From Waste to Worth: Integrating Textile Byproducts into Composites

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Summary

The growing volume of textile waste presents both environmental challenges and opportunities for sustainable material development. Repurposing textile fibres from cotton, wool, polyester, nylon, and other sources into composite materials offers an effective strategy to reduce reliance on landfills while conserving natural resources. Textile waste–based composites have been applied in construction, automotive components, furniture, sound-absorption materials, polymer concrete, and packaging. Expanding the use of textile waste in composite systems supports circular-economy principles and provides a practical pathway for sustainable waste management.

By valorizing textile waste in high-value applications, the environmental burdens associated with landfilling and incineration are reduced, as is energy consumption and the demand for virgin raw materials.

Textile Waste and Opportunities for Composite Materials

Global population growth over recent decades, driven by migration and socio-economic transformation, has intensified demand for natural resources and increased environmental pressures. The global population of approximately 7.6 billion is projected to reach 9.8 billion by 2050, with nearly 70% residing in urban areas [1, 2]. Rapid urbanization exacerbates climate change impacts, water scarcity, land degradation, and biodiversity loss, underscoring the urgent need for sustainable resource management. This growth directly increases textile consumption and accelerates waste generation, necessitating effective waste-management strategies. Textile fibres are essential across a wide range of industries; however, their production relies heavily on primary resources and contributes significantly to environmental pollution.

The textile sector is responsible for approximately 10% of global carbon emissions [3]. Cotton, the most widely used natural fibre, is typically cultivated in water-intensive monocultures, often using genetically modified seeds, which can lead to soil degradation and biodiversity loss [4, 5]. The production of one kilogram of cotton requires between 7,000 and 29,000 litres of water and 0.2–1.1 kilograms of oil [6, 7]. Wool production also imposes environmental burdens, including land erosion and methane emissions from livestock [8, 9]. Synthetic fibres (including polyester, nylon, acrylic, and polypropylene) account for nearly 70% of global textile production. Derived primarily from petroleum and manufactured through energy-intensive processes, these fibres generate substantial carbon emissions throughout their life cycles [7, 10].

Recycling textiles offers significant environmental advantages compared with landfilling or incineration, which release leachate, greenhouse gases, dioxins, and heavy metals into the environment [11, 12]. The fast-fashion industry, characterized by short garment lifespans and rapid product turnover, has further accelerated textile waste generation. Global fashion waste reached approximately 92 million tons in 2015 and is projected to increase to 148 million tons by 2030 [13]. In the European Union, approximately 5.8 million tons of post-consumer textile waste are generated annually, with only about one-quarter being recycled or incinerated [14, 15]. Initiatives such as the **New South Wales Circular Threads Program** aim to reintegrate discarded textiles into new value chains; however, economic feasibility, fibre degradation, and residual hazardous chemicals remain key challenges [16–18]. As a result, multi-stage recycling strategies are increasingly being explored to maximize material recovery and enable applications beyond conventional textile reuse [19].

The textile sector generates nearly 100 million tons of waste annually while consuming approximately 80 trillion litres of water worldwide [20–22]. Global textile production has increased from 78 million tons to more than 103 million tons over the past decade, driven by population growth and evolving fashion trends [23]. Cotton dominates natural fibre production, while polyester leads synthetic fibre output [24]. Cotton accounts for approximately 24% of textile waste, with denim alone generating about 2.16 million tons annually, most of which is landfilled [25–28]. High-value fibres such as silk contribute an estimated 11 million tons of waste each year. Shortened garment lifespans and increasing production rates indicate that textile waste will continue to rise alongside projected population growth, which is expected to reach 8.6 billion by 2030, 9.8 billion by

2050, and 11.2 billion by 2100 [29–31].

Regional data further illustrates the magnitude of textile waste generation. The global textile and apparel market is projected to exceed 100 million tons by 2025, growing at a compound annual rate of 3.7% [32]. In 2018, global fibre production surpassed 107 million tons [33]. Annual textile waste generation is expected to reach approximately 26 million tons in China, 12.4 million tons in the United States, and 1 million tons in the United Kingdom [32]. Between 1998 and 2009, textile waste in the United States increased by 40%, while only about 2% was diverted from landfills, motivating zero-landfill targets by 2037 [34]. In the European Union, approximately 5.6 million tons of textile waste were generated by 2013, with only 20% reused or recycled and 1.5 million tons exported [35]. China produces more than 20 million tons annually while recycling less than 10% [36]. Similar challenges are reported in regions such as Hong Kong, Portugal, and Spain, highlighting the environmental risks and resource losses associated with landfill and incineration disposal [37–39].

