Wisdom Journal of Science and Technology 1(1), 17-27, June 2025
https://doi.org/10.64848/WJST.1.1.2025.17-27

WISDOM JOURNAL
of Science & Technology

REVIEW ARTICLE

Recycling and upcycling of synthetic textile fibres: Paving a new path of sustainability

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Abstract: The rapid speed of technological innovation and the fast development of quick fashion have deepened global environmental problems, especially because of the massive increase in waste from fashion. Among them, synthetic fibres—mainly made of oil-based polymers like polyester, nylon, and acrylic—are in the great majority. While inexpensive and durable, such fibres are responsible for an enormous contribution to environmental degradation since they cannot be decomposed biologically. This review considers developing methods of recycling and upcycling synthetic textile fibres involving mechanical, chemical, and biotechnological processes and evaluating their potential for a circular textile economy. Although mechanical recycling is practised, it causes fibre degradation over time. In contrast, chemical processes such as glycolysis and depolymerization provide high-purity products at the cost of high energy and financial inputs. However, biotechnological solutions, namely enzymatic recycling through fungal lipases and bacteria, offer an environment-friendly solution, although scalability and infrastructure are currently humongous setbacks. The convergence of digital technologies like AI, blockchain, and IoT has become a game-changing solution, enhancing sorting, traceability, and lifecycle management in textile supply chains. This review also addresses the role that supportive policy landscapes like Extended Producer Responsibility (EPR) and the European Green Deal, a set of policy initiatives by the European Commission to make the EU's economy sustainable, can play in encouraging companies to make changes and innovate approaches to managing waste. Also welcomed is the advent of biodegradable and bio-based synthetic fibres and hybrid blends created to allow for disassembly, which marks hopeful developments for reducing virgin material dependence. In total, recycling and upcycling of man-made fibres not only reduce the amount of waste that goes to landfills but also present the potential for generating value-added products. This article highlights the importance of collaboration across sectors, public education, and technological breakthroughs to overcome the current constraints. By doing this, the textile industry can steer towards a sustainable, resilient, and environmentally conscious future.

Keywords: *Recycling textile waste, Technological advancement, Synthetic fibres, Biochemical recycling, Textile, Circular fashion, Biodegradable*

Introduction

The global textile industry, while a significant contributor to the economy, is also a major source of urgent environmental challenges. With over 92 million tons of textile waste produced annually, a substantial portion of which is synthetic fibres, immediate and decisive action is imperative to address these pressing issues. Synthetic fibres, such as polyester, nylon, and acrylic, derived from petroleum-based polymers, are

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Received: 25/04/25, Accepted: 18/05/25, Published Online: 04/06/25

popular due to their durability and cost efficiency. This underscores the critical importance of continuous innovation and development in achieving a sustainable future [1].

Recycling and Upcycling play crucial roles in these issues. It focuses on converting waste into reusable products and creating high-quality products such as moisture-wicking active wear, insulation materials, Construction composites, and man-made cellulosic fibres [2], [3]. The strategies being used are a circular economy, an economic system aimed at eliminating waste and the continual use of resources, reducing waste generation, and using fewer resources. Ideally, waste management can be done by changing the buying behaviour of the customer or producing cloth, which can be used for a more extended period, and many new concepts are being added in the fashion industry, like rental clothes [4]. The discarded clothes are also reused by other customers through second-hand shops. Therefore, when the garment is no longer wearable, the recycling technique comes into play, like in synthetic fibres like polymer, nylon, microfibers, rayon, and spandex, which can be recycled by different production processes. This review report will focus mainly on recycling synthetic fibres and technological advancements like biodegradable fibre production, which can lead to fantastic opportunities for further innovation.

Globally, as the emphasis on sustainability is growing, the United Nations Sustainable Development Goals (SDGs) have prioritized the waste management of synthetic fibres for policymakers, producers, and consumers [5].

Current State of Recycling Synthetic Fibers

In the present day, the most used method of recycling synthetic fibres is mechanical recycling, especially in thermoplastics like polyethylene terephthalate (PET) [6]. The recycling process presents the shredding of collected raw synthetic fibres, which are then melted and re-extradited to preserve their polymer structure. However, repeating the same method over and over of recycling reduces the quality of the fibres, making it unsuitable for further high-performance applications [4].

