analysis here because the rule framework depends directly on fibre composition, colour labels, garment categories, and component-level material structure.

Garment-level data were collected from online product pages of H&M and Uniqlo in the United Kingdom and Australia. These two retailers were selected because their parent companies, H&M Group and Fast Retailing, rank second and third among major global apparel manufacturers and retailers by annual sales, after Inditex/Zara (Fast Retailing, 2025). They therefore provide policy-relevant examples of contemporary large-scale fast-fashion and mass-market apparel design, but they are not intended to represent the entire apparel market. The United Kingdom and Australia were selected as one Northern Hemisphere market and one Southern Hemisphere market to capture seasonal variation in garment offerings while keeping retailer selection constant. The dataset spans men's, women's, and children's clothing and includes disclosed fibre composition, material percentages, colour descriptions, product-structure cues, and garment category. The analytical unit was defined as the colour-specific garment variant rather than the original product-page record because colour and composition may vary across variants of the same nominal product. This was especially important for Uniqlo, where one product page could contain multiple colour variants and, in some cases, variant-specific composition information.

To reduce temporal inconsistency in the product pool, URL collection and product-detail scraping were separated. Product URLs were first collected within a concentrated time window for each retailer-region website, defining the product pool before detailed product information was extracted. Rather than relying on manual browsing or page-by-page visual pagination, product URLs were collected from the publicly accessible listing endpoints used by the retailer product-listing pages. This approach allowed the URL pool to cover the product records returned for the in-scope clothing categories on each retailer-region website at the time of collection. All harmonized records retained two timestamps: the time when the product URL was collected and the time when the corresponding product details were scraped. URL collection occurred between 24 and 26 March 2026, while product-detail scraping was completed between 24 March and 8 April 2026. Thus, although detailed scraping took place over a longer period, it was applied to a

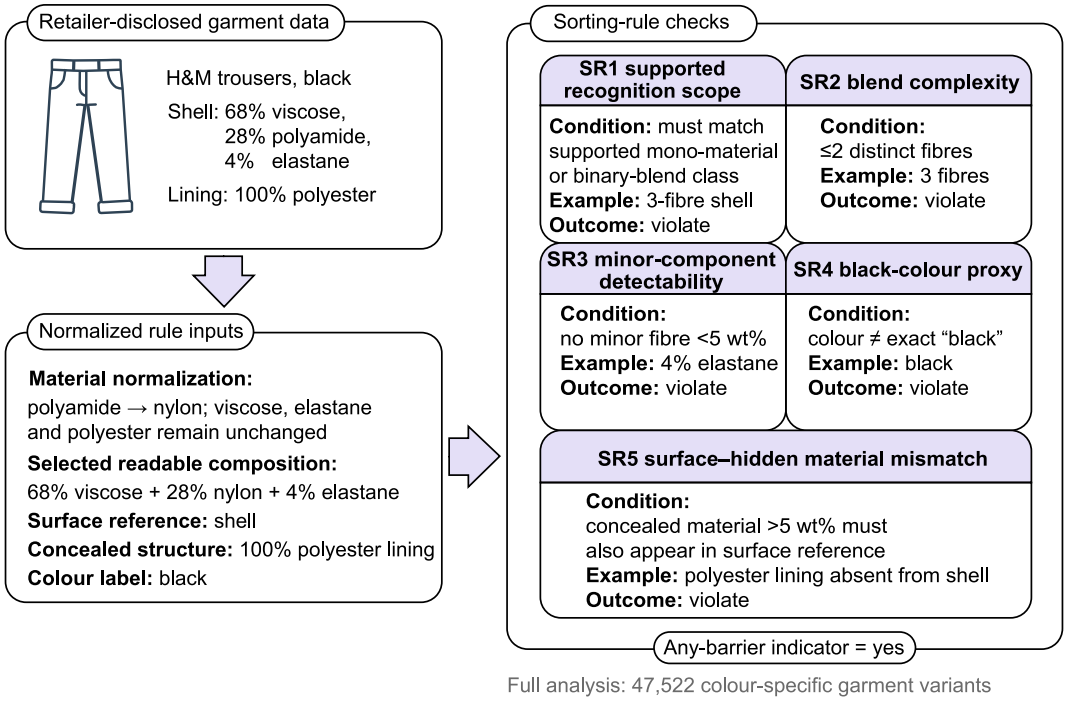

Fig. 1. Analytical framework for translating retailer-disclosed garment data into sorting-rule indicators. Detailed rule definitions and sensitivity specifications are provided in Section 2.4.

fixed URL pool, reducing the risk of mixing products from changes in online product offerings.

The preprocessing pipeline converted raw product-page records into a harmonized variant-level dataset suitable for rule-based sorting assessment. The raw scraped dataset contained 47,834 product-page records. Records with missing material or colour information were removed, leaving 47,570 records. H&M records were already represented at the colour-variant level through product-page URLs, whereas Uniqlo records were expanded by colour. The cleaned H&M records and expanded Uniqlo records were then harmonized into a common schema, producing 51,994 variant-level records.

Material names were standardized by mapping synonymous or analytically equivalent labels to canonical terms, for example nylon and polyamide, elastane and spandex, and polyester and PES. Garment categories were harmonized across retailers using a rule-based procedure because the scraped category information differed in structure and granularity between retailer websites. The procedure combined retailer-native taxonomies, product names, and product descriptions with sorting-oriented grouping logic informed by the Sorting for Circularity Europe sorting handbook (Circle Economy and Fashion for Good, 2022). Accessories, footwear, and unallocated records were outside the scope of the garment-sorting analysis and were removed, reducing the dataset from 51,994 to 48,244 garment variants.

Finally, retailer-disclosed component labels embedded in composition strings were parsed and normalized into a structured component-level representation. Raw component labels such as shell, body, lining, padding, and pocket lining were mapped to standardized component names and broader garment-component classes, including surface, lining, filling, pocket, trim, panel, decoration, and other. This component taxonomy was used to identify the most likely readable outer component

Table 1
Dataset-size changes across preprocessing steps.

Step	Input records	Removed/unresolved records	Output records	Main purpose
Raw scraped records	47,834	264 unique records removed; among these, 264 lacked material information, 134 lacked colour information, and 134 lacked both	47,570	Remove records without the minimum material–colour information needed for rule evaluation
Uniqlo colour-variant expansion	2593 cleaned Uniqlo records	23 unresolved expanded rows	7017 Uniqlo variant rows	Convert Uniqlo product-page records into colour-specific garment variants
Cross-retailer harmonization	44,977H&M records +7017 Uniqlo variant records	0	51,994	Align H&M and Uniqlo into a common variant-level schema
Material normalization	51,994	0	51,994	Add canonical material labels while preserving original material text; 9392 records changed after normalization
Category normalization and scope filtering	51,994	3750 removed: 2648 accessories, 1087 footwear, and 15 unallocated records	48,244	Assign parent and detail garment categories and remove out-of-scope records
Component normalization and consistency filtering	48,244	722 removed: 4 without usable material text and 718 with inconsistent component percentages	47,522	Parse component-level composition and retain records suitable for rule evaluation
Rule-evaluation dataset	47,522	–	47,522	Final dataset used for rule-based compatibility assessment

Note: The increase from 47,570 cleaned product records to 51,994 harmonized variant-level records occurs because Uniqlo product-page records were expanded into colour-specific garment variants. H&M records were already treated as colour-specific variants through product-page URLs.

and distinguish concealed internal layers from visible surface materials. During component normalization, four rows without usable material text and 718 rows with component percentage sums exceeding the accepted consistency threshold were removed. The final rule-evaluation dataset therefore contained 47,522 garment variants and formed the basis for all analyses reported in the Results section. Table 1 summarizes the main dataset-size changes.

