

# Review on Sustainability in the Textiles and Apparel Industry: A Comprehensive Analysis of Environmental and Social Impacts

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## Abstract

The global textile and apparel industry is undergoing a pivotal structural shift, positioned at the convergence of rapid economic growth and significant environmental and social disruption. Boosted by evolving consumer behaviors, intensified regulatory enforcement, and increasing resource constraints, the industry is transitioning toward a circular and low-carbon model. This in-depth review examines data and trends from 2024 to 2026 to assess the industry's complex sustainability challenges. This study systematically analyzes data and trends from 2024 to 2026 to assess the industry's multifaceted sustainability challenges. It presents a comprehensive review of environmental degradation, focusing on carbon and water footprints, the widespread contamination of aquatic ecosystems by microplastics, and the pronounced toxicity of per- and polyfluoroalkyl substances (PFAS). Concurrently, this study examines the significant occupational health and human rights vulnerabilities in major South Asian manufacturing hubs, which are further intensified by climate change and exploitative supply chain dynamics. Furthermore, the study assesses the effectiveness of emerging technological interventions, including blockchain-enabled traceability, advanced biochemical dyeing techniques, and next-generation biomaterials such as mycelium and bio-based polyamides. Finally, this review underscores the value-action gap in consumer purchasing behavior and the rapid expansion of the circular resale economy, offering strategic insights to better align industry practices with global ecological limits.

## Introduction

The modern global fashion and textile ecosystem constitutes a significant economic force, yet it continues to function largely within an unsustainable linear model of resource extraction, production, and rapid disposal. As of 2025, the global textile market reached an estimated valuation of \$660 billion, rising from \$618 billion in the previous year and reflecting an average annual growth rate of 6.8%, despite ongoing geopolitical tensions and broader inflationary pressures. This financial expansion is accompanied by a substantial surge in physical output. Global fiber production reached a record 132 million tonnes in 2024 which is more than double the level observed in 2000 & equivalent to the continuous production of approximately four tonnes of fiber per second. If same trend follows over the then the aggregate fibre production is expected to hit 169 million tonnes by 2030.

This scale of hyper-production imposes a severe and well-documented burden on planetary health. It is openly known that textile sector is major contributor to anthropogenic pollution, accounting for approximately 2% to 10% of global greenhouse gas emissions, depending on the life cycle boundaries applied. To remain aligned with the 1.5°C climate pathway established under the Paris Agreement, industry emissions must decline by nearly 45% by 2030. However, current projections suggest a potential increase exceeding 40% in the absence of systemic intervention.

The following analysis examines the structural bottlenecks, evolving regulatory landscape, and emerging innovations shaping the industry's transition toward a more sustainable, resilient, and equitable operational model.

## Environmental Impacts of Textile Production

### Life Cycle Assessments and Carbon and Water Footprints

A Life Cycle Assessment (LCA) offers a quantitative evaluation of environmental impacts across the full cradle-to-gate or cradle-to-grave continuum, encompassing metrics such as global warming potential, eutrophication, acidification, water consumption, and land use. Across the sector, synthetic fibres made from fossil fuel majorly polyester dominates global market, having market share of 59%, among which 88% is purely Virgin Petrochemical based polyester.

While both natural and synthetic fibers pose distinct ecological risks, their impact profiles differ substantially. The total carbon footprint of global textile production is estimated at 42,624.12 MT CO<sub>2</sub>, alongside an energy footprint of 248.38 PJ and a substantial water footprint of 80.71 billion liters. Within the manufacturing value chain, the spinning and initial processing stages typically account for the highest carbon and energy intensities, largely due to dependence on coal-based power generation in key production regions.

Conventional cotton, for example, is highly resource & labor intensive, contributing significantly to water consumption and acidification due to intensive agrochemical use. In contrast, organic cotton substantially reduces chemical pollution but requires greater land area to achieve comparable yields. Animal-derived fibers, such as wool, exhibit relatively high carbon footprints, driven primarily by innate methane emissions from sheep and the energy-intensive scouring processes necessary to clean raw fleece.