Biotechnological solutions, which utilize enzymes to degrade synthetic fibres into reusable materials, are emerging as potential game-changers in the recycling industry. This innovative approach, with its potential to overcome the limitations of conventional methods, offers a hopeful and promising outlook for the future of recycling. Although scalability and cost barriers currently limit its widespread adoption, the use of enzymes and liquids, such as commercial fungal lipases and various bacteria, to dissolve synthetic fibres for regulatory or other uses offers a promising avenue for future research and development as explained by Tripathi et al. [7].

Chemical recycling presents limitations, such as breaking the polymers into monomers for re-polymerization. Different technologies, such as depolymerization and glycolysis, are more often used to produce polyester fibres. These methods yield very high purity yields, and production is almost equivalent to newly formed fibres [8].

Recent advancements in enzymatic recycling offer a better, eco-friendly alternative. This method uses biological catalysts to break down polymers, reducing energy use and consumption and harmful by-products (Figure 1) [1].

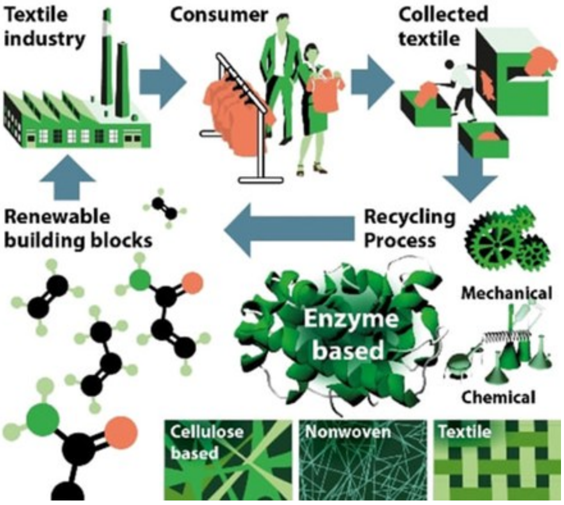

Figure 1 Recycling processes [9]

Environmental and Economic Impact

Recycling and upcycling synthetic fibres play a crucial role in reducing the environmental waste generated by the textile industry (Figure 2). By diverting waste from landfills, reducing gas emissions, and preventing water and soil contamination, these practices make a significant and encouraging contribution to environmental sustainability [4]. The European Environment Agency estimates that recycling one ton of polyester saves 7,000 litres of water and reduces consumption by 60%, underscoring the positive impact of these practices, as mentioned by Midolo et al. [11]. Treating water waste materials, particularly in pollution redemption, can utilize synthetic waste materials to repurpose them environmentally (Figure 3). This reduces contaminants and curbs environmental degradation. Reusing synthetic fibres offers cost-effective solutions, provides value-added products, and performs sustainable practices [13].

It generates new revenue streams for the business and branding products such as eco-friendly construction materials and textile industries. Bio-upcycling techniques such as viscose/polyamide textile blends transform waste into biopolymers and fibres, reducing the reliance on virgin synthetic materials and the greenhouse effect [3].

Figure 2 Synthetic textile and plastic waste (self-captured)

Figure 3 Plastic waste collected from seas [10]

From an economic perspective, upcycling and recycling man-made fibres are of tremendous value to businesses and society. It minimizes the use of virgin raw materials, thus decreasing the cost of manufacture in the long run. Businesses can exploit alternate revenues while improving their corporate image through sustainability positioning by recycling aged textiles for value-added products such as building products, insulating panels, and high-end textile fabrics [3]. Developing the circular economy in textiles also provides employment opportunities in sorting, processing, and innovation-based industries. Extended Producer Responsibility (EPR) policies also prompt businesses to invest in effective waste management systems, making compliance a competitive advantage [5]. Although initial investment in recycling facilities may be high, long-term cost savings and market incentives may offset these expenses, making sustainability economically attractive to the textile industry. New initiatives like the European Green Deal, a set of policy initiatives by the European Commission with the overarching aim of making Europe climate neutral by 2050, and extended producer responsibility (EPR) programs, which make producers responsible for the entire life cycle of their products, are paving the way for a more sustainable future. By encouraging companies to adopt these kinds of sustainable practices, these initiatives address synthetic waste accumulation and reduce the environmental footprint [11].

Advancements in Upcycling Technologies

The recycling industries are now witnessing significant new ways of innovation that aim to enhance efficiency and sustainability. For example, integrating waste textiles into the circular economy has become a crucial focus, with upcycling the fibres from waste into high-value products like biopolymers, construction materials, and man-made cellulose fibres [11]. Different hybrid processes also combine mechanical and chemical processes to have better ways of overcoming individual limitations, therefore improving the overall production and the quality of the recycled fibres [3].

