Eco-Friendly Techniques for Textile Waste Management: A Circular Systems Approach Integrating Advanced Recycling and Policy Mechanisms

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Abstract

The textile industry is one of the most resource-intensive and polluting sectors globally, generating approximately 92 million tonnes of waste annually. Conventional waste management strategies have proven inadequate in addressing the scale and complexity of textile pollution, which encompasses synthetic fiber contamination, chemical effluents, and landfill overload. This paper examines eco-friendly techniques for textile waste management through the lens of a circular economy framework, integrating advanced mechanical, chemical, and biological recycling methodologies with robust policy mechanisms. Drawing on recent empirical studies, legislative frameworks, and technological innovations, the paper identifies critical gaps in current approaches and proposes an integrative circular systems model that aligns technological capacity with regulatory governance. The paper also evaluates extended producer responsibility (EPR) schemes, green procurement policies, and international cooperation frameworks as levers for systemic transformation. Findings suggest that a multi-stakeholder, technology-inclusive, and policy-driven approach is essential for achieving meaningful reductions in textile waste and advancing the global sustainability agenda.

Keywords: textile waste, circular economy, advanced recycling, extended producer responsibility, eco-innovation, sustainable fashion, polymer recycling, biodegradable fibers

1. Introduction

The global textile and apparel industry generates staggering quantities of waste at every stage of production, distribution, and consumption. According to the Ellen MacArthur Foundation (2017), the fashion industry produces approximately 92 million tonnes of solid waste per year, and projections suggest this figure will increase to 134 million tonnes by 2025 if current consumption trajectories persist. The environmental consequences are profound: textile manufacturing is responsible for approximately 20% of industrial water pollution globally, while synthetic fibers such as polyester shed microplastics into aquatic ecosystems during laundering (Boucher & Friot, 2017). Beyond environmental degradation, inefficient textile waste management undermines economic value, as an estimated $500 billion of clothing value is lost annually due to underutilization and insufficient recycling (Ellen MacArthur Foundation, 2017).

Traditional linear models of production and consumption—characterized by the 'take-make-dispose' paradigm—are fundamentally incompatible with sustainable development goals. The transition toward a circular economy, defined by the principles of designing out waste, keeping materials in use, and regenerating natural systems, offers a compelling alternative framework (Geissdoerfer et al., 2017). Within this framework, textile waste management is no longer merely a post-consumer concern but a systemic challenge requiring integrated upstream design, midstream processing innovation, and downstream policy governance.

This paper addresses the gap between emerging eco-friendly recycling technologies and their systemic adoption by examining the convergence of technological capability, economic viability, and institutional frameworks. While individual technologies such as enzymatic hydrolysis or chemical solvolysis have been explored in isolation, the literature lacks comprehensive models that integrate advanced recycling methods with coherent policy architectures. This paper seeks to fill this gap by proposing a circular systems model for textile waste management that is both technologically inclusive and policy-responsive.

The research objectives are threefold: first, to survey and critically evaluate current eco-friendly techniques for textile waste recycling; second, to examine how circular economy principles can be operationalized through policy mechanisms; and third, to synthesize these dimensions into an integrative systems framework applicable at national and international scales. The paper proceeds as follows: Section 2 provides a theoretical background on the circular economy and textile waste. Section 3 reviews eco-friendly recycling technologies. Section 4 examines policy mechanisms. Section 5 proposes an integrative circular systems model. Section 6 discusses challenges and recommendations. Section 7 concludes.

2. Theoretical Background: Circular Economy and Textile Waste

2.1 The Circular Economy Paradigm

The circular economy (CE) is an economic model predicated on the elimination of waste and the continual use of resources. Unlike the traditional linear economy, which follows a take-make-dispose trajectory, the CE is regenerative by design, aiming to decouple economic growth from finite resource consumption (Murray et al., 2017). Underpinned by the principles of the cradle-to-cradle design philosophy (McDonough & Braungart, 2002), the CE envisions products and materials cycling continuously through biological and technical loops.

Several theoretical frameworks have been proposed to operationalize the CE within specific sectors. Kirchherr et al. (2017) conducted a systematic review of 114 definitions of the circular economy and identified key recurring dimensions: resource circularity, systemic thinking, sustainable development objectives, and multi-level governance. For the textile sector, these dimensions translate into design for disassembly, closed-loop fiber recycling, extended product lifespans, and regulatory incentives that align market behavior with circular objectives.

