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Abstract

1 The rapid expansion of the global textile and apparel industry has resulted in an enormous increase in post-consumer textile waste having serious environmental and economic ramifications. Since fashion items contain mixed fibres, dyes, chemical finishes, and wear conditions and stains differently and with different levels of moisture, post-consumer textiles are extremely heterogeneous. They are also often combined with non-textile components such as zippers, buttons, elastane threads or coatings. This heterogeneity makes it very sensitive to recycling conditions, i.e., the quality of the feedstock. If textile fractions are not well sorted and the grades of textile materials are inconsistent, the amount of costs in preprocessing become higher, the stability of the process is inferior, and often the recycled fibres do not fulfil the high-quality requirements that are required for high-value uses.

In this term paper we emphasize the difficulties involved in sorting and grading for post-consumer textile waste and review the recent developments that try to produce reliable feedstock for recycling. We discuss manual and automated sorting systems as well as sensor-based fibre identification, machine learning classification, contaminant removal/preprocessing methods and products and the role of digital product information systems in traceability. Our analysis highlights the importance of future studies to examine issues related to hybrid sensing, pathway-specific grading standards, scalable automation, and policy and business mechanisms to promote investment in high-quality sorting and grading infrastructure. By highlighting that fully automatic circular solutions do not exist yet, we make the argument to have consistent recycled output based on an integrated, sustainable approach like diverse innovations, standardized grading in processing and system-level coordination across the textile value chain.

Introduction

Recycling of textiles has ceased to be a niche sustainability issue, and has become a necessity at the systems level due to the sheer amounts of waste generated by global clothing production, as well as the fact that much of discarded textiles are currently sent to the landfills or incinerators, where they are reused to generate more waste without reusing the embedded materials and energy (Tang, 2023; Abbas-Abadi et al., 2025). But, as opposed to comparatively homogenous waste streams, e.g., clear PET bottles, post-consumer textiles are multi-attribute materials: they are not exclusively polymers or cellulose, but also chemical formulations, color systems, and assembled hardware. This heterogeneity is the key technical cause that fiber-to-fiber recycling rates are not high and that recycled fabric products frequently fail to satisfy quality standards in using in apparel (Frontiers in Sustainability, 2022; Tang, 2023).

According to the literature, sorting and grading are the most leveraged interventions since they manage the technical feasibility of downstream and product quality. This is because sensor based sorting and artificial intelligence has advanced very rapidly in the recent years particularly by the use of near-infrared spectroscopy (NIR) to categorize fiber composition, occasionally with the complement of convolutional neural networks that enhance classification under more complicated spectra (Cura et al., 2021; Riba et al., 2022; Faghih and Saki, 2025). Studies on blended-fabric recycling also demonstrate that it is possible to obtain good results when separation and chemical recycling are employed but only when feedstock specifications are stringent i.e. sorting and grading are not optional but rather mandatory (Choudhury et al., 2024; Mäkelä et al., 2017). Simultaneously, traceability literature highlights information asymmetry (unknownness of composition, unknownness of finishes, unknownness of previous use) as one of the biggest obstacles, and digital traceability can mitigate it in case of data standards and incentives alignment (Kumar et al., 2017; Alves et al., 2024; Domskienė and Gaidule, 2024).

Past studies in the area of textile recycling and the concept of circularity can be classified into three broad streams. The former stream is concerned with automated recognition, that is, with the introduction of machines that can efficiently and rapidly determine the type of fibers a piece of clothing is composed of (cotton, polyester, mixes of the two, etc.). This is primarily Near-Infrared (NIR) spectroscopy, image-based systems, and model-based classification. The essential works in this regard are Cura et al. (2021) and Riba et al. (2022), who demonstrated a good step in this regard even with mixed and challenging materials. The second stream is the

focus on end-of-life recovery pathways, that is, what would happen to clothes that are not wearable anymore. It looks at the performance of the various recycling technologies (mechanical, chemical and molecular/ advanced depolymerization) under the influence of real-world feedstock: high variability, blends, dyes, finishes and contamination. Mishra (2025), Abbas-Abadi et al. (2025), and Lanz et al. (2024) can also contribute to understanding the strong and weak aspects each approach can work best and under what conditions. The third stream is system enablers the larger picture stuff that is required to make high-quality sorting and recycling actually scale up. These are circular business model (rental, repair, resale, take-back programs), traceability (to monitor fiber provenance and provenance), governance/finance mechanisms capable of paying and establishing adequate sorting infrastructure. Islam et al. (2022), Kumar et al. (2017), and Alves et al. (2024) are the relevant studies in this case. These three streams taken together provide a rather full picture of where the field is heading to a more circular textile economy.

