Sustainable Fashion Technologies

Stitching sustainability into style

WIPO

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Contents

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Disclaimer

Executive summary

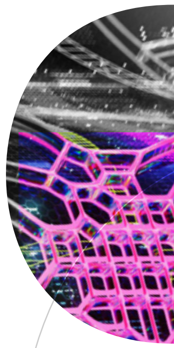

Photo: Getty Images/luchezar

Fashion is an integral part of society and culture. It tells a story about who we are, where we come from and what matters to us. The global fashion industry, valued at approximately USD 1.7 trillion and employing over 300 million people worldwide, is a major contributor to humanity's global negative environmental impact, accounting for 2% of global carbon emissions and 20% of industrial water pollution. The industry is currently dominated by a "fast fashion" model: a system built on low-cost production, high consumption rates and rapid disposal, which reinforces the industry's unsustainable linear production system.

Innovation and technology offer pathways to mitigate these harms. This report identifies and maps sustainable technologies across key stages in textile production, focusing on critical points of the value chain, including raw material cultivation, textile processing, garment manufacturing, distribution, and end-of-life management. It focuses on technologies addressing environmental concerns. A caveat: it bears noting that a technology that reduces one form of pollution may exacerbate another, leading to inevitable trade-offs. Further, these technologies could have negative social or economic effects. Understanding these complexities will be central to advancing real change.

The technologies explored in this report include alternatives to petroleum-based and synthetic fibers, waterless dyeing techniques, bio-based materials and recycling innovations, among others. The emphasis is on shifting the fashion industry toward a circular economy, where resources are reused and recycled in a closed-loop system to minimize waste and environmental impact. By reimagining production systems using sustainable technologies, the goal is to help the industry pivot toward a more sustainable pathway.

Key findings include:

- Technology innovations such as lab-grown cotton, bio-based polyester, and waste-to-fiber recycling show promise in addressing the critical environmental impact points in the fashion supply chain, namely fiber cultivation and extraction, textile processing, and end-of-life management.
- Many promising innovations are not commercially viable or face difficulties in scaling. High implementation costs, lack of infrastructure and funding, market fragmentation and a sector-wide lack of response largely driven by fashion and market trends are key barriers to the widespread adoption of sustainable technologies.
- Growing interest in sustainability and efficient production methods from brands, retailers and investors signal an opportunity toward scaling innovative solutions in the sector.
- Broader adoption in diverse contexts is dependent on supporting small and medium-sized enterprises and integrating traditional knowledge and nature-based solutions into modern practices.
- Regulatory and market incentives are needed. Voluntary initiatives have yielded only limited progress. Recent legislation in the European Union that mandates greater transparency and accountability in supply chains can encourage fashion companies to adopt sustainable practices.

To mitigate the negative environmental impact of the fashion industry, a fundamental shift toward sustainable practices is needed. This includes curbing production rates, embracing circular business models and deploying new technologies that can limit waste, pollution and carbon emissions. Achieving meaningful change also requires collaborative efforts across the supply chain, investment in innovation, supportive legislation, and increased consumer awareness. Through these collective efforts, the industry will be able to transition toward a more sustainable future for fashion and for the planet.

Introduction

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From linear to circular

In 2023, fashion[1] was estimated to be a USD 1.7 trillion industry employing over 300 million people in its extended value chain (McKinsey & Co., 2023). Textile and garment manufacture are major export industries in many countries, such as Bangladesh, the People's Republic of China, India and the Socialist Republic of Viet Nam (WTO, 2023), supporting employment, industrialization and economic growth. However, as manufacturing and distribution are increasingly organized in global supply chains located across multiple countries, it is challenging to establish consistent and mutually agreed sustainability indicators. It is also challenging to achieve traceability needed to monitor sustainability indicators for brands to be accountable.

The production of garments and textiles involves many processes of material transformation from raw material to finished product, which are responsible for a significant amount of industrial pollution and environmental damage (Niinimäki *et al.*, 2020). Textile and garment manufacturing account for:

- an estimated 2% (over 1 billion metric tonnes) of global carbon emissions (Sadowski *et al.*, 2021);
- 20% of all industrial water pollution (Ellen MacArthur Foundation, 2017);
- nearly 5% of the world's pesticides and 10% of insecticides for cotton growing (International Cotton Advisory Committee, 2019);
- up to 35% (between 200,000 and 500,000 tonnes) of microplastics entering marine environments each year (European Environment Agency, 2021);
- use of around 79 trillion liters of water;
- over 92 million tonnes of textile waste per year (Niinimäki *et al.*, 2020).

It has been estimated that by 2050 the fashion industry could account for over a quarter of the global carbon budget (Ellen MacArthur Foundation, 2018).[2] This projected share is disproportionately large, given there are sectors with much higher emissions intensity, such as utilities, materials and energy (S&P Global, 2022).

A critical issue in fashion is the industry's growth trajectory, seen in the proliferation and dominance of fast fashion. This refers to cheap manufacture of low-priced trend-led items that encourage consumers to purchase new items frequently. Fast fashion exacerbates the industry's environmental impact owing to increased volume in production and shorter use time of items produced before disposal. Further, fast-fashion items more often contain a mix of synthetic materials, most commonly polyester, which contribute to fossil fuel consumption, environmental pollution and textile waste, in addition to being more difficult to recycle (Changing Markets Foundation, 2021). In fact, very little clothing is recycled, making it evident that the fashion supply chain is linear, not circular. In 2016, a report by McKinsey estimated

1 The fashion industry consists of four levels: the production of raw materials, principally fibers and textiles but also leather and fur; the production of fashion goods by designers, manufacturers, contractors, and others; retail sales; and various forms of advertising and promotion (Britannica, 2023).

2 The carbon budget is a calculation of the amount of greenhouse gases (GHG) that can be emitted to keep the average increase in global temperature to within a maximum threshold of 2°C above preindustrial levels, and preferably no more than 1.5°C as per the Paris Agreement, the legally binding international treaty on climate change agreed at the UN Climate Change Conference (COP21) in 2015. To keep global warming to within 1.5°C, carbon emissions need to be reduced by 45% by 2030 and reach net zero by 2050 (UN, 2023).

that global production had surpassed 100 billion garments per year by 2014, but there are no verifiable statistics published more recently. However, as global fiber production doubled between 2000 and 2022, from 58 million to 116 million tonnes (Textile Exchange, 2023), most of which is destined for clothing (Niinimäki *et al.*, 2020) it can be deduced that the annual number of garments being produced has since surpassed 100 billion. A fundamental shift in the fashion system is the need to slow down production, while making more efficient use of materials and products in existence. These issues highlight the imperative for decision-makers to legislate toward a more sustainable fashion industry, and for the fashion industry to address its environmental responsibilities and shift toward a more circular and sustainable business model.

Scope

This publication is centered around critical points in the value chain, namely agriculture/extraction, textile and garment manufacture, transport and end of life, and is not a comprehensive collection of all sustainable fashion technologies available. Unlike a life cycle assessment, it does not consider the consumer use phase. While the term "sustainability" is generally understood to refer to various social, environmental and economic dimensions, the technologies in this brief mainly address environmental challenges. Although the focus of this report is not on social responsibility or technologies that primarily impact workers, communities and livelihoods, there are associated benefits for workers and communities in reducing pollution and carbon emissions or supporting resource conservation and biodiversity, such as health, disease resistance, food and nutrition security.

Methodology

This report looks at a variety of sustainable technologies designed to reduce fashion's environmental impact. It begins by identifying key environmental impact areas in the fashion supply chain in terms of water usage, chemicals input, energy consumption or waste generation. This is followed by a description of some of the technologies under development or that have been deployed that may help mitigate various environmental impacts of fashion value chain from fiber growth/extraction to end of life. The report also highlights, where possible, the role of intellectual property (IP) in catalyzing green technology innovation. In any event, it sets out the underlying importance of IP in developing green technologies.

A systematic review of relevant fashion industry and greentech publications, academic literature, and fashion tech and sustainable fashion competitions and awards from 2014 to 2023 was conducted. The aim is to help stakeholders understand the landscape and state of the art in sustainable fashion technologies, analyze trends and challenges, and identify opportunities within the most impactful areas for technology and innovation.

The academic literature provided an overview of the subject area and research directions but very few identifiable technologies that could be or are currently being deployed in the fashion industry. Subsequently, focus on startups and entrepreneurial activity in industry publications, competitions, accelerators and trade fairs led to the identification of most of the technologies in the sample. While not exhaustive, these sources provide a broad and rich insight into the scope of current and potential future solutions.

The selection criteria for the technologies that are part of this research were as follows:

- relevance to sustainable fashion and textile industry
- lower environmental impact
- durability and recyclability
- biodegradability
- material and energy efficiency

Over 200 sustainable fashion technologies were identified and mapped to five key production stages, shown in the figure below. In this report the reader will find a selection of 34 technologies and innovation practices. The complete list of 200 technologies identified as relevant for sustainable textiles can be found in a dedicated collection on the WIPO GREEN database. The technologies range from algae-based polyester alternatives to the use of blockchain technology to communicate environmental sustainability. Most technologies focus on innovation around raw materials and textile production processes, where the greatest environmental impact occurs. Evidence of increased levels of investment by global brands, impact investors and retailers toward sustainable innovation startups is promising for scaling technologies.

Key stages in textile and fashion production and associated sustainable technologies

Raw material cultivation /extraction	– Improving soil health and maximizing crop efficiency – Utilizing waste as a raw material – Alternative renewable fibers – Lab-grown cotton
Textile manufacture	– Raw material production – Textile dyeing and processing – Wastewater and effluent treatment
Garment manufacture	– Mass customization – On-demand manufacturing – Zero-waste manufacturing
Distribution	– Optimization of logistics – Packaging, returns management – Supply chain traceability
End of product life	– Automated sorting – Recycling pre- and post-consumer textile waste

The focus of this review is to spotlight innovative technologies that offer more sustainable alternatives to the status quo outlined in the Introduction and have potential for scale and commercialization. Breakthrough technologies play a key role but reliance on the commercialization and widespread adoption of new technologies could lead to missed opportunities. In many parts of the world, numerous technologies are unaffordable and difficult to access. Therefore, sustainable techniques and practices based on traditional knowledge, nature-based solutions and adaptation of existing solutions to meet the unique challenges of various regions and sectors are needed in order to facilitate technology uptake (WIPO, 2023) and avoid missed opportunities. The following sections outline the types of technologies that have emerged in key production stages, with examples of promising technologies that aim to address:

- greenhouse gas (GHG) emissions
- raw material demand and textile waste
- water usage
- energy usage
- hazardous chemicals
- transport related emissions in supply chains

The term innovation – used in the sections titled "Innovation example" – covers all intellectual creativity that could result in a solution. Technology relates to any physical entity or technique, with or without additional equipment, that is deployed to resolve a specific challenge (WIPO, 2023).

While Figure 1 splits out the stages of agricultural cultivation/fiber extraction and textile manufacture, the identified technologies in these areas often address both stages. Innovations in the stages of agricultural cultivation/fiber extraction and textile manufacture are largely focused on novel materials, so there is overlap between technologies that present alternatives to current practices of extraction for synthetics and cotton growing and those that focus on textile manufacture. Some companies work across fiber production as well as yarn and/or textile manufacture. There is also some overlap between agricultural cultivation/fiber extraction/textile manufacture and end of life, where technologies provide alternatives to using virgin resources by regenerating pre- or post-consumer textile waste into new fibers or materials. For the purpose of clarity in this report's structure, the review of technologies within the agriculture and extraction stages will be combined, and textile-to-textile opportunities will be presented within the end-of-life stage.