2.2 Textile Waste: Scope and Composition

Textile waste encompasses a broad range of materials generated across the value chain, including pre-consumer waste (manufacturing offcuts, unsold inventory) and post-consumer waste (discarded garments and household textiles). The composition of textile waste is highly heterogeneous, comprising natural fibers (cotton, wool, silk), synthetic fibers (polyester, nylon, acrylic), and blended fabrics that combine multiple fiber types (Sandin & Peters, 2018). This compositional complexity is a principal barrier to recycling, as blended textiles require separation technologies that remain costly and energy-intensive at scale.

Global textile waste flows are uneven, with high-income countries generating the largest volumes of post-consumer waste while exporting significant quantities to low- and middle-income countries under the guise of charitable donations or second-hand trade (Brooks, 2019). Countries such as Ghana, Kenya, and Pakistan have become de facto dumping grounds for low-quality second-hand textiles, creating localized environmental burdens while undermining domestic textile industries. This geopolitical dimension of textile waste underscores the need for internationally coordinated waste management frameworks.

2.3 Environmental Impact of Textile Waste

The environmental footprint of textile waste is multidimensional. Landfilling—the predominant disposal method globally—generates methane emissions as organic fibers decompose and leaches chemical dyes and treatment agents into soil and groundwater (Muthu, 2014). Incineration, while reducing volume, releases dioxins, furans, and heavy metals into the atmosphere, particularly when synthetic fibers are involved (Payne, 2015). Microplastic pollution, driven by synthetic fiber shedding during use and end-of-life processing, represents an emerging environmental crisis, with recent studies detecting microplastic contamination in Arctic ice, deep ocean sediments, and human blood (Pirc et al., 2016).

The social dimensions of textile waste are equally significant. Informal waste picking and processing in low-income countries exposes workers to hazardous chemicals and occupational health risks. The fast fashion industry's production model, which generates rapid trend cycles and short product lifespans, externalizes the true cost of garment disposal onto communities and ecosystems that lack the infrastructure or regulatory capacity to manage the resulting waste streams responsibly.

3. Eco-Friendly Techniques for Textile Waste Recycling

3.1 Mechanical Recycling

Mechanical recycling is the most established and widely deployed textile recycling technology, involving physical processes such as shredding, garnetting, and carding to convert waste textiles into fibrous raw materials. The outputs of mechanical recycling—recycled fibers or nonwoven materials—are used in insulation, stuffing, industrial wiping cloths, and lower-grade apparel (Palm et al., 2014). The primary advantages of mechanical recycling are its relatively low capital cost, energy efficiency, and technological readiness.

However, mechanical recycling is subject to significant limitations. The process degrades fiber length and quality with each cycle, resulting in a progressive downgrading of material properties that ultimately limits recyclability to a finite number of passes. Blended fabrics present particular challenges, as automated fiber separation at the scale required for commercial recycling remains technically and economically constrained (Sandin & Peters, 2018). Current mechanical recycling processes are most effective for pure cotton or wool textiles, which can be shredded and respun into lower-count yarns for use in the automotive, construction, or bedding industries.

Recent advances in mechanical recycling technology have sought to address these limitations. High-tech garnetting machines capable of preserving longer fiber lengths, combined with near-infrared (NIR) sorting systems that automatically classify textiles by fiber composition and color, are improving the quality of mechanically recycled outputs (Zamani, 2014). These technological improvements, while promising, require substantial capital investment and are not yet accessible to small- and medium-scale recyclers in developing countries.

3.2 Chemical Recycling

Chemical recycling represents a more sophisticated and potentially higher-value approach to textile waste management. Unlike mechanical recycling, which preserves fiber form while degrading quality, chemical recycling depolymerizes textile polymers into their constituent monomers or oligomers, which can then be repolymerized into virgin-equivalent fibers. This closed-loop potential makes chemical recycling a cornerstone technology for achieving true circularity in synthetic textile streams (Pensupa et al., 2017).