2.3. Barriers in NIR-based automated textile sorting

This section reviews barriers reported in the literature on NIR-based textile sorting and fibre-to-fibre recycling and links them to the five sorting-rule domains used in this study: supported recognition scope (SR1), blend complexity (SR2), minor-component detectability (SR3), black-colour proxy (SR4), and surface–hidden material mismatch (SR5). Section 2.4 then explains how these domains were mapped to observable retailer-data attributes and operationalized as rule-based pass conditions and sensitivity specifications.

The first barrier domain is supported recognition scope (SR1). Current NIR-based systems classify garments within trained or documented class sets. Materials or blends outside those sets may be rejected, assigned to residual streams, or classified unreliably (Becker et al., 2024; Circular Copenhagen, 2022; Gorla et al., 2026). This limitation reflects current technological capabilities rather than a fixed physical ceiling, because recognition coverage can expand through additional calibration data, spectral libraries, and classification models. The empirical question addressed by SR1 is therefore whether current retailer-disclosed compositions fall within literature-reported recognition envelopes.

A second barrier concerns blend complexity (SR2). Overlapping spectral signals generally become harder to separate as the number of fibre types increases, particularly when the blend ratios are not well represented in the calibration data. Current industrial documentation states that compositions with three or more fibre types are harder to sort accurately and that present operation focuses primarily on mono-material textiles (Valtech, 2026). The $\leq$2-fibre boundary used here therefore represents a practical threshold under current industrial conditions, rather than a claim that selected ternary blends could never become classifiable. However, robust evidence for the reliable, general-purpose classification of ternary and more complex blends at industrial scale remains limited.

A related but distinct barrier concerns minor-component detectability (SR3). Low-share secondary components may remain unresolved in general-purpose sorting, especially when they contribute only weakly to the measured spectrum. This is particularly relevant for elastane and other minor components, which may still affect downstream recycling purity even when they are difficult to detect or quantify reliably (Becker et al., 2024; Cura et al., 2021; Mahlamäki et al., 2025; Matoha, 2026).

Surface-related effects provide the basis for the fourth and fifth rule domains. A retailer label of “black” establishes that a black colourant system was used, but it does not reveal whether the colour was produced through fibre-specific dyes, pigments, or carbon black. Carbon black is documented in some textile applications, including black dope-dyed polyester, while conventional black textiles can also be produced through dye systems (Ai et al., 2023; Mamun Kabir and Koh, 2017). Because black and dark textiles are reported to have lower NIR recognition reliability and carbon black is a particularly strong NIR absorber (Valtech, 2026), the observable colour label was retained as a proxy for elevated optical risk (SR4), not as proof of carbon-black content or inevitable sorting failure.

In addition, NIR-based textile sorting is inherently surface-dominant: coatings, laminates, linings, fillings, bonded layers, and other concealed structures can make the exposed surface insufficiently representative of the garment as a whole because the measured spectrum is dominated by the outermost accessible layer (Becker et al., 2024; Matoha, 2026; NewRetex, 2026). This motivates the surface–hidden material mismatch rule domain (SR5).

The literature also identifies operational factors such as moisture, dirt, wrinkles, contamination, and feed presentation. These factors can affect realised sorter performance, but they arise during use, collection, handling, or sorting rather than being fixed garment-design attributes. They also cannot be inferred reliably from online retailer product metadata (Stipanovic et al., 2026). They were therefore treated as outside the scope of the rule-based product-design assessment.

Table S1 in the Supplementary information provides the barrier-to-indicator mapping, including barriers retained as SR1–SR5 and operational barriers excluded from the product-design assessment. Supplementary Note S1 and Tables S7–S8 document the sampling-structure robustness analyses, while Supplementary Note S2 provides additional interpretation of the SR4 black-colour proxy.

2.4. Rule derivation, operationalization, and sensitivity specifications

Building on the sorting-rule domains introduced in Section 2.3, this section defines how each domain was measured using retailer-disclosed product data. Each rule was expressed as a baseline pass condition, meaning the main criterion used to determine whether a garment variant met the corresponding sorting requirement in the main analysis. Where alternative plausible boundaries could be justified from the reviewed literature or from the observable structure of the data, sensitivity specifications were defined to test how the results changed under more permissive or more restrictive assumptions. The resulting rule outputs should therefore be interpreted as product-design indicators of potential sorting constraints, not as direct predictions of realised sorter performance.

Each rule was converted into a binary pass/violation variable at the colour-specific garment-variant level. A garment variant was counted as violating a rule when its disclosed design attributes fell outside the corresponding baseline pass condition. The main outputs were calculated as the share of garment variants violating each rule and the aggregate share violating at least one rule under a given rule specification.

The rules differ in the observable input used for evaluation. SR1–SR3 use the selected readable composition, because these rules depend on the material composition that a surface-based NIR system is most likely to classify. SR4 uses the normalized colour label of each colour-specific garment variant. SR5 uses the selected surface reference and concealed structural components, because the relevant question is not only which materials are present, but where they are located in the garment. A material declared in the total composition may be visible to NIR if it occurs in the shell or outer surface, but effectively hidden if it occurs only in a lining, filling, padding, or internal layer. SR5 therefore compares the selected surface reference with concealed structural components rather than aggregating all disclosed materials into one total composition.

The selected readable composition was derived from the normalized component structure. For SR1–SR3, it was defined as the first component classified as a surface component; if no surface component was available, the first disclosed component was used as a fallback. For SR5, the surface reference was selected separately: an explicit coating was treated as the readable surface where present; otherwise, the first surface component was used, with the first disclosed component as fallback. Concealed structures were identified from normalized lining- and filling-related component classes and names. The executable rule implementation is provided with the analysis code referenced in the Data availability section.

The rule domains differ in whether their boundaries were fixed or varied in sensitivity analysis. SR1 and SR3 use lower-bound, baseline, and upper-bound specifications because supported recognition scope and detectable-share thresholds vary across technologies and studies. SR4 and SR5 also use alternative definitions to test uncertainty in the observable proxy and concealed-structure boundary. SR2 was retained as a fixed current-practice indicator because industrial documentation

explicitly identifies three-or-more-fibre mixtures as harder to sort accurately, while the reviewed class sets were dominated by mono-materials and selected binary blends. This fixed boundary is not interpreted as a permanent technical limit. However, robust evidence for reliable, general-purpose classification of ternary and more complex blends at industrial scale remains limited. Table 2 summarizes the operational rules and their sensitivity specifications.