Key challenges on environmental impact in fashion

Photos: Unsplash/Pexels Googledeepmind, john o nolan; Getty Images/Onandter_sean

This section highlights how the biggest environmental impacts in fashion's value chain occur in a range of manufacturing processes, from fiber production and textile processing to water consumption and microplastics.

The critical points in the value chain that have high environmental impact are agriculture/fiber extraction, textile processing, transportation and end of life (Niinimäki *et al.*, 2020). Textile raw materials are derived from natural or synthetic fibers, with cotton being the most commonly used natural fiber and polyester the leading synthetic fiber and the most commonly used material overall (Textile Exchange, 2022). The extraction of synthetic fibers requires significant energy, as they are derived from polymers, which are primarily sourced from petroleum.

Outsourcing of environmental responsibility

Negative environmental impacts are concentrated in textile- and garment-manufacturing countries, and those countries that import secondhand clothing. This is the result of the vertical disintegration of the industry and mass outsourcing of production and waste management to countries with lower labor cost.

To achieve economies of scale and scope, the various processes in industrial production are carried out by a network of different companies and suppliers, rather than by one company. Fashion brands and retailers rarely own factories but are solely engaged in the design, sourcing and distribution of products, with the manufacturing of textiles and garments carried out by independent subcontractors.

One of the consequences of this structural change is a shift in the balance of power in the supply chain from manufacturers to retailers, who can outsource accountability for environmental responsibility and place the negative externalities of production on suppliers in developing countries.

There are many examples of environmental pollution and degradation resulting from industrial production in developing countries, but such industrial activity is likely to be part of an extensive supply chain. Therefore, a systemic approach looking at the whole textile value chain needs to be taken to analyze the externalities of its production and consumption process. Evolving legislation on due diligence will address this issue by placing the onus on fashion companies to assume responsibility for their supply chains.

Harmful chemicals and water usage

Environmental degradation can have severe socioeconomic effects on the health, well-being and quality of life of people affected by textile production. Harmful chemicals in pesticides used in conventional cotton farming leach into the waterways and can lead to neurological and reproductive health problems. For example, the use of agrochemicals in Indian cotton farming villages creates toxic landscapes that cause physical and mental suffering and distress in farmers, with significantly higher suicide rates than the national average (Kannuri and Jadhav, 2018).

Vast amounts of water are needed for growing cotton, and for textile dyeing, processing and finishing. In Bangladesh, the world's second biggest ready-made garment exporter and manufacturing hub, supporting 4 million workers, alarming depletion in groundwater levels has been attributed to the garment industry, due to the high use of water by many textile mills (Ahmed and Jaiswal, 2023).

Toxic chemicals used in textile processing, if not contained within a closed-loop system, present a risk to the environment, workers and communities as they can be bio-accumulative, hormone-disruptive and carcinogenic to both humans and wildlife (Perry, 2017).

Dyeing cotton involves a substantial demand for water, with an estimated usage of approximately 125 liters per kilogram of cotton fibers during the dyeing and finishing processes. In addition to the volume of water required, significant energy is consumed to heat water and generate steam for achieving the desired finish.

Synthetic textiles are a major source of microplastics, which pervade global ecosystems and are present in marine and land animals and humans (Boucher and Friot, 2017; European Environment Agency, 2021). Microplastics are shed throughout the life cycle of synthetic textiles but most are shed during the consumer use phase, after domestic washing of garments (Periyasamy and Tehrani-Bagha, 2022). Current solutions focus on the consumer use stage (filters for domestic washing machines), while innovations for adapted textile construction remain exploratory.

An energy toll of fashion through energy usage and greenhouse gas emissions

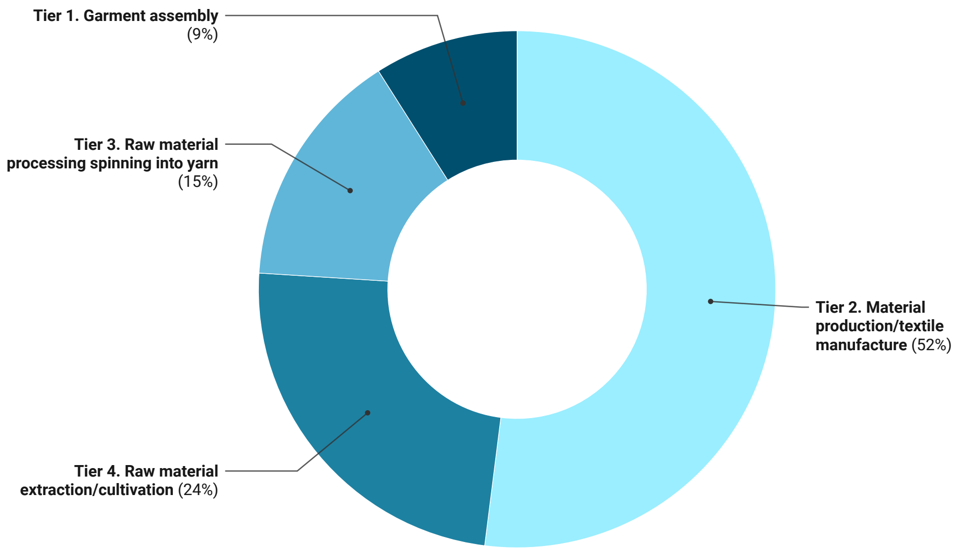
Critical stages for high energy usage are the extraction of synthetic fibers and cultivation of natural ones, and the subsequent textile production process. Synthetic fibers require more energy than natural fibers during extraction and production (Niinimäki *et al.*, 2020; Sadowski *et al.*, 2021) and the EU Textile Strategy (European Commission, 2022) notes that growing demand for textiles fuels inefficient use of nonrenewable resources, such as fossil fuels for production of synthetic fibers.

There is a well-established link between the growth of synthetics, which account for 69% of fiber production, and the fast-fashion business model (European Commission, 2022). Traditional wet processing for textile production requires high levels of thermal energy to heat up vast tanks of water for pretreatment, dyeing, printing and finishing. A shift to dry processing would significantly reduce emissions during textile manufacture (Apparel Impact Institute and Fashion for Good, 2021).

Fashion's high carbon footprint is a result of high energy use in production processes and is influenced by the source of the energy used, for example coal or renewable sources (Niinimäki *et al.*, 2020). The energy grid of most production countries is coal-based, with year-on-year growth in electricity generation from coal in major production countries including the People's Republic of China, Bangladesh, India and the Socialist Republic of Viet Nam from 2010 to 2021 (Stand.Earth, n.d.).

In their working paper, Sadowski *et al.* (2021) estimated the total GHG emissions for the apparel industry in 2019 using data from the Sustainable Apparel Coalition, Higg and Textile Exchange, split by proportion into each supply chain tier as displayed in Figure 1.

Figure 1. GHG emissions for the apparel industry



Source: Sadowski et al. (2021).

Challenges with leather

Industrial mass consumption of animal leather has a significant environmental impact in terms of carbon emissions, deforestation, water pollution and land overuse (Common Objective, 2021).

Leather is a by-product of the meat industry, as the greatest value of livestock is in the meat not in the hide, so the carbon footprint of cattle rearing is usually attributed to the meat industry not the fashion industry. Most leather for footwear and clothing comes from cows (Common Objective, 2021), and beef has the highest carbon footprint of all foods (Poore and Nemecek, 2018).

The most popular way of tanning leather uses chromium, a type of heavy metal which in some forms has been declared carcinogenic, or cancer-causing. The waste from chrome tanning, which contains leftover chromium, often ends up polluting waterways, posing a risk to the health of leather workers and local communities (Common Objective, 2021). While metal-free leather tanning is possible and gaining traction, it is a less popular system than chrome tanning owing to its costs and energy-intensity.

Fragmented supply chains increase transportation carbon footprints

Mass outsourcing of production to benefit from lower labor costs has led to a geographically fragmented supply chain with various operations situated in disparate locations, so there is a higher carbon footprint from the transportation of goods during their processes of transformation from fiber to finished product.

In order to make finished products available for consumers to buy as quickly as possible, air freight is an increasingly popular transportation method for fashion, but this has a significantly higher carbon footprint than sea freight (Niinimäki *et al.*, 2020). However, the carbon footprint of garment transportation is relatively insignificant compared to that of production processes such as fiber extraction, yarn spinning and textile manufacture (Peters *et al.*, 2021).

Less than 1% of textiles are recycled into new textiles

Textile waste management is an increasing problem, as most is incinerated, sent to landfill or exported to developing countries, where it may end up in landfills or open dumps (United States Environment Protection Agency, 2023; Changing Markets Foundation, 2023; National

Geographic, 2024). In Europe alone, over 15 kilograms of textile waste is generated per person, of which 85% is discarded clothes and home textiles from consumers.

In 2022, still less than 1% of the global fiber market comes from pre- and post-consumer recycled textiles (Textile Exchange, 2023). The potential for improvement is vast, with some projections suggesting that fiber-to-fiber recycling could reach 18 to 26% of gross textile waste by 2030 (McKinsey & Co., 2022).

Recycling does not mean “new textiles.” While the reuse of textiles as feedstock for other industries may provide certain economic advantages, it does little to advance the circular fashion economy. More specifically, the current trend of using plastic waste to manufacture fashion products – often framed as “sustainable” – in reality neither addresses the industry’s own waste problem nor mitigates the negative environmental consequences of using plastic textiles. These clothes and garments continue remaining synthetic, thereby shedding microplastics into ecosystems and human bodies alike.

A major challenge to meaningfully incorporating recycling within this industry is the broad-based use of blended textiles. For example, materials like elastane, which is a common addition to fabrics, used to improve flexibility and fit, are almost impossible to separate and recycle, and no viable methods currently exist to process them at scale.

Even when recycling is made technically feasible, the process carries forward the industrial chemicals embedded in the original fabric, which in turn perpetuates their presence in new garments. In addition to this, the accelerating trend, largely driven by fast fashion, of combining multiple raw materials in a single garment adds a further layer of complexity. While intended to enhance the garment’s texture and cost efficiency in production, it makes separation and recycling prohibitively complex.

High online shopping return rates

Online shopping has a high returns rate, with clothing the most returned category of goods bought online (Statista, 2023a). Between 25% and 50% of clothing items bought online are subsequently returned to the retailer, depending on the type of clothing and time of year (Butler, 2022; Circular, 2023). In 2022, the highest online fashion returns rates in Europe were seen in Switzerland, with 45% of all online fashion orders subsequently returned (Statista, 2023b). Returns increase carbon emissions owing to the extra transportation for returning items and textile waste, as returned items may end up in landfill (Renwick, 2020) rather than being resold.

Prevalence of linear business model

The fast-fashion business model obstructs progress toward a circular fashion economy. The ever-changing nature of fashion trends means there is a dual focus on speed to market and low cost in supply chain operations. This means that commercial interests supersede environmental and social concerns, resulting in corners being cut and a preference for cheaper and/or less sustainable options such as virgin polyester over recycled polyester, or air freight over sea freight.

Coupled with overproduction – an estimated one-third of all clothing produced is never sold (Niinimäki *et al.*, 2020) – high resource consumption and GHG emissions are inevitable in the fashion industry’s current business model, resulting in significant threats to environmental sustainability.

The linear system of production and consumption – that is, using finite virgin resources to make items that are not used to their full potential before being disposed of, and low-quality, disposable clothes ending up incinerated, landfilled or dumped in the natural environment – remains prevalent.

In a circular system, products are designed to last, and existing products and materials are kept in use for as long as possible at their highest value, through sharing (swapping/renting/reselling), repairing, reusing, upcycling or recycling.

Mitigating fashion's environmental impact

Increasing awareness of the scale of fashion's negative environmental impact and the limitations of voluntary initiatives has spurred policymaker scrutiny to mandate action and reporting across the supply chain (Business of Fashion and McKinsey & Co., 2023).