Several chemical recycling pathways are under active development. Glycolysis and methanolysis are transesterification processes applicable to polyester (PET) textiles, cleaving ester bonds to yield diols and dimethyl terephthalate (DMT) or bis(2-hydroxyethyl) terephthalate (BHET), which can be purified and repolymerized into new PET fiber (Sinha et al., 2010). Hydrothermal processing, using water as a reaction medium under elevated temperature and pressure, offers an environmentally benign alternative to solvent-based methods for both natural and synthetic fibers. Ionic liquid dissolution, pioneered for cellulosic fibers, selectively dissolves cotton while leaving synthetic components intact, enabling efficient fiber separation in blended textiles (Navone et al., 2020).

Chemical recycling for nylon recovery has advanced significantly with the commercialization of caprolactam recovery processes. Aquafil's Econyl process, for example, chemically regenerates nylon 6 from fishing nets, carpet waste, and textile offcuts, producing a fiber with equivalent performance to virgin nylon at substantially reduced environmental impact (Aquafil, 2019). Similarly, several startups and established chemical companies are scaling solvolysis processes for polyester recovery, with Carbios's enzymatic depolymerization platform representing a breakthrough in bio-catalytic chemical recycling that achieves near-complete monomer recovery under mild process conditions (Tournier et al., 2020).

3.3 Biological Recycling

Biological recycling leverages microbial and enzymatic systems to degrade and valorize textile waste, particularly cellulosic and protein-based fibers. Enzymatic hydrolysis of cotton using cellulase enzyme cocktails can convert cotton waste into glucose-rich hydrolysate suitable for fermentation into biofuels, bioplastics, or platform chemicals (Pham et al., 2019). Similarly, protease enzymes are capable of hydrolyzing wool and silk proteins into amino acid mixtures with potential applications in cosmetics, animal feed, and specialty chemicals.

Composting of natural fiber textiles offers a low-technology, decentralized approach to biological waste management, particularly for textiles free of synthetic treatments and dyes. Recent research has explored vermicomposting of cotton textile waste as a means of generating nutrient-rich compost while diverting organic materials from landfill (Sandin & Peters, 2018). However, the presence of chemical finishes, dyes, and fire retardants in most commercial textiles complicates composting and limits its applicability to minimally processed natural fiber waste streams.

Biotechnology is also enabling novel fiber-to-fiber biological cycling pathways. Ioncell-F technology, developed at Aalto University, dissolves cotton textile waste using ionic liquids and regenerates it as high-tenacity lyocell-type fibers with superior mechanical properties (Sixta et al., 2015). This technology exemplifies the integration of chemical and biological principles in next-generation recycling and represents a significant advance toward closed-loop cotton cycling. Fungal mycelium-based composites have been proposed as biodegradable substitutes for synthetic textile backing materials, offering additional pathways for biological waste reduction.

3.4 Upcycling and Design-for-Circularity

Beyond end-of-life recycling, upcycling—the transformation of waste textiles into higher-value products—represents an important complementary strategy within the circular economy framework. Upcycling ranges from craft-scale activities, such as the conversion of denim offcuts into fashion accessories, to industrial-scale processes that rework post-consumer textiles into premium performance fabrics. The value proposition of upcycling lies in its ability to extend material lifespans and capture embedded value without energy-intensive reprocessing (Cuc & Tripa, 2018).

Design for circularity (DfC) is an upstream intervention that seeks to eliminate waste before it arises by embedding recyclability into product design. Key DfC principles applicable to textiles include mono-material construction (avoiding blends), the elimination of non-recyclable accessories such as metal zippers and resin coatings, the use of water-soluble adhesives, and the adoption of modular product architectures that facilitate component-level repair and replacement (Bocken et al., 2016). Several fashion brands, including Patagonia, Eileen Fisher, and Mud Jeans, have piloted DfC principles through product take-back programs and leasing business models, demonstrating commercial viability alongside environmental benefits.

4. Policy Mechanisms for Circular Textile Waste Management

4.1 Extended Producer Responsibility

Extended producer responsibility (EPR) is a policy instrument that shifts the financial and logistical responsibility for end-of-life product management from consumers and municipalities to producers and brand owners. EPR schemes for textiles have been implemented in a small number of jurisdictions, most notably France, which in 2007 established the REP Textile, Linge de Maison et Chaussures (TLC) scheme under the Grenelle II environmental legislation (Lindqvist, 2014). Under this scheme, textile producers and importers are required to finance and organize collection, sorting, and recycling infrastructure, funding the Eco-TLC organization that manages the system.

