

Research Article

Textile Waste Recycling: Emerging Technologies, Environmental Challenges, and Sustainable Solutions

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Abstract

The textile and apparel industry has been identified as one of the most resource-intensive sectors globally, with substantial environmental burdens arising from fiber production, dyeing, finishing, and disposal. Textile recycling represents a critical pathway toward sustainable resource management and circular economy implementation. The rapid expansion of global textile production and consumption has intensified the accumulation of textile waste, creating urgent environmental, economic, and social concerns. This review synthesizes current knowledge on textile waste streams, with emphasis on the classification of natural, synthetic, and blended materials and the unique challenges they present for recycling. Emerging technologies including advanced mechanical recycling, chemical depolymerization, enzymatic treatments, and fiber-to-fiber regeneration are critically assessed for their efficiency, scalability, material recovery rates, and environmental footprints. The review further examines key environmental challenges such as microplastic pollution, hazardous chemical release, landfill overuse, and high energy demands associated with traditional waste management pathways. In response to these issues, sustainable solutions such as circular economy frameworks, eco-design principles, closed-loop manufacturing, and policy interventions are discussed. The paper highlights successful global initiatives and industry innovations that demonstrate the feasibility of achieving a circular textile system. Finally, research gaps and future directions are identified to support the transition toward resource-efficient, low-impact textile waste management. This review provides a comprehensive foundation for stakeholders seeking to enhance sustainability across the textile value chain.

Keywords

Textile Recycling, Circular Economy, Mechanical Recycling, Chemical Recycling, Sustainability, Waste Management

1. Introduction

Post-industrial and post-consumer textile waste has accumulated at an unprecedented rate due to the world's fast growth in textile manufacturing and consumption. The textile sector is a major contributor to resource depletion, landfill usage, and greenhouse gas emissions, with an estimated 92 million tons of trash generated annually [12]. Conventional disposal techniques like landfilling and incineration result in a significant loss of valuable raw materials in addition to de-

grading the environment [3]. As a result, recycling textiles has become an important way to minimize waste, recover resources, and lessen the impact on the environment. Based on 15 peer-reviewed research published between 2018 and 2025, this report examines the technological, environmental, and socioeconomic aspects of textile recycling. Textile Waste Generation and Global Context.

One of the biggest and fastest-growing industrial industries

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in the world, the textile and garment industry is becoming more widely acknowledged as a significant cause of environmental deterioration [13]. The production of textile waste at the pre- and post-consumer phases has increased due to rapid industrialization, population growth, and changing consumption habits. Less than 15% of the more than 90 million tons of textile waste produced worldwide each year is recycled or used again [6]. Toxic gasses, microfibers, and greenhouse emissions are released when most of it is burned or dumped in landfills [18].

Global attention has recently been drawn to the development of cutting-edge recycling technology and circular economy (CE) activities due to the desire for sustainable textile production [14]. By using mechanical, chemical, biological, and thermal techniques, textile waste recycling provides a practical means to recover valuable fibers, lessen resource consumption, and reduce environmental contamination. But even with major technological advancements, the industry still faces a number of obstacles, such as fiber deterioration, a lack of waste segregation systems, economic impracticability, and low customer awareness [17].

Defective materials, production leftovers, and post-consumer clothing are the main sources of textile waste worldwide. According to [10], developed economies like the United States, the United Kingdom, and Japan produce the most textile waste per person, while emerging economies like Ethiopia and India are seeing a sharp increase in textile waste as a result of growing industries and rising living standards. Poor recovery rates are caused by ineffective collecting and sorting processes, which exacerbate the issue. According to studies underdeveloped countries frequently encounter extra obstacles such poor infrastructure, low consumer awareness, and lax enforcement of policies [5, 2] Textile waste originates from multiple stages of production and consumption, including fiber preparation, fabric formation, garment manufacturing, and post-consumer disposal. *Pre-consumer waste* (e.g., yarn waste, fabric cuttings, and off-spec materials) is relatively homogeneous and easier to recycle. *Post-consumer waste*, on the other hand, consists of discarded garments with complex fiber blends, dyes, and finishes, making recycling more difficult [16].

2. Recycling Methods

2.1. Mechanical Recycling

The most well-known method is mechanical recycling, which involves tearing, shredding, or carding textile waste into fibers that can be spun into new yarns [4]. Although this method uses less energy than producing virgin fiber, it frequently results in fiber shortening and decreased mechanical strength, hence recycled fibers are best suited for low-value applications such nonwovens, cushioning, and insulation [1]. Product quality has increased as a result of technological advancements like blended with virgin fibers and enhanced

fiber opening machinery. For mechanical recyclers, sorting by fiber composition and color is still a major obstacle [9].