Even though there is improvement, it is limited. Most high-accuracy classification performances are achieved on controlled datasets that are not entirely representative of the real post-consumer noise of dyes, finishes, multi-layers garments, moisture and contamination; these can bias spectral signatures and poor generalization of the model (Cura et al., 2021; Riba et al., 2022). There are also economic limitations to industrial deployment: sorting facilities are run on narrow margins, advanced sensors, maintenance of calibrations and integration of AI demand both capital and human resources (Faghieh and Saki, 2025; Abbas-Abadi et al., 2025). Lastly, grading is frequently viewed as less formal than sorting; most systems end with what fiber is this? and fail to quantify anything hard about how recycleable this item can be, based on contamination, finishes and construction, which is a crucial requirement of consistent collections of recycled materials (Tang, 2023; Mishra, 2025).

Accordingly, the objectives of this term paper are to (1) clarify why heterogeneity undermines recycling economics and fiber quality, (2) synthesize the major technical challenges specific to sorting and grading post-consumer textiles, (3) review current strategies that have demonstrated practical potential in open-access research, (4) propose future research directions that close the gap between lab performance and industrial robustness, and (5) articulate an integrated pathway—technical plus governance—toward consistent and usable recycled textile outputs (Faghieh & Saki, 2025; Abbas-Abadi et al., 2025; Domskienė & Gaidule, 2024).

Methodology

This term paper is a narrative synthesis following open-access journal sources on the subject with a focus on textile sorting, grading, and recycling preparedness. The preference was directed to peer-reviewed open-access sources, which directly answer (i) identification and separation technology including NIR spectroscopy, short-wave infrared, imaging, and AI; (ii) recycling limitations based on the quality of the feedstock (mechanical recycling degradation, chemical recycling selectivity, elastane challenges); and (iii) information systems and traceability mechanisms that are applicable to reduce composition uncertainty. Such a discussion combines results across disciplines since the sorting and grading of performance is a result of the interaction of material science, sensing/AI, process engineering, and circular-economy governance and not a result of any single technology (Faghieh and Saki, 2025; Abbas-Abadi et al., 2025; Tang, 2023).

Challenges of **Sorting and Grading of Post-Consumer Textile Waste**

The latter **is the** initial obstacle, which is intrinsic material heterogeneity at more than one scale. Two garments that are labeled as cotton could differ in the level of fiber maturity, twist of the yarn, structure of the fabric, type of dye, a finishing chemistry (softeners, resins, water repellents), and mechanical damage caused by wear and laundering. All of them alter the behavior of the given material in mechanical opening, dissolution, depolymerization, and re-spinning, and, therefore, it is possible to state that a single form of composition sorting cannot produce a consistent recycled product (Mishra, 2025; Abbas-Abadi et al., 2025). This issue is aggravated by blended fabrics. The majority of waste streams are dominated by cotton polyester blends, polyester viscose blends, and garments containing elastane, but blends have to be separated (usually impractical at the fiber level) or have to be dissolved or depolymerized by a specific chemistry that selectively doesn't damage the other component (Choudhury et al., 2024; Mäkelä et al., 2017).

The second issue is contamination and non-textile content, as it introduces measurement noise and risk in the process. Spectral signals change under the influence of stains, oils, soil, and moisture that may confuse optical identification; they also change chemical recycling through addition of side reactions, catalyst poisoning or solvent contamination. Non-target polymers and metals are introduced through trims, threads, coatings and accessories and they are required to be eliminated in order to preserve equipment and stabilize output. Theoretically, the expense

and fiber loss of the extraction of these items is a significant factor leading to the motivation of recyclers to take in only a limited range of feedstock or downcycle to low-value products (Abbas-Abadi et al., 2025; Tang, 2023).

