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Circular Fashion: Creating a Sustainable Clothing Economy

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Abstract
The global fashion industry has become emblematic of the environmental and social crises of consumerism. Fast fashion, characterized by short product lifespans, low prices, and rapid turnover, drives unsustainable resource extraction, carbon emissions, and waste accumulation. In 2023, global fiber production reached an unprecedented 124 million tonnes, while textile waste was estimated at over 92 million tonnes annually (Textile Exchange, 2024; UNEP, 2025). The environmental impacts are severe, accounting for 8–10% of global greenhouse gas emissions, 20% of wastewater, and significant microplastic pollution. Circular fashion, grounded in circular economy principles, offers an alternative paradigm that emphasizes longevity, repairability, recyclability, and closed-loop material systems. This paper provides a comprehensive analysis of circular fashion as a pathway to building a sustainable clothing economy. It synthesizes academic literature, industry reports, and policy frameworks published between 2019 and 2025, integrating statistical data with case-based evidence. Technical advances in mechanical, chemical, and enzymatic recycling are explored, with emphasis on Carbios' enzymatic depolymerization of PET, solvent-based separation of blends, and AI-driven automated sorting. The analysis also evaluates new business models including product-service systems (rental, resale, repair), extended producer responsibility (EPR), and digital product passports for traceability. Findings indicate that while circular fashion has significant environmental potential, systemic barriers remain: blended fibers, economic costs of advanced recycling, inconsistent collection systems, and consumer rebound effects. A techno-economic roadmap is presented, highlighting short-, medium-, and long-term interventions. Ultimately, achieving circular fashion at scale requires collaboration among designers, manufacturers, policymakers, and consumers, supported by regulatory mandates and investments in technology. The article concludes that circular fashion is both a moral and economic imperative, capable of redefining the future of global apparel systems.

Keywords: *Circular fashion; textile recycling; enzymatic recycling; eco-design; extended producer responsibility (EPR); product-service systems; techno-economic analysis; textile waste management*

1. INTRODUCTION

The modern fashion industry represents a paradox: it is simultaneously an engine of global economic growth and employment, and a driver of significant ecological degradation. According to the Textile Exchange (2024), total fiber production reached approximately 124 million tonnes in 2023, with polyester alone accounting for more than half of this output. At the same time, the United Nations Environment Programme (2025) reported that the industry generates over 92 million tonnes of textile waste annually, much of which is landfilled or incinerated. These flows of material embody a linear "take-make-dispose" model that is fundamentally at odds with planetary sustainability.

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The environmental burden of fashion manifests in multiple dimensions. The sector contributes 8–10% of global greenhouse gas emissions, a share greater than international aviation and shipping combined (Imran, 2023). It is the second-largest industrial consumer of water, with dyeing and finishing processes polluting rivers and aquifers in countries with weak regulatory frameworks (Niinimäki et al., 2020). Synthetic fibers such as polyester shed microplastics during laundering, with an estimated half a million tonnes entering the oceans annually (UNEP, 2025). Landfilling and incineration of discarded textiles exacerbate waste management challenges and contribute further emissions.Fast fashion business models amplify these pressures. Brands release up to 24 collections per year, encouraging overconsumption and disposability (Joy et al., 2012). Garment lifespans have declined sharply, with some studies estimating that the average item of clothing is worn fewer than ten times before disposal (Ellen MacArthur Foundation, 2017). Price deflation and marketing strategies normalize wasteful behavior, while globalized supply chains externalize environmental and social costs to low-income producer countries.In response, circular economy concepts have gained traction as a strategic framework to decouple economic growth from resource consumption. The circular economy emphasizes closing loops through reuse, repair, remanufacturing, and recycling, thereby retaining materials at their highest utility (Geissdoerfer et al., 2017). Circular fashion, as a subfield, adapts these principles to textiles, envisioning clothing systems that minimize virgin material inputs, extend product lifecycles, and regenerate natural systems. This paper aims to explore circular fashion in depth, evaluating its technical, economic, and policy dimensions. It begins with a review of existing literature and conceptual frameworks, followed by an overview of methods and data sources. Subsequent sections analyze the components of circular fashion: eco-design, extended use through new business models, collection and sorting systems, recycling technologies (mechanical, chemical, enzymatic), and enabling policies. Case studies illustrate practical implementations, while challenges and bottlenecks are critically assessed. The paper concludes with a roadmap outlining steps toward a sustainable clothing economy.