Upcycling technologies are also redefining how synthetic fibre waste is being utilized, transforming it into valuable products with better functionality and environmental benefits. For example, PET bottles (Figure 4) are increasingly being recycled into high-performance textiles, such as moisture-wicking fabrics used in different active wear like raincoats, umbrellas, boots, etc. This way of recycling not only reduces landfill waste but also helps meet the growing demand for sustainable materials in the fashion industry [2]. New innovations in material science have also enabled the development of composite materials from synthetic waste. These composites are then used in construction, aerospace, and automotive industries, etc. Additionally, advancements in recycling technology, such as chemical treatments, have improved their structural properties, making them more suitable and demandable by industries [7].

Figure 4 Sorting process of PET bottle wastes [12]

Many regional advancements, such as Europe's mapping textile waste recycling technologies, reveal the importance of frameworks and driving innovations—for instance, initiatives in Spain for effective and coordinated waste collection [1]. Collaborative efforts among designers, manufacturers, and researchers are also upcycling innovation in this field. For instance, new initiatives are being held in the European Union, such as creating designer apparel from water waste and second-hand textile products. These projects highlight environmental awareness and upcycle economic potential [14].

Digital Technologies in Textile Recycling

Digitalization of the textile recycling sector is increasingly considered the necessary drive to sustainability. Emerging technologies such as artificial intelligence (AI), blockchain, and the Internet of Things (IoT) are being used to sort machines and supply chains to reverse inefficiencies and un-traceability [4]. Circular fashion demands a good grasp of material flows, and digital technologies are crucial in ensuring recycling routes are more transparent and traceable.

Blockchain, for instance, offers a secure and tamper-proof mechanism to record every step of a textile product's life cycle—from raw material sourcing to end-of-life recycling. This facilitates increased trust and accountability among players in the textile value chain. Additionally, AI-powered image recognition technology is being used in sorting plants to detect and sort fibres more precisely than traditional manual processes. This directly enhances recycling efficiency and minimizes contamination during processing [4]. Additionally, digital twins and analytics can reduce wastage by simulating the impact of design choices on recyclability. With smart manufacturing trending among industries, IoT-based sensors in clothing can monitor usage habits and set optimal end-of-life strategies, as shown by Hallikas et al. [15]. Digital technologies also enhance material tracing and supply chain risk management, vital in a complex and globalized textile value chain.

A digitally empowered textile sector reinforces extended producer responsibility (EPR) through the ability of producers to trace the lifecycle of their products and impose take-back programs. A feedback loop can inform design changes based on real reuse or recycling experiences, minimizing total waste creation [15].

Innovative Ideas for Waste Management

Biodegradable synthetic fibres present a promising solution for the growing environmental concerns associated with synthetic waste generation. The dual functionality of natural, synthetic polymers in biomedical and environmental applications highlights their detailed degradation rates and importance for specific needs [16]. It gives a broader perspective on the sustainability aspects of natural-fibre-reinforced polymers and their potential to reduce dependence on petroleum-based products [17]. It emphasizes the significance of biodegradable alternatives for medical equipment by addressing the problems of mechanical strength and regulatory barriers and points out major advancements in material science [18].

Investigating the basic structure composition of plant fibres into composites focuses on innovative treatment methods to enhance the compatibility of the products and performance in contemporary applications [19]. The global trajectory of plastic use is projecting significant shifts toward bioplastics by 2050 while underscoring the challenges of scalability and cost-effectiveness [20].

Innovations in synthetic fibre blends are transforming the production, consumption, and recycling of textiles. Due to their heterogeneity, traditional fibre blends like cotton-polyester are notoriously difficult to recycle. Recent efforts have, however, sought to develop blends that can easily be broken down or upcycled [21], offering a new pathway to upcycle cotton-polyester blends into new man-made cellulose fibres. Their research is a classic example of a solvent-based solution to the selective dissolution of cotton without damaging the polyester. Isolated fibres are then reorganized into high-value textile materials, offering a desirable solution to one of the biggest recycling headaches for the industry.