Complexity of measurement in industrial constraint is the third challenge. Real time sorting will be sensitive in terms of throughput, low latency, and performance which is not affected by varying lighting, motion of garments, folds, multi-layer thickness, and surface finishes. The drawback of near-infrared spectroscopy is its ability to identify polymers and cellulose within a short time, with automated pilots proving to be possible with spectral libraries and air-jet separation (Cura et al., 2021). There is an augmentation in the capabilities of classification of mixtures and noisy spectra with deep-learning methods but they demand large representative samples and the management of calibration (Riba et al., 2022; Faghieh and Saki, 2025). Hierarchical classification of textiles can also be conducted with the help of short-wave infrared methods, but in the case of industrial translation, continuous change instead of sharp classifications should be anticipated (Bonifazi et al., 2024).

Lack of standard grading measures that are associated with the recycling results is the fourth challenge. In a great number of industries the grading is normalised: in paper, there are brightness and contamination indices; in plastics there are melt-flow areas and tolerances of impurity. Textiles do not usually have universal and measurement-based grading which forecasts recyclability and quality of output. In the absence of standardized grades, sorting facilities are unable to provide regular supply matching the requirements of the recyclers, and recyclers are unable to price feedstock upon predictable yield and quality. This is a fundamental cause of why the quality of recycled fiber is highly diverse and why scaling is still a challenge (Tang, 2023; Mishra, 2025).

The fifth issue is information asymmetry and unreliability on labeling. Labelling of care might be missing, incorrect, or vague (“mixed fibers; no percentages). Use of labels Even when the labeling is accurate, it seldom conveys finishes, recycled material, additive chemistry or construction Information that would be important in choosing the recycling pathway. The research on traceability underlines the absence of data as the main limitation of the recycling system and the fact that high-quality data can decrease the uncertainty of sorting, however, only when the supply-chain actors trust the interoperability of data models (Kumar et al., 2017; Alves et al., 2024). Digital product passports in textiles Work states that structured material information can be used to make circularity choices, such as sorting and recycling, but barriers

to implementation are associated with governance and adoption (Domskienė and Gaidule, 2024).

The sixth issue is economic viability in fluctuating markets. The business case may fail even where sorting technology is technically feasible because recycled fiber prices may not be able to justify the entire cost of collection, preprocessing, sorting, and quality assurance. The sorting capacity is not a sufficient condition to provide the benefits of circularity when the volumes of consumption and waste increase at a faster rate than high-quality recycling infrastructure, which means that sorting and grading should be accompanied by policy and market tools that can reward quality and punish disposal (Tahkapiia et al., 2025). Circular business models reviews indicate that circularity based on recycling needs value capture coordination, rather than technical solutions (Islam et al., 2022).

Lastly, there is the seventh challenge which is pathway coupling: various recycling technologies demand different grades. Mechanical recycling is somewhat tolerant of variability, but loses fibers on shortening as well as strength, and fiber-length and input integrity are significant (Mishra, 2025). Near-virgin quality can be obtained using chemical and molecular recycling but generally this needs a more rigorous composition control, low contamination and standard profiles of additives (Choudhury et al., 2024; Abbas-Abadi et al., 2025). Hence, it is impractical that one universal grade exists, grading should be pathway-specific, meaning that attributes being measured should be associated with what is needed by the chosen recycling path.

Current Strategies for Textile Waste Sorting and Grading

One of them is automated sensor-based identification (primarily near-infrared spectroscopy). NIR-based automated sorting lines are automated identification of measured spectra with reference libraries and can directly sort items with the help of air jets, which can be scaled to large volumes as an alternative to manual sorting (Cura et al., 2021). The further advancement of this method is deep-learning based on resolving discriminative spectral patterns and classifying both pure textiles and typical binary mixtures, which is essential given that blends are widespread in post-consumer waste (Riba et al., 2022). Practically, the success of the industrial process is conditional on the constant calibration, representative training data, and preprocessing algorithms eliminating the sensitivity to moisture, dyes, and surface effects (Faghieh and Saki, 2025).