2. LITERATURE REVIEW

Conceptual foundations of the circular economy

The circular economy (CE) has emerged as a paradigm shift from the linear model of production and consumption. Geissdoerfer et al. (2017) define CE as "a regenerative system in which resource input and waste, emissions, and energy leakage are minimized by slowing, closing, and narrowing energy and material loops." In textiles, this translates into designing garments for durability, promoting repair and reuse, and deploying technologies for fiber-to-fiber recycling.The Ellen MacArthur Foundation (2017) has been instrumental in popularizing CE concepts for fashion. Their "New Textiles Economy" report emphasizes four key interventions: phasing out hazardous substances, improving clothing utilization, radically improving recycling, and transitioning to renewable inputs. These principles frame much of the academic and policy discourse around circular fashion.

Environmental impacts of linear fashion

Extensive research has documented the environmental footprint of the linear fashion system. Niinimäki et al. (2020) estimate that textile production contributes approximately 20% of global wastewater and 10% of carbon emissions. The water intensity of cotton cultivation is well known; producing a single cotton T-shirt requires ~2,700 liters of water (Chapagain et al., 2006). Synthetic fibers, while less water-intensive, introduce microplastic pollution during use-phase laundering (Henry et al., 2019).

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Landfilling of textiles results in methane emissions as natural fibers decompose anaerobically, while incineration contributes directly to greenhouse gas emissions. Studies by Sandin and Peters (2018) further show that most recycled textiles are downcycled into low-value applications such as insulation or wiping cloths, limiting their contribution to circularity.

Business models for circular fashion

Academic literature highlights the potential of business model innovation to extend garment lifespans. Bocken et al. (2016) propose "product-service systems" (PSS) where consumers pay for access rather than ownership, as exemplified by clothing rental platforms. Schor and Fitzmaurice (2017) discuss collaborative consumption models that reduce new production demand. Pal and Gander (2018) caution, however, that logistics and laundering in rental models may offset environmental benefits if not managed efficiently. Resale markets, facilitated by digital platforms such as Thred Up and Vestiaire Collective, have grown exponentially, indicating consumer willingness to participate in circular business models. The GlobalData (2023) report estimated that the second hand clothing market could reach USD 350 billion by 2030.

Technological innovations in recycling

Mechanical recycling, while common, leads to fiber degradation and limited reuse (Sandin & Peters, 2018). Chemical recycling methods, such as glycolysis and methanolysis, depolymerize polyester into monomers that can be repolymerized into virgin-quality fibers (Ioniqa, 2021). Enzymatic recycling has advanced rapidly, with Carbios (2024) developing PET-depolymerizing enzymes capable of producing textile-grade rPET under industrial conditions.For cotton, research into cellulose dissolution and regeneration (e.g., Ioncell, Renewcell) has yielded fibers such as Circulose®, which can be spun into new textiles. The integration of these technologies promises to shift recycling from downcycling to true closed-loop systems.

Policy frameworks and regulation

The European Union has been a frontrunner in promoting circular textiles through its Circular Economy Action Plan (European Commission, 2020). The strategy includes eco-design requirements, mandatory recycled content, and EPR schemes for textiles. National initiatives, such as France's Refashion program, further demonstrate policy's role in driving systemic change.Despite these advances, challenges remain. Kirchherr and Piscicelli (2019) identify barriers including technological immaturity, economic viability, consumer acceptance, and lack of policy enforcement. Literature consistently emphasizes the need for multi-stakeholder collaboration to overcome these barriers.

3. METHODOLOGY

This study employs a **qualitative synthesis and integrative review approach**, combining multiple data sources to develop a comprehensive assessment of circular fashion

Data sources

1. **Academic literature**: Peer-reviewed journal articles published between 2015 and 2025 covering circular economy, textile recycling, life cycle assessment (LCA), and sustainable business models.

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2. **Industry reports**: Publications by Textile Exchange, Ellen MacArthur Foundation, WRAP, UNEP, and corporate disclosures (Carbios, H&M, Patagonia).
3. **Market analyses**: Reports by Grand View Research, Fortune Business Insights, and GlobalData providing statistical data on recycling market size, resale growth, and fiber production trends.
4. **Policy documents**: EU circular economy directives, national EPR schemes, and UN Sustainable Development Goal (SDG) reports relevant to textiles.

