The environmental price of fast fashion

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Abstract | The fashion industry is facing increasing global scrutiny of its environmentally polluting supply chain operations. Despite the widely publicized environmental impacts, however, the industry continues to grow, in part due to the rise of fast fashion, which relies on cheap manufacturing, frequent consumption and short-lived garment use. In this Review, we identify the environmental impacts at critical points in the textile and fashion value chain, from production to consumption, focusing on water use, chemical pollution, CO_2 emissions and textile waste. Impacts from the fashion industry include over 92 million tonnes of waste produced per year and 79 trillion litres of water consumed. On the basis of these environmental impacts, we outline the need for fundamental changes in the fashion business model, including a deceleration of manufacturing and the introduction of sustainable practices throughout the supply chain, as well a shift in consumer behaviour — namely, decreasing clothing purchases and increasing garment lifetimes. These changes stress the need for an urgent transition back to 'slow' fashion, minimizing and mitigating the detrimental environmental impacts, so as to improve the long-term sustainability of the fashion supply chain.

In recent years, the fashion industry has received abundant criticism over its limited consideration of social and environmental issues, placing the non-financial costs of fashion on the global public agenda. The environmental impacts of the fashion industry are widespread and substantial. For example, although there is a range of estimates, the industry produces 8-10% of global CO_2 emissions[1,2] (4-5 billion tonnes annually). The fashion industry is also a major consumer of water[4] (79 trillion litres per year), responsible for ~20% of industrial water pollution from textile treatment and dyeing[103], contributes ~35% (190,000 tonnes per year) of oceanic primary microplastic pollution[1] and produces vast quantities of textile waste[2] (>92 million tonnes per year), much of which ends up in landfill or is burnt, including unsold product[5,6].

The rising environmental impact (and awareness thereof) can be attributed to the substantial increase in clothing consumption and, therefore, textile production (FIG. 1). Global per-capita textile production, for instance, has increased from 5.9 kg to 13 kg per year over the period 1975–2018 (REF.[7]). Similarly, global consumption has risen to an estimated 62 million tonnes of apparel per year, and is projected to reach 102 million tonnes by 2030 (REF.[4]). As a result, fashion brands are now producing almost twice the amount of clothing today compared with before the year 2000 (REF.[8,14]).

Indeed, the drastic increase in textile production and fashion consumption is reflected in the emergence of fast fashion, a business model based on offering consumers frequent novelty in the form of low-priced, trend-led products[9,10]. Fast fashion relies on recurring consumption and impulse buying, instilling a sense of urgency when purchasing[9,10]. This business model has been hugely successful, evidenced by its sustained growth, outperformance of more traditional fashion retail and market entry of new players such as online retailers, who can offer more agility and faster delivery of new products more frequently[9]. As a result, brands are now producing almost twice the number of clothing collections compared with pre-2000, when fast-fashion phenomena started[8,14], and the overall increase in clothing-production demand is estimated to be 2% yearly[11].

The rising consumption and efficiency in production of fashion products has, in turn, driven the price of clothing very low[8]. For example, despite an increase in the number of items owned, the average per person expenditure on clothing and footwear in the EU and UK has decreased from ~30% in the 1950s to 12% in 2009 and only 5% in 2020 (REFS[12,13]). Low costs further amplify the phenomenon of buying more and wearing items less frequently[9,14,15], facilitating the fast-fashion model. In the USA, the average consumer now purchases one item of clothing every 5.5 days (REFS[14,16]), and in Europe, a 40% increase in clothing purchases was observed during the period 1996–2012 (REFS[5,17]). As a result, more new clothes are bought per person per year, quantified as 14.5 kg in Italy, 16.7 kg in Germany, 26.7 kg in the UK and between 13 kg and 16 kg of textiles across Denmark, Sweden, Norway and Finland[17–20]. The average garment-use time

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Key points

- The textile and fashion industry has a long and complex supply chain, starting from agriculture and petrochemical production (for fibre production) to manufacturing, logistics and retail.
- Each production step has an environmental impact due to water, material, chemical and energy use.
- Many chemicals used in textile manufacturing are harmful for the environment, factory workers and consumers.
- Most environmental impacts occur in the textile-manufacturing and garment-manufacturing countries, but textile waste is found globally.
- Fast fashion has increased the material throughput in the system. Fashion brands are now producing almost twice the amount of clothing today compared with before the year 2000.
- Current fashion-consumption practices result in large amounts of textile waste, most of which is incinerated, landfilled or exported to developing countries.

has, consequently, decreased by 36% compared with 2005 (REF.[14]), with evidence in the UK, Norway and elsewhere suggesting disposal after little use, especially for impulse purchases[15,21–24]. While these examples draw on literature from the Global North, increasing economic development and population growth in emerging markets has also brought greater consumption and taste for Western-style clothing to the Global South.