The second approach is that of hierarchical classification and sensor fusion in which the identification is not attempted in a single step. Hierarchical classification procedures based on the use of short-wave infrared spectroscopy have been created in order to identify textile categories, as per the requirements of industry, such coarse sorting (e.g., natural vs. synthetic) could be followed by finer sorting (e.g., cotton vs. viscose, PET vs. PA) (Bonifazi et al., 2024). In practical systems, the spectral sensing with imaging can be combined to resolve the instances when spectral signals are unclear because of finishes or multi-layered clothing on the surfaces. According to the open-access overview of the sorting of textiles using AI, computer vision and machine-learning pipelines are becoming more and more associated with sensor-data to enhance robustness and throughput (Faghieh & Saki, 2025).

The third approach involves the formulation of recycling-ready concepts of grading which imparts the qualitative waste properties into quantifiable indices. Even though literature more frequently discusses sorting, but not grading, recent reviews specifically mention grading as the missing link between identification and repeated recycled production, especially when it comes to mechanical recycling when fiber damage and contamination have a strong impact on fiber quality (Mishra, 2025; Tang, 2023). Practically, this approach entails the determination of quantifiable properties, including the level of contamination, moisture content, presence of elastane, color category and mechanical integrity and plotting them on recycler acceptance criteria and yields. Due to the impossibility of visual grading at scale, it in turn naturally merges with sensor-based measurement, especially imaging to identify surface defects, and spectroscopy to identify chemical/fiber composition (Cura et al., 2021; Bonifazi et al., 2024).

Fourthly is that of targeted separation and re-recycling technologies on blended fabric, which essentially produces technology-based grades. As an example, the selective **separation of cotton, polyester, and elastane fibers in mixed fabrics** has been also mentioned as a key feature of circular textiles where an important focus is placed on the concept of molecular recycling, like the selective dissolution or depolymerization of one polymer in the blend (Choudhury et al., 2024). Previous open-access studies on combined recycling pathways of PET and cotton also indicate that separation is a dominating constraint during the first order and that process development needs to be accompanied with effective separation into appropriate input streams (Mäkelä et al., 2017). There is the strategic implication that grading should be able to detect not only composition but also blend structure and elastane content since even low percentages of elastane can interfere with mechanical recycling and make chemical recycling more

” 1

11 challenging by introducing the additional polymer classes and additives (Choudhury et al., 2024; Abbas-Abadi et al., 2025).

The fifth strategy is the enhancement of preprocessing and the management of contamination. Textile waste management and mechanical recycling review articles indicate again and again that the processing happens through preprocessing, which is where most of the costs and fiber waste are made, but it is inevitable: the trims have to be removed, the textiles have to be size-reduced, and the contaminants have to be controlled (Tang, 2023; Mishra, 2025). Chemical recycling pathways may be occasionally tolerant to color and some additives but are intolerant to unknown chemicals and thus preprocessing and grading needs to filter high-risk products and divert them accordingly instead of combining all products into a single stream (Abbas-Abadi et al., 2025). The mapping of recycling technologies opens access to the idea that collecting, pretreating, and routing are interdependent; in case pretreatment is inefficient, the performance of downstream processes and the consistency of output are poor (Lanz et al., 2024).

The sixth strategy entails integrating traceability and digital information systems in the sorting operations. The traceability research suggests that the idea of sustainability at scale involves all parties involved in the supply-chain and that the traceable information will bring direct benefits to recycling by minimizing the uncertainty, making it easier to sort materials, and increasing accountability (Kumar et al., 2017). Decentralized / blockchain traceability systems have been suggested to capture batch-level data and calculate environmental/social impact scoring which, when standardized, can be used in sorting and grading decisions not only by fiber type (Alves et al., 2024). The complementary studies of traceability application in textile supply chains reveal that the factors affecting the adoption can be systematically grouped, which means that technical feasibility is not the sole impediment; the organizational preparedness and data governance are also issues (Gardas et al., 2019). Similar findings about the role of digital products passport research in textiles note that the material information at the product level can be used to support the processes of circularity and recycling, barely it is implemented using standardized information, ensuring data quality, and coordinating the work of the ecosystem (Domskienė and Gaidule, 2024).