Analytical framework

The analysis is structured around four pillars of circular fashion:

- **Design for circularity** (eco-design, material innovation).
- **Extended product use** (repair, resale, rental).
- **End-of-life systems** (collection, sorting, recycling technologies).
- **Enabling environment** (policy, economics, consumer behavior).

Each pillar is analyzed in terms of technological feasibility, environmental performance, and economic viability. Where possible, comparative data are synthesized to illustrate trends (e.g., growth in enzymatic recycling capacity, resale market size).

Limitations

While the synthesis approach allows broad coverage, several limitations exist. First, many recycling technologies are in pilot or demonstration stages, and data may be proprietary or subject to change as they scale. Second, LCA studies vary in scope and assumptions, complicating direct comparison. Third, consumer behavior data often rely on surveys that may not accurately predict long-term adoption. These limitations are acknowledged in the interpretation of findings.Excellent — let's continue with the **Main Analysis Sections** of Article 1. These will form the technical core (~2000 words) and bring us closer to the 5000-word target.

4. DESIGN FOR CIRCULARITY

Principles of eco-design

Circular fashion begins with design decisions that determine 80% of a garment's environmental impact (Ellen MacArthur Foundation, 2017). Eco-design incorporates durability, modularity, repairability, and recyclability as fundamental criteria rather than afterthoughts. The objective is to create garments that can circulate multiple times within the economy before reaching end-of-life.

Practical eco-design interventions include:

- **Mono-material garments**: Reducing blends simplifies recycling. A 100% polyester jacket, for example, is compatible with enzymatic or chemical depolymerization, while polyester-cotton blends require complex separation (Agrawal & Kaushik, 2014).
- **Design for disassembly**: Using detachable fastenings and minimizing adhesives allows components to be easily separated for recycling (Goldsworthy, 2017).

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- **Timeless aesthetics**: Styles designed for longevity avoid rapid obsolescence, reducing turnover (Fletcher, 2014).
- **Material innovation**: Development of bio-based and biodegradable fibers (e.g., PLA, lyocell) that can integrate into biological nutrient cycles (Muthu, 2020).

Challenges in eco-design adoption

Despite growing interest, adoption of eco-design principles faces barriers. Designers often lack technical knowledge of recycling constraints, and fast fashion's cost pressures discourage investment in longevity. Furthermore, supply chains are fragmented, making it difficult to ensure compatibility of trims, dyes, and fabrics with recycling processes. Policy instruments such as the EU's Eco-design for Sustainable Products Regulation (2024 draft) seek to address these barriers by mandating durability and recyclability standards.

5. EXTENDED USE AND BUSINESS MODELS

Repair and maintenance

Repair is one of the most effective strategies for extending garment lifespans. Patagonia's "Worn Wear" program offers free or low-cost repairs, reportedly extending product life by 2–3 years (Fletcher, 2014). Academic studies show that doubling garment lifespans can reduce life-cycle environmental impacts by up to 44% (WRAP, 2017).

Resale and second-hand markets

The global second-hand apparel market is booming. According to GlobalData (2023), it is projected to grow from USD 177 billion in 2022 to USD 350 billion by 2030. Platforms such as ThredUp, Vestiaire Collective, and Depop provide digital marketplaces where consumers buy and sell pre-owned clothing. This growth reflects shifting consumer attitudes toward sustainability and affordability.

Rental and subscription models

Rental services such as Rent the Runway and subscription boxes (e.g., Le Tote) provide access without ownership. Research by Pal and Gander (2018) highlights that rental models reduce resource use per wear but raise logistical challenges: transport emissions, packaging waste, and energy-intensive cleaning. Optimized logistics and durable garment design are essential for environmental benefits to materialize.

Collaborative consumption and swapping

Community-driven initiatives such as clothing swaps, libraries, and local sharing platforms foster collaborative consumption. These models rely on social networks and trust, offering low-cost, localized pathways to circularity.

6. COLLECTION AND SORTING INFRASTRUCTURE

Importance of collection systems

Without efficient collection, textiles cannot be looped back into the economy. Currently, collection rates vary widely: in the EU, ~38% of textiles are collected separately, while in the U.S. the figure is closer to 15% (EPA, 2022). The majority of discarded textiles are landfilled or incinerated.