**Table 1: Life Cycle Assessment and Environmental Footprints of Major Textile Fibers**

Fiber Type	Carbon Footprint (kg CO <sub>2</sub> e per kg fiber)	Primary Environmental Concerns and Footprint Drivers
<b>Wool</b>	~13.89 kg - 19.0 kg	Enteric methane emissions from livestock, highly energy-intensive scouring and processing.
<b>Acrylic</b>	~11.53 kg	Direct reliance on petrochemical feedstocks, severe microplastic shedding during laundering.

<b>Cotton (Conventional)</b>	~8.30 kg	Extreme water consumption for irrigation, severe pesticide and insecticide runoff causing eutrophication.
<b>Silk</b>	~7.63 kg	Energy-intensive temperature regulation for cultivation, ethical concerns regarding the destruction of silkworms.
<b>Nylon / Polyamide</b>	~7.31 kg	High thermal energy required for polymerization, significant nitrous oxide (N <sub>2</sub> O) emissions during synthesis.
<b>Polyester</b>	~6.40 kg - 27.2 kg*	Non-biodegradable, deep petroleum reliance, extensive microplastic release.
<b>Linen (Flax)</b>	~4.50 kg	Land use requirements, though generally possessing lower chemical and water irrigation requirements than cotton.

(Note: Variances in the literature, such as the 6.4kg versus 27.2kg estimates for polyester, reflect differing LCA boundaries, such as emissions calculated per square meter of woven fabric versus per kilogram of raw extruded fiber.)

### Chemical Management and the Phase-Out of Per- and Polyfluoroalkyl Substances

Chemical wet processing, including dyeing, finishing, and advanced material treatments, constitutes a critical pressure point within the industry’s environmental profile. Historically, the sector has depended extensively on per and polyfluoroalkyl substances (PFAS), commonly referred to as “forever chemicals,” to deliver durable water repellency, stain resistance, and wrinkle resistant finishes in performance apparel. These fluorinated compounds are defined by exceptional environmental persistence, readily bioaccumulate in aquatic systems, and have been strongly associated with serious adverse human health effects.

Between 2024 and 2026, a major and highly coordinated regulatory shift emerged aimed at accelerating the phase out of PFAS in consumer textiles. This legislative momentum was initially led by several jurisdictions in the United States. In California, Assembly Bill 1817 introduced a comprehensive ban on PFAS in textiles. New York enacted Bill S1322/A994, which prohibits the sale of new apparel containing intentionally added PFAS starting January 1, 2025. In the same time period, Minnesota passed Amara’s Law, establishing broad restrictions across multiple product categories, including carpets, juvenile products, and textile furnishings.

This localized legislative pressure rapidly expanded to the international level. The European Union introduced stringent restrictions across member states, including France and Denmark, while the European Chemicals Agency advanced a broad restriction under the REACH framework aimed at phasing out these chemicals across the continent.

Voluntary industry standards have increasingly aligned with regulatory crackdowns to reduce brand liability exposure. The Bluesign® standard introduced a strict requirement for all approved products to be free of intentionally added PFAS by January 2025, with a full removal of previously exempt products from its chemical guidance scheduled for January 2026. Similarly, the Zero Discharge of Hazardous Chemicals (ZDHC) Roadmap to Zero Program has expanded its digital compliance framework through the “Suppliers Roadmap to Zero,” aimed at strengthening sustainable chemical management and enforcing adherence to its Manufacturing Restricted Substances List across global supply chains. A key secondary effect of these broad restrictions is intensified innovation pressure on chemical developers, who are now accelerating the development of non-toxic, bio based durable water repellents capable of meeting the stringent performance requirements of outdoor and activewear applications.

### The Microplastics Crisis and Mitigation Technologies

The shedding of micro and nano-plastics from synthetic textiles is a major global ecological crisis. Garments made from petroleum-based fibers release large quantities of microfibers into aquatic environments during domestic laundering and through industrial effluents generated in wet processing. Studies indicate that a single wash cycle of polyester garments can release up to 700,000 microplastic fibers.

Industrial chemical treatments further intensify this shedding. Durable press wrinkle resistant finishes applied to cotton synthetic blends can release around 14,200 microfibers per gram of fabric, while high temperature dyeing of polyester yarn can emit nearly 900 microplastics per gram before consumer use.

