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REVIEW ARTICLE

From Sorted Bale to Spinnable Fibre: A Critical Synthesis of Fibre-to-Fibre Recycling Pathways for Post-Consumer Textiles

Where mechanical, solvent-based, chemical and composite routes actually compete, and what the evidence does and does not support

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ABSTRACT

Fibre-to-fibre recycling is often presented as the logical destination for post-consumer textiles, yet the supplied evidence describes a fragmented pathway set rather than a single transition. This review synthesises ten source records spanning mechanical yarn development [1], lubricant-assisted tearing [9], closed-loop wet spinning of denim [5], infrared-based automated sorting [4], mixed-waste composites [10], and broader reviews of recycling technologies, barriers and waste flows [3][7][8], together with bibliometric and socioeconomic analyses [2][6]. Three findings recur. First, sorting and pre-treatment, not spinning, appear to be the binding constraints: manual sorting is identified as a bottleneck [4], and automated near-infrared and hyperspectral approaches are framed as promising but not yet the norm [7]. Second, mechanical recycling can yield yarns fit for weaving and knitting, but the evidence is uneven across fibre types, with 100% recycled wool, polyester and silk reported as spinnable while cotton and rayon required blending with virgin fibre [1], and fibre length loss identified as a distinct mechanism that lubricant pre-treatment can mitigate [9]. Third, solvent and chemical routes can deliver higher-quality outputs but carry energy and solvent burdens [7], and the one closed-loop demonstration supplied is a single denim/cellulose case [5], not a generalisable platform. Socioeconomic and barrier evidence indicates that demand, business models and policy, rather than fibre science alone, shape adoption [6][8]. The synthesis is deliberately cautious: the sources differ in scale, method and geography, several are reviews rather than primary studies, and no supplied record reports full life-cycle or cost comparisons across pathways. Practical implications for design and manufacturing are framed as conditional design rules rather than prescriptions.

Keywords: fibre-to-fibre recycling; post-consumer textiles; mechanical recycling; automated sorting; regenerated cellulose fibres; textile waste policy; design for recycling

SECTION 01

Why fibre-to-fibre is a pathway problem, not a technology problem

The case for diverting post-consumer textiles from disposal is well established in the supplied literature, but the numbers differ by geography and year in ways that matter for interpretation. One review reports that worldwide 75% of textile waste is landfilled while 25% is recycled or reused [3]; a United States-focused study reports that of waste generated, 66% goes to landfill, 19% is combusted with energy recovery and only 15% is recycled [6]. These are not contradictory so much as differently bounded: they describe different waste streams, reference years and accounting conventions, and neither should be treated as a global constant. What both support is the conclusion that landfilling remains the dominant destination and that recycling rates are low relative to generation [3][6].

A second framing issue is that 'recycling' in these accounts aggregates heterogeneous activities. The same review that quantifies landfilling also distinguishes reuse, fibre regeneration, composting, anaerobic digestion, fermentation and thermal recovery, and argues that reuse is preferred over recycling [3]. A later review organises the space by mechanism: mechanical fibre recycling, polymer recycling by melting or dissolving, chemical recycling including solvolysis and pyrolysis, biological methods, and gasification as a fallback [7]. Fibre-to-fibre recycling, strictly understood as returning waste textiles to new textile fibres, therefore occupies only part of a wider hierarchy, and claims about 'recycling' in aggregate statistics should not be read as claims about closed-loop fibre production.

A third issue is that the pathway literature is unevenly mature. Some supplied records are primary experimental studies with measured yarn or composite properties [1][5][9][10]; others are reviews [3][7], a bibliometric and systematic review [2], a sensing and classification study [4], a socioeconomic analysis [6], and a multi-criteria barrier assessment [8]. Treating these as commensurable evidence would be a category error. The synthesis below therefore separates what has been demonstrated at bench or pilot scale from what has been asserted at review level, and flags where the two are being conflated in common narratives.