2.5. Robustness analyses for sampling structure

Two additional robustness analyses assessed whether the pooled results were influenced by retailer–region composition or by products represented by multiple colour variants. First, the SR1–SR5 and aggregate lower-bound, baseline, and upper-bound calculations were repeated separately for H&M Australia, H&M United Kingdom, Uniqlo Australia, and Uniqlo United Kingdom. Second, because colour variants of the same parent product may or may not differ in material composition, variants were grouped by retailer and parent product identifier. Each parent product was treated as one equally weighted analytical unit using the share of its observed colour variants flagged by each rule. Full methods and results are reported in Supplementary Note S1 and Tables S7–S8.

3. Results

3.1. Overall prevalence and overlap of design–sorting mismatch

Around half of the evaluated garment variants contained at least one sorting-relevant design barrier. The final analytical dataset contained 47,522 garment variants, including 41,077H&M variants and 6445 Uniqlo variants. Under the baseline defined in Section 2.4 and Table 2, 23,908 variants violated at least one sorting-relevant rule, corresponding to 50.3% of the dataset. The estimate remained high under the lower-bound and upper-bound sensitivity specifications: 45.0% under the lower bound and 64.0% under the upper bound. Even under comparatively permissive assumptions, therefore, nearly half of the analysed garment variants contained at least one disclosed design feature likely to constrain, complicate, or reduce the reliability of NIR-based automated sorting (Fig. 2a).

The most prevalent barriers were related to recognition scope and material complexity, but optical and structural constraints also affected a non-negligible share of garments. SR1 supported recognition scope was the largest individual barrier, flagging 36.4% of variants under the baseline definition, with a sensitivity range from 28.2% under the lower bound to 44.7% under the upper bound. SR2 blend complexity flagged 20.0% of variants. SR3 minor-component detectability flagged 17.3% under the baseline 5 wt% threshold, ranging from 9.4% under the lower bound to 31.5% under the upper bound. SR4, the black-colour proxy for optical risk, flagged 13.7% of variants under the baseline exact-“black” definition and 18.0% under the broader contains-“black” definition. SR5 surface–hidden material mismatch affected 8.2% of variants under the baseline definition, increasing to 19.2% when any hidden layer was treated as a barrier (Fig. 2a).

The overlap analysis shows that design–sorting barriers often clustered within the same garments, although some barriers also appeared as stand-alone constraints, as illustrated in Fig. 2b. The largest baseline intersection combined SR1, SR2, and SR3, indicating that recognition-scope mismatch, blend complexity, and minor-component detectability often co-occurred in compositionally complex garments. At the same time, large single-rule intersections also appeared, especially SR1-only and SR4-only cases. This implies that sorting mismatch has a twofold structure: some garments accumulate multiple composition-related barriers, while others are constrained by one dominant mechanism, such as limited recognition scope or black-colour optical risk.

The robustness analyses produced the same substantive ordering. Portal-specific baseline any-barrier shares ranged from 46.6% for H&M Australia and 49.0% for H&M United Kingdom to 63.4% for Uniqlo Australia and 64.4% for Uniqlo United Kingdom. When each of 35,860 parent products received equal total weight, the baseline any-barrier estimate was 48.0%, compared with 50.3% in the colour-variant

Table 2
Operational sorting rules and sensitivity specifications used to assess garment compatibility with NIR-based automated textile sorting.

Rule	Sorting-rule domain	Observable input	Baseline pass condition	Sensitivity specifications	Supporting information
SR1	Supported recognition scope	Selected readable component composition after material-name harmonization	Passes if the selected readable composition fully matches the baseline supported-recognition-scope definition: 6 mono-material classes and 6 binary blend classes	Lower-bound violation estimate: extended supported-recognition-scope definition, 13 mono-material classes +12 binary blend classes. Upper-bound violation estimate: restricted supported-recognition-scope definition, 6 mono-material classes +5 binary blend classes.	Literature sources, SR1 supported-recognition-scope definitions, and material-name harmonization are summarized in Tables S2–S4.
SR2	Blend complexity	Number of distinct fibre types in the selected readable component composition	Passes if the selected readable composition contains no more than two distinct fibre types	Fixed rule; no sensitivity specification applied	Literature mapping is summarized in Table S1.
SR3	Minor-component detectability	Percentage shares of non-dominant fibres in the selected readable component composition	Passes if every non-dominant fibre is present at ≥5 wt%	Lower-bound/permissive: 3 wt% threshold. Upper-bound/restrictive: 10 wt% threshold	Literature sources and threshold specifications are summarized in Tables S5–S6.
SR4	Black-colour proxy	Normalized colour label of each colour-specific garment variant	Passes if the normalized colour label is not exactly “black”	Lower-bound/baseline: exact black. Upper bound: colour label contains “black”	Literature mapping and proxy rationale are summarized in Table S1.
SR5	Surface–hidden material mismatch	Selected surface reference and concealed lining/filling components from the normalized component structure	Passes if no concealed component contains a material >5 wt% that is absent from the selected surface reference	Alternative definition: dominant-material mismatch. Baseline: >5 wt% concealed-material mismatch. Broader definition: any hidden layer.	Literature mapping and surface–hidden mismatch rationale are summarized in Table S1.

Note: The selected readable composition was derived from the normalized component structure and used for SR1–SR3. For SR5, the surface reference was selected separately, with explicit coatings treated as the readable surface where present and concealed structures identified from normalized lining- and filling-related component classes and names. Here, wt% refers to percentage by weight in the disclosed material composition. Sensitivity specifications are robustness checks of rule definitions rather than predictions of realised sorter performance. SR5 is not presented as a conventional lower-to-upper range because the dominant-material and >5 wt% definitions apply alternative mismatch criteria, whereas the any-hidden-layer scenario is broader and includes concealed structures without a material mismatch.