Mitigation requires an integrated multi-tiered approach covering both upstream design and downstream capture. Research shows fabric architecture is a key determinant of shedding rates. Tightly woven structures such as 2 by 2 twill shed significantly fewer fibers than loosely knit single jersey fabrics, where exposed loops experience greater friction and abrasion. Likewise, construction methods are critical; laser cutting fabric edges thermally seals polymers and reduces microplastic release by over one third compared to scissor cutting and overlock stitching.

At consumer and municipal levels, mechanical filtration remains the primary defense. While wastewater treatment plants can capture a large share of microplastics, the recovered material accumulates in sewage sludge, creating a secondary pollution pathway when used as agricultural fertilizer and entering soil ecosystems. To reduce emissions at source, advanced washing machine filtration systems have been developed and are increasingly deployed.

**Table 2: Efficacy of Microplastic Filtration and Mitigation Interventions**

Filtration Technology / Device Category	Application Type	Efficacy (Microfiber Reduction)	Maintenance and Operational Requirements
<b>Internal Built-in Filters (e.g., Xeros XF1)</b>	Machine Integrated	Up to 90%	Requires periodic manual cleaning (approximately every 1-3 weeks).
<b>External/Aftermarket Filters (e.g., Filtrol 160)</b>	External Attachment	88% - 90%	Necessitates periodic filter cartridge replacement or manual cleaning.

<b>Washing Bags (e.g., Guppyfriend)</b>	Laundry Accessory	Up to 86%	Requires the manual removal of accumulated fibers from the bag's interior after washing.
<b>Retrofit Kits (e.g., PlanetCare, CleanR)</b>	External Attachment	80% - 82%	Requires regular aftermarket filter replacement.
<b>In-Drum Catchers (e.g., Cora Ball)</b>	Laundry Accessory	~26%	Entails the manual cleaning of the device's porous structural spines.

Crucially, advanced filtration systems provide compounding environmental benefits. Pilot studies indicate that engineered systems can capture microplastics with up to 90% efficiency while also reducing Chemical Oxygen Demand(COD) by 92% and Suspended Solids by 80%, delivering a dual improvement in wastewater quality before effluent enters municipal treatment facilities.

### Innovations in Sustainable Dyeing

Traditional textile dyeing is highly resource intensive, requiring full immersion of fabrics in synthetic chemical baths for several hours at elevated temperatures, often reaching up to 130°C. This conventional process consumes large volumes of freshwater and generates toxic effluents that continue to damage waterways in major manufacturing regions across the Global South. Recent advances in sustainable chemistry, biotechnology, and bioengineering are beginning to disrupt this linear model.

Emerging technologies are focused on significant reductions in raw resource inputs. For instance, Ever Dye technology uses a bio sourced pigment derived from vegetal waste and natural minerals, combined with an organic polymer binding agent to enable electrostatic dye attachment at room temperature within 30 minutes. This substantially reduces thermal energy demand by eliminating the need for high temperature boiler systems. Similarly, the Nano Dye system alters the molecular charge of cotton through a single drop in pretreatment, enabling up to 99% dyestuff exhaustion into the fabric. This near complete absorption eliminates solid dye waste in effluent, removes the need for chemical salts, and reduces freshwater use by 75% along with a 90% reduction in energy consumption.

Biological alternatives are also scaling rapidly. Organizations such as Colorifix use synthetic biology to engineer microorganisms that produce and deposit color directly onto textiles without petrochemical solvents. In parallel, the industry is advancing supercritical carbon dioxide dyeing, which eliminates water use entirely, along with plasma technologies and digital precision dyeing systems developed by companies like Alchemie Technology that apply dye with high spatial accuracy to minimize waste.

### Social and Labor Dynamics in Global Supply Chains

The structural architecture of the modern fast fashion model is defined by persistent downward pressure on unit costs, delayed purchase orders, and extremely compressed manufacturing lead times. This configuration systematically incentivizes social and labor exploitation. Retailers positioned at the highest tiers of the value chain impose stringent commercial terms that cascade through fragmented and vulnerable production networks, largely concentrated in South and Southeast Asia, including Bangladesh, India, Pakistan, Sri Lanka, and Vietnam.