The French EPR model has demonstrated significant potential for scaling textile collection infrastructure, achieving collection rates well above the European average. However, critics have noted that the system has been slow to incentivize genuine recycling as opposed to reuse and export, partly because fee structures do not sufficiently differentiate between high-quality recycling outcomes and lower-value reuse or export disposal (Ljungkvist et al., 2020). Reforming EPR fee modulation to reward recyclable product design and penalize hazardous material use would strengthen the incentive alignment between producer behavior and circular economy objectives.

The European Union's Circular Economy Action Plan (2020) established a comprehensive policy framework for textiles, proposing mandatory EPR schemes across member states and signalling the integration of ecodesign requirements, recycled content standards, and supply chain transparency obligations into future EU textile regulation (European Commission, 2020). These policy commitments represent a significant step toward the systemic transformation of the European textile sector and provide an institutional foundation for more binding legislative instruments anticipated in subsequent years.

4.2 Green Public Procurement

Green public procurement (GPP) leverages the purchasing power of public sector institutions to create demand for sustainable textiles and recycled fiber products. Government expenditure on textiles—including uniforms, healthcare linen, military clothing, and institutional bedding—represents a substantial market segment. By specifying minimum recycled content requirements, ecolabel compliance, or supply chain transparency criteria in public procurement contracts, governments can stimulate investment in recycling infrastructure and signal market demand for circular textile products (Brammer & Walker, 2011).

Several countries have implemented GPP criteria for textiles, including Germany's Blue Angel ecolabel requirements for textiles procured under federal contracts, and Denmark's incorporation of the Nordic Swan Ecolabel in public textile procurement specifications. The EU's GPP criteria for textiles, published in 2017, provide harmonized sustainability standards applicable to public purchasers across member states (European Commission, 2017). Evidence suggests that consistent application of GPP criteria can reduce lifecycle environmental impacts of procured textiles by 30–50% compared to conventional procurement (Tukker et al., 2008).

4.3 Regulatory Standards and Ecolabels

Regulatory standards and ecolabeling schemes serve as complementary instruments that establish baseline environmental performance thresholds and communicate sustainability credentials to consumers and businesses. The Global Organic Textile Standard (GOTS), the OEKO-TEX Standard 100, and the Bluesign System are internationally recognized certification schemes that cover chemical restrictions, water use, energy efficiency, and labor standards in textile production. While these standards address the production phase of the textile lifecycle, emerging certifications are beginning to incorporate end-of-life recyclability and recycled content criteria.

Mandatory chemical restrictions under regulations such as REACH in the European Union and the Restricted Substances List (RSL) maintained by organizations like ZDHC are increasingly important in enabling downstream recycling. Hazardous finishing chemicals, flame retardants, and azo dyes that are permissible in current production but incompatible with recycling processes represent a systemic barrier to closed-loop fiber cycling. Aligning chemical use regulations with recycling infrastructure requirements—ensuring that chemicals present in textiles at end of life are compatible with available recycling pathways—is a necessary condition for effective circular systems (Payne, 2015).

4.4 International Trade and Cooperation Frameworks

Textile waste management is inherently transboundary in character, given the global nature of textile supply chains and the cross-border flows of second-hand clothing and waste. The Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal provides the primary international legal framework governing hazardous textile waste exports, though its applicability to non-hazardous textile waste is contested. The 2019 Basel Convention amendments strengthening controls on plastic waste exports have prompted calls for analogous measures covering synthetic textile waste (UNEP, 2019).

Bilateral and multilateral trade agreements increasingly incorporate sustainability provisions that intersect with textile waste management objectives. The EU-Vietnam Free Trade Agreement's chapter on trade and sustainable development references commitments to the circular economy, while potential Carbon Border Adjustment mechanisms may create indirect incentives for low-carbon textile production and waste management in exporting countries. Developing dedicated international frameworks for sustainable textile trade that incorporate waste management performance criteria represents an important avenue for global policy development.