In another study, Midolo et al. [11] investigated the application of synthetic and natural fibre blends in green building uses like acoustic panels and insulation. These composite materials redirect waste to landfills and bring a value-added option to traditional building products. The success of these blends in buildings opens new avenues for textiles to maintain their life cycles beyond fashion [22], highlighting how thermal treatment processes such as annealing can improve the structural integrity of mixed synthetic fibres. Such processes are essential to guarantee that recycled or upcycled fibres can achieve the mechanical specifications of contemporary textiles. When used in conjunction with advanced spinning technologies, blended fibres can now equal or even excel past conventional materials in elasticity, durability, and aesthetics.

Further innovation manifests itself as bio-based synthetic blends, where recycled synthetics are mixed with bio-based polymers to introduce biodegradability without compromising performance. Thus, there is a hybrid solution that meets economic and environmental objectives.

However, scaling up these innovations will present challenges. Blends should be designed to consider end-of-life conditions, e.g., separability by chemicals or mechanical means [21]. This affirms that pre-treatment and sorting technologies must evolve to mass recycling such fibre blends.

Design-for-disassembly ideologies are gaining traction as sustainability gains more emphasis in designers' consciousness. These entail designing clothing using products and materials that can be easily sorted and recycled by existing or future technologies. Coupled with traceability systems based on blockchain, these innovations can guarantee that synthetic blends cannot become an environmental liability.

Challenges in Textile Recycling

The complexity of textile waste production streams produces many significant challenges for recycling. The biggest issue is the presence of mixed fibre waste, such as polyester-cotton mixtures, which are very difficult to separate using conventional methods. In these processes, chemical treatments are often required to isolate individual components, which is very resource-intensive and costly [23]. Moreover, blended textiles like cotton-polyester mixes complicate the recycling process [21].

The economic difficulty of recycling synthetic fibres remains a concern because of high-cost chemical processes and larger infrastructure development requirements. The lack of this availability hinders widespread adoption. However, the growing demand for sustainable products increases the regularity of compliance and investments in this sector. For example, the European Union also focuses on Circular economy principles, which have accelerated the research and development of new innovative recycling ideas and technologies [5], [24].

Another challenge is that it might be contaminated by dyes, coatings, and other chemical finishes that could have been used during its manufacturing process. These contaminations affect the efficiency of the recycling process and decrease the quality of the recycled fibres. However, advanced technologies like solvent-based extraction and thermal depolymerization are now creating better ways of solving these issues [25].

Although biodegradable fibres offer a potential new direction away from conventional synthetic fibres, upscaling their production is fraught with several challenges. The material performance ranks high among these challenges. Several biodegradable fibres, like polylactic acid (PLA), polyhydroxyalkanoates (PHAs), and starch polymers, remain as mechanically strong and heat-resistant as required for general use in textiles [18].

In addition, biodegradable fibres tend to have a short lifespan and are prone to premature degradation in specific environmental conditions. This may be an issue in fashion uses where strength is paramount. Verschatse et al. [26] performed in-situ SEM mechanical testing on electro-spun polymeric nanofibers and concluded that microscale deformation considerably impacts the lifespan of these biodegradable substitutes. New products that balance sustainability, strength, and durability must be invented for biodegradables to become substitutes for traditional fibres at scale.

Economic constraints also act as a barrier to scalability. Greater raw material expense, specialized processing equipment, and lower production rates make biodegradable fibres significantly more expensive than their petroleum-based counterparts [18]. In contrast to the synthetic fibres manufactured at scale with established technologies, bio-based fibres remain in the nascent stages of commercialization, and there is little manufacturing infrastructure present worldwide.

Additionally, standardization problems exist. The absence of universal testing and standards makes it difficult to assess the environmental claims of biodegradable textiles. This absence of clarity does not encourage big brands and customers to use such materials.

Environmental impact evaluations add to the complexity of scalability. Though such fibres are described as green, such as feedstock agricultural production of corn for PLA, deforestation, uncontrolled water usage, and pesticide contamination may be produced unless produced ethically. Closed-loop systems based on waste biomass for the production of biodegradable fibre are thus being developed as a more environmentally friendly option [18].

Research is moving toward composite structures with synthetic and biodegradable constituents to overcome such challenges. However, retaining complete biodegradability in hybrids remains a work in progress. Advanced treatment processes such as controlled annealing and nano-reinforcement are being explored to improve the properties of such fibres [22].

Consumer perception is also the biggest barrier in textile recycling because many consumers differentiate recycled products from new-formed products, comparing their inferior quality and durability. Education campaigns that provide consumers with improved aesthetics and functional properties of recycled products can be a critical way of overcoming this stigma [27].