2.2. Chemical Recycling

Depolymerizing synthetic or cellulosic fibers into monomers or other chemical feedstocks that can be repolymerized into new fibers is known as chemical recycling. Polyester and nylon textiles respond very well to this technique [7]. Recent research has examined glycolysis, hydrolysis, and metanalysis as promising methods [2]. Fiber-to-fiber recycling has demonstrated significant promise for cellulose-based textiles by enzymatic hydrolysis or ionic liquid-based dissolution and respinning techniques [11]. Despite these developments, widespread implementation is constrained by high energy requirements and chemical costs.

2.3. Biological/Other Methods

Biological recycling techniques break down natural fibers like cotton and wool into biosurfactants or reusable polymers by using microbes or enzymes. This strategy, while still in its infancy, has environmental benefits, such as low energy usage and little harmful byproducts [6]. Enzymatic hydrolysis has shown promise in recent pilot experiments for the recovery of cellulose fiber and the conversion of biosynthetic polymers (Sustainable Strategies, 2025). Future recycling advances may find the best path through a combination of chemical and biological processes.

2.4. Challenges in Textile Recycling

Textile recycling has several technological, financial, and regulatory obstacles in spite of its potential. Because of their chemical incompatibilities, blended textiles with cotton-polyester or elastane components are especially challenging to recycle. Inadequate sorting technology, inconsistent labeling, and subpar collection infrastructure are additional significant obstacles [8]. Because of their inferior quality and greater processing costs, recycled fibers frequently perform badly economically when compared to virgin materials [10]. Socially, both developed and emerging nations continue to have low levels of consumer engagement in textile return schemes.

3. Opportunities and Circular Economy Approaches

Significant prospects for resource conservation and economic resilience are presented by the shift to a circular textile sector. Reducing textile waste is becoming more widely acknowledged through the use of upcycling, design for recyclability, and material traceability [7]. Extended producer responsibility (EPR) programs are one example of a policy intervention that might encourage industry compliance and

innovation [10]. More effective separation of fiber kinds and hues is also made possible by developments in automated sorting and artificial intelligence [2]. All things considered, textile recycling is highly compatible with the Sustainable Development Goals, especially SDG 12 (Responsible Consumption and Production).

4. Case Studies or Regional Insights

Case studies show that different countries have different results. While government-led programs have enhanced textile collecting systems in Korea, effective sorting and take back programs have helped increase recycling rates in the United Kingdom. Ethiopia and other African countries, on the other hand, struggle with infrastructure, public awareness, and the growth of the recycled fibers market. Initiatives in craft manufacturing and community-based upcycling, however, have demonstrated the ability to create jobs while cutting waste [15].

5. Conclusion and Future Directions

Recycling textiles offers a practical solution to adopt the circular economy and manage materials sustainably. Each of the three approaches mechanical, chemical, and biological has advantages and disadvantages of its own, indicating that hybrid strategies would deliver the best results. Manufacturers, researchers, policymakers, and consumers must work together to overcome the current obstacles. Scalable chemical and biological recycling technologies, better sorting and labeling systems, and regulations encouraging producer accountability and circular design should be the main focus of future research.

Mechanical, chemical, biological, and thermal recycling techniques offer practical means to recover fibers, lessen their negative effects on the environment, and promote circular economy projects. Although mechanical recycling is still the most popular method, it is frequently constrained by mixed-fiber clothing and fiber deterioration. Although chemical recycling has promise for damaged and blended textiles, large-scale application is hampered by high prices and technical complexity. Energy recovery and upcycling offer more chances for sustainable resource use, whereas biological recycling in particular, composting of waste natural fiber has shown advantages for the environment and agriculture. Although technology has advanced, a number of obstacles still exist. Low public awareness, insufficient legal frameworks, limited infrastructure for garbage collection and segregation, and financial difficulties in scaling recycling operations are a few of these. Developing nations like Ethiopia and India encounter additional challenges because of inadequate funding, a shortage of trained labor, and unofficial recycling programs that are not incorporated into official waste management plans.

Prospects for the Future: Technological Innovation: To effectively recycle blended fibers and intricate clothing, further advancements in chemical and mechanical recycling technologies are necessary. Priority should be given to research into energy-efficient procedures and eco-friendly solvents.

Policy and Regulation: Higher collection rates and formalized recycling systems can be achieved by the implementation of supportive policies, such as Extended Producer Responsibility (EPR) and incentives for sustainable textile practices.

Public Awareness and Education: Improving recycling efficiency requires educating consumers and industry stakeholders about sustainable consumption patterns, the advantages of recycling, and the segregation of textile waste. Integration of the Circular Economy: Promoting resource recovery plans, upcycling projects, and circular fashion company models can lessen reliance on landfills while generating income.

Author Contributions

Tesfaye Worku is the sole author. The author read and approved the final manuscript.

Conflicts of Interest

The author declares no conflicts of interest.

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