5. An Integrative Circular Systems Model for Textile Waste Management

5.1 Model Architecture

Building on the review of recycling technologies and policy mechanisms, this paper proposes an Integrative Circular Systems Model (ICSM) for textile waste management. The ICSM is conceptualized as a multi-level, multi-stakeholder framework that aligns technological, economic, and regulatory dimensions across the textile value chain. The model comprises four interconnected subsystems: (1) Design and Production Circularity, (2) Collection and Sorting Infrastructure, (3) Advanced Recycling Technology Ecosystem, and (4) Policy and Governance Architecture.

The Design and Production Circularity subsystem encompasses upstream interventions aimed at reducing waste generation and maximizing end-of-life recyclability. This includes DfC principles applied at the product design stage, material transparency requirements enabled by digital product passports, and producer partnerships with recycling facilities to ensure design choices are compatible with available processing technologies. The feedback loop between recycling operators and product designers is a critical feature of the ICSM, ensuring that technological constraints and opportunities in recycling inform design decisions in real time.

5.2 Collection and Sorting Infrastructure

Effective collection and sorting infrastructure is the foundational enabling condition for all downstream recycling activities. The ICSM envisions a tiered collection network comprising retail take-back programs, municipal textile drop-off points, and household collection services, supported by EPR financing mechanisms. Automated sorting technology using near-infrared spectroscopy, X-ray fluorescence, and machine learning-based image recognition systems plays a central role in the ICSM, enabling high-throughput, accurate classification of textile waste by fiber type, color, and quality grade (Morley et al., 2009).

The ICSM emphasizes the importance of collection infrastructure in regions with limited existing capacity, including low- and middle-income countries. Innovative models such as informal sector integration—formalizing and supporting existing waste pickers and second-hand clothing traders—offer culturally appropriate and economically efficient approaches to collection in these contexts. Digital platforms connecting waste generators with recyclers, analogous to the circular economy digital marketplaces emerging in other material sectors, can facilitate transparency and efficiency in textile waste flows.

5.3 Advanced Recycling Technology Ecosystem

The advanced recycling technology ecosystem within the ICSM is organized around a hierarchy of preferred recycling pathways, analogous to the waste management hierarchy but calibrated to the specific characteristics of textile waste. Fiber-to-fiber recycling—whether mechanical or chemical—is the preferred pathway, preserving the highest material value. Where fiber-to-fiber recycling is not technically feasible, fiber-to-polymer or fiber-to-monomer chemical recycling is preferred. Biological recycling and energy recovery represent lower-preference options applicable where higher-value pathways are unavailable.

Crucially, the ICSM recognizes that no single recycling technology is universally applicable. The optimal recycling pathway for a given textile waste stream depends on fiber composition, chemical treatment history, contamination level, and local technology availability. The ICSM therefore proposes a modular technology matching system, in which textile waste inputs are characterized and matched to the most appropriate available recycling pathway through decision-support algorithms informed by life cycle assessment (LCA) data. This adaptive technology matching approach maximizes resource recovery while minimizing environmental trade-offs.

5.4 Policy and Governance Architecture

The policy and governance architecture of the ICSM integrates the policy mechanisms reviewed in Section 4 into a coherent regulatory framework that operates across national, regional, and international scales. At the national level, mandatory EPR schemes with robust fee modulation, binding recycled content standards, and chemical use regulations compatible with circular recycling are the foundational instruments. At the regional level, harmonized standards—such as those being developed within the EU—reduce market fragmentation and enable economies of scale in recycling infrastructure investment. At the international level, strengthened trade frameworks governing second-hand textile flows and hazardous waste exports complement domestic regulatory regimes.

Governance of the ICSM requires multi-stakeholder institutional arrangements that include industry, civil society, academia, and government. Co-regulatory approaches, in which industry associations participate in the development and enforcement of performance standards, have demonstrated effectiveness in accelerating compliance and innovation in comparable sectors such as electronics waste management (Lifset, 1993). Public-private investment platforms that de-risk investment in advanced recycling technologies through blended finance mechanisms—combining public grants, concessional loans, and private equity—are essential for scaling novel recycling technologies from pilot to commercial deployment.

6. Challenges, Limitations, and Recommendations

6.1 Technological and Economic Challenges

Despite significant advances in textile recycling technology, several critical challenges impede the transition to closed-loop textile systems. The techno-economic viability of advanced chemical recycling processes remains uncertain at commercial scale. High capital and operating costs, combined with the need for consistent, high-quality sorted feedstock, create significant barriers to investment in chemical recycling facilities (Pensupa et al., 2017). Price competition from virgin synthetic fibers—particularly fossil fuel-derived polyester, whose cost is sensitive to petroleum prices—undermines the economic competitiveness of recycled alternatives.

