Role of Bio-Based Fibers in Sustainable Textile Development: Environmental Benefits and Future Prospects

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Abstract

The textile industry significantly contributes to environmental pollution through high water consumption, carbon emissions, and chemical waste. Bio-based fibers have emerged as sustainable alternatives to conventional synthetic textiles due to their renewability, biodegradability, and lower environmental impact. This review examines natural, regenerated, and bio-engineered bio-based fibers and their role in sustainable textile production. Fibers such as hemp, flax, jute, lyocell, and polylactic acid (PLA) demonstrate reduced water use, chemical consumption, energy demand, and carbon emissions. The study also highlights the importance of circular economy practices and sustainable processing technologies in minimizing environmental burdens. Despite challenges related to cost, scalability, and processing, advancements in bio-based textile technologies offer strong potential for environmentally responsible and circular textile production aligned with the United Nations Sustainable Development Goals (SDGs).

Keywords: Eco-friendly textiles, bio-based fibers, sustainable development, biodegradable fibers, circular economy, sustainable processing, environmental sustainability, textile innovation.

Introduction

The concept of sustainability was formally introduced in 1987 in the Brundtland Report, defined as “meeting the needs of the present without compromising the ability of future generations to meet their own needs” (1). Eco-friendly textiles refer to fabrics produced using sustainable materials and processes that minimize environmental impact through reduced water and energy consumption, limited chemical usage, and the incorporation of renewable or recycled resources. Bio-based fibers such as flax, hemp, jute, lyocell, and polylactic acid (PLA) are increasingly being explored as alternatives to petroleum-based fibers. Studies indicate that these fibers reduce water demand by **60 ± 3%** and chemical load by **45 ± 2%**, while biodegradable composites exhibit over **95% degradation within 180 days** under controlled composting conditions (2).

In addition, bio-engineered fibers—developed through microbial fermentation and genetic engineering—such as recombinant spider silk, bacterial cellulose, and polyhydroxyalkanoates (PHAs), offer enhanced mechanical properties and reduced environmental footprints. These innovations highlight the potential of bio-based textiles in advancing sustainable development. However, despite increasing research in this area, a comprehensive synthesis comparing different categories of bio-based fibers and their quantified environmental benefits remains limited. Therefore, this review aims to analyse the types, properties, environmental advantages, and challenges of bio-based fibers in the context of sustainable textile development.

1. Bio-based Fibres: Types and Characteristics

Bio-based fibers are defined as textile materials derived wholly or partially from renewable biological sources, including plant, animal, and microbial feedstocks. In comparison with conventional fossil-fuel-based synthetic fibers, bio-based fibers demonstrate enhanced environmental performance due to their renewable origin, potential biodegradability, and reduced consumption of water, energy, and carbon-intensive resources, while still providing acceptable mechanical and functional properties. Accordingly, their adoption contributes to a measurable reduction in the environmental footprint of textile manufacturing and aligns with global sustainable development objectives.

In recent years, bio-based fibers have gained increasing attention in textile research as next-generation materials capable of addressing critical challenges such as microplastic pollution and resource inefficiency. The existing literature broadly classifies these fibers into natural bio-based fibers, regenerated bio-based fibers, and bio-engineered fibers, **as illustrated in Figure 1**. Previous studies further indicate that a wide range of experimental treatments and processing strategies are being explored to optimize their structural, mechanical, and functional performance, enhance biodegradability, and enable effective circularity. Collectively, these advancements position bio-based fibers as key contributors to the development of a more sustainable and circular textile industry.

The classification of bio-based fibers into major categories is presented in Figure 1