Increasing awareness by consumers, businesses and policymakers has put environmental sustainability in the fashion industry at the forefront of the public agenda. Environmental sustainability that supports the transition to a low-carbon, resource-efficient economy is governed by a number of voluntary initiatives (for example, the UN Fashion Charter and Sustainable Apparel Coalition), environmental, social, governance (ESG) reporting for investors, and increasingly regulation and legislation.

Tracking the origin of resources used in the fashion industry dates back to the Dodd–Frank Act on conflict minerals in 2012 in the US, and legislation continues to evolve with compulsory mapping and disclosure requirements. As self-regulation and voluntary initiatives have not achieved the desired transformation, new EU and US legislation has and will soon come into force that requires brands and manufacturers to intensify initiatives to reduce carbon emissions and waste (Business of Fashion & McKinsey & Co., 2023).

The Corporate Sustainability Reporting Directive, a new piece of EU legislation that comes into force in 2024, requires all large companies to publish regular reports on their environmental and social impact activities via a standardized framework, and establish due diligence procedures to address adverse impacts of their actions on human rights and the environment, including along their value chains worldwide.

The EU's Carbon Border Adjustment Mechanism subjects the import of certain goods into the EU to a levy, although textiles are not yet included. It is designed to address "carbon leakage," where companies relocate production activities to countries with less stringent climate policies, resulting in an increase in emissions in those countries.

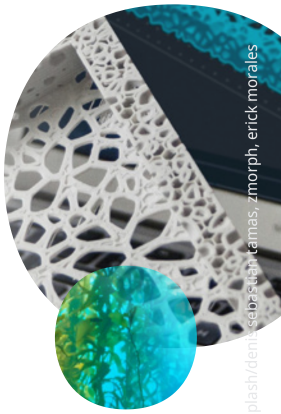
New York State's Fashion Act (or Fashion Sustainability and Social Accountability Act) will legally enforce brands to disclose and address their environmental and social impacts. Companies with annual revenues over USD 100 million who wish to sell to the New York market must set and achieve science-based emissions targets, implement public global supply chain maps and publish details on the management of chemical usage.

The Science Based Targets Initiative (SBTi) provides sector-specific concrete guidance for companies to reduce emissions through target setting and associated pathways for delivering on targets. Companies in the fashion industry can also complete a GHG emissions inventory in accordance with the GHG Protocol which sets the standards for companies, cities, and countries to measure and track GHG emissions (GHG Protocol, 2023). According to this protocol, the greenhouse emissions of a company can be classified as follows:

- Scope 1 emissions are direct emissions from company-owned and -controlled resources.
- Scope 2 emissions are indirect emissions from the generation of purchased energy, from a utility provider (such as purchased electricity, steam, heat and cooling).
- Scope 3 emissions are all indirect emissions not included in scope 2 that occur in the value chain of the company, including both upstream and downstream emissions.

Scope 3 emissions are the largest emission sources in the value chain. However, they can be difficult to measure owing to the industry's reliance on a global network of suppliers.

Stages in the fashion and textiles value chain with high innovation potential for environmental benefits



Photos: Unsplash/denis sebastian tamas, zmorph, erick morales

This section presents an overview of sustainable innovative fashion technologies that can cut waste, save resources, and reduce pollution in fashion – from material production to recycling, retail, and logistics – delivering environmental benefits across the value chain.

Technology and innovation can play a particularly important role during the production of materials and the processing of textile waste. The table below summarizes the key areas of interest that have potential to reduce water, chemicals, energy and textile waste in fashion production and retailing. Within some areas, innovations are contextually focused, for example for specific materials such as cotton, polyester and man-made cellulosic fibers (MMCFs). In other areas, innovations may have wider application beyond fashion and textiles, for example in distribution and logistics, and switching from coal to renewable fuel sources in industrial operations.

Overview of sustainable fashion technologies in key fashion supply chain stages

Production stage	Type of technology		Examples of technologies from the WIPO GREEN database with ID number	
Raw material cultivation /extraction	Improving soil health and maximizing crop efficiency		Biomede	148824
			Cropin	148702
			Wadhwani AI	148832
	Utilizing waste as a raw material		ECONYL®	148608
			Fairbrics	148825
			Green Whisper	148876
	Alternative renewable fibers		Algaeing	148592
			SaltyCo	148831
	Lab-grown cotton		Galy	148823
Textile manufacture	Manufacturing process technologies, including:	Raw material production	Ananas Anam	148631
			SINGTEX Group	148693
			Vegea Company	148692
		Textile dyeing and processing	Deven Supercriticals	148941
			DyeCoo	148687
			NTX	148947
			Werewool	148681
		Wastewater and effluent treatment	COLOURizd	30016

Production stage	Type of technology	Examples of technologies from the WIPO GREEN database with ID number	
Garment manufacture	Mass customization	Excess Materials Exchange	148774
		Unspun	148734
	On-demand manufacturing	Unmade	148778
	Zero-waste manufacturing	SXD	148771
		Synflux	148772
Distribution	Optimization of logistics	Reflaunt	148816
	Packaging, returns management	Perfitly	148793
		7 Looks	148781
	Supply chain traceability	Bext360	148804
		Oritain	148802
		Papertale	148820
End of product life	Automated sorting	Matoha	148763
		PICVISA	148767
		Spectral Engines	148760
	Recycling pre- and post-consumer textile waste	Circular Systems SPC	148709
		DePoly	148764
		Pure Waste Textiles	148723
		Tereform	148758
		Worn Again Technologies	148589

The role of intellectual property in promoting green innovation


Photos: Unsplash/Markus Spiske, Getty Images

This section examines the role of intellectual property (IP) in fostering innovation, protecting traditional knowledge, and enabling green technology transfer. It also addresses some of the challenges and opportunities for IP in the circular economy.

Progress, whether measured by our capacity to confront environmental challenges posed by the fashion industry or by economic progress through supporting green business models, is driven by innovation and human ingenuity, and made to profit through market creation (Karuppiah *et al.*, 2023). Fundamentally, innovation is linked to IP rights (see, for example, Fink, 2009; more generally, Fink *et al.*, 1999). These rights, which encompass patents, trademarks, copyrights and industrial designs, function as instruments that shape incentives and behaviors within the innovation landscape. Put differently, the IP system offers creators a time-bound exclusivity over their intellectual efforts while also serving the broader public interest.

Intellectual property as a public good

In fact, the IP system is premised on the principle that knowledge is a quasi-public good (Tanzi, 2017). In the absence of legal protections, there is a risk of increased ease with which novel ideas can be appropriated and replicated by someone who is not the inventor. IP provides security that gives confidence to an inventor to dedicate significant resources to research and development knowing that, within a certain time frame, the benefits cannot be freely adopted by competitors (WIPO, n.d.). IP rights grant innovators a time-bound period of control over the invention which could be used for commercializing. Increasing the potential for return on investment may act as a catalyzing agent, encouraging the allocation of capital and talent toward the pursuit of new knowledge and its practical application.

Besides this, the IP system also plays an important role in the broader dissemination of knowledge. The patent regime, for instance, operates on a quid pro quo: in exchange for the grant of exclusive rights, inventors are obligated to provide a sufficiently detailed disclosure of their invention (see generally, Lee, 2024). This requirement transforms tacit knowledge into explicit information, enriching the public domain and providing a foundation upon which future innovation can build.

The vast repositories of patent information also serve as a valuable resource for the direction of technological development and identifying new areas for scientific and commercial inquiry for researchers and entrepreneurs (Kwakwa and Oksen, 2024; see also Borthakur, 2023). Further, IP rights facilitate the process of technology transfer and collaborative ventures. Licensing agreements enable rights holders to strategically disseminate their innovations, reaching markets and applications that might otherwise remain inaccessible. Such arrangements can foster a more rapid and widespread adoption of new technologies.

Examples of potentially relevant IP types for fashion technologies include patents for new materials and processes, trademarks linked to sustainable branding and design rights for eco-friendly products. At the same time, protecting traditional knowledge and nature-based solutions linked to fashion – such as natural dyeing techniques, regenerative farming methods and ancient manual textile production methods – within the IP framework can present challenges, particularly as these types of innovation are often developed collectively over many generations in different cultural contexts and therefore may not meet the novelty criteria required for patent protection. Additionally, these innovations are typically passed down orally, making legal ownership difficult to establish. International instruments such as the Nagoya Protocol and the WIPO Treaty on Intellectual Property, Genetic Resources and Associated Traditional Knowledge aim to address some of these gaps.

WIPO and WIPO GREEN

As a specialized agency of the United Nations, WIPO aims to foster a balanced and effective international IP system that enables innovation and creativity for the benefit of all. Firstly, it serves as a forum for international cooperation including by providing a platform for its Member States to engage in dialogue and negotiate international agreements. Secondly, it provides IP services which support innovation processes. Agreements such as the Patent Cooperation Treaty (PCT) and the Madrid System for trademarks attempt to streamline complex and costly process of seeking international IP protection by offering a centralized mechanism for innovators to pursue protection in multiple jurisdictions. Other services include databases such as Patentscope which allows users to access millions of patent documents, including PCT applications.

Another such database is the WIPO GREEN, which is the database that hosts all the technologies in this report. The WIPO GREEN database contains over 140,000 green technologies, experts and needs, and is a free public resource. Based on seekers and solution providers' uploads, it seeks to address the green technology information gap by providing accessible information on solutions available or upcoming.

Intellectual property in the circular economy

Another issue that warrants a more detailed analysis is the role of IP in the circular economy, a model that keeps resources in circulation and reduces waste (Calboli, 2024). Key processes such as reuse, repair, refurbishment and recycling often require the approval of the owner of the IP right. For instance, putting a substantially transformed product onto the market might constitute a breach of the IP owner's rights. A right to repair might not apply if the changes to the product are too significant.

These tensions might warrant considering how certain IP elements are exercised or interpreted in the circular economy. In practice, companies that are proponents of circular economy have to consider their role as enablers of strong circularity by adopting collaborative practices (Capponi *et al.*, 2025). At the policy level, some suggest that specific exceptions for repair and upcycling and a broader interpretation of the exhaustion principle should be considered.

Extraction of raw materials/textile manufacture

Photos: Phycolabs; Unsplash/timothy dykes; freepik

This section reviews innovations in areas such as sustainable fibers, materials, and processes, from bio-based and waste-derived textiles to waterless dyeing and circular production systems. These technologies aim to reduce the fashion industry's environmental footprint.

Technologies focusing on alternatives to petroleum- or animal-based fibers, or improvements to cotton growing and extraction of synthetic fibers, aim to realize versatile and high-performance fibers with low environmental impact at low production cost. Other technologies focus on more sustainable alternatives to yarn and textile manufacturing, dyeing and finishing processes with fewer harmful chemicals and lower water and energy requirements.

Bio-based alternative raw materials can replace cotton-, animal- and petroleum-based fabrics. Many forms of agricultural waste can be used to produce materials for fashion applications. These include regeneratively grown natural fibers and closed-loop recycled fibers. Nature-based solutions make use of renewable fibers such as hemp or kapok and agricultural waste that can be transformed into fibers with fewer harmful chemicals. However, it is notable that very few of the waste materials are from garments.

While many of these technologies hold promise, there is a pressing need to prioritize and invest in viable and environmentally benign fiber-to-fiber recycling technologies to enable the fashion industry to deal with its own waste (European Commission, 2022). High-quality recycling (as distinct from downcycling) supports a circular fashion economy by ensuring that the quality of the material is preserved or recovered for reuse in products with the same market value and allows further recyclability of the same quality at end-of-life.