The seventh strategy is to match sorting capacity with more general measures of the circular economy. System dynamics work implies that the sole emphasis on increasing sorting capacity can be inadequate without addressing consumption reduction and upstream design alterations

however, sorting and recycling are still required to achieve the type of circularity (Tähkää et al., 2025). It has been demonstrated in the literature of circular business models that recycling-based business models need value capture systems along the chain, which has a direct impact on the decision to finance and maintain high-quality sorting and grading (Islam et al., 2022). Integrated deployment representing the combination of technology, business models, and policy incentives to maintain a uniform quality of feedstock and stable demand of recycled outputs is the most practical current strategy.

One of the seventh strategies is the matching sorting capacity to wider circle-economy actions. System dynamics work recommends that increasing the sorting capacity is not possible to achieve full circularity, without including consumption reduction and changes in the upstream design; however, the sorting and recycling remains a requirement (Tähkää et al., 2025). Circular Oriented business model literature indicates that recycling-oriented business models demand value capture mechanisms along the chain that can directly result in whether high quality sorting and grading shall be funded and maintained (Islam et al., 2022). Integrated deployment is thus the most viable current approach which involves the use of technology, business models and policy incentives working together to ensure the sustainability of quality feedstock and steady demand of output that is recycled.

Future Research Directions

Future studies must be refocused on the concept of recycling-grade consistency in actual after-consumer scenarios, i.e., its performance should be tested on industrial noise change parameters like moisture change, dye/finish dissimilarity, garment movement and folding, multiple-layers, and contamination. The open-source systematic review of AI-assisted textile waste sorting mentions that, even though performing automation is promising, the effective implementation of the technology requires better datasets, verified benchmarking, and considerate interaction of sensing and machine-learning models (Faghieh and Saki, 2025). In terms of research-design, the next edition of research ought to document not just accuracy, but also the false-accept/false-reject costs, throughput, calibration drift and misclassification propagation into the recycled fiber quality and processing cost.

Hybrid detection systems are a very promising trend since one can anticipate blind spots of single sensors. The NIR spectroscopy can group most fibers within a less time, but finishes, dyes and moisture may distort spectra and decrease confidence; short-wave infrared may

provide additional sensitivity; and computer vision can provide structural indications and find non-textile objects. It has already been shown that automated NIR sorting lines and hierarchical SWIR-based identification procedures are possible, which can be followed by the formal sensor fusion instead of isolated sensing (Cura et al., 2021; Bonifazi et al., 2024). Uncertainty estimation should also be used in the hybrid methods to ensure that low-confidence items are bypassed to manual checks or other avenues without contaminating the high purity recycling streams. The deep-learning of the NIR spectrum of pure and mixed textiles shows how the capacity of models can be used, but the future research should focus on the domain adaptation and maintenance of calibration to avoid the loss of precision as composition of waste varies in seasons or regions (Riba et al., 2022; Faghieh & Saki, 2025).

Pathway-specific grading science is a second major line of research direction. The existing sources identify grading as an important but less developed process in comparison to fiber identification (Mishra, 2025; Tang, 2023). Further efforts towards work are to develop predictive indices on the grading of recyclers which should estimate the result that is relevant to recyclers, like the probability of retaining of the fiber length in mechanical recycling, probability of solvents contamination in dissolution recycling, probability of catalyst poisoning in depolymerization, and possibility of colour control. This involves the connection between quantifiable inputs (spectral characteristics, imaging-based defect characteristics, moisture/contamination characteristics) and process output (yield, viscosity/molecular weight distribution, tensile characteristics, dye uptake, and spinning characteristics). In the absence of such predictive links, sorting has been composition-based and recycled products have not been consistent even when fibers are separated.

A third avenue of research is to come up with traceability systems that can be actually used by sorting lines. The research on traceability and digital product passport suggests that enhanced data can remake the circular operation, yet in reality sorting facilities must require machine-readable and standardized and minimal-but-sufficient fields that directly correlate with routing decisions (Kumar et al., 2017; Domskienė and Gaidule, 2024). The studies on blockchain-traceability platforms demonstrate that there is one path to decentralizing recordkeeping, but it requires the standardization of data and quality of data, not necessarily ledger technology (Alves et al., 2024). Future studies should thus involve information schemas of attributes with relevance to recyclability (fiber percentages, the presence of elastane, finishes, coating, dye

class, repair/repair history), the mechanism to verify that no greenwashing or false labeling occurs and cross-brand, sorter, and recycler interoperability.