Types of Textile Waste

Population growth has driven a steady increase in textile production, which in turn has led to a significant rise in textile waste generation [40]. This waste stream is generally categorized into industrial, pre-consumer, and post-consumer textiles, reflecting differences in their sources, material composition, and potential pathways for recovery and recycling [40,41].

Industrial textile waste originates from applications such as ropes, conveyor belts, medical textiles, and carpets and is often relatively uniform, facilitating collection and recycling (Figure 1). However, high-performance fibres, including fire-retardant, chemical-resistant, and specialty materials, remain difficult to recycle due to complex formulations and contamination. Single-use medical textiles represent a growing waste stream that could be diverted from incineration if appropriate sterilization and recycling protocols were implemented [28]. The global technical textile market, valued at approximately 175.73 billion USD, highlights the significance of industrial and specialty textiles in overall waste generation [42]. Targeted waste-management strategies are therefore essential to address the challenges associated with high-performance and specialized textile applications.
applications.

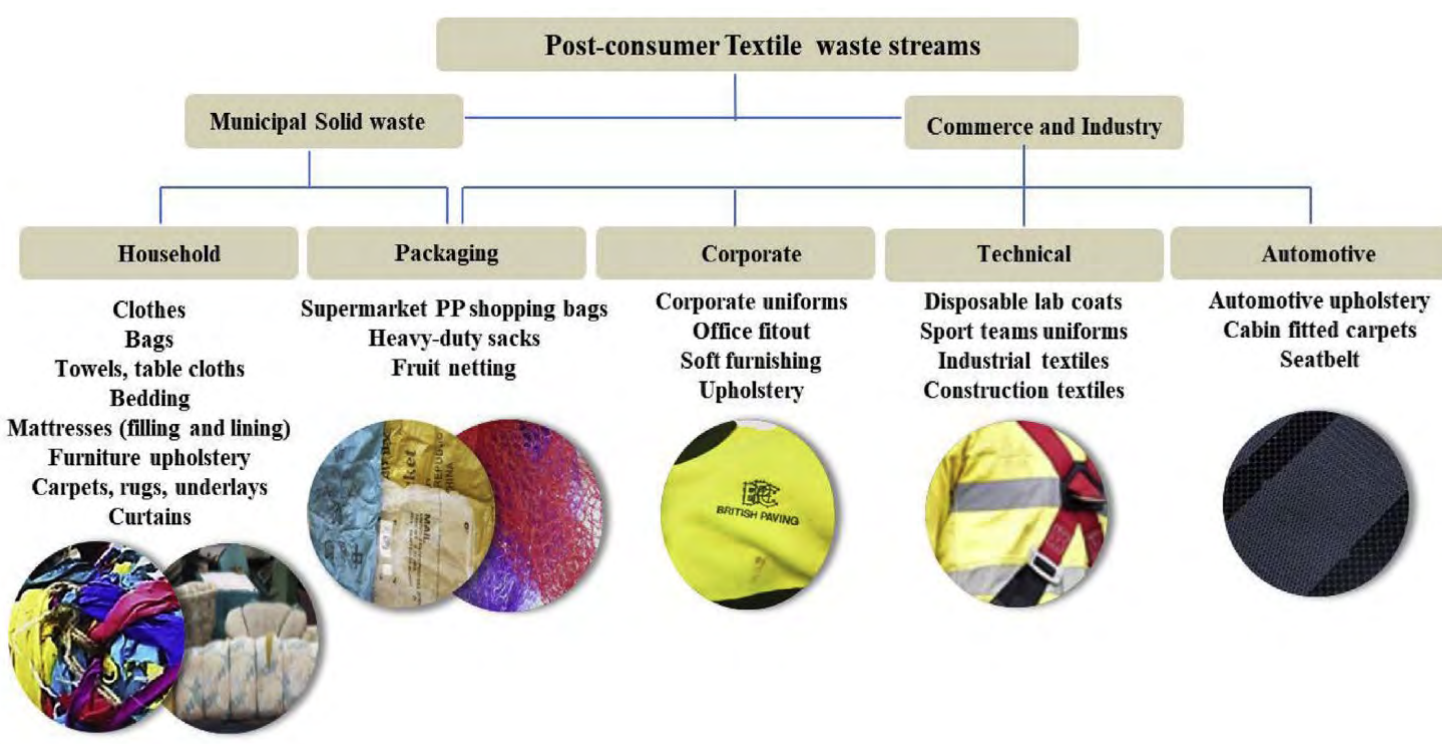

Figure 1: Typical Post-Consumer Textile Waste Streams [31].

Composites from Textile Waste

Composite materials, consisting of a reinforcement phase embedded within a matrix, provide a promising pathway for the sustainable utilization of textile waste. Reinforcements contribute strength and stiffness, while matrices bind and protect fibres from environmental degradation. Composite matrices may be thermosetting or thermoplastic; thermosets typically offer superior mechanical performance but are difficult to recycle, whereas thermoplastics generally exhibit lower stiffness but improved recyclability [43]. Large volumes of textile fibre waste are currently landfilled or incinerated each year, contributing to groundwater contamination, greenhouse gas emissions, and significant resource loss [44]. Recycling textile fibres into composite materials reduces environmental impacts, conserves energy, and decreases reliance on virgin raw materials throughout the product life cycle [45, 46]. Textile waste fibres have been successfully incorporated into composites using recycled nylon and polypropylene from carpet waste [47], polyamide from tire waste [48], and natural fibres such as cotton [49], polyester [50], wool [51], and silk [52] derived from woven, nonwoven, and knitted fabrics. Resulting composites have been applied in construction materials [46], sound-absorption systems [53], automotive components [54], furniture [55], polymer concrete [50], and food-packaging applications [56].