Sorting technologies

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Advancements in sorting are pivotal to producing high-quality feedstock for recycling. Technologies include:

- **Near-infrared (NIR) spectroscopy**: Identifies fiber composition by reflectance patterns.
- **Automated robotics**: AI-enabled systems can detect, grasp, and separate garments at scale.
- **Digital product passports**: Embedding QR codes or RFID tags provides data on material composition and care history (European Commission, 2020).

Economic challenges

Collection and sorting are labor-intensive and costly. Without EPR or subsidies, many operators export collected textiles to low-income countries, where they may end up in informal waste streams. To prevent burden-shifting, local recycling capacity must be expanded alongside collection.

7. RECYCLING TECHNOLOGIES

Mechanical recycling

Mechanical recycling involves shredding and re-spinning fibers. It is cost-effective and requires low energy but reduces fiber length and quality, often relegating outputs to nonwovens, insulation, or blended yarns (Sandin & Peters, 2018). While suitable for cotton and wool, it cannot achieve closed-loop fiber-to-fiber recycling at scale.

Chemical recycling

Chemical recycling depolymerizes polymers into monomers that can be repolymerized into virgin-quality fibers. Key approaches include:

- **Glycolysis**: Decomposes polyester into bis-hydroxyethyl terephthalate (BHET).
- **Methanolysis**: Converts PET into dimethyl terephthalate (DMT).
- **Hydrolysis**: Produces terephthalic acid (TPA) and ethylene glycol (EG).

Companies such as Ioniqa and Eastman Chemical are piloting chemical recycling plants with outputs suitable for textile-grade PET. While promising, chemical recycling requires high energy and chemical inputs, raising LCA concerns.

Enzymatic recycling

Enzymatic recycling has emerged as a breakthrough technology. Carbios, in collaboration with Novozymes and Indorama Ventures, has developed engineered enzymes capable of depolymerizing PET textiles into their constituent monomers (Carbios, 2024). These monomers can then be repolymerized into high-quality PET suitable for fibers and bottles.

Advantages of enzymatic recycling include:

- Lower energy and temperature requirements.
- High selectivity, reducing contamination by-products.
- Compatibility with colored and mixed PET streams.

Challenges include enzyme production costs, feedstock preprocessing, and scalability. However, with the opening of Carbios' demonstration plant in 2024, industrial viability is approaching (Carbios, 2024).

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Emerging technologies for cotton and blends

For cellulose-based fibers, processes such as Renewcell's Circulose® dissolve used textiles and regenerate them into new fibers. Ioncell, a Finnish innovation, uses ionic liquids to dissolve cellulose and re-spin it into new fibers. Separating cotton-polyester blends remains challenging, though solvent-based fractionation methods are advancing.

8. CASE STUDIES

Patagonia – Repair and Resale Economy

Patagonia is widely recognized as a pioneer of circular fashion practices. Its *Worn Wear* program offers repair services, resale platforms, and upcycling workshops. In 2019 alone, the company repaired over 100,000 garments, extending their lifespan by an average of 2–3 years (Patagonia, 2020). Patagonia also sells second-hand clothing online, normalizing the idea of reuse in premium outdoor apparel. Its focus on durability at the design stage complements downstream repair initiatives, making it a leading example of integrated circularity.

H&M and Inditex – Take-Back Programs

Global fast fashion retailers such as H&M and Zara (Inditex) have launched take-back initiatives, where customers return unwanted textiles in-store. While millions of garments have been collected, critics argue that downstream infrastructure is insufficient: much of the material is exported to Africa and Asia, often overwhelming local waste systems (Niinimäki et al., 2020). Nonetheless, these initiatives demonstrate how large-scale retail networks can mobilize consumer participation and feed material into recycling streams.

Carbios – Enzymatic PET Recycling

Carbios exemplifies technological innovation in textile circularity. Its enzymatic PET recycling process, developed with Novozymes, selectively depolymerizes polyester textiles into TPA and EG. In 2024, Carbios opened a demonstration plant in Clermont-Ferrand, France, signaling industrial readiness (Carbios, 2024). Partnerships with Indorama Ventures (the world's largest PET producer) aim to scale production to hundreds of kiloton annually by the late 2020s. This case illustrates how biotech solutions can transform waste into virgin-equivalent feedstock.