The quality gap between recycled and virgin fibers remains a persistent challenge for market acceptance. Mechanically recycled fibers are generally shorter and weaker than virgin fibers, limiting their application in high-performance textiles. While chemical recycling can produce virgin-equivalent fibers, the process economics are currently unfavorable relative to virgin production. Investments in process optimization, catalyst development, and energy integration are needed to reduce the cost and improve the performance of chemical recycling outputs.

6.2 Policy and Institutional Challenges

Policy implementation faces significant challenges related to regulatory fragmentation, enforcement capacity, and political economy. In the absence of harmonized international standards, EPR schemes and recycled content requirements in one jurisdiction may simply shift waste disposal burdens to countries with weaker regulations, a phenomenon known as waste leakage. Developing comprehensive international governance frameworks that prevent waste leakage while respecting national sovereignty and development needs is a complex diplomatic challenge (UNEP, 2019).

The fast fashion business model poses particular institutional challenges, as it is premised on high product volumes and low prices that are fundamentally at odds with circular economy principles. Voluntary corporate sustainability commitments, while important signals of intent, have proven insufficient to drive systemic change in the absence of binding regulatory requirements. Mandatory due diligence and supply chain transparency requirements, as proposed in the EU Circular Economy Action Plan (European Commission, 2020), provide a stronger mechanism for ensuring that brands take responsibility for the full lifecycle environmental impact of their products.

6.3 Recommendations

Based on the analysis presented, this paper offers five strategic recommendations for advancing eco-friendly textile waste management through the ICSM framework. First, governments should establish mandatory EPR schemes for textiles with performance-based fee modulation that rewards DfC and high-quality recycling outcomes. Second, public investment in textile sorting and advanced recycling infrastructure should be prioritized in national circular economy strategies, with particular emphasis on creating regional hubs that provide economies of scale. Third, chemical use regulations should be harmonized with circular recycling requirements, ensuring that chemicals present in textiles at end of life are compatible with available recycling processes. Fourth, digital product passports should be mandated across the textile sector to enable efficient identification and sorting of textile waste by composition, treatment history, and recyclability. Fifth, international development finance institutions should direct blended finance toward scaling advanced recycling technologies in low- and middle-income countries, preventing the emergence of a two-tier global circular economy that concentrates recycling capacity in high-income nations.

7. Conclusion

The textile industry's environmental footprint demands urgent and systemic transformation. This paper has demonstrated that eco-friendly textile waste management is neither a simple technological challenge nor a purely regulatory problem, but a complex socio-technical system requiring integrated interventions across design, collection, recycling, and governance dimensions. The Integrative Circular Systems Model proposed in this paper provides a comprehensive framework for organizing these interventions in a coherent and mutually reinforcing manner.

Advanced recycling technologies—mechanical, chemical, and biological—offer promising pathways for closed-loop fiber cycling, but their commercial viability depends on supportive policy environments, consistent feedstock quality, and continued technological innovation. Policy mechanisms, including EPR, green procurement, regulatory standards, and international cooperation frameworks, are indispensable complements to technological development, shaping market incentives and creating institutional conditions for circular economy transition.

The ICSM's emphasis on adaptive technology matching, multi-stakeholder governance, and international equity addresses limitations in existing circular economy frameworks that often treat recycling as a technical problem solvable in isolation from social, economic, and political contexts. Future research should focus on validating the ICSM in diverse regional and sectoral contexts, quantifying the environmental and economic benefits of integrated circular textile systems through life cycle assessment, and exploring the social dimensions of circular economy transition—including just transition frameworks for workers in conventional textile waste sectors.

As the global community mobilizes around the United Nations Sustainable Development Goals and the Paris Agreement on climate change, textile waste management emerges as a critical nexus of environmental, economic, and social sustainability. The integrative circular systems approach advocated in this paper offers a roadmap for transforming the textile sector from a linear, polluting industry into a regenerative system that creates value, reduces environmental burden, and supports sustainable livelihoods across the global value chain.

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