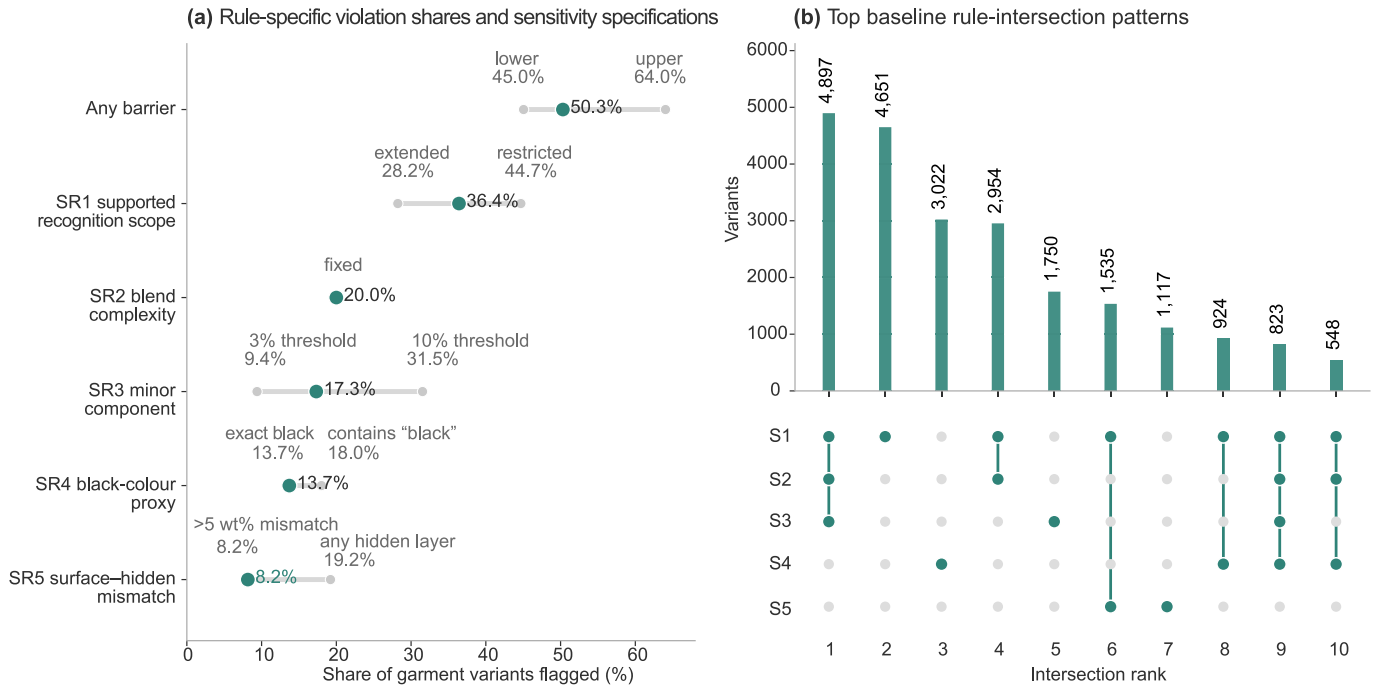

Fig. 2. Prevalence, sensitivity, and overlap of sorting-relevant design barriers. Panel (a) shows rule-specific violation shares under the baseline and sensitivity specifications. Grey endpoints indicate alternative rule definitions, while coloured dots indicate the baseline or fixed rule definition. For the aggregate any-barrier result, the endpoints represent the lower- and upper-bound combinations. The aggregate any-barrier range combines boundary specifications across rules and is not the sum of individual rule rows. Panel (b) shows the ten most frequent baseline rule-intersection patterns, ranked by the number of garment variants in each pattern. Single-rule intersections indicate variants violating only one rule, whereas connected dots indicate variants simultaneously violating the connected rules and not violating the unconnected baseline rules.

analysis. Individual-rule estimates remained close to the main results, 34.3% for SR1, 18.2% for SR2, 16.5% for SR3, 13.3% for SR4, and 8.0% for SR5, and the rule ranking was unchanged (Tables S7–S8). These results indicate that the pooled finding is not solely generated by one retailer–region portal or by products represented by more colour variants.

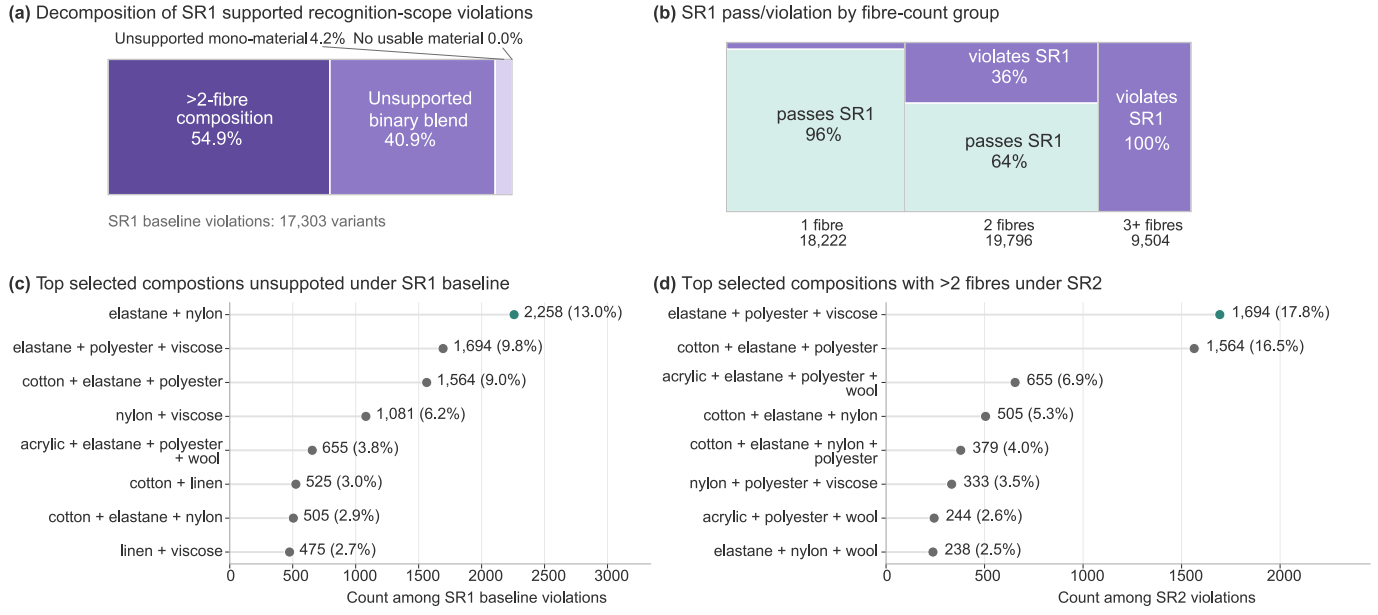

Fig. 3. Supported recognition scope and blend-complexity diagnostics. Panel (a) decomposes SR1 supported-recognition-scope violations under the baseline definition. Panel (b) shows SR1 pass/violation status by fibre-count group in the selected readable composition. Panel (c) reports the most frequent selected readable compositions that are unsupported under the SR1 baseline definition. Panel (d) reports the most frequent selected readable compositions with more than two fibre types under SR2. Counts in panels (c) and (d) are diagnostic counts among variants violating the respective rule. The restricted, baseline, and extended SR1 supported-recognition-scope definitions are listed in Table S3.

3.2. Composition-related mismatch: unsupported recognition scope, blend complexity, and elastane-dominated minor components

The dominant source of design–sorting mismatch was not the presence of rare or unknown fibres, but the mismatch between contemporary apparel compositions and the supported recognition scope of current sorting systems. Under the baseline definition of SR1, 36.4% of garment variants did not fully match the supported recognition scope. The decomposition of SR1 failures shows that unsupported mono-materials played only a minor role, accounting for 4.2% of SR1 failures. Most SR1 violations were instead caused by selected compositions with more than two fibres, which accounted for 54.9% of SR1 failures, and unsupported binary blends, which accounted for 40.9% (Fig. 3a). This means that the barrier is mainly a finite class-set problem: common apparel materials are often present, but in combinations that fall outside the supported mono-material and binary-blend classes.