SECTION 02

Sorting and pre-treatment as the real bottleneck

Across the supplied records, the constraint most consistently identified is upstream of the spinning or dissolution step. One review states plainly that improved collection systems, automation of sorting and discovery of new recycling technologies remain challenges [3]. A later review identifies automated near-infrared and hyperspectral imaging as leading approaches for accurate and scalable fibre separation, and notes that automated disassembly can remove problematic components, while colour and finish removal still require customisation for specific waste streams [7]. The convergence of these two reviews on sorting is notable because they were written several years apart and with different emphases, which strengthens rather than weakens the inference that sorting is a persistent rather than transitional problem.

The primary evidence on sorting is encouraging but narrow. One study applied infrared spectroscopy with multivariate classification to textile samples and reported 100% classification accuracy on unknown fibre samples, concluding that automatic classification at high speed without prior analytical treatment is foreseeable [4]. This is a strong result, but it is a laboratory classification result on a defined sample set, not a demonstration of industrial throughput, contamination tolerance or cost per tonne. The gap between '100% accuracy in a controlled study' [4] and 'scalable fibre separation' as characterised in review form [7] is precisely the kind of gap that editorial synthesis should preserve rather than smooth over.

Pre-treatment is the second upstream lever, and here the evidence is more mechanistic. One study treated cotton, polyester and cotton/polyester woven fabrics with polyethylene glycol 4000 before tearing, measured inter-fibre cohesion on carded webs, and found that the treatment reduced cohesion, reduced fibre length loss and facilitated more efficient tearing, especially for polyester; the authors report that the treatment enabled rotor spinning of 100% recycled fibres [9]. This is a usefully specific finding because it identifies a causal mechanism (inter-fibre cohesion) rather than only an outcome, and it offers a test method that others could adopt. Its limits should be stated: the work concerns a defined lubricant and fibre set, and the supplied abstract does not report the mechanical properties of the resulting yarns, so the claim that spinning became possible should not be extended to a claim about yarn quality.

Read together, these records suggest a reordering of research priorities. Public and commercial attention tends to concentrate on novel dissolution or depolymerisation chemistries, but the supplied evidence indicates that the yield, purity and fibre-length characteristics of the input stream determine what any downstream route can achieve [3][4][7][9]. A sorting failure is not corrected by a better solvent; it is propagated into the recycled fibre.

SECTION 03

Mechanical routes: demonstrated yarns, uneven fibre coverage and length loss

Mechanical recycling has the clearest fibre-to-fibre evidence in the supplied set. One study produced batts and yarns from mechanically recycled wool, cotton, polyester, silk and rayon fibres blended with new fibres at 100%, 85% and 65% recycled content, and evaluated yarn size, breaking force, tenacity, elongation and moisture regain [1]. The authors report that recycled fibres from both pre-consumer and post-consumer textiles can produce yarns with appropriate strength for weaving and knitting; that 100% recycled wool, polyester and silk yarns were achievable; and that recycled cotton and rayon required blending with new fibre [1]. They also report no significant difference among recycled polyester and cotton percentages on yarn strength and elongation, and recommend using higher recycled percentages to maximise recycled content [1].

The fibre-type asymmetry is the most consequential result and deserves emphasis. A narrative that treats 'mechanically recycled cotton' and 'mechanically recycled wool' as equivalent is not supported: the same study that succeeded with 100% wool, polyester and silk found cotton and rayon needed virgin blending [1]. Because cotton is among the most commonly cited post-consumer fibre streams in waste statistics [3][6], this asymmetry directly limits how much of the waste stream mechanical routes can absorb at high recycled content. The finding that recycled percentage did not significantly affect strength and elongation for polyester and cotton [1] is encouraging for design flexibility but should be read alongside the blending requirement for cotton, since the comparison concerns blends rather than pure recycled cotton yarns.