Given the global proliferation of fast fashion and the volume of items produced (and wasted), the fashion industry represents a key environmental threat[26]. Indeed, considerations of pollution and waste were not of primary concern for fast-fashion producers and retailers, with the emphasis instead on reduced cost and increased speed of delivery to the market[25,27]. However, with public attention now very much on the climate crisis, environmental degradation and sustainability more broadly (for instance, the United Nations Sustainable Development Goals; namely, SDG 12 and 13), the industry (producers, retailers and consumers alike) is being forced to seek more sustainable practices and to take note of its environmental impacts[1].

In this Review, we outline the global supply chain before discussing the environmental impacts of fast fashion, specifically, water use, chemical pollution and CO_2 emissions. Fashion-related waste is subsequently detailed, followed by guidance and perspectives on how the industry can be changed to become more sustainable, including decreasing garment production and waste, and increased garment use and lifetime.

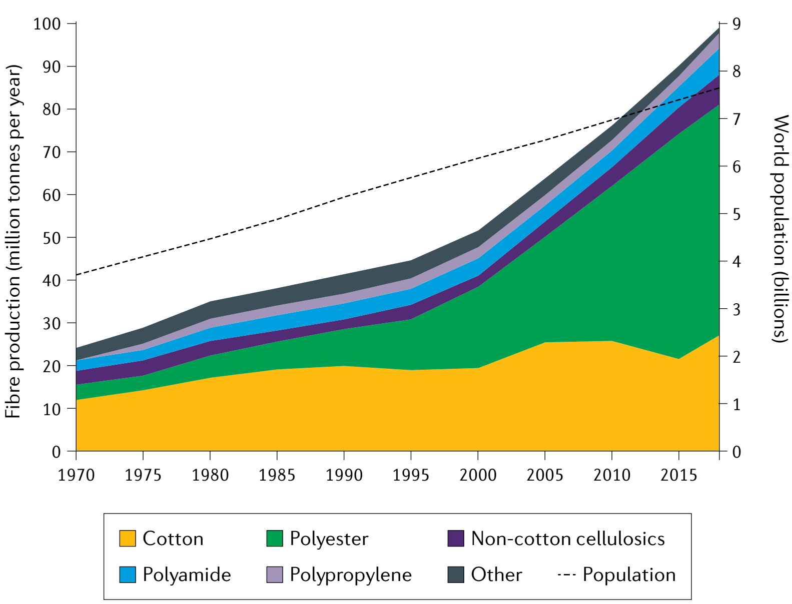


Fig. 1 | **Growth in global population and textile production by fibre type.** Fibre types include cotton, polyester, non-cotton cellulosics, polyamide and polypropylene, with silk and wool represented together as 'other'. Growth in world population is also depicted. By the 2010s, textile-production growth overtook world-population growth, largely driven by the rise of cheap manufacturing and fast fashion.

Global supply chains

The fashion supply chain is characterized by vertical disintegration and global dispersion of successive processes, spanning a number of industries from agriculture (for natural fibres) and petrochemicals (for synthetics) to manufacturing, logistics and retail (FIG. 2). The global shift of textile and garment production to lower-labour-cost countries led to a substantial decline of production in many developed countries, in some cases to the point of extinction, with concomitant increased complexity and reduced transparency through the supply chain. It is often difficult for downstream manufacturers to know where raw materials have come from and how they were processed[28]. This section will discuss this complexity in the supply chain and the many steps a garment will go through in the manufacturing process.

60% of global fibre production is destined for the fashion industry, the rest being used for interiors, industrial textiles, geotextiles, agrotextiles and hygienic textiles, among other uses[14,29,30]. Of this textile production, polyester (a synthetic) accounted for 51% (54 million tonnes) in 2018, followed by cotton at 25% (26 million tonnes) (FIG. 1). Polyester dominates production due to its performance characteristics and cost-efficiency, and is projected to increase further as consumers in emerging Asian and African economies begin to adopt Western lifestyles and dress[31].