The relationship between SR1 and SR2 is partly nested but not identical. Garments with more than two distinct fibres necessarily fall outside the mono-material and binary-blend classes used in SR1, but SR1 also captures simpler compositions that are unsupported because the specific mono-material or binary blend is not included in the supported class set. SR2 therefore isolates blend-count complexity, whereas SR1 captures the broader question of whether the selected composition matches a documented supported class.

This distinction is visible in the relationship between fibre count and SR1 pass/violation status in Fig. 3b. One-fibre compositions almost always passed the baseline SR1 rule, with 96.1% passing. Two-fibre compositions occupied an intermediate position: 35.8% failed because the specific binary blend was outside the supported class set. Compositions with three or more fibres failed SR1 by construction because the operational SR1 class sets contain mono-materials and selected binary blends. This result reflects the current evidence boundary used in the analysis and should not be read as proof that all ternary compositions are fundamentally unclassifiable.

The leading diagnostic compositions make this mechanism concrete. The most frequent SR1 baseline violations included elastane + nylon, elastane + polyester + viscose, cotton + elastane + polyester, nylon + viscose, and acrylic + elastane + polyester + wool (Fig. 3c). These are common apparel blends used to achieve elasticity, comfort, drape, warmth, and durability. Similarly, the leading SR2 violations were dominated by combinations such as elastane + polyester + viscose and cotton + elastane + polyester (Fig. 3d). The result therefore points to a mismatch between routine multi-fibre garment design and the current general-purpose industrial sorting envelope, while leaving open the possibility that selected additional classes could be supported as calibration data and models develop.

The minor-component rule reveals a more specific composition-related barrier: low-share stretch fibres dominate the SR3 signal, as shown in Fig. 4. Under the baseline 5 wt% threshold, SR3 flagged 17.3% of garment variants. The sensitivity range was substantial, from 9.4% under the 3 wt% threshold to 31.5% under the 10 wt% threshold, confirming that the estimated magnitude depends strongly on the assumed SR3 threshold. However, the material pattern was highly stable. Elastane accounted for 86.2% of baseline SR3 diagnostic observations, indicating that SR3 is primarily an elastane-related minor-component detectability barrier in this dataset, rather than a broad low-share-material problem distributed evenly across fibres (Fig. 4a). Other minor components, including nylon, polyester, viscose, wool, elasto-multiester, metallised fibre, acrylic, and linen, appeared much less frequently (Fig. 4b).

3.3. Surface readability: black-colour proxy and surface–hidden material mismatch

Surface readability created a second type of mismatch: even when a garment has a detectable fibre composition, the signal available to an NIR system may be optically weakened or materially unrepresentative of the garment as a whole. Under the baseline definition, 6515 variants (13.7% of the dataset) carried the exact normalized colour label “black” and were flagged by the SR4 optical-risk proxy (Fig. 4c). The broader contains-black definition increased this share to 18.0%. These values describe the prevalence of the observable colour proxy; they do not

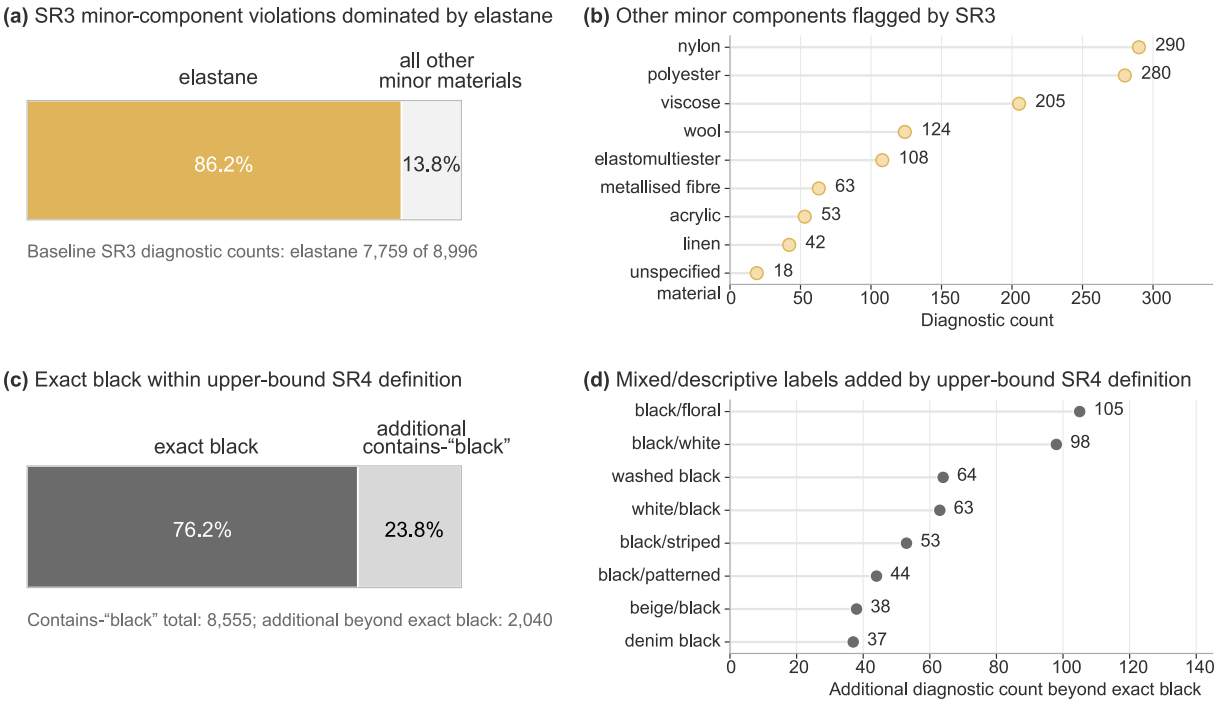

Fig. 4. Minor-component detectability and black-colour proxy diagnostics. Panel (a) shows the dominance of elastane among baseline SR3 diagnostic observations. Panel (b) reports other minor components flagged by SR3 after excluding elastane. Panel (c) compares exact-black labels with additional contains-black labels under the broader SR4 contains-“black” definition. Panel (d) reports the mixed and descriptive black labels added by this broader definition beyond exact black.

estimate carbon-black content or realised sorting failure. The additional labels captured by the broader definition included mixed and descriptive black colour names (Fig. 4d).