## Human Rights Abuses and Freedom of Association

Extensive human rights due diligence has consistently documented widespread abuses across major textile production hubs. Recent investigations highlight severe cases of forced and child labor embedded in deep tier supply chains. In Myanmar, reports indicate the use of militarized forced labor involving adults and children in rubber production linked to the apparel industry, while in Nepal an estimated 7,500 children are engaged in forced labor in carpet weaving and embellished textile work concentrated in the Kathmandu Valley. In Tamil Nadu, India, supply chain mapping across 29 spinning mills has identified persistent risks of workers being subjected to forced labor conditions in the production of yarn and fabrics for global markets.

The structural inability of workers to advocate for improved conditions is reinforced by systemic constraints on collective representation. A 2024 analysis by the Business & Human Rights Resource Centre found that international fashion brands often circumvent independent trade unions in favor of weaker, management aligned representative structures. These arrangements dilute collective bargaining power and contribute to sustained poverty wages, excessive working hours, and unsafe working environments. Survey data further indicates low worker trust, with 50% of garment workers stating that brand commitments to freedom of association are largely symbolic and rarely lead to meaningful intervention during labor disputes.

## Occupational Health Hazards and Climate Vulnerability

The convergence of accelerating climate change and labor intensive manufacturing presents an escalating risk to worker safety and survivability. Small and medium scale apparel manufacturers in regions such as Sri Lanka are structurally ill equipped to handle increasing extreme weather events. Empirical surveys of apparel workers in the Biyagama and Katunayake Export Processing Zones highlight severe occupational health impacts directly linked to climate induced hazards.

High ambient temperatures combined with trapped humidity inside factory environments result in significant thermal stress, reported by 81.25% of surveyed workers. This heat exposure leads to dehydration, chronic headaches, and reduced cognitive performance, contributing to a measurable rise in industrial accidents, particularly needle prick injuries. In addition, poor ventilation and continuous exposure to fibrous dust result in 95% of workers experiencing persistent respiratory issues and gastrointestinal illnesses, further aggravated by localized flooding.

Changing climate conditions and flood events have also expanded vector breeding habitats, contributing to a dengue fever incidence rate exceeding 10% among workers over a five year period. Collectively, these findings indicate that without targeted adaptation measures such as improved ventilation systems, thermal regulation, and structured vector control, both workforce health and regional export competitiveness face severe and potentially destabilizing risks.

## Transitioning to a Circular Economy

To fundamentally decouple economic growth from intensive virgin resource extraction, the industry is transitioning toward a circular economy model. This framework is structured around three core principles: eliminating waste and pollution through design, continuously circulating products and materials at their highest value, and actively regenerating natural systems.

## Alternative Biomaterials and Regenerative Textiles

Material innovation is increasingly bypassing petrochemical synthetics and resource intensive natural fibers in favor of bio engineered and regenerative alternatives. These materials are derived from agricultural waste streams or rapidly renewable biological inputs, substantially reducing life cycle impacts while maintaining functional performance.

The development of bio-based polyamides represents a key advancement in sustainable synthetics. Innovations such as EVO by Fulgar use sebacic acid derived from castor oil to produce a 100% bio based high performance yarn. Since the castor plant requires minimal water and can grow on arid non arable land, it avoids competition with food crops. The

resulting textile is 25% lighter than conventional polyester, offers improved thermal insulation, and provides natural odor resistance, while significantly lowering carbon emissions and fossil fuel dependence.

In the luxury and accessories segment, mycelium-based materials, commonly known as mushroom leather, are reaching commercial viability. Produced through vertical farming systems powered by renewable energy, fungal biomass is processed into durable leather alternatives that eliminate methane emissions, land degradation, and toxic tanning chemicals associated with animal leather production. Similarly, Piñatex utilizes agricultural waste from pineapple cultivation, converting discarded leaves into cellulose fibers that are mechanically bonded into non-woven textiles. This enables vegan, breathable, and durable materials used by brands such as Hugo Boss and H&M without requiring additional land or water inputs.