Raw materials and the circular economy

Circular processes utilizing pre- and post-consumer plastic waste or carbon dioxide captured from industrial fumes can produce virgin-grade alternatives to synthetic fibers such as polyester or nylon. Bio-based polyester alternatives from renewable agricultural feedstocks such as plant starch, algae, corn and sugar are abundant and offer biodegradability and industrial compostability.

However, a recent comparative study found that bio-based fibers had higher environmental impacts than polyester in terms of acidification, eutrophication, ecotoxicity, water and land use, which all increase with the bio-content and relate to the first-generation feedstock (agriculture and transport) (Ivanović *et al.*, 2021).

Isolating squid genes led to the development of a bioengineered protein-based fiber that reduces microfiber pollution. Bypassing the need for agricultural land and chemicals for cotton farming can be achieved with lab-grown cotton through cellular agriculture, where cells are placed into bioreactors and grown into cotton fibers. There are also technologies that focus on improving soil health and maximizing crop efficiency for cotton.

Leather-like materials can be fabricated from apple waste, grape waste, citrus waste, shrimp shells, brewer's saved grain, garden and park waste, mycelium and bacterial cellulose. Other bio-based waste resources that can be transformed into materials suitable for fashion applications include coffee grounds, pineapple leaf, milk and bananas.

Agricultural waste can be used instead of trees for producing viscose and in textile processing, for example to produce natural dyes at scale and to produce industrial enzymes for textile bio-polishing, desizing and bio-scouring.

Water use

There is a pressing need for textile manufacturing to shift from wet processing to dry processing technologies that need very little to no water to reduce energy needed to heat vast amounts of water and the reliance on coal for thermal energy (Accenture, 2023). Carbon dioxide (dry) dyeing technology is well established for synthetics (de Oliveira *et al.*, 2024) and there are various other means of waterless dyeing such as using microbes, producing pigment and ink from algae, wood waste or textile fibers from pre- and post-consumer textile waste.

Other alternatives include fiber dyeing for polyester yarn by melting color pigments and recycled polyester mass together before it is extruded to fiber and spun into yarn and even DNA sequencing to engineer microorganisms to produce, deposit and fix pigments onto textiles. Some technologies focus on wastewater treatment, for example by mimicking biological membranes for water purification, using microbial fuel cells or electro-coagulation.

Innovation example

Ancient vegan silk, also known as peace silk, this production method refers to any type of silk that is produced without harming or killing the silkworms. In conventional silk production techniques, the cocoons are steamed, boiled, or dried in the sun, thereby killing the silk larvae inside. Peace silk was first patented in India in the early 2000s as Ahimsa silk and until today it is made on a small scale with the involvement of rural silk farmers, who are usually women (Khanna, 2019). Other types of vegan silk manufacturers work with cactus or eucalyptus as origin materials.

Technology solutions

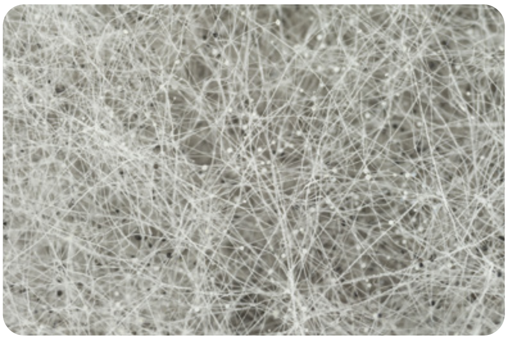
Regenerated nylon yarn from pre- and post-consumer waste

ECONYL® (Database ID 148608)

ECONYL® was an early pioneer of waste regeneration to reduce reliance on fossil fuels for synthetic fibers. It launched on the market in 2011 as a 100% regenerated virgin-grade nylon yarn made from pre- and post-consumer plastic waste such as fishing nets, fabric scraps, carpet and industrial plastic, which can be infinitely reused. Collected waste is cleaned and shredded, depolymerized to extract nylon, polymerized, spun into yarn, and then used for producing textile products. The material has the same performance characteristics as virgin nylon and is used by thousands of fashion brands around the world, including luxury, sportswear, outdoor and intimates players. The producer company Aquafil claims it reduces the climate impact of nylon by up to 90% compared with standard nylon made from petroleum. Prada pledged to replace virgin nylon with ECONYL® by 2021 and in 2023 Stella McCartney launched its first closed-loop circular garment – a parka made entirely from ECONYL® that is designed for disassembly so it can be sent back to Aquafil to be recycled into new ECONYL® yarn at the end of its useful life. However, owing to its synthetic nature, it sheds microfibers and is not biodegradable.

- Contracting type: For sale
- Readiness level (TRL): Scaling up (TRL 9)
- Country of origin: Italy
- Contact: WIPO GREEN Database

Mycelium-based biodegradable leather substitute



Ecovative (Database ID 148958)

The material MycoComposite™ is a combination of mushroom mycelium, cultivated from filamentous fungi on organic feedstocks and shredded plant fibers, such as kenaf, hemp stalks and other plant-based agro-waste. The mycelium binds the material together into a natural composite for a range of applications. The process requires little energy and the final product is 100% bio-based and biodegradable. The AirMycelium™ technology enables large-scale production of 100% pure mycelium, with applications such as Forager™ as a sustainable replacement for leather. However, the industrial-scale growth of mycelium materials raises concerns about the carbon footprint tied to nonlocally sourced growth substrates. Its latest round of funding in 2023 raised USD 30 million to scale its Forager business into a world-class supplier of sustainable textile products suitable for fashion applications.

- Contracting type: For sale, licensing (MycoComposite)
- Readiness level (TRL): Scaling up (TRL 9)
- Country of origin: United States
- Contact: WIPO GREEN Database

Synthetic fiber technology that converts waste carbon emissions into polyester pellets

Fairbrics (Database ID 148825)

This company has pioneered a process to collect carbon dioxide emissions from industrial fumes that would otherwise be released into the atmosphere, which are then reacted with a catalyst and solvent to produce chemicals used in polyester synthesis. These chemicals are polymerized to form polyester pellets, which can be spun into yarn and then into fabric for apparel applications. Using carbon dioxide instead of fossil fuels to manufacture polyester, Fairbrics is developing the first synthetic fiber that could achieve a potential net positive impact on climate change, as the process reduces reliance on coal and petroleum to produce polyester. It is scaling its Belgian plant and has received funding from the EU's Horizon Europe research and innovation program to valorize sustainable PET textile products from carbon dioxide waste streams at industrial scale.

- Contracting type: For sale
- Readiness level (TRL): Scaling up (TRL 9)
- Country of origin: France
- Contact: WIPO GREEN Database

Bio-based and biodegradable polyester alternative

Kintra Fibers (Database ID 149137)

This company has succeeded in producing a fully bio-based and biodegradable synthetic alternative to PET polyester that aligns with apparel performance requirements. By using 100% bio-based inputs (for example, corn and sugar) instead of traditional polyester (PET) that relies on fossil fuels, Kintra Fibers has achieved a 95% reduction in emissions, a 30% decrease in water usage and 20% less energy consumption. The new fiber is biodegradable in aerobic environments and the resin and yarns are produced on the same equipment as PET. This means that specialist new infrastructure is not necessary, which could help the company scale quickly and competitively. In 2023, the company raised USD 8 million in funding and partnered with several retailers in a commercial pilot.

- Contracting type: For sale
- Readiness level (TRL): Technology development/prototype (TRL 5-6)
- Country of origin: United States
- Contact: WIPO GREEN Database

Agro-waste based cellulosic fiber pulp for viscose

The Hurd Co. (Database ID 148939)

Founded in 2019, The Hurd Co. has developed a technology for producing MMCF pulp called agrilose™ from agricultural waste. This addresses the problem of deforestation, as MMCF is usually made from trees. The pulp can be used to make lyocell or viscose/rayon, with the same quality and price as tree pulp. Its patented technology has a significantly lower environmental impact, using 50% less water and 90% less energy than the conventional pulping processes. The agro-waste in question is hemp, which is harvested for CBD and protein as well as traditional hemp fiber, but most of it is thrown away or burned. The Hurd Co. uses 70% of this waste for their pulping process. The company was selected for the Fashion for Good Accelerator Program in 2021 and the Los Angeles Cleantech Incubator in 2020.

- Contracting type: For sale
- Readiness level (TRL): Scaling up (TRL 9)
- Country of origin: United States
- Contact: WIPO GREEN Database

Waterless coloration process for recycled polyester

We aRe SpinDye (Database ID 148961)

We aRe SpinDye has introduced Waterless Dyeing, an innovative method for coloring polyester yarns and textiles with notable sustainability benefits. The process involves integrating color directly into the molten plastic solution before filament formation, minimizing water and chemical usage. In contrast to conventional methods, Waterless Dyeing achieves a remarkable 75% reduction in water consumption, a 90% decrease in chemical usage and a 30% cut in carbon dioxide emissions. The resulting fabrics exhibit vibrant colors, have exceptional durability and are produced with full transparency and certification.

- Contracting type: For sale
- Readiness level (TRL): Scaling up (TRL 9)
- Country of origin: Sweden
- Contact: WIPO GREEN Database

An industrial technology to color cellulosic yarn with a reduced environmental impact

COLOURizd™ (Database ID 148964)

COLOURizd's patent-pending QuantumCOLOUR dyeing technology injects pigment and a binder directly into the yarn, using only 0.95 liters of water per kilogram of colored yarn and producing zero effluent, enabling a transition to dry processing in dye factory environments. This almost eliminates water consumption, achieving a reduction of 98% in water consumption alongside zero wastewater and harmful chemical discharge, a 73% decrease in carbon footprint and 50% reduction in energy use compared to traditional wet dyeing. The technology simplifies and streamlines the 30 or more steps of conventional yarn dyeing into a five-step process; it is suitable for synthetic and cellulosic yarns and for high volume production. Current clients include fashion brands such as Gant, Lee and Wrangler, as well as other sustainable fiber producers such as Renewcell and Circulose, and chemical dye specialist Archroma. In 2023, COLOURizd was a finalist in both the H&M Foundation Global Change Award and Fast Company's Innovation by Design Awards.

- Contracting type: For sale
- Readiness level (TRL): Scaling up (TRL 9)
- Country of origin: Hong Kong, China
- Contact: WIPO GREEN Database

Textile fibers derived from macroalgae

Phycolabs (Database ID 148889)

Textile fibers derived from macroalgae, such as those pioneered by companies like Phycolabs, offer a groundbreaking and sustainable approach to textile production. Harvested from renewable macroalgae in an environmentally friendly manner, these fibers undergo extraction, processing, and transformation into yarns and fabrics. Noteworthy advantages include biodegradability, minimized chemical usage and potential carbon sequestration benefits from macroalgae cultivation. Some macroalgae-derived textiles also possess natural antimicrobial properties, making them suitable for diverse fashion applications.

- Contracting type: For sale
- Readiness level (TRL): Scaling up (TRL 9)
- Country of origin: Brazil
- Contact: WIPO GREEN Database

Technology to turn agricultural waste into biodegradable textile fabric

Rethread Africa (Database ID 148891)

Rethread Africa is revolutionizing sustainable circular fashion by employing innovative technology to transform agricultural waste into biodegradable textile fabric. The company collaborates with small-holder farmers, collecting materials such as maize husk residue, providing extra income while reducing waste. The meticulous breakdown of these materials results in fibers that are spun into yarn, creating a versatile, eco-friendly textile. This process requires only 1% of the water used in traditional cotton production, significantly cuts carbon dioxide emissions by 80% and reduces eutrophication by 51%. The material naturally decomposes, enriching the soil and lessening landfill impact. Rethread Africa's forward-thinking approach extends to exploring water hyacinth for athleisure wear, promoting sustainability and supporting local farming communities.