SR5 surface–hidden material mismatch captured a different surface-readability problem: the material detected at the exposed surface may not represent concealed layers that would enter the same recycling route. Under the broader any-hidden-layer definition, SR5 flagged 9133 variants, corresponding to 19.2% of the dataset, showing that concealed structures are common (Fig. 5a). The alternative dominant-material mismatch definition flagged 8.6% of variants, compared with 8.2% under the baseline >5 wt% concealed-material mismatch definition. The gap between the broader and baseline definitions shows that concealed structures are common, but only a smaller subset introduces a material mismatch under the baseline rule. This distinction is important because the sorting issue is not the mere presence of a lining or hidden layer, but whether that concealed structure introduces materials that are absent from the selected surface reference and therefore invisible to a surface-dominant NIR classifier.

The leading SR5 signatures illustrate this surface–hidden mismatch. The most common cases included shell elastane + nylon with polyester or cotton lining, cotton shell with polyester lining, nylon shell with polyester lining, and polyurethane coating with polyester lining (Fig. 5b). The generic lining label dominated the concealed-component diagnostics, accounting for 77.6% of baseline SR5 diagnostic counts, while more specific labels such as padding, cup lining, filling, inner layer, sleeve lining, hood lining, and body lining appeared much less frequently (Fig. 5c).

3.4. *Category-level patterns of sorting-relevant barriers*

The category-level breakdown adds a further dimension to the results: categories associated with stretch, body fit, insulation, or layered construction showed the highest levels of design–sorting mismatch (Fig. 6). Socks/hosiery had the highest overall mismatch, with 99% of variants flagged by at least one baseline rule, followed by bras/lingerie at 90%. Several other categories also showed high aggregate any-barrier shares, including trousers, outerwear gilets, outerwear coats, sweaters/cardigans, swimwear, and outerwear jackets.

These patterns suggest that sorting-relevant barriers are closely linked to product function. Categories designed for elasticity and body fit, such as socks/hosiery and jeans, were mainly shaped by composition-related barriers, especially SR2 blend complexity and SR3 minor-component detectability. Categories involving more complex garment construction, such as bras/lingerie, swimwear, and outerwear, showed stronger contributions from SR5 surface–hidden material mismatch, reflecting linings, fillings, padding, or other concealed structures. Overall, the category-level results reinforce that compatibility with NIR-based sorting is not only a material-composition issue, but also a garment-function and construction issue.

4. Discussion

This study shows that sorting-relevant design barriers are widespread in the current offerings of two large fast-fashion and mass-market retailers. Under the baseline definition, 50.3% of 47,522 colour-specific variants violated at least one rule, with a lower- to upper-bound range of 45.0–64.0%. Supplementary robustness analyses across retailer–region portals and equal-parent-product weighting produced similar aggregate estimates and the same rule ordering. The largest individual barrier was supported recognition scope, followed by blend complexity, minor-component detectability, the exact “black” label used as a proxy for optical risk, and surface–hidden material mismatch. These values estimate the prevalence of disclosed design features in retailer catalogues, and they are not sales-weighted, waste-stream-weighted, or realised sorting-failure rates.

The main implication is that technological development and design simplification should be treated as complementary strategies. Controlled studies show that NIR-based models can achieve high classification

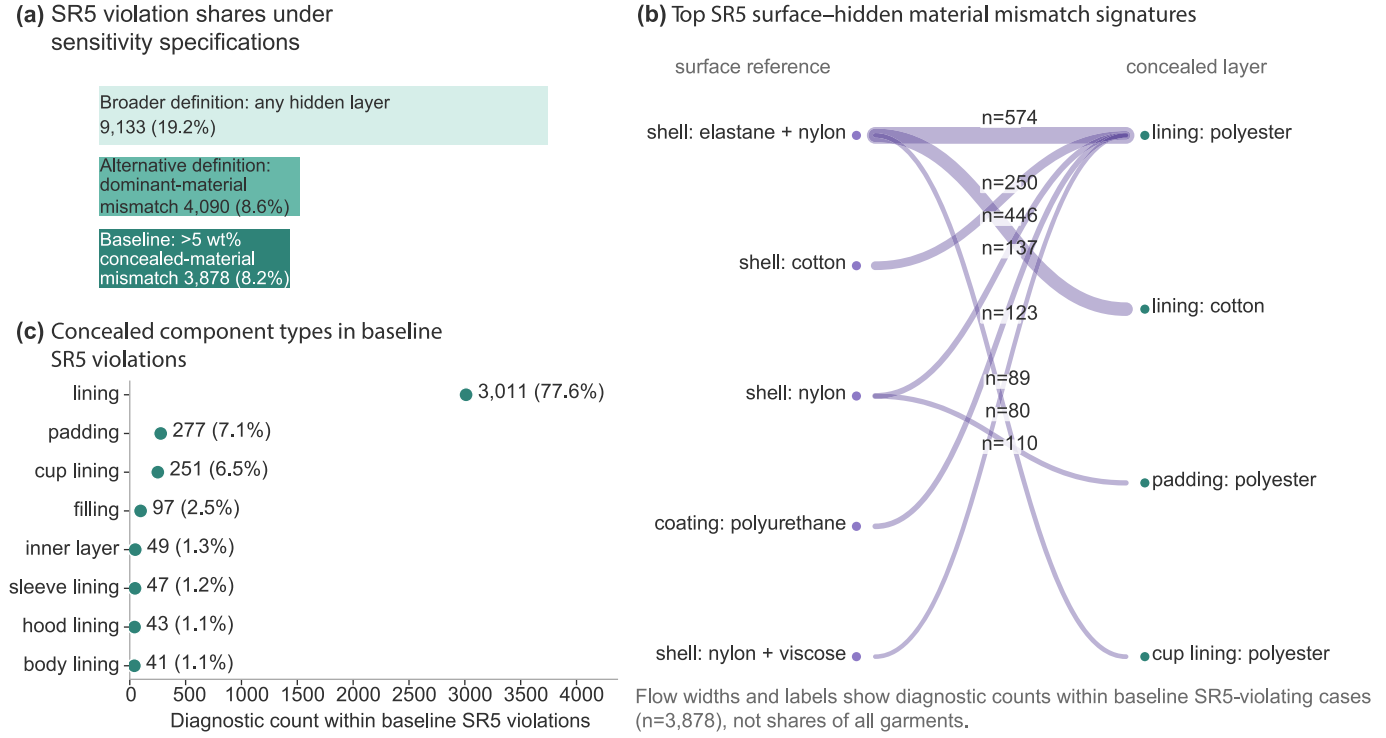

Fig. 5. Concealed structures and SR5 surface–hidden material mismatch. Panel (a) compares SR5 violation shares under the broader any-hidden-layer definition, the alternative dominant-material mismatch definition, and the baseline >5 wt% concealed-material mismatch definition. Panel (b) shows the top SR5 surface–hidden material mismatch signatures under the baseline definition. Flow widths and labels indicate diagnostic counts within baseline SR5-violating cases, not shares of all garments. Panel (c) reports the concealed component types contributing to baseline SR5 violations.