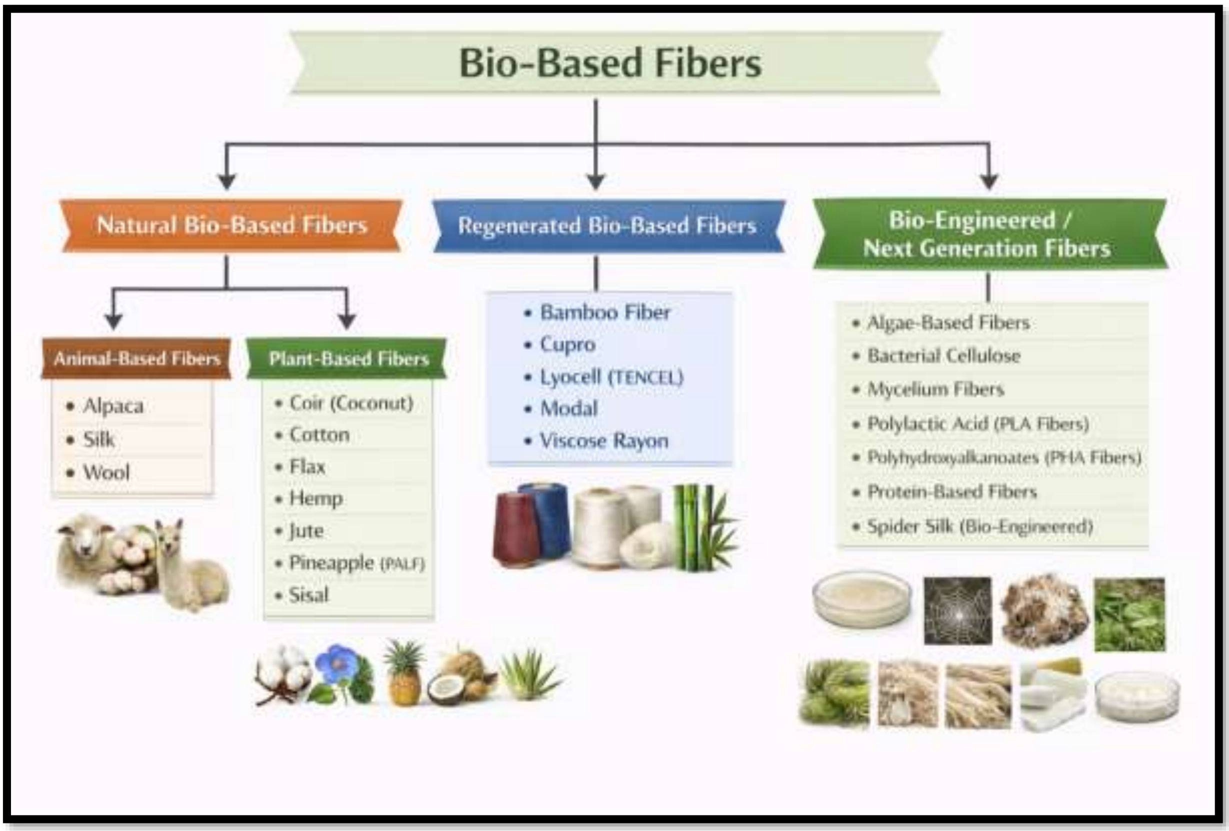

Figure 1: Classification of Bio-Based Fibers (Source: Author's compilation)

1.1. Natural Bio-based Fibers

Natural bio-based fibers are obtained directly from biological sources and include plant fibers (bamboo, cotton, flax, hemp and jute) and animal fibers (silk and wool). Plant-based fibers are characterized by lower energy demand and, in many cases, reduced water and chemical inputs, particularly when organically cultivated. Fibers such as flax and hemp require minimal irrigation and agrochemicals, making them environmentally favourable alternatives to conventional cotton. Animal fibers are renewable and biodegradable, although their sustainability depends on ethical sourcing and land-use management.

1.2. Regenerated Bio-based Fibers

Regenerated bio-based fibers are produced by chemically processing natural polymers, primarily cellulose, into spinnablefibers. Examples include viscose, modal, and lyocell. Among these, lyocell is considered the most sustainable due to its closed-loop production system**,** which recovers and reuses solvents and water, thereby significantly reducing chemical discharge (3). Regenerated fibers combine the comfort and biodegradability of natural fibers with improved uniformity and mechanical performance.

1.3. Bio Engineered Fibers

Bio-engineered fibers are advanced textile materials produced using biotechnology, genetic engineering, and microbial fermentation rather than direct extraction from plants or animals. These fibers are designed to replicate or enhance the properties of natural fibers while significantly reducing environmental impacts. Typical examples include bacterial cellulose, recombinant spider silk proteins, polylactic acid (PLA), polyhydroxyalkanoates (PHA), and protein-based fibers derived from soy or milk, which are synthesized through controlled biological processes. Bio-engineering enables precise tuning of fiber characteristics such as strength, elasticity, biodegradability, and functionality, making them suitable for applications ranging from apparel and technical textiles to medical and composite materials. By relying on renewable feed stocks, lower water and chemical inputs, and potentially closed-loop production systems, bio-engineered fibers represent a promising pathway toward sustainable and circular textile manufacturing.

1.4. Environmental Advantages of Bio- based Fibre

Bio-based fibers generally exhibit lower water consumption, reduced chemical usage, and decreased energy demand compared to conventional synthetic fibers. Their biodegradability minimizes long-term environmental pollution and solid waste accumulation. Additionally, plant-based fibers contribute to carbon sequestration during biomass growth, partially offsetting emissions generated during processing.