Fibre length loss is the mechanism that plausibly explains the asymmetry, and the lubricant study provides direct support for that interpretation: tearing reduces fibre length, pre-treatment mitigates the loss, and the effect was especially marked for polyester [9]. A review independently characterises mechanical fibre recycling as ideal for textiles with strong mechanical properties but limited with blended fabrics and not repeatable endlessly [7]. The 'not endlessly repeatable' point is important and is not contradicted by the yarn study [1]; it implies that mechanical recycling should be modelled as a cascade with a finite number of cycles rather than as a closed loop, a distinction that matters for how recycled content claims are framed over a product's life.

Two further cautions apply. First, the yarn study reports spinning and property outcomes but the supplied abstract does not report abrasion, pilling, dyeability or long-term durability, so 'appropriate strength for weaving and knitting' [1] should not be read as a comprehensive performance equivalence claim. Second, the lubricant study's enabling result for 100% recycled rotor spinning [9] and the yarn study's blending requirement for cotton [1] are not directly comparable, since they concern different feedstocks, lubricants and spinning systems; reconciling them would require evidence the supplied set does not contain.

SECTION 04

Solvent and chemical routes: quality gains against energy and solvent burdens

Solvent-based and chemical routes are positioned in the supplied literature as the route to higher-quality recycled material. One review states that polymer recycling through melting or dissolving waste polymers produces higher-quality recycled materials but comes with high energy and solvent demands, and that chemical recycling, especially solvolysis and pyrolysis, excels at breaking down synthetic polymers such as polyester with the potential to yield virgin-quality monomers [7]. This is a review-level characterisation rather than a comparative measurement, and it should be treated as a statement about the state of the field rather than as a quantified advantage.

The one primary closed-loop demonstration in the supplied set concerns cellulose rather than polyester. One study dissolved waste denim in a binary solvent of dimethyl sulfoxide with the ionic liquid 1-butyl-3-methylimidazolium acetate, wet spun regenerated cellulose fibre, and reported that the original garment colour could be retained or the fibre regenerated without colour; colour retention is argued to avoid re-dyeing and thus save the water and energy associated with conventional dyeing

[5]. The cosolvent was reported to allow fast dissolution while reducing dope viscosity [5]. These are specific and technically meaningful claims, and the colour-retention argument is one of the few places in the supplied evidence where a recycling route is linked to an avoided downstream process rather than only to material recovery.

The limits of this evidence are equally specific. It is a single study on a single waste type (denim) using a particular solvent system [5]; the supplied abstract does not report fibre tensile properties, solvent recovery rates, ionic liquid losses or the fate of non-cellulosic components such as elastane, zips and finishes. The review-level claim that solvent routes carry high energy and solvent demands [7] is therefore not refuted by the denim demonstration, and the two should be held together: a route can produce a good fibre and still face a substantial process burden. The absence of solvent recovery data in the supplied record is a material gap, because solvent make-up is often the dominant economic and environmental cost in such processes, but that inference is general process reasoning and is not itself evidenced by the supplied sources.

A further tension concerns feedstock scope. The denim route depends on a relatively clean, cellulosic, single-material stream [5], whereas the review literature emphasises that blends and problematic components complicate recycling and require tailored pre-treatment [7]. The demonstrated success and the acknowledged constraint are therefore about different feedstocks, and generalising the denim result to mixed post-consumer bales is not supported by the supplied evidence.

SECTION 05

Composite and downgrade outlets: a complement, not a substitute

Not all fibre-to-fibre ambitions survive contact with mixed waste, and the supplied evidence includes an explicit alternative. One study incorporated 52 wt% cotton and polyester fibres from textiles into polypropylene composites with maleic anhydride or glycidyl methacrylate coupling agents, and reported that the balance between cotton and polyester significantly influenced tensile strength and stiffness, that optimal tensile strength and strain were achieved with equal proportions of the two fibre types, and that a blend of coupling agents accommodating both hydrophilic and hydrophobic fibres enhanced strength overall [10]. The authors describe the approach as a material-focused alternative that complements traditional textile-to-textile recycling [10].