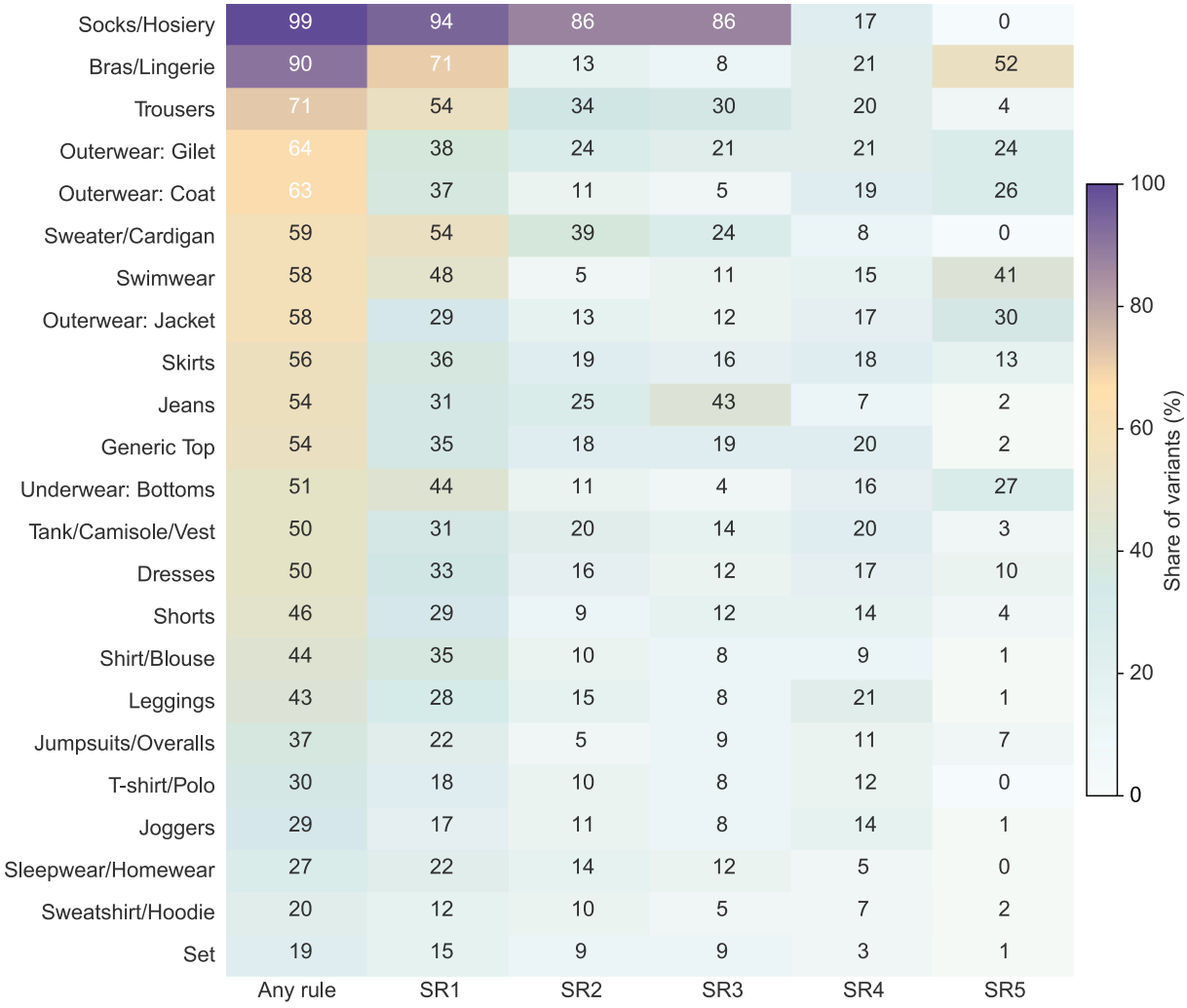

Fig. 6. Category-level profiles of sorting-relevant design barriers. The heatmap shows the share of garment variants in selected high-prevalence categories flagged by at least one baseline rule and by each baseline rule separately. Categories are shown for the highest any-rule shares among categories with at least 100 garment variants. Category labels were derived from the harmonized retailer taxonomy and sorting-oriented category normalization described in Section 2.2, informed by the Sorting for Circularity Europe sorting handbook (Circle Economy and Fashion for Good, 2022). The full category-level output tables are available through the repository described in the Data availability section.

accuracy for predefined pure-fibre and selected binary-blend classes, while targeted work on polyester-containing textiles demonstrates that selected blend systems can be quantified and translated into application-specific sorting categories (Becker et al., 2024; Riba et al., 2022). These advances confirm that present recognition envelopes can expand. However, such gains remain dependent on route-specific training classes, representative calibration samples, and the purity requirements of downstream recyclers; they do not eliminate the value of simpler and more predictable garment compositions. A recent Danish textile-anatomy assessment illustrates the wider systems consequence: among textiles directed toward recycling, 53% were estimated to require disruptor removal, 36% were expected to be incinerated because of textile complexity, and only 11% were directly available to recycling routes; after existing high-quality recycling capacity was considered, less than 2% of the textile market could enter high-quality fibre-to-fibre recycling (Logan et al., 2025). SR1 and SR2 should therefore be interpreted as current compatibility indicators whose numerical boundaries may evolve, while the broader need to align product anatomy with sorter and recycler requirements remains.

The dominance of elastane in minor-component detectability barriers shows why this is a design trade-off rather than a simple material-ban issue. Low-share elastane improves stretch, fit, and shape retention in products such as socks, trousers, jeans, underwear, and other fitted garments. However, the same small fractions that are useful during wear may be difficult for general-purpose NIR systems to resolve and may still affect downstream recycling purity, especially in recycling routes that require high-purity cotton, polyester, or wool streams (Becker et al., 2024; Cura et al., 2021; Mahlamäki et al., 2025; Matoha, 2026). The issue is therefore not whether elastane should always be avoided, but whether its use is compatible with the intended sorting and recycling pathway. Design guidance should distinguish between tolerable elastane use and elastane use that undermines high-purity recycling routes, rather than treating all small additives as negligible.

The surface-related findings point to a different form of mismatch: observable surface attributes do not fully disclose either optical compatibility or the material anatomy of the whole garment. The 13.7% exact-black share should not be interpreted as a sorting-failure rate. Experimental automated-line evidence indicates that colour effects are not uniform: many coloured textiles remain classifiable, whereas elevated absorption or noise has been observed for particular dark materials and aged garments, suggesting that wavelength selection and model development may mitigate part of the problem (Cura et al., 2021). Industry-facing waste assessments nevertheless treat colour, alongside fibre composition and disruptors, as a separate determinant of

recycling-route suitability (Fashion for Good, 2022). SR4 therefore identifies a sizeable information gap: a generic black colour label cannot reveal whether the underlying colourant system is NIR-compatible. This supports both the development of NIR-compatible black colourants and machine-readable disclosure of relevant colourant or finish information. SR5 represents a more persistent information mismatch because a surface scan cannot directly establish the composition of concealed linings, fillings, coatings, or bonded layers. Textile-anatomy evidence shows that such layers and other garment components materially affect pretreatment needs and the quantities and qualities available for recycling (Logan et al., 2025). Component-level disclosure and design simplification therefore remain necessary even where surface-fibre recognition improves.