- Contracting type: For sale
- Readiness level (TRL): Scaling up (TRL 9)
- Country of origin: Kenya
- Contact: WIPO GREEN Database

Transforming carbon waste into polyester for the fashion industry

LanzaTech (Database ID 149101)

LanzaTech, a biotech startup, has innovated a technology that transforms carbon emissions into useful products, notably for the textile industry. The process involves capturing emissions from sources like steel mills, converting them into ethanol via fermentation and then transforming the ethanol into the building blocks of polyester. This is done in collaboration with India Glycols Limited and Far Eastern New Century. The end product, a waste-gas-based polyester, matches virgin polyester in appearance and functionality. LanzaTech has partnered with Lululemon to create the first yarn and fabric from captured carbon emissions.

- Contracting type: For sale
- Readiness level (TRL): Scaling up (TRL 9)
- Country of origin: United States
- Contact: WIPO GREEN Database

Garment manufacture

Overproduction is a critical issue during garment manufacture and technologies are focused on aligning demand to production in real time to enable a shift to on-demand manufacturing, as well as reducing cutting room waste. There are several examples of software enhanced with artificial intelligence to reduce material wastage and support zero-waste manufacturing, identify the value of waste materials or products, find high value reuse options for waste materials, and connect demand directly to production for on-demand manufacturing to reduce overproduction and waste. Cutting room waste for woven fabrics can be eliminated through 3D-weaving of yarn directly into garments on an on-demand basis, which also powers on-demand mass customization to reduce overproduction, although these technologies are not yet commercially available.

Innovation example

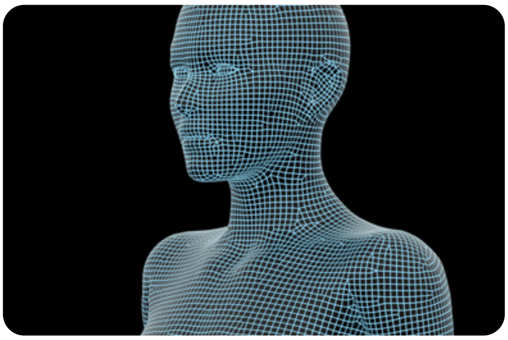
On-demand production

On-demand production

This is a method of manufacturing garments in response to customer orders, instead of producing large quantities in advance. In this manner, only the items that have been ordered by customers are produced, so there is little excess inventory (Samuel, 2023). Kornit Digital, based in Israel, provides on-demand production for brands and manufacturers.

Technology solutions

AI-powered software solutions for zero-waste pattern cutting



Synflux (Database ID 148772)

Speculative fashion lab and research collective Synflux, founded in 2019, has pioneered a method using 3D scanning, computer-aided design (CAD) software and machine learning algorithms to find the optimum garment pattern that eliminates fabric waste from the cutting stage. The method allows custom sizing and fit, as well as customization of garment shape, fabric and color to reflect personal style. The software program generates optimized pattern pieces comprised of rectangles and straight lines that can be modeled with CAD software to produce a fashion pattern. The next step to develop the technology for large-scale production is to work with major fashion brands for proof of concept.

- Contracting type: For sale
- Readiness level (TRL): Scaling up (TRL 9)
- Country of origin: Japan
- Contact: WIPO GREEN Database

3D-weaving yarn into garments to reduce cutting waste

Weffan (Database ID 148777)

Weffan is pioneering a garment manufacturing method that designs out waste, by 3D-weaving yarn into garments and thereby merging textile production and garment manufacturing into one step and minimizing fabric and resource waste from cutting. It uses existing jacquard loom technology as a base. In 2022, the company collaborated on 3D-woven concept trousers with fashion brand Liquid Editions and went on to win the Design Futures Innovation Prize 2022 for this collaboration. In 2023, Weffan exhibited at ITMA 2023 in Milan, the world's largest textile and garment technology trade show, and partnered with Future Fashion Factory, a UK-based R&D partnership exploring and developing new digital and advanced textile technologies to support the UK fashion and textiles industry. This enabled prototyping and proof of concept in a factory setting, which could support further collaborations with fashion brands to expand the options of styles that could be produced using this method.

- Contracting type: For sale
- Readiness level (TRL): Technology development/prototype (TRL 5-6)
- Country of origin: United Kingdom
- Contact: WIPO GREEN Database

Vega™ 3D technology seamlessly weaves yarn directly into garments

Unspun (Database ID 148734)

Founded in 2015 with an on-demand custom jeans offer to consumers, Unspun has now pioneered a 3D-weaving technology called Vega™ that weaves yarn directly into garment pieces, at speed. The process combines textile production and cutting of pattern pieces into one step, removing cutting waste from the conventional weave–cut–sew process. It eliminates the need for large order quantities, reducing the likelihood of overproduction and waste, while empowering localized production in micro-factories to reduce transportation distances of conventional offshore production. Garments could also be unwoven and rewoven into new products, powering a circular business model by creating a new life for the yarns over and over again. USD 14 million funding raised in 2023 will enable it to develop the robotic manufacturing technology needed for scaling the concept.

- Contracting type: For sale
- Readiness level (TRL): Scaling up (TRL 9)
- Country of origin: United Kingdom
- Contact: WIPO GREEN Database

AI-powered platform for zero-waste patterns to eliminate fabric waste

SXD (Database ID 148771)

SXD has developed an AI-powered platform that combines sketch and fabric information into zero-waste patterns that can auto-adjust across sizes, fabrics and styles. The method of multiobjective optimization eliminates fabric waste during the cutting stage of production, which in conventional design process can amount to between 10 to 30% of the fabric becoming waste. SXD has worked with fashion brands Albirds, Desigual and Woolrich. In 2023, the company delivered a proof of concept for a major European brand by transforming four of its best-selling items into zero-waste products and was the sole design category winner of the H&M Foundation's Global Change Award.

- Contracting type: For sale
- Readiness level (TRL): Scaling up (TRL 9)
- Country of origin: United States
- Contact: WIPO GREEN Database

Digital matching service to route waste materials to reuse options

Excess Materials Exchange (Database ID 148774)

Founded in 2017, Excess Materials Exchange is an AI-powered digital platform to match waste materials with their highest value use potential, supporting a circular system of reuse at the highest value. Since businesses often have to pay to dispose of waste, this B2B matching service supports financial as well as environmental goals – the company estimates that the financial value of material flows increases by 110% when routed to their highest reuse potential as opposed to disposal, while the environmental footprint reduces by 60 percent, by extending the use value and minimizing the amount of materials that go to landfill or incineration. By working across multiple sectors, the opportunities for matches are increased – for example, coffee grounds from a restaurant could be used to extract pigment for ink, bioplastics or fibers. Biotechnology company Fruitleather Rotterdam uses fruit waste to produce a leather-like material (Database ID 148563). The platform provides every material with a digital passport, then tracking and tracing identifiers match the materials to their digital twin, enabling materials to be followed through their lifecycle and a quantification of the financial, environmental and social impact to be made.

- Contracting type: For sale
- Readiness level (TRL): Scaling up (TRL 9)
- Country of origin: Netherlands
- Contact: WIPO GREEN Database

Platform that connects demand directly to production for on-demand manufacturing to reduce overproduction waste

Unmade (Database ID 148778)

Established in 2014, Unmade is a software as a service (SaaS) subscription platform to support on-demand production and avoid overproduction of clothing, while lowering carbon emissions and reducing waste. The software interface allows customers to customize items within parameters predefined by the brand. The customer data is then translated into production data and can be sent to any factory partner and even directly to specific machines within the factory. This enables customized items to be manufactured at the same cost and speed as mass-produced items. The company partnered with Rapha cyclewear to allow customers to create their own unique, digitally printed team kit and with New Balance to power custom products for all major sports in its teamwear business. Funding rounds have enabled Unmade to continue its global expansion and development of its technology, as well as improvements in serving existing customers.

- Contracting type: For sale
- Readiness level (TRL): Scaling up (TRL 9)
- Country of origin: United Kingdom
- Contact: WIPO GREEN Database

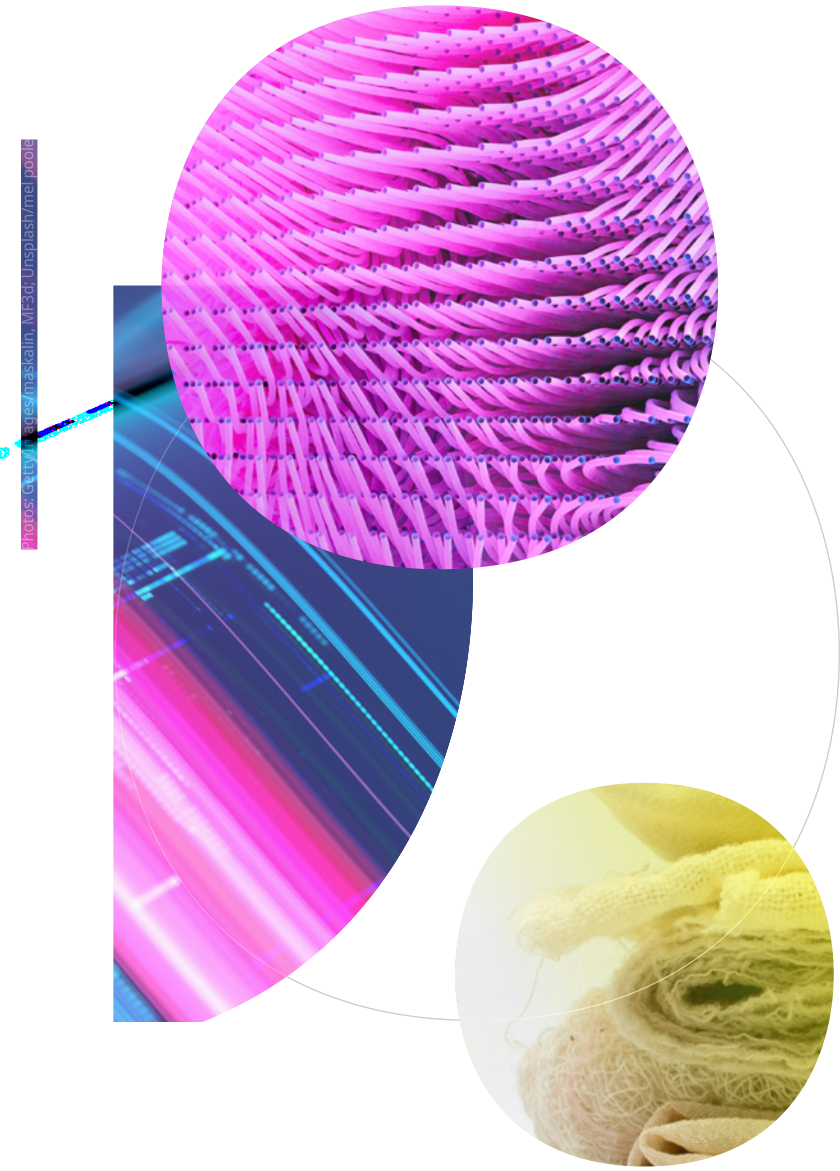
Mechanical recycling to make 100% recycled fabric from 60% preconsumer textile waste and 40% plastic waste

Rewoven (Database ID 148603)

In South Africa, textile waste constitutes 6.5% of total landfill waste, amounting to around 6 million tons. Cape Town-based project Rewoven, initiated in 2018 by Tshepo Bhengu, Esethu Cenga and Lonwabo Mgoduso, has successfully diverted over 1 million kilograms of textile waste from landfills during its ongoing commercial pilot phase. Driven by a commitment to sustainability, positive impact and entrepreneurship, Rewoven provides a cost-effective, accessible and reliable solution for textile waste disposal. The project not only promotes recycling but also introduces circular practices, producing and retailing products from recycled textiles, thus minimizing water usage, avoiding dyeing and reducing carbon emissions. The emphasis on circularity is evident as the retailed fabric can be recycled at the end of its useful life.