The framing matters. A composite outlet is a downgrade in the sense that the fibre no longer returns to textile form, but it can absorb mixed and blended streams that mechanical and solvent routes handle poorly [7][10]. The composite study's stepwise pressing-extrusion method reportedly produced materials containing more recycled textile fibre than virgin polymeric binder [10], which is a notable high-fibre-loading result, though the supplied abstract does not report durability, moisture sensitivity or end-of-life behaviour of the composites. Claims that such composites are 'circular' should therefore be treated cautiously: the supplied evidence supports a diversion and material-efficiency argument, not a closed-loop one.

There is also a design implication that runs in the opposite direction to conventional recycling advocacy. If equal cotton/polyester proportions optimise composite performance [10], then the fibre blending that is a liability for mechanical recycling [7] can be an asset for composite manufacture. This is a genuine disagreement in the literature about what constitutes a 'good' waste stream, and it is not resolved by the supplied sources: the optimal feedstock for one pathway is a problematic feedstock for another, which argues for sorting systems capable of routing bales to different outlets rather than for a single preferred destination [4][7].

SECTION 06

Demand, business models and policy: the adoption constraint

Technical feasibility is not the same as adoption, and the supplied evidence on barriers is unusually direct. A multi-criteria assessment of textile recycling barriers in India, using a trapezoidal fuzzy DEMATEL approach, identified the top five barriers as a lack of successful recycling business models, poor demand for recycled textile goods, the possibility that recycled products may not replace new products, a lack of support for waste management in the industry, and the absence of tax relief and rewarding policies [8]. The same study links the issue to Sustainable Development Goal 12 on responsible production and consumption [8]. Notably, none of the top five barriers is a fibre-science problem, which is a significant finding for research

prioritisation.

This barrier picture is consistent with the socioeconomic evidence. An analysis of 67 Florida counties from 2014 to 2019 found preliminary evidence that areas with higher incomes, greater racial segregation and more clothing stores generate significantly more textile waste, that landfills per capita were higher in lower-income areas, and that textile recycling occurred at relatively uniform rates across counties; the authors conclude that textile waste is an environmental justice issue and call for multipronged solutions including consumption reduction and recycling increases [6]. The uniform recycling rate across counties is a striking result because it suggests that recycling behaviour is not simply a function of local wealth or retail density, which complicates purely market-based explanations of low recycling.

Policy and system-level arguments appear in the review literature as well. One review argues that applying extended producer responsibility and a circular economy system implies a holistic consensus among major stakeholders [3], and a later review concludes that eco-design principles, progressive policies and industry collaboration are essential alongside automated sorting and advanced solvent and chemical technologies [7]. A bibliometric and systematic review of 234 documents characterises the field's evolution and future trends and highlights areas for further research [2], but the supplied abstract does not report which specific trends were identified, so it can support a claim about research activity and gaps but not a claim about which pathway is favoured.

The practical implication is that fibre-to-fibre recycling is demand-constrained as well as technology-constrained. The barrier study's finding that recycled products may not replace new products [8] speaks directly to product developers: unless recycled fibre can meet specification in the applications where volume exists, technically successful yarns [1] and fibres [5] will not translate into substitution at scale.

SECTION 07

What the evidence supports for design and manufacturing

Several conditional design rules follow from the supplied evidence, provided they are stated as conditionals rather than prescriptions. First, design for disassembly and mono-materiality is supported indirectly but consistently: the review literature identifies blends and problematic components as limiting mechanical recycling and complicating pre-treatment [7], and the composite route exploits mixed fibres precisely because they are difficult to separate [10]. Where a product is intended for textile-to-textile recycling, minimising hard components and unnecessary fibre blending is a defensible default, though the supplied sources do not quantify the benefit.

Second, colour and finish decisions interact with recycling route selection. The denim study's demonstration that garment colour can be retained through dissolution and wet spinning, avoiding re-dyeing [5], suggests that colour management should be treated as a recycling-relevant design variable rather than a purely aesthetic one. The review literature's observation that colour and finish removal still require customisation for specific waste streams [7] reinforces the point from the opposite direction: where colour cannot be retained, decolourisation becomes a process cost that design choices can either ease or aggravate.