Regenerated cellulosic and algae-based textiles are also gaining market traction. Tencel, produced from sustainably sourced wood pulp in a closed loop system that recycles approximately 99% of solvents, offers a biodegradable alternative to conventional synthetics. Experimental materials incorporating seaweed and chitosan, a biopolymer derived from mushroom and shellfish waste and pioneered by companies like TomTex, are further expanding low impact textile options without compromising functional or aesthetic performance.

### Resale, Rental, and Circular Business Models

The most immediate and effective strategy for reducing a garment's environmental footprint is extending its active use phase. As a result, secondhand resale, rental, and repair models are fundamentally reshaping conventional retail systems.

Driven by integrated digital platforms, AI enabled authentication systems, and shifting consumer perceptions of used goods, the global secondhand apparel market reached an estimated \$256 billion in 2025 and is projected to reach \$367 billion by 2029. Importantly, this segment is currently growing at a rate two to three times faster than the primary apparel market.

**Table 3: Economic Trajectory of the Global Secondhand Apparel Market**

Year	Projected Market Valuation (USD Billions)	Market Growth Dynamics
2021	\$141 B	Baseline established during initial post-pandemic retail shifts.
2023	\$197 B	Accelerated by rapid inflation and consumer price sensitivity.
2025	\$256 B	Branded resale internalizations begin to scale globally.
2027 (Projected)	\$317 B	AI-driven reverse logistics unlock deeper profitability.
2029 (Projected)	\$367 B	Expected to grow 2.7X faster than the overall global apparel market.

## Supply Chain Governance and Regulatory Frameworks

To effectively address voluntary corporate greenwashing, global regulators are shifting from soft law guidelines toward enforceable, punitive legislation. This emerging compliance regime compels brands to implement comprehensive, multi-tier supply chain mapping alongside verifiable disclosure requirements.

### Global Legislative Mandates and Certifications

The European Union's current legislative agenda represents one of the most extensive regulatory interventions in global textile governance. Central to this framework is the Ecodesign for Sustainable Products Regulation, which directly influences product design by requiring higher durability, improved reparability, and minimum recycled content thresholds.

In parallel, the Corporate Sustainability Reporting Directive mandates detailed, standardized corporate disclosure of environmental performance, with particular emphasis on Scope 3 emissions. These indirect value chain emissions account for over 96% of the total carbon footprint of major apparel brands.

Furthermore, the Corporate Sustainability Due Diligence Directive obliges companies to systematically audit and mitigate human rights and environmental risks across their entire n tier value chains, extending accountability to the deepest levels of raw material extraction. The revised Waste Framework Directive, alongside expanding Extended Producer Responsibility schemes, shifts the financial responsibility for end-of-life waste collection and recycling from municipalities back to producers, undermining the economics of planned obsolescence.

In the absence of harmonized global regulation, third party certification systems serve as key mechanisms for validating sustainability claims. The Global Organic Textile Standard (GOTS) requires a minimum of 70% certified organic fibers while enforcing strict ecological and labor criteria throughout processing and manufacturing. The Organic Content Standard ensures end to end traceability of organic inputs from farm to final product, while the Cotton made in Africa standard addresses specific socio economic and agronomic conditions within Sub-Saharan cotton farming regions.

### Artificial Intelligence and Blockchain Traceability

The structural opacity of the global textile supply chain—where raw materials are grown in one region, spun in another, and chemically finished elsewhere—results in an estimated \$98 billion in annual losses due to systemic inefficiencies, fraud, and the infiltration of counterfeit materials.

To meet the granular traceability requirements of emerging regulatory frameworks such as the EU's Digital Product Passport, the industry is increasingly adopting artificial intelligence and blockchain technologies. Blockchain systems provide a decentralized, tamper resistant ledger that records each stage of the supply chain, from raw material sourcing to final retail distribution. As a single source of verified data, these systems reduce compliance audit times for mills by an average of 40% and shorten cross border dispute resolution cycles by approximately sixfold.

When integrated with AI and advanced data analytics, these platforms can continuously monitor supply chain activity and flag anomalies such as unauthorized subcontracting, abrupt emissions spikes, or the use of uncertified raw materials. With the blockchain enabled supply chain market expanding at an estimated annual rate of 18.8%, digital traceability is increasingly shifting from a competitive differentiator to a core regulatory and operational requirement.