Processing textile waste into composites remains challenging because natural and synthetic fibres exhibit distinct mechanical and chemical behaviours, requiring selective separation and tailored treatment methods. Depending on fibre composition and matrix selection, the resulting composites may be biodegradable or non-biodegradable [57–87]. Advances in mechanical and chemical recycling technologies have improved fibre recovery and composite performance, supporting more effective circular material flows. Mechanical blending of mixed textile fibres, such as cotton–polyester blends, into thermoplastic matrices, including polypropylene or polyamide, can yield composites with balanced strength, stiffness, and thermal stability, particularly when compatibilizers such as maleic anhydride or glycidyl methacrylate are employed. These hybrid composites can be manufactured using conventional extrusion and moulding equipment commonly available in the plastics industry, providing an accessible and scalable pathway for near-term adoption in automotive, furniture, and construction sectors.

Recycled textile fibres have also been integrated into nonwoven insulation materials that exhibit thermal and acoustic performance comparable to mineral wool while offering reduced energy use and lower carbon footprints. When incorporated into cementitious or hybrid concrete systems, textile fibres enhance crack resistance, impact strength, and toughness, while permanently encapsulating non-biodegradable fibres within durable infrastructure. The illustrated composite panel manufacturing process demonstrates a scalable mitigation strategy, converting mixed textile waste into value-added components through mechanical shredding, melt blending, and compression moulding (Figure 2). This approach can be implemented within existing polymer processing or municipal recycling facilities with minimal equipment modification, making it a practical circular-economy intervention.

To fully realize these benefits, automated fibre-sorting technologies and standardized certification systems are critical. **Near-infrared (NIR)** spectroscopy and optical recognition systems enable the separation of natural and synthetic fibres, improving feedstock consistency. Certification frameworks such as the **Global Recycled Standard (GRS)** and ISO-compliant labelling systems enhance traceability and consumer confidence. From an engineering perspective, mechanical recycling combined with automated sorting and certified verification represents the most practical near-term strategy. Medium-term priorities include optimizing processing parameters and compatibilizer chemistry, while long-term solutions may incorporate chemical depolymerization and design-for-disassembly principles to achieve a fully closed-loop textile-to-composite manufacturing system.