One fourth research direction is the design of recyclable materials and design to be sorted. Experiments on blended fabric recycling demonstrate that separation is one of the significant obstacles and that selective dissolution or depolymerization may be useful, but the pathways are still challenged when garments are composed of a variety of polymer classes and as well as containing elastane and complex finishes (Choudhury et al., 2024; Abbas-Abadi et al., 2025). The future studies should then focus more on fiber blends and structures that maintain their performance but allow easier separation such as using compatible polymers, reversible bonding, or recognizable tracers without affecting their safety. In industry, this would be represented by so-called sorting-friendly product architecture where clothes are manufactured in such a way that end-of-life identification and disassembly can be done at low preprocessing costs and with increased feedstock purity.

The fifth possible research direction is intensive techno-economic evaluation of large-scale sorting and grading systems. It is always mentioned in the reviews that advanced sorting is a promising technology that is capital-intensive and that expenses, maintenance, and labor restrain its adoption (Abbas-Abadi et al., 2025; Faghieh and Saki, 2025). The future research will need to compare excluding total system cost (CAPEX, OPEX, calibration and model maintenance, reject handling, contamination losses) and value uplift of the better-quality recycled outputs. It must be pathway-specific since the value of purity varies: chemical recycling can be worth sorting at higher cost because of near-virgin output value, and mechanical recycling can require the sorting at ultra-low cost due to lower value of products and fiber degradation (Mishra, 2025).

One of the last directions of research is to combine technological solutions with policy frameworks and strategies of a circular economy in such a way that quality sorting becomes economically viable. At the level of the system, it is indicated that the expansion of sorting capacity might be ineffective without upstream actions and joint incentives, but sorting is still required in the case of circular textiles (Tahkapaa et al., 2025). The circular business model literature confirms that the models that focus on recycling necessitate coordination and value capture since otherwise the system reverts to low-grade downcycling or disposal (Islam et al., 2022). Further investigation ought to then consider policy tools and market practices to encourage the quality of feedstock, punish unidentifiable or in-recyclable product designs and



encourage communal infrastructure in automating sorting, to stabilize supply and demand of high-quality recycled fibers.

Conclusion



Post-consumer textiles are chaotic to recycle due to heterogeneity being structural: garments are assemblages of products made out of several fibers, colors, chemical finishes, and accessories, and their properties are modified by the wear and contamination. The existing sources of open research literature substantiate the belief that the key technical and economic vehicles to enhancing the quality of recycled fiber and improving the cost of processing are reliable sorting and grading. Near-infrared spectroscopy Automated sensor-based sorting has demonstrated practical usage in automated lines, and deep learning can be applied to blends, but robust operation in the real world requires representative data, calibration discipline and strategies to hybridize sensing (Cura et al., 2021; Riba et al., 2022; Faghih and Saki, 2025). Blended fabric recycling technologies and chemical pathway recycling technologies can produce higher-valued products, but due to the increased demands on the tightness of the feedstock, the pathway of the grading science becomes pathway specific instead of generic (Choudhury et al., 2024; Mäkelä et al., 2017). The information asymmetry can be decreased using traceability and digital product passport strategies, but these strategies need standardization, governance, and incentives to adoption to become operationally useful to sorting lines (Kumar et al., 2017; Alves et al., 2024; Domskienė and Gaidule, 2024).



Integrated: measurement-based standards of grading predicting the results of recycling; industrial sensor fusion and AI with uncertainty-aware routing; preprocessing innovations eliminating non-textile components without losing too much fiber; coordinated policies and business models of the circular economy that will finance well-operating sorting infrastructure, are the most justifiable approach to the issue. When these factors are in coordination, recycled products will be more predictable and reusable, and the recycling of textile to textile will be technically feasible and even economically scalable (Abbas-Abadi et al., 2025; Mishra, 2025; Islam et al., 2022).



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