### Consumer Behavior and Economic Realities

Despite substantial technological advancements and operational gains at the manufacturing level, a major friction point persists at the end consumer stage. A central paradox in contemporary fashion consumption, identified by behavioral economists, is the "value action gap."

### The Value-Action Gap and Greenwashing

Extensive demographic research shows that younger cohorts, particularly Gen-Z and Millennials, hold strong pro environmental and ethical values, with up to 66% of consumers reporting that they consider sustainability metrics during

purchasing decisions. However, their actual behavior often contradicts these stated preferences, with continued reliance on ultra-fast fashion models characterized by low cost, synthetic garments and rapid product turnover.

This value action gap is driven by three interconnected barriers. First, economic constraints play a dominant role. Amid inflation, macroeconomic uncertainty, and limited disposable income, consumers are generally unwilling or unable to absorb the higher costs associated with sustainably produced apparel. Higher prices reflect structural factors such as living wages, certified organic sourcing, and localized production, making affordability a primary determinant at the point of purchase.

Second, trust in sustainability claims is significantly weakened by widespread misinformation. In 2024, audits indicated that approximately 59% of corporate sustainability claims in the sector were vague, misleading, or not verifiable. This lack of credibility leads consumers to default to familiar low-cost fast fashion brands due to uncertainty and skepticism.

Third, behavioral and psychological mechanisms shape consumption patterns. Rapid trend cycles driven by algorithmic social media platforms encourage impulse buying and overconsumption, often overriding stated environmental intent. At the same time, a low perceived impact of individual choices fosters consumer apathy, reinforcing inaction. Addressing this gap requires stronger third-party certification systems and Digital Product Passports to provide transparent, verifiable information on garment origin and environmental impact.

### **Economic Performance of Sustainable vs. Traditional Fashion**

The economic performance of the fashion industry highlights a growing divergence between brands that embed sustainable resilience and those dependent on high volume, trend driven models. In 2024 and 2025, the luxury sector outperformed broader market benchmarks, absorbing the costs of sustainability initiatives and supply chain traceability due to higher margins and a more affluent consumer base. In contrast, non-luxury segments underperformed, prompting increased caution among private equity investors toward fast fashion portfolios exposed to trend volatility.

Looking ahead, the textile industry now faces mounting climate related risks. Economic models suggest that extreme weather events could threaten approximately \$65 billion in apparel exports and place nearly one million jobs at risk in key production economies by 2030. In this context, brands that integrate sustainability as a core risk management strategy, rather than a purely marketing function, are better positioned to mitigate supply chain disruptions, regulatory exposure, and long-term market instability.

### **Conclusion**

The last two years (2024–2026 period) have firmly established sustainability not as a peripheral or optional marketing initiative, but as a core determinant of operational viability in the global textile and apparel sector. The long-standing era of linear, resource intensive extraction is being accelerated toward closure by stringent legislative mandates led by the European Union, alongside the physical limits imposed by planetary ecosystems.

To remain both economically viable and legally compliant over the coming decade, textile manufacturers and apparel brands must undertake a systemic transformation across three primary dimensions. First, industrial processes must be rapidly decarbonized and detoxified, requiring a shift away from virgin fossil-based polyesters toward bio polymers, certified organic inputs, and next generation biomaterials, as well as the elimination of PFAS in favor of biologically derived dyeing and finishing systems.

Second, fragmented supply chains must be fully transparent and traceable. The integration of blockchain and artificial intelligence is increasingly becoming a compliance necessity rather than an optional enhancement, enabling verification under emerging human rights and environmental due diligence regulations while reducing exposure to legal, financial, and reputational risks linked to labor violations in South Asian production hubs.

Finally, brands must decouple revenue growth from virgin material consumption by embedding circular business models into core strategy. Scaling resale, rental, and fiber to fiber recycling systems allows companies to capture value in the rapidly expanding secondhand market while reducing carbon, water, and waste intensity. Ultimately, the long-term viability

of the industry depends on its ability to internalize environmental externalities. Through radical transparency, biomimetic innovation, and strengthened labor governance, the sector has the potential to transition from a major polluter to a structurally regenerative economic system.

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