- Contracting type: For sale
- Readiness level (TRL): Early commercial demonstration/adoption/dissemination (TRL 8)
- Country of origin: South Africa
- Contact: WIPO GREEN Database

Distribution



Photos: Getty Images/maskalin, MF3d; Unsplash/mel poole

This section explores some of the digital tools in fashion, from AI-driven logistics and blockchain traceability to "re"-commerce platforms, demand forecasting, and virtual try-on solutions enhancing sustainability and consumer experience.

AI-enhanced software can predict and optimize logistics to improve efficiency and reduce carbon emissions; however, there is no evidence of any fashion-specific technologies in this space.

There are a number of technologies that aim to unravel complex supply chains to improve transparency and verification of data, protecting brand reputations and helping businesses to comply with ESG regulations. Many are based on blockchain, while others use physical marker technologies or forensic science to prove product origin. While blockchain systems store information in a reliable way, they assume input of correct information and lack a connection to the physical item itself, which may go through many processes of transformation, from cotton field to retail store. If fibers are mixed or exchanged at any one point in the supply chain, only a physical marker system would be able to detect it.

There are also many SaaS platforms focused on powering the circular economy through recommerce opportunities such as branded resale that can be integrated into the retailer's website. Others aim to reduce resource waste from overproduction by more accurately forecasting trends and consumer demand.

Finally, several technologies address the returns challenge in fashion ecommerce by providing styling suggestions or accurate size recommendations and virtual try-on options to increase shopper confidence, for example with an AI-based stylist, size recommendation using augmented reality/virtual reality/AI or mobile body-scanning technology.

Technology solutions

Blockchain traceability platform for fabrics

Textile Genesis (Database ID 148782)

The TextileGenesis™ SaaS platform makes sustainable fabrics fully traceable throughout an entire fashion supply chain. It is custom built for premium and sustainable textiles such as wood-based fibers, sustainable cotton, recycled polyester, specialty filaments, silk, wool and cashmere. It aims to deliver radical transparency from fiber to retail, and prove the authenticity and provenance of sustainable textiles against generics throughout the material lifecycle at product-article and lot-level to industry fiber standards using proprietary digital token traceability technology. TextileGenesis™ was one of five winners of H&M Foundation's Global Change Award in 2020 and the development of the technology has benefited from scaled pilots with global retailers such as H&M and Bestseller. The company has partnered with other leading organizations in the sustainable supply chain landscape including textile mills, sustainable fiber producers, ESG standards and industry organizations to drive scalability in traceability.

- Contracting type: For sale
- Readiness level (TRL): Scaling up (TRL 9)
- Country of origin: Hong Kong, China
- Contact: WIPO GREEN Database

DNA markers to trace and authenticate products along supply chains

Haelixa (Database ID 148821)

Haelixa physically tags source fibers using DNA technology to ensure supply chain transparency and product integrity. The DNA marker creates a unique and reliable fingerprint, with the origin and journey information safely embedded into the product at all times giving a forensic proof of the origin, authenticity and integrity of the product. The marker is dissolved in liquid and then sprayed onto the textile product. The application can easily be integrated into existing automated production processes and is harmless yet strong enough to withstand all industrial processing. Forensic testing proves the origin, authenticity and integrity of the product, ensuring that the materials used are those claimed and proving sustainability statements. Haelixa has won over 20 awards and was the overall winner and sustainability winner at leading sports industry trade show ISPO Munich's startup competition ISPO Brandnew Founders Fight in 2023. The company works with brands, retailers and industry associations including C&A, OVS, the Woolmark Company and Cotton Connect.

- Contracting type: For sale
- Readiness level (TRL): Scaling up (TRL 9)
- Country of origin: Switzerland
- Contact: WIPO GREEN Database

Traceability technology using forensic and data science to verify the origin of products and raw materials

Oritain (Database ID 148802)

Founded in 2008, Oritain's methodology is based on analytical chemistry and employs forensic and data science to measure product origin by detecting naturally occurring elements (isotopes and trace elements) in a product or raw material to create a unique chemical fingerprint that is then stored on a database and is tamperproof. Product or material samples can be tested at different points in the supply chain using statistical models to verify the sample against the origin fingerprint. Because the technology measures what is inside the material, rather than relying on labels or applications onto the material, the fingerprint is tamperproof and cannot be replicated or destroyed, so can be used to ensure compliance with regulations such as the US's Uyghur Forced Labor Prevention Act. Oritain raised USD 57 million in funding in 2023 to further develop the technology and expand into new markets and industries. It counts global fashion brands such as Country Road, Shein, Theory and Lacoste, as well as garment manufacturers, textile producers and industry associations, among its clients.

- Contracting type: For sale
- Readiness level (TRL): Scaling up (TRL 9)
- Country of origin: New Zealand
- Contact: WIPO GREEN Database

Digital resale solutions for brands and retailers

Reflaunt (Database ID 148816)

Founded in 2018, Reflaunt is a white-label resale platform that creates branded online marketplaces for fashion brands and retailers to take back and resell preowned clothing and accessories. The technology connects brand websites to secondhand marketplaces and enables consumers to resell past purchases on the brand's website to earn shopping credits. Items are given a second life, supporting a shift toward a circular fashion business model. Reflaunt raised USD 11 million in its first round of funding in 2022 and is part of LVMH's accelerator initiative La Maison des Startups, which aims to bring innovations to the luxury market. The technology offers different service levels from concierge resale, take-back, access to distribution network, and branded resale, and is aimed at premium and luxury brands, with clients including Harvey Nichols, Net-a-Porter, Balenciaga and Ganni.

- Contracting type: For sale
- Readiness level (TRL): Scaling up (TRL 9)
- Country of origin: Singapore
- Contact: WIPO GREEN Database

White-label technology intelligently routes, identifies, prices and lists items

Trove (Database ID 148779)

Established as a peer-to-peer resale platform in 2012, Trove pivoted to a B2B business model in 2016 and offers AI-based white-label technology and end-to-end operations to power branded resale for premium and luxury brands. In 2017, it partnered with Patagonia, Eileen Fisher and REI, which were the pioneers of branded resale. Since then, the company has set up partnerships with other brands such as Lululemon, Levi's and Canada Goose, supporting them to keep high-quality, durable items in use for longer. The company is a B Corp and has raised over USD 122.5 million in funding to enable its vision to scale resale solutions for a circular fashion business. The technology uses computer vision and machine learning algorithms to identify and optimize pricing and merchandising options for millions of unique items in every part of their circular journey. For items that are not sellable, Trove provides access to a network of "next best use" organizations. Trove also provides item-level sustainability metrics on emissions savings and waste diverted from landfill to its partners.

- Contracting type: For sale
- Readiness level (TRL): Scaling up (TRL 9)
- Country of origin: United States
- Contact: WIPO GREEN Database

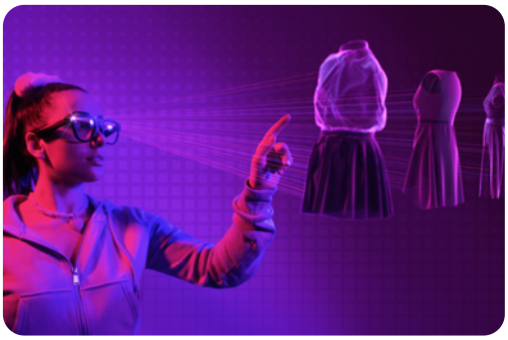
Image-based predictive analytics software to reduce overproduction

Heuritech (Database ID 148632)

Founded in 2013, Heuritech uses AI to analyze real-world images shared on social media to generate actionable insights that help fashion brands forecast trends and consumer demand more accurately. By producing only what people want to buy, brands can optimize sell-through and reduce overproduction and unsold stock based on inaccurate predictions. Its image recognition technology is capable of scanning over 3 million images a day, applying deep learning techniques to recognize over 3,000 fashion details such as colors, shapes or materials. The company's ultimate aim is to build a computer vision pipeline that can analyze clothing very precisely and at scale from millions of images each day. It won the inaugural LVMH Innovation Award in 2017, which enabled a strategic focus on the luxury sector, and counts many luxury fashion and sportswear brands among its clients, including Dior, Louis Vuitton, Moncler and Adidas.

- Contracting type: For sale
- Readiness level (TRL): Scaling up (TRL 9)
- Country of origin: France
- Contact: WIPO GREEN Database

Mobile body-scanning technology using a smartphone



3DLOOK (Database ID 148780)

Established in 2016, 3DLOOK is a user-friendly SaaS product that enables brands and retailers to digitally measure customers' bodies for size and fit recommendations and virtual try-on. The technology accurately measures the customer's shape and size using just two photos on any background and provides data-driven size and fit recommendations and photorealistic virtual try-on for in-store or online shopping, increasing consumer shopping confidence and helping brands to reduce returns.

- Contracting type: For sale
- Readiness level (TRL): Scaling up (TRL 9)
- Country of origin: United States
- Contact: WIPO GREEN Database

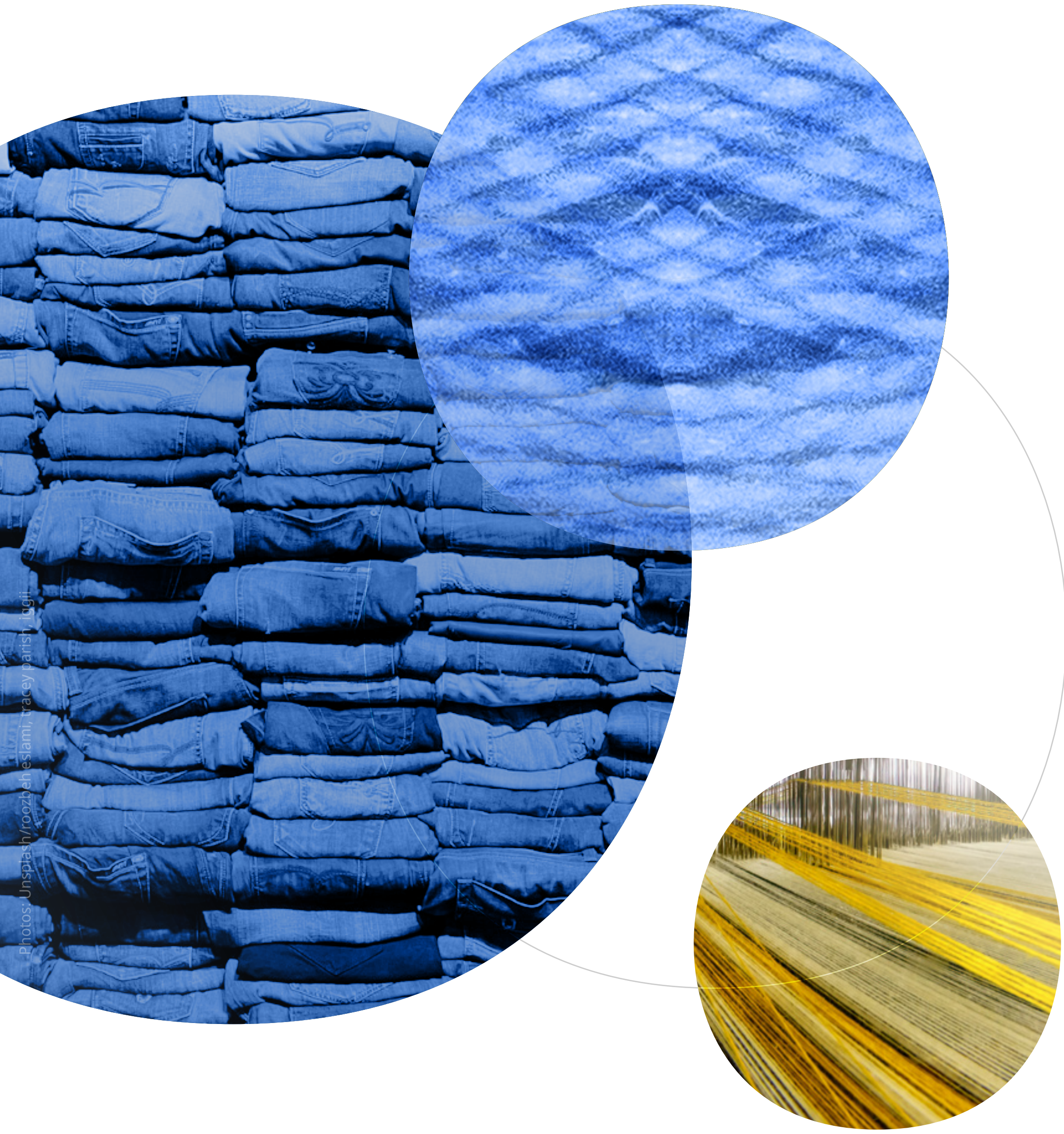
Web based software for supply chain traceability with blockchain