Future Outlook

The textile industry is now moving towards sustainability, which hinges on the widespread adoption of recycling and upcycling technologies. While some significant ideas and progress have been made, it is still far from achieving a fully circular economy. Investments in these sectors are crucial for overcoming technical development barriers, such as improving the efficiency of the sorting process and other processing technologies. This highlights the continuous innovation and development happening to achieve a sustainable goal in textile recycling and upcycling.

Consumer behaviour is also playing a vital role in this goal. Educating people about the environmental and economic benefits of recycled and upcycled synthetic fibre products can foster great sales and production. Aiming for sustainable, high-quality products and reducing global textile waste, biodegradable synthetic fibres will become key in the transition toward sustainable materials, but further innovation in durability, scalability, and cost reduction will be needed.

Further, collaborating with the government, different industries, and academia will also help recycling companies with their financial support and technological development. Joint efforts can help in large-scale solutions and establish a global standard of textile waste management, unlocking new economic opportunities and a clean environment.

Figure 5 draws attention to the global statistics overview of the growing problem of plastic/biodegradable and synthetic fibre waste created from it, calling for immediate government responses. Although the production of plastics is increasing and expansion further unfolds globally, governments have a growing need to formulate much stronger policy frameworks dealing with waste generation and its environmental impacts. By 2035, carbon waste from plastics is expected to be at par with fish waste, which bodes an even more compelling reason for immediate action. Governments must put stricter regulations on single-use plastics, develop recycling technologies to manage plastic wastes and compel industries to switch to biodegradable alternatives. Countries in developing states must be helped to implement adequate waste management strategies.

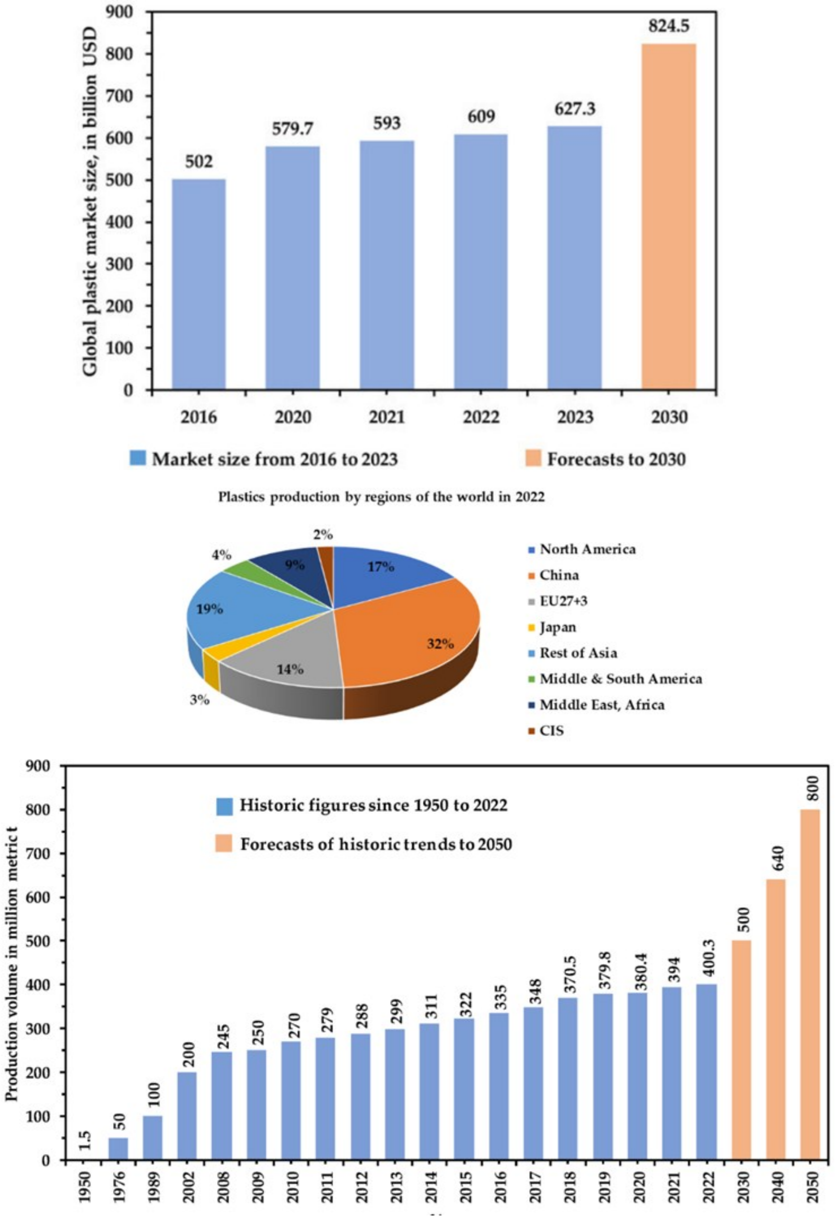

Figure 5 Global statistics of plastic waste generation [28]