These findings suggest three policy directions for textile circularity. First, design-for-recycling should explicitly include design-for-sorting: garments with simpler fibre compositions, supported blend structures, disclosed minor components, and fewer concealed material mismatches are more compatible with current sorting infrastructures. Second, producer-responsibility schemes should account for sorting-relevant design barriers so that producers placing highly complex or hard-to-sort garments on the market contribute appropriately to downstream sorting and recycling costs, building on approaches such as France's Refashion eco-modulated textile fees and Australia's Seamless circular-design stewardship model (Refashion, 2026; Seamless Australia, 2025). Third, information policy should address both completeness and reliability. Digital Product Passports (DPPs) should include component-level information—shell, lining, filling, coating, minor-fibre shares, and relevant finishes or colourant chemistry where available—while market-surveillance and supply-chain assurance should verify that disclosed data correspond to actual products. Existing EU fibre-labelling law already requires accurate fibre names and percentages; the policy need is stronger verification, enforcement, and component-level transparency rather than merely digitizing unverified declarations (European Parliament and Council of the European Union, 2011).

Textile DPP pilots demonstrate how product information could be linked to garments and used during sorting. In the Trace4Value pilot, more than 3000 Kappahl and Marimekko garments were equipped during production with unique QR-code carriers, allowing product information stored across distributed data sources to be retrieved through application programming interfaces using a persistent identifier (Trace4Value, 2025). TEXAID installed RFID/NFC-enabled intelligent sorting stations in 2022, and a subsequent supplier-reported pilot integrated RFID-based identification into Valvan's Fibersort, an automated NIR-based textile-sorting system. Testing with 300 RFID-tagged garments reportedly achieved identification accuracy of up to 99.9% at approximately one garment per second. Although these pilots do not demonstrate universal industrial deployment, they illustrate a feasible architecture in which a physical data carrier links a persistent product identifier to digitally stored information on garment composition and other characteristics. Because the information is stored digitally rather than solely on the physical carrier, washing would not alter the underlying record. Damage to or removal of the carrier could nevertheless break the link between the garment and that record, making carrier durability and fallback identification through NIR or other sensors important for practical implementation. This information could complement NIR-based identification, particularly for blended fibres, coatings, and accessories that are difficult to identify through spectroscopy alone (Avery Dennison, 2026; TEXAID, 2022). The architecture is consistent with the EU Ecodesign for Sustainable Products Regulation (ESPR), which requires a digital product passport to be connected through a physical data carrier to a persistent unique product identifier, with the underlying data remaining machine-readable and interoperable (European Union, 2024). The EU DPP Registry became operational in July 2026, although textile-specific requirements and practical issues related to carrier durability and removal, read rates, data completeness, and legacy garments remain unresolved (European Commission, 2026b).

Several limitations remain. First, the catalogue sample represents offered colour-specific variants, not products sold, used, discarded, or received by sorting facilities. Sales volumes, market shares, garment lifetimes, consumer behaviour, reuse, collection systems, and brand-specific contributions to future waste streams were unavailable (Laitala and Klepp, 2020; Millward-Hopkins et al., 2023; Nencková et al., 2020). Portal-level and equal-parent-product robustness analyses reduce concern that the pooled estimate is driven by one portal or by products with many colourways, but they do not convert the results into a sales- or waste-stream-weighted estimate. The findings should therefore be generalized to the sampled retailers' offerings, not directly to post-consumer textile flows.

Second, the framework evaluates retailer-disclosed information rather than laboratory-verified garment composition. The physical composition of a garment may differ from the information reported online because of incomplete disclosure, labelling errors, or inconsistencies across supply-chain records (European Commission, 2026a). Such discrepancies could produce both false-negative and false-positive rule flags. Future DPP and online-disclosure systems should therefore be supported by appropriate verification, supply-chain traceability, and enforcement of textile-labelling requirements.

Third, the framework excludes operational conditions, including moisture, dirt, wrinkles, deformation, contamination, ageing, and feed presentation, and cannot verify pigment chemistry, coating thickness, print coverage, or hardware composition. These factors can further affect realised sorting performance (Stipanovic et al., 2026; Valtech, 2026). The fast-fashion and mass-market scope is analytically relevant because rapid assortment turnover and short-lived use increase material throughput, but the five rule mechanisms are not unique to fast fashion. Other segments may show different profiles: outdoor apparel may have more coatings and layered structures, while luxury, sportswear, workwear, and other markets may differ in fibre choices and construction (Niinimäki et al., 2020). Comparative research across market segments and validation against physical NIR scans and post-consumer waste streams are therefore required.

5. Conclusions

Across 47,522 colour-specific variants from two large fast-fashion and mass-market retailers, 50.3% exhibited at least one baseline sorting-relevant design barrier. Supported recognition scope was the largest barrier, followed by blend complexity, minor-component detectability, the exact “black” label used as a proxy for optical risk, and surface–hidden material mismatch. These estimates describe disclosed product-design characteristics rather than realised sorting failures or future waste-stream prevalence.

The results support a combined response. Sorting technologies and recognition libraries should continue to expand, while garment design should reduce avoidable material complexity and concealed incompatibilities. Component-level digital information can complement surface-based sensors, but it must remain accessible at end of life and be supported by accurate, verified disclosure. Future research should validate the rule indicators through physical scanning, compare fast-fashion and non-fast-fashion segments, and link product offerings to sales, use, collection, and post-consumer sorting streams. Circular textile policy should therefore align design, information, verification, sorting infrastructure, and recycler feedstock requirements rather than relying on any one intervention alone.

CRediT authorship contribution statement

Kai Li: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Grit Walther:** Writing – review & editing, Visualization,

Validation, Supervision, Project administration, Funding acquisition, Conceptualization.

Data and code availability

The harmonized garment-variant dataset and its construction workflow are archived on Zenodo at doi:https://doi.org/10.5281/zenodo.20006389, with documentation provided in the corresponding GitHub repository at https://github.com/kai-li-1994/garment-variant-dataset. This release includes the component-normalized garment-variant dataset used as input to the present analysis, together with the scripts, normalization documentation, and processing summaries used to construct the dataset.

The NIR sorting-rule evaluation workflow and associated analysis outputs are archived on Zenodo at doi:https://doi.org/10.5281/zenodo.20145842, with documentation provided in the corresponding GitHub repository at https://github.com/kai-li-1994/garment-sorting-rule-analysis. The workflow generates the rule-level and aggregate results, together with portal-level and equal-parent-product robustness analyses. The release includes row-level rule flags, rule-level summaries, aggregate any-barrier summaries, material, colour, and category diagnostics, robustness outputs, and scripts for generating Figs. 2–6. Fig. 1 is a non-quantitative schematic prepared separately using Adobe Illustrator and is therefore not generated by the analysis code.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2026.09.008.

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