Renewcell – Textile-to-Textile Recycling of Cellulose

Renewcell's Circulose® process recycles cotton-rich textiles into new cellulose fibers. In 2023, Renewcell opened a commercial plant in Sweden with capacity to process 60,000 tonnes of textiles annually (Renewcell, 2023). The output material is already used by brands such as H&M and Levi's. This case shows how cellulose regeneration technologies can address natural fiber waste streams.

9. POLICY ANALYSIS

Extended Producer Responsibility (EPR)

EPR schemes place responsibility for end-of-life management on producers. France's *Refashion* program requires fashion companies to finance textile collection and recycling, distributing over €150 million annually for infrastructure (European Commission, 2020). The EU is drafting legislation to extend EPR across all member states by 2027. Such schemes create financial incentives for eco-design and provide stable funding for collection and sorting systems.

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Eco-Design Regulations

The proposed EU Eco-design for Sustainable Products Regulation (2024 draft) mandates durability, recyclability, and information-sharing standards for textiles. This legislation could transform design practices, requiring labels with recyclability data and durability testing. Globally, similar policies are emerging: Japan mandates recycling targets for textiles, while India's 2022 EPR framework for plastics is expected to expand to textiles.

Fiscal Incentives and Public Procurement

Governments can accelerate circularity by offering tax credits, subsidies for recycling plants, and preferential procurement of recycled-content textiles. For example, the Netherlands has committed to 50% circular procurement by 2030, including uniforms and public textiles (Government of the Netherlands, 2021). These measures create market pull for circular textiles.

Consumer Awareness Campaigns

Public awareness campaigns, such as the UK's *Love Your Clothes* initiative by WRAP, encourage consumers to repair, reuse, and recycle. These campaigns complement regulatory measures by influencing behavior and increasing collection rates.

10. Bottlenecks and Barriers

Despite progress, significant barriers remain:

1. **Fiber Blends**: Cotton-polyester blends account for ~30% of global textiles, but separation technologies are not yet industrially viable.
2. **Economic Costs**: Enzymatic and chemical recycling require high capital investment, making outputs more expensive than virgin materials unless supported by regulation.
3. **Infrastructure Gaps**: Collection and sorting capacity lags far behind the volume of discarded textiles.
4. **Consumer Behavior**: Low participation in take-back programs and rebound effects (buying more because clothing feels "sustainable") undermine impact.
5. **Policy Fragmentation**: Regulations vary across regions, complicating global supply chains.

11. Roadmap for Scaling Circular Fashion

Short-Term (2025–2028)

- Implement standardized digital product passports with fiber composition data.
- Scale collection and sorting hubs with EPR funding.
- Expand resale and repair platforms with logistic optimization.

Medium-Term (2028–2035)

- Deploy multiple industrial-scale enzymatic PET recycling plants.
- Develop cost-effective separation for cotton-polyester blends.
- Implement mandatory minimum recycled content in textiles (e.g., 25% by 2030 in EU markets).

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- Increase consumer incentives for repair and reuse through tax reductions.

Long-Term (2035–2050)

- Achieve global harmonization of eco-design standards.
- Integrate biological nutrient cycles (biodegradable fibers) with technical loops (synthetics recycling).
- Transition fashion business models to service-based models, decoupling utility from virgin production.
- Ensure just transitions for workers in garment-producing regions by coupling circularity with social equity policies.

12. CONCLUSION

Circular fashion represents a necessary evolution of the apparel system, addressing the unsustainable resource and waste flows of fast fashion. By redesigning products for longevity, expanding resale and rental models, and scaling advanced recycling technologies, the industry can move toward a sustainable clothing economy. Case studies of Patagonia, Carbios, and Renewcell illustrate that circularity is not only technically feasible but already underway.However, systemic transformation requires coordinated policy frameworks (EPR, eco-design mandates), investment in infrastructure, and active consumer participation. Technical barriers such as fiber blends and recycling costs must be addressed through research, innovation, and regulatory incentives. Ultimately, circular fashion is both a sustainability imperative and an economic opportunity. By embracing circularity, the fashion industry can reduce its 92 million tonnes of annual waste, cut its 8–10% contribution to global emissions, and redefine clothing as a regenerative system rather than a disposable commodity. The pathway to a sustainable clothing economy is challenging but achievable through collective action.

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