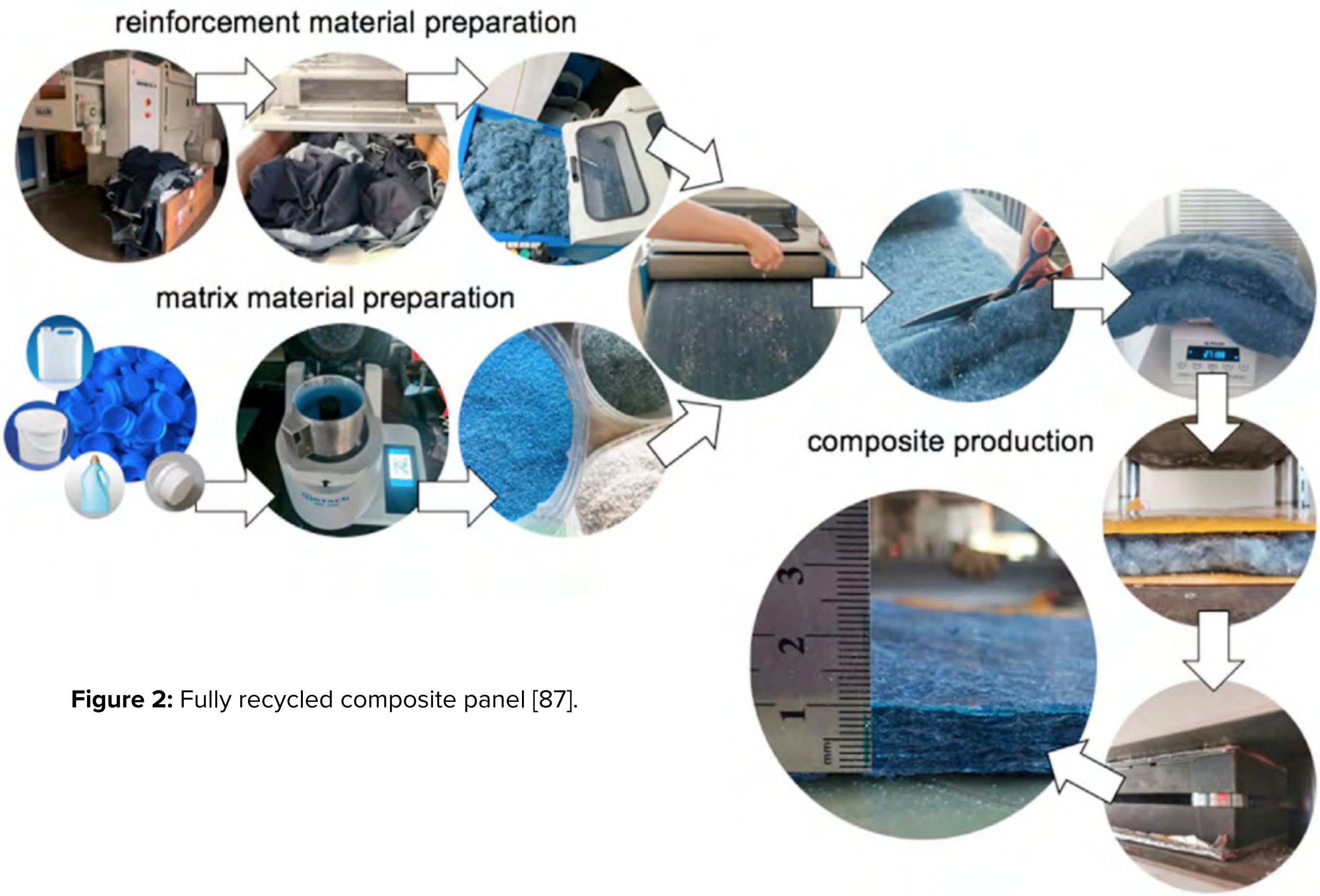

Figure 2: Fully recycled composite panel [87].