Satma CE (Database ID 148788)

Satma CE, a cloud-based SaaS application, utilizes blockchain technology to establish end-to-end traceability in the waste-to-value supply chain, addressing complexities in waste management. Developed by the India-based Satma CE, the software tackles challenges in traceability by recording data throughout stages like collection, segregation, recycling and processing. The system introduces modules for enhanced traceability in waste collection and segregation, including monitoring financial inclusion of waste-picker entrepreneurs. It meticulously records details like waste quantities, workforce requirements, material quality checks and batch sales, improving vendor evaluation. Brands using materials from reclaimed waste can now achieve complete traceability, not just of products but also of the environmental and social impact, marking a significant breakthrough in the waste management sector.

- Contracting type: For sale
- Readiness level (TRL): Scaling up (TRL 9)
- Country of origin: India
- Contact: WIPO GREEN Database

End of product life



Photos: Unsplash/roozbeheslami, tracey parish, iggii

This section highlights end-of-life textile innovations, spanning mechanical and chemical recycling, automated sorting, upcycling traditions, and the infrastructure essential for scaling circular solutions.

End of product life technologies focus on scaling fiber-to-fiber recycling and transforming pre- or post-consumer textile waste into new fibers and/or other textile products. Mechanical recycling is a mature and efficient process by which textiles are cut and shredded into fibers that can be used for diverse applications. Chemical recycling is more suitable for multicolored textiles as fibers are broken down to basic building blocks at either polymer or monomer level.

There has been a surge in innovative recycling technologies that can handle multiple varieties of textile materials (Fashion for Good and Circle Economy, 2022). However, while chemical recycling can help address the challenge of recycling blended materials that contain for instance polyester, it is much more energy-consuming than mechanical recycling and could distract from efforts that aim to increase the recyclability of textiles through their design and composition.

Managing textile waste

Textile waste is highly varied, so automated sorting technologies are utilized to increase sorting efficiency of nonrewearable items according to fiber composition/color. Examples of technologies to enable automated sorting solutions for textile waste include near-infrared (NIR) spectroscopy, color optical sensors, AI and robotics, and hyperspectral imaging systems with AI to accurately detect fiber composition and presence of contaminants.

Garments need to be prepared for recycling and there are technologies to enable preprocessing, for example heat-dissolvable thread to enable fast removal of zips and buttons on an industrial scale and delamination of multimaterial products. Some technologies aim to separate mixed blends for easier recycling using depolymerization, oxidation, enzymes or molecular regeneration. Others are able to deal with the complexity of the textile waste stream including unsorted, dirty end-of-life plastics and fibers (which cannot typically be recycled owing to complex blends, dyes, contaminants and so on) and transform them into virgin-grade raw materials without separating blends. Further technologies focus on material regeneration processes to turn textile waste into valuable alternative products for interior decoration and shopfitting.

Although significant investment is still required to enable scaling of fiber-to-fiber recycling, there are a number of technologies that enable the transformation of textile waste into new textile fibers through circular processes that utilize pre- and post-consumer textile waste. While it is promising to see multiple technological innovations in this aspect, infrastructure development is needed to collect, sort and prepare textile waste for distribution to processors so that they can use it as feedstock in the production of regenerated textiles or to otherwise valorize the waste.

Fiber-to-commodity product recycling is the first stage of scaled-up recycling but “downcycling” can be perceived negatively as the end products are less valuable than the original clothing items. However, the process for downcycling textile waste into industrial materials such as insulation, felts or rags is well established, creates local employment and utilizes local supply chains (Leal Filho *et al.*, 2019).

The EU Horizon 2020 research and innovation project RESYNTEX (2015–2019) successfully demonstrated the viability of transforming textile waste into feedstocks for chemicals and textiles. Industrial symbiosis between textile recycling and chemical industry sectors underpinned the conceptualization of a new value chain from textile waste collection to generation of secondary raw materials.

Innovation example

Upcycling: an ancient cultural tradition

The skillful art of turning used materials into something valuable has been practiced in many different cultures for generations. It serves as a way to showcase cultural traditions while also being mindful of the resources used to produce a garment. In India it is practiced in the production of *kantha*, an embroidery technique done by layering and stitching together old saris and cloth scraps. In Japan, a mending technique called *sashiko* involves a running stitch and geometric patterns. In the People's Republic of China, *bai jia yi* is a traditional patchwork technique used to create garments and other lifestyle items by stitching together small scraps of fabric. Several contemporary luxury brands have recently followed this trend, for instance Prada diffusion brand Miu Miu through its limited collection of Upcycled by Miu Miu dresses dating from 1930s to the 1980s and Hermès's Petit h workshop, which transforms scraps of leftover materials into precious objects (Bala, 2021).

Technology solutions

Chemical recycling technology for blended textiles

Circ (Database ID 148614)

US-based B Corp Circ is a chemical recycling technology that addresses one of the industry's biggest recycling challenges by providing a solution for recycling blended textiles without destroying either fiber. It uses patented hydrothermal processing to separate polyester and cotton fibers into virgin-equivalent, market-grade dissolving pulp and petroleum monomers that can be sold to manufacturers and fiber producers. Previous attempts to separate polyester from cotton in polycotton blends resulted in the destruction of one fiber or the other, but Circ enables both fibers to be recovered and reused for textile applications. As polycotton makes up half of all textile waste, this technology could potentially divert a significant amount from landfill back into circulation. Circ closed two rounds of funding in 2022 and 2023, in which a number of large fashion companies participated, including Inditex, Zalando and Youngone, and which will enable it to build facilities for industrial scaling.

- Contracting type: For sale
- Readiness level (TRL): Scaling up (TRL 9)
- Country of origin: United States
- Contact: WIPO GREEN Database

High-quality regenerated polyester for textile industry

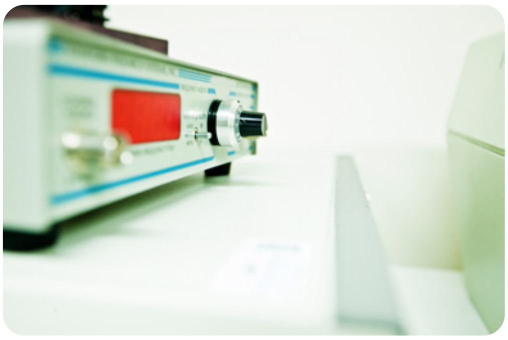
Ambercycle (Database ID 148750)

Ambercycle has pioneered an award-winning molecular regeneration technology to produce high-quality regenerated polyester material, which enables materials to be used over and over again and offsets almost half the carbon emissions associated with virgin-polyester production. Industry-wide adoption of the material is predicted to offset more than 15% of fashion's overall global emissions. To date, Ambercycle has raised around USD 50 million to support commercial-scale production of its premium regenerated polyester.

The process involves shredding and purifying textiles at a molecular level, transforming them into regenerated pellets. These pellets are then utilized to create Cycora® fabrics through spinning. The resulting fabrics mirror the strength and versatility of conventional petroleum-based alternatives, but with a considerably reduced environmental impact.

- Contracting type: For sale
- Readiness level (TRL): Scaling up (TRL 9)
- Country of origin: United States
- Contact: WIPO GREEN Database

Fabrics identification solution for waste sorting



Matoha (Database ID 148763)

Matoha was established in 2017 to improve the accuracy of manual sorting of plastic and textile waste for recycling. The founders developed an easy-to-use handheld spectroscopy machine for identifying the material composition of textile waste. NIR scanners are used to measure how different materials interact with infrared light. The spectra are processed by material identification machine learning algorithms that determine the composition of the material, which is displayed as the weight percentages of the detected textile components. Challenges arise from surface coatings, finishing variations and the thinness of fabrics, influencing recognition outcomes. Matoha's expertise in harnessing NIR spectroscopy addresses these challenges, ensuring accurate identification and segregation of textile materials in recycling lines.

- Contracting type: For sale
- Readiness level (TRL): Scaling up (TRL 9)
- Country of origin: United Kingdom
- Contact: WIPO GREEN Database

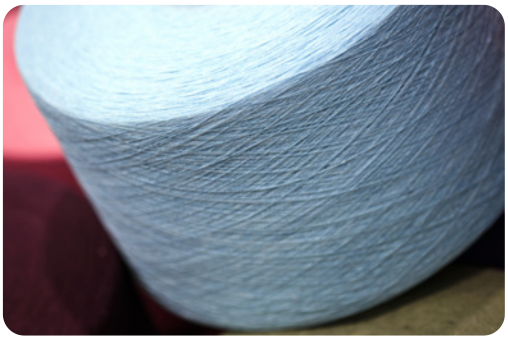
Advanced recycling solution capable of transforming unsorted and contaminated end-of-life fibers into high-quality raw materials

DePoly (Database ID 148764)

DePoly's chemical recycling technology is able to deal with unsorted, dirty and mixed plastics and fibers from post-consumer packaging, textiles, fashion and post-industrial streams, which cannot typically be recycled owing to complex blends, dyes and contaminants. Depolymerization converts all PET plastics and polyester textiles back into their original monomers, which are virgin quality and can be sold back to relevant industries to make new products. The technology works at room temperature and standard pressure. As it does not require waste inputs to be washed, presorted, premelted or separated, it is a solution for materials that are not suitable for conventional recycling systems and would otherwise be incinerated or landfilled, for example polyurethane blended polyester items from the sportswear industry. DePoly was founded in 2020 and by 2023 was operating a pilot plant capable of processing 50 tonnes. After raising USD 13.8 million in seed funding for scaling, it plans to build a showcase plant capable of processing 500 tonnes of waste input.

- Contracting type: For sale
- Readiness level (TRL): Scaling up (TRL 9)
- Country of origin: Switzerland
- Contact: WIPO GREEN Database

Regenerated cellulosic yarn from cotton textile waste



Evrnu (Database ID 148601)

Pre- and post-consumer textile waste with a high cotton content is collected, shredded, chemically purified into a liquid pulp, then extruded into a lyocell fiber, which can be tailored to meet desired performance properties. The fiber can then be spun into yarn and the resulting textiles can be regenerated through the same process over again. The regenerated fibers are soft, absorbent and stronger than virgin cotton and polyester, offering high performance across a range of textile and fashion applications. While regenerated synthetic fibers are well established, this is the first commercially available technology that can transform cotton textile waste into new textiles. Launched in 2022, Nucycl® was also recognized as one of *Time* magazine's 200 Best Inventions of 2022. The producer company Evrnu has collaborated with fashion brands including Zara, Pangaia, Levi's, Bestseller's Object and Adidas × Stella McCartney on capsule collections, and its first commercial manufacturing facility is due to be completed in 2024 for large volume production of Nucycl®.