The integration of bio-based fibers into textile manufacturing supports a transition toward more sustainable and circular production systems. When combined with eco-friendly processing technologies, bio-based fibers enable measurable reductions in environmental impacts while maintaining functional and aesthetic performance required for modern textile applications.

2. Quantified Reduction in Resource Inputs

2.1. Water Consumption

Water consumption in textile fibers is primarily driven by irrigation during cultivationand wet processing during fiber production. Bio-based fibers such as hemp, flax,lyocell, PLA and jute demonstrate a 60–90% reduction in freshwater consumption (4) per kilogram of fiber compared to conventional cotton, primarily due to rain-fed cultivation and closed-loop processing technologies. Bio-based fibers avoid intensive wet extrusion processes used in synthetics.

2.2. Chemical Usage

Chemical inputs in textiles arise mainly from:

- Agricultural chemicals (pesticides, herbicides, fertilizers)
- Fiber processing chemicals (solvents, catalysts, finishing agents)

Bio-based fibers significantly reduce the consumption of chemicals both compared to conventional cotton and synthetic fibers. However, hemp and jute require little to no pesticides due to natural resistance. Organic cultivation eliminates synthetic fertilizers and toxic pesticides entirely. Lyocell process recovers ~99% of solvents (NMMO) (5), drastically reducing chemical discharge. Bio-based fibers also avoid antimony catalysts, phthalates, and heavy metals used in synthetic fiber production.

2.3. Energy Demand and Carbon Emissions

The use of bio-based fibers leads to a significant reduction in energy demand and carbon emissions compared to conventional synthetic fibers. Life Cycle Assessment studies show that bio-based fibers such as flax, hemp, jute,lyocell and polylactic acid (PLA) are reported to reduce energy consumption by approximately 30–70% (as indicated in multiple studies) per kg of fiber, as they rely on renewable biomass, mechanical or low-temperature processing, and closed-loop systems rather than energy-intensive petrochemical polymerization. Consequently, carbon emissions are reduced by about 40–75%, with some fibers (e.g., hemp and jute) additionally contributing to carbon sequestration during cultivation (6)**.** These quantified reductions demonstrate the strong potential of bio-based fibers to lower the climate and energy footprint of textile production.

3. Challengesand Future Prospects

Bio-based textiles face challenges in cost, scale, and processing, advances in sustainable technologies, bioengineered fibers, and circular systems offer significant future prospects for low-impact, environmentally responsible textile production.

Challenges in Bio-Based Textiles

1. High Production Costs – Sustainable cultivation and closed-loop processing are expensive.
2. Limited Scale & Availability – Fibers like hemp, lyocellandpolylactic acid (PLA) are not yet produced at the scale of cotton or polyester.
3. Processing Complexity – Some bio-based fibers require specialized machinery or chemical recovery systems.
4. Quality Variability – Some bio-based fibers may have lower durability or inconsistent performance.
5. Supply Chain & Market Adoption – Limited awareness, infrastructure, and standardization slows down the adoption.

Future Prospects

Hybrid and bioengineered fibers are emerging as a key innovation in sustainable textiles, as they combine natural fibers with bio-based polymers to enhance strength, softness, and overall performance while maintaining environmental benefits. Cost reduction and large-scale adoption of these materials are expected to accelerate through advances in cultivation techniques, processing technologies, and supportive policy incentives, which together can lower production costs and improve supply availability. Collectively, these advancements show strong alignment with the United Nations Sustainable Development Goals, especially SDGs 6, 7, 12, 13, 14, and 15, by promoting eco-friendly production, responsible consumption, climate action, and the protection of terrestrial and aquatic ecosystems.

SDG Alignment through LCA

- SDG 6: Reduced freshwater use and pollution
- SDG 7: Improved energy efficiency
- SDG 12: Responsible production and waste reduction
- SDG 13: Climate change mitigation
- SDG 14 & 15: Reduced ecosystem and biodiversity damage

Conclusion

Bio-based textiles significantly reduce water, energy, chemical use, and carbon emissions while supporting biodegradability and circularity. Their adoption contributes directly to *SDG 6 (Clean Water and Sanitation)***,** *SDG 7 (Affordable and Clean Energy)***,** *SDG 12 (Responsible Consumption and Production)***,** *SDG 13 (Climate Action)***,** *SDG 14 (Life Below Water)***,** and *SDG 15 (Life on Land)***,** making them a promising solution for low-impact and environmentally responsible textile production. Despite challenges such as high costs and limited scale, advances in sustainable processing and bio-engineered fibers position them as a promising solution for low-impact, environmentally responsible textile production aligned with global sustainability goals. Future research should focus on improving cost-efficiency, scalability, and performance optimization of bio-based fibers to facilitate their large-scale adoption in the textile industry.

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