Global Recycling and Policy Frameworks

Waste-management capabilities vary widely between developing and developed regions. The European Union has implemented comprehensive directives addressing environmentally responsible waste generation, including regulations covering packaging waste, landfilling and incineration, pollution prevention, end-of-life vehicles, and electronic waste. Japan enforces waste-management and public-sanitation regulations encompassing recycling of containers, packaging, construction materials, home appliances, and food waste [87]. In the United States, the **Environmental Protection Agency** regulates hazardous waste, recycling programs, chemical safety, pollution control, oil spills, and toxic substances [88]. Regulations governing organic waste have become increasingly stringent. In 2016, the European Union banned the landfilling of organic materials, including most textile waste [89]. Textile and agricultural by-products are now prioritized waste streams; however, effective recycling systems remain limited. In 2020, textile waste generation reached approximately 1.7 million tons in the United Kingdom, 15.1 million tons in the United States, and 26 million tons in China, while recycling rates remained low [23, 27].

In Canada, textile recycling remains minimal, with nearly 98% of textile waste sent to landfills. In 2020, approximately 280 kilotons of synthetic textiles were discarded [90]. A 2023 **University of Waterloo** study reported that Canadians generate nearly 500 million kilograms of textile waste annually, with approximately 85% disposed of in landfills [91]. While programs such as Recycle BC operate in parts of British Columbia, nationwide participation remains limited. Textiles account for approximately 7% of plastic waste in Canadian landfills, ranking third after packaging and automotive materials [92]. As textiles have only recently been recognized as a distinct waste category, no unified national definition currently exists; the **American Society for Testing and Materials (ASTM)** defines textiles as fibres, yarn intermediates, yarns, fabrics, and end-use products that retain the strength, flexibility, and functional properties of the original material.

These findings underscore the urgent need to expand textile-recycling infrastructure in Canada. Strengthening recycling programs, improving policy coherence, and increasing public awareness are essential steps toward reducing landfill dependency and advancing a circular economy for textiles.

Conclusions

Rapid growth in textile production has led to escalating textile waste and associated environmental impacts. Conventional disposal through landfilling and incineration results in resource loss and greenhouse gas emissions, whereas the conversion of textile waste into composite materials offers a technically viable and environmentally beneficial alternative. Textile waste–based composites can be produced using established mechanical recycling routes and conventional polymer-processing technologies, enabling near-term implementation within a circular-economy framework. Advances in fibre sorting, compatibilization, and processing have demonstrated that mixed textile waste can be incorporated into thermoplastic and cementitious matrices with competitive mechanical, thermal, and acoustic performance while reducing reliance on virgin raw materials. Despite this potential, large-scale adoption remains limited by fragmented collection systems, inadequate sorting infrastructure, inconsistent waste definitions, and insufficient policy support, particularly in Canada. Addressing these barriers requires coordinated action across engineering and regulatory domains, with engineers playing a key role in system design, process optimization, life-cycle assessment, and standard development. To stimulate policy discussion and accelerate implementation, the following targeted actions are recommended:

1. **Integrate textiles into Extended Producer Responsibility (EPR) frameworks**, requiring producers and importers to finance collection, sorting, and recycling systems, with eco-modulated fees that incentivize recyclable and mono-material textile designs.
2. **Establish standardized national definitions and reporting requirements for textile waste** to enable consistent data collection, performance benchmarking, and evidence-based policymaking.
3. **Invest in centralized textile sorting and pre-processing infrastructure**, including near-infrared and optical fibre-identification technologies, through public funding and public–private partnerships.
4. **Prioritize high-value textile-to-composite applications through targeted incentives**, such as tax credits, innovation grants, and landfill surcharges, to discourage downcycling and energy recovery.
5. **Incorporate recycled textile composites into public procurement policies, building codes, and infrastructure standards** to create stable market demand and reduce adoption risks.
6. **Support certification, labelling, and traceability systems** aligned with established standards to ensure material quality, transparency, and consumer confidence.
7. **Fund applied research and pilot-scale demonstration projects** that bridge laboratory research and industrial implementation, with emphasis on durability, scalability, and life-cycle performance.

Together, these measures provide a realistic pathway toward an integrated circular system in which textile waste is systematically diverted from landfills and transformed into high-value composite materials. By aligning engineering innovation with supportive policy frameworks, textile waste can be repositioned from an environmental liability to a strategic resource within sustainable materials manufacturing.

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