In contrast, developed states such as the U.S. and the U.K. must provide leadership by implementing excellent waste management systems since they incidentally have the highest per capita production of plastic waste. All such policies must be healthy for the entire world to ensure the continuity of implementing policies such as EPR and increase awareness programs. Sustainability and research investments are effective ways of bringing the government into alignment on the issue of synthetic fibre waste and a clean and healthy environment.

Conclusion

The recycling and upcycling of synthetic textile fibres represent key steps forward in mitigating the immediate environmental and economic concerns related to the global textile industry. According to this report, because synthetic fibres are less expensive than their natural counterparts and more durable, the textile market has been dominated by synthetic fibres derived primarily from petroleum-based polymers such as polyester, nylon, and acrylic. Their massive production, however, also winds up hugely contributing to enormous waste generation, resource depletion, and environmental degradation. The existing recycling processes (mechanical, chemical, and biochemical) provide much promise toward addressing these problems, but each is a victim of limitations in one or many places. Mechanical recycling is widely underway but compromises the fibre's quality in several infrequent cycles. Chemical recycling has increased purity since some polymers can be reverted to their monomer components; however, it is still resource-hungry and costly. There are emergent biotechnological methods for recycling, enzymatic recycling being one, but these indeed come with issues surrounding scalability and economic feasibility. These inhibit the feasibility, which accentuates necessity-rich innovation to raise efficiency, decrease cost, and increase broad acceptance. On the other hand, upcycling has grown into an innovatively transformative approach that diverts waste from landfills and fosters the development of high-value products.

Innovations in, for example, converting synthetic waste into biopolymers, advanced composites, and functional textiles show upcycling's potential to redefine waste as a resource. This aligns with the principles of a circular economy, which optimizes sustainability by reducing virgin inputs and minimizing environmental footprints. Still, despite such development, challenges remain. Mixed fibre composition sets in motion contamination with dyes and chemical finishes while the prohibitive cost of production remains among the great hindrances to achieving meaningful recycling outcomes. Most important, perhaps, is the public's perception that recycled products are inferior in quality, which suggests that awareness campaigns may help the possessor's mind-set and promote sustainable consumption patterns. Education and engagement will also be critical to eliminating barriers and improving the demand for environmentally friendly products. On a global scale, the regulatory responsibilities of politically recognized waste management programs such as the European Green Deal and Extended Producer Responsibilities (EPR) set a stage for innovation and investment in textile waste management. In turn, they have encouraged manufacturers toward sustainable production practices, improved waste collection methods, and the integration of recycling and upcycling technologies. Only strong institutional collaboration among government, industry, researchers, and consumers will succeed in scaling solutions and addressing the challenges of textile waste systems. Recycling and upcycling synthetic fibres entail great environmental and economic benefits. Environmentally, they reduce greenhouse gases, conserve water, and avert contaminants to soil and water. Economically, they open additional revenue streams, generate new jobs, and facilitate economic alternatives to the existing fossil fuel-based manufacturing process. Accordingly, recycling and upcycling foster sustainable development by adding value to waste while countering additional environmental impacts in the textile industry. Yet, to realize a whole circular economy in textiles, future efforts must focus on innovation, infrastructure investment, and scalable technologies. Emerging sorting and processing methods, coupled with advances in material science, can solve technical limitations and improve recycled fibre quality.

Meanwhile, fostering a collaborative outlook across sectors can accelerate progress and set international sustainable textile waste management standards. In conclusion, the recycling and upcycling of synthetic textile fibres are essential in achieving environmental sustainability and economic resilience in the textile industry. While challenges still loom, the achievements so far promise transformative change. If we leverage innovations and invest in consumer education and policy support, the world can gather some good prospects for a sustainable future. When the sum of this works out together, it will change the legacy of the textile world from waste and pollution into maturity and regeneration within the framework of sufficiency for the continuance of a healthier planet for future generations.

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