- Contracting type: For sale
- Readiness level (TRL): Scaling up (TRL 9)
- Country of origin: United States
- Contact: WIPO GREEN Database

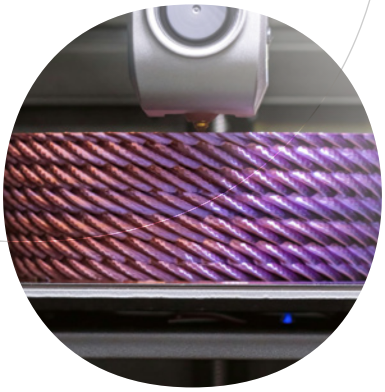
Low impact regenerated fibers from textile waste

PurFi (Database ID 148837)

This technology combines chemical and mechanical recycling of mixed textile waste in a rejuvenation process that maintains the integrity of the underlying fiber to produce virgin-quality fibers that can be rejuvenated a further 17 times, and at scale. While recycled fibers must usually be blended with virgin fibers to make textiles, the PurFi process enables textiles to be produced with 100% recycled fibers. The process is less resource intensive than manufacturing virgin polyester, polyamide or cotton, using up to 96% less water and 90% less energy, and generating 85% to 90% fewer GHG emissions. The proprietary process meticulously disassembles fabric into original yarn, refining it to its initial fiber state, preserving length, and removing undesirable short fibers. The quality of the revitalized fibers makes it suitable for various textile applications. Partnering with Arvind Ltd, an Indian textile company, PurFi's technology offers a traceable 360-degree circular solution.

- Contracting type: For sale
- Readiness level (TRL): Scaling up (TRL 9)
- Country of origin: United States
- Contact: WIPO GREEN Database

Synthesis and future direction



This section explores collaboration, market barriers, and trade-offs in scaling sustainable fashion technologies, highlighting SME innovation, technology adoption, and the shift toward a "just" and circular economy.

Critical success factors that influence sustainable innovations in textiles include access to R&D funding, opportunities for stakeholder collaboration, and customer expectations in the marketplace.

Working with suppliers

Stakeholder collaboration supports access to funding and opportunities for scaling innovations in global supply chains. Enabling mechanisms to support the implementation of environmental innovations can be distinguished based on the actors involved – namely, those enabled by lead firms (in this case, fashion brands or retailers), those enabled by suppliers, those collectively enabled and those enabled by governments (Asian Development Bank, 2023).

For fashion brands and retailers, senior commitment is needed to drive sustainability strategies across supply chains. Strategic partnerships and long-term commitments by lead firms are needed to scale innovations such as alternative materials. For example, in 2023, Inditex signed a three-year contract to purchase regenerated polyester from Ambercycle to support the construction of the latter's first commercial-scale factory to produce their textile-to-textile recycled polyester Cycora®. In 2025, Lululemon signed a 10 year off-take agreement with Samsara Eco to source recycled polyester and nylon, supporting commercialization efforts for the latter's enzymatic recycling technology.

However, such offtake agreements – where a company agrees in advance to purchase a manufacturer's output – are less common in the fashion industry than in other sectors (Sadowski *et al.*, 2021). Often, suppliers are expected to take the most risk in terms of investing capital in machinery and staff training (Finamore, 2023).

Supporting small and medium-sized enterprises to drive sustainability

There are also opportunities in supporting small and medium-sized enterprises (SMEs) to become driving forces toward a more sustainable fashion industry (European Commission, 2019). SMEs represent the vast majority of businesses in the fashion sector and are also leading the way on sustainability, as evidenced by many of the examples in this report.

The 2021 Fashion Accountability Report showed that SMEs outperformed large companies by 28 points on average, as they tended to provide more information on their sustainability credentials and focused on product durability and phasing out fossil fuel-based fabrics. SMEs are driving forces for a more sustainable fashion industry and key enablers for new technology adaptation, as well as key enablers for utilizing traditional knowledge techniques and nature-based solutions.

One way of harnessing the potential of SMEs is through setting up accelerator programs that support development and scaling by providing access to expertise, coaching, funding and market access. For example, LVMH's La Maison des Startups was established in 2017 to accelerate collaboration between LVMH and startups whose solutions have potential in the luxury industry. This program provides workspace, coaching and access to LVMH's ecosystem of 75 Maisons.

In 2022, Amazon launched its Sustainability Accelerator, a three-month program offering cash grants, expertise and mentoring, and access to Amazon's networks, to support high-potential startups developing new recycling technologies or creating products with reduced impact on the environment to scale their businesses.

However, there is a fundamental mismatch between the funding landscape for innovation and the finance model of the fashion industry, which is focused on buying end products not committing to upstream material development, and this system prevents startup innovators from making a difference. Low-cost production is another market entry barrier because brands do not have the incentive to invest in sustainable or circular options. Extended producer responsibility (EPR) could help to address this imbalance in the marketplace as funding from EPR schemes could support the transition needed to develop industrial-scale infrastructure for collecting, sorting and processing textile waste and narrow the gap between low-priced virgin fibers and more sustainable alternatives.

Market needs and challenges

In terms of the marketplace, recycling technologies must be cheaper, more energy efficient and less polluting than conventional processes for producing virgin fibers (Baloyi *et al.*, 2023). Commercial adoption and disruptive potential of alternative materials to virgin polyester and cotton will depend on their ability to match or exceed on cost, sustainability and performance (WTiN, 2023; Sadowski *et al.*, 2021). Can the manufacturing process utilize existing machinery, or is specialized machine development required? Is the enabling technology cheaper and/or better than conventional materials? For example, does it compete on headline costs or post-processing and product production expenses? Does it compare favorably in terms of sustainability and performance to conventional materials? (WTiN, 2023).

In addition to considerations of impact on people and planet, fashion sourcing decisions involve a careful balancing act of aesthetics, quality, price and performance. Hence, the design appeal and performance characteristics of alternative yarns and materials should match or exceed what is currently available to brands and designers from virgin, fossil fuel-based sources. The impact of technological innovations should be assessed in terms of not only carbon and pollution reduction but also their economic impact upon enterprises.

Challenges include the fashion industry's high degree of fragmentation and lack of commitment to long-term order volumes, long and capital-intensive innovation cycles, difficulty of deploying capital into emerging markets, and unequal power relations between brands and suppliers (Apparel Impact Institute and Fashion for Good, 2021). Firm size, resource limitations (technical or managerial) and operational performance objectives may also affect the take-up of sustainable innovations (Islam *et al.*, 2021). Market adoption challenges such as cost barriers and consumer preferences should also be acknowledged. The entrenched fashion system, driven by economies of scale and low cost, presents a barrier to seeing next-generation solutions come to scale (Peters, 2024).

Despite consumers' increasing environmental awareness, there is an attitude–behavior gap whereby consumers' claimed preferences do not always translate into actual purchasing behavior, as this is also influenced by other factors such as price, quality and other product attributes (Rese *et al.*, 2022). The lack of significant market demand for sustainable textiles (as seen in piecemeal commitment to alternative materials and processes, such as "capsule collections" rather than full product ranges) explains some of the industry resistance to change.

In addition to investment in technology and a shift in buyer-supplier relationship dynamics, effective legislation is needed to spur action on an industry-wide scale (Doyle, 2024). EPR is a reminder to all that producers must consider the options for disposal of their products when they are discarded, regardless of whether mass recycling could be profitable.

Trade-offs and unintended consequences

Sustainability initiatives can result in unintended negative consequences whereby the solution to one problem could cause or exacerbate a different problem somewhere else (Cernansky, 2021). Not all solutions intended to support more environmentally sustainable practices actually do so; for example, bio-based polyester alternatives have higher environmental impacts in certain areas than polyester itself. Another example is of certain chemical recycling technologies that require large amounts of energy (Zero Waste Europe, 2020), which could result in a higher carbon footprint than other virgin materials such as cotton. Many technologies use waste from other sectors, but the fashion industry needs to prioritize fiber-to-fiber recycling to close the loop for textile products (European Commission, 2022). Synthetics are inherently unsustainable as they are produced from fossil fuels and shed microplastics that persist in our environment (Changing Markets Foundation, 2021).

While some new materials claim to be biodegradable as they can decompose quickly in industrial composting conditions, this may not be achievable (or happens at a considerably slower rate) in the natural environment or in anaerobic digesters, which some municipalities use for compostable waste.

The nature of agricultural feedstock raises ethical questions regarding the potential competition with food crops for first-generation biomass feedstocks (corn, sugarcane, edible oils) compared to second-generation feedstocks such as agro-waste (Rosenboom *et al.*, 2022). While the industry needs to scale next-generation materials such as textile-to-textile recycling, plant-based leather substitutes, and materials made from carbon dioxide to reduce emissions in line with SBTis, some of these technologies are in early stages of development so emissions data are based on a lab environment, which may have a different energy mix to commercial production locations (Sadowski *et al.*, 2021).

Scalability is important but, while some nature-based solutions may not reach industrial scale, they help to reintegrate marginalized communities in an environmentally friendly way. Many luxury brands have started to recognize and invest in this production model, which aligns the social and environmental bottom lines. The British brand Vivienne Westwood has worked with the United Nations program Ethical Fashion Initiative on several collections developed with African female artisans, for example using recycled metal found in Kenyan slums and the ancient Bogolan fabric making technique from Mali.

There are no definitive criteria for a sustainable fashion product. Standards such as OEKO-TEX or EU Ecolabel go some way to identifying criteria for determining whether a product has been manufactured using sustainable methods, but they only address specific parts of the production process. No standard covers the entire process from raw material to end product, or end of life. For example, cotton is a natural fiber that is biodegradable but the finishes applied during textile processing to improve material performance slow down the rate of biodegradability for the end fabric and the active compounds of finishing formulations are mostly not biodegradable (Zambrano *et al.*, 2021).

Natural fibers are not necessarily better than synthetic, as fiber choice is only one part of a complex picture and fibers still have to be grown, dyed, finished, sewn and transported – all of which have different environmental impacts. Furthermore, the focus of sustainability research and innovation is primarily on materials for fabrics, not the manufacturing of trims and accessories, such as buttons, zips, hardware and embellishments, which is a substantially neglected area of research (Islam *et al.*, 2021).

Technology and the growth challenge

A sustainable production process does not necessarily result in a sustainable garment if it is barely used before disposal. For the fashion industry to meet its carbon emissions targets by 2030, a fundamental slowing of production and consumption is needed (Coscieme *et al.*, 2022; Niinimäki *et al.*, 2020), so the focus should be on prevention of overproduction and reuse of existing products. However, with greater economic growth comes greater resource consumption and the desired transformation to a slower, more circular economy is not yet occurring at the necessary magnitude and pace. The fashion industry needs to completely rethink the current system of overproducing clothes, so they are made to be repaired, reused and recycled at the end of life. Making clothes that are aesthetically pleasing and designed to last is important for encouraging emotional attachment to garments that can also be passed on or shared, not thrown away.

This report has focused on environmental aspects and does not consider whether or how sustainable fashion technologies can positively impact workers, communities, and livelihoods in terms of their socioeconomic effectiveness. However, as socioeconomic aspects of sustainability are closely bound with environmental impacts, further work is needed to uncover the impact of technological solutions on working conditions for the majority of manual workers in fashion supply chains. This would support a just transition toward a net-zero carbon future that is fair and inclusive, creating decent work opportunities and leaving no one behind (ILO, 2015).

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Sustainable Fashion Technologies shows how innovative green technologies can help the global fashion industry to manage and reduce environmental damage. Increasing interest from brands and investors, alongside new legislative frameworks, are creating avenues for a more sustainable resource management. Innovation and creativity can help advance a paradigm shift in textile manufacturing and production that results in a circular economy for fashion.

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