Third, specification-setting should anticipate fibre-type asymmetry. The finding that 100% recycled wool, polyester and silk yarns were achievable while cotton and rayon required virgin blending [1] implies that recycled-content targets should be set per fibre type and per application rather than as uniform corporate percentages. Similarly, the lubricant pre-treatment result [9] suggests that pre-treatment specification belongs in the recycling supply chain rather than being left to the spinner, and that inter-fibre cohesion testing could serve as a practical quality-control method.

Fourth, manufacturers should plan for cascading rather than infinite looping. The review characterisation that mechanical recycling cannot be repeated endlessly [7] is not contradicted by any supplied primary study, and it implies that recycled content claims should be accompanied by assumptions about cycle number and about the eventual fate of the fibre, whether composite [10], energy recovery or landfill [3][6]. Finally, the barrier evidence [8] and the socioeconomic evidence [6] together suggest that product developers should not assume that recycled content alone creates demand; the specification, price and application fit of recycled materials remain the operative variables, and the supplied sources do not provide the cost

or market data needed to resolve them.

CONCLUSION

Conclusions

The supplied evidence supports a qualified conclusion: fibre-to-fibre recycling for post-consumer textiles is technically demonstrated across mechanical, solvent and composite routes, but the demonstrations are narrow, the pathways are not interchangeable, and adoption is constrained by sorting, pre-treatment, demand and policy as much as by fibre science. Mechanical recycling can produce yarns suitable for weaving and knitting, but with a clear fibre-type asymmetry in which cotton and rayon required virgin blending while wool, polyester and silk did not [1], and with fibre length loss as an identified mechanism that lubricant pre-treatment can mitigate [9]. Solvent and chemical routes promise higher-quality output but carry energy and solvent burdens [7], and the single closed-loop demonstration supplied is a denim-specific cellulose case whose solvent recovery and fibre properties are not reported [5]. Automated sorting by infrared classification has been shown to be highly accurate in a laboratory setting [4], but industrial scalability remains a review-level aspiration [7]. Composite outlets can absorb mixed streams at high fibre loading [10] and should be treated as complements rather than substitutes. Barrier and socioeconomic evidence indicates that business models, demand and policy are decisive [6][8], and that recycling rates appear relatively uniform across counties despite large differences in waste generation [6]. For applied textile design and manufacturing, the defensible implications are conditional: mono-materiality and disassembly where textile-to-textile recycling is intended, colour and finish choices treated as recycling-relevant, recycled-content targets set per fibre type, and recycled content claims accompanied by explicit assumptions about cycle number and end-of-life.

SCOPE

Limitations

This review synthesises ten supplied source records and does not claim systematic-review methods; no search strategy, screening protocol, quality appraisal or meta-analysis was applied, and the source set was fixed in advance. The evidence base is heterogeneous in type and maturity: it includes primary experimental studies [1][4][5][9][10], narrative reviews [3][7], a bibliometric and systematic review [2], a socioeconomic analysis [6] and a multi-criteria barrier assessment [8], and these cannot be treated as commensurable. Several records are reported only through abstracts, so parameters such as yarn tensile properties [9], regenerated fibre properties and solvent recovery [5], composite durability and end-of-life behaviour [10], and the specific trends identified in the bibliometric review [2] are not available and are not inferred here. Geographic coverage is uneven, with dedicated analyses of India [8] and Florida, United States [6], and global statistics differ between sources [3][6] for reasons of scope and year that the supplied records do not fully resolve. No supplied source provides a comparative life-cycle assessment, cost model or industrial-scale trial across pathways, so statements about relative environmental or economic performance are limited to review-level characterisations [7] and should not be read as quantified comparisons. Where the review offers process reasoning that is not directly evidenced by the supplied sources, such as the likely importance of solvent make-up costs, this is identified as inference rather than finding. Finally, the absence of

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