Yarn manufacture follows fibre production, and includes spinning and, sometimes, wet processing, such as dyeing. Textiles are manufactured from yarns through knitting or weaving and use a lot of water and energy through wet processes such as bleaching, dyeing and finishing. Furthermore, textile manufacturing creates excessive waste. Finished textiles are transported to garment manufacturers for assembly (cutting and sewing). In addition to textiles, trims (sewing threads, buttons, zippers, linings, labels and lace, for example) are used in garment construction, which remains labour-intensive, and, as a result, sourcing decisions are largely determined by labour costs.

Often, each step of garment production occurs in a different country, which increases the logistic steps between processes[9], depending on economic decisions. Given that developing countries generally hold the competitive advantage in manufacturing and labour costs[32], textile production has, therefore, shifted to these nations (FIG. 2). China, for example, dominates the market, exporting $109.9 billion USD worth of textiles and $158.4 billion worth of clothing each year[33]. While the market

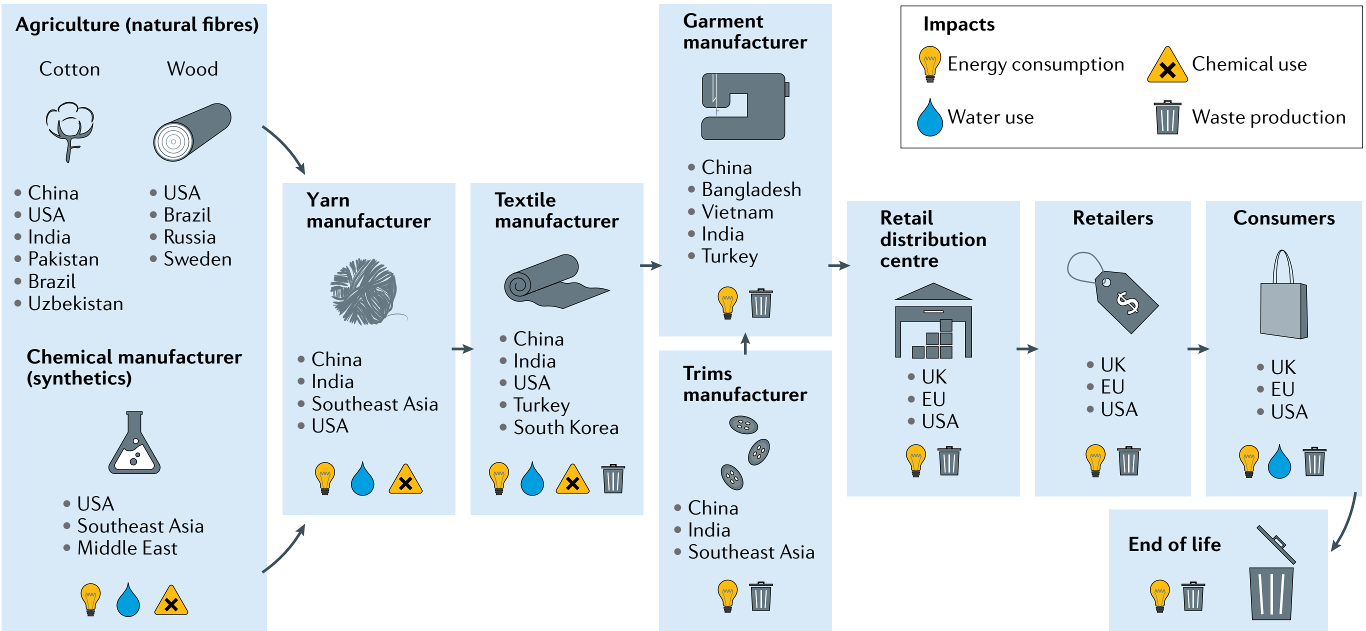


Fig. 2 | **Garment-manufacturing supply chain.** The key stages of the fashion supply chain with the geographic location and broad-scale environmental impacts (energy use, water use, waste production and chemical use) for each stage of the process. The garment supply chain is globally distributed, with much of the initial fibre production and garment manufacturing occurring in developing countries, while consumption typically occurs in developed countries.

share in clothing export from China has decreased in recent years, the textile exports have grown as countries such as Bangladesh, Cambodia, Vietnam, Pakistan and Indonesia demand increased supplies[34]. However, whereas manufacturing is mostly located in the Global South, the design processes are done in the Global North, often the EU or USA, where brands' main offices are. The distance makes it hard to avoid mistakes during production planning, causing unnecessary pre-consumption waste from manufacturing.

After manufacturing, garments are shipped in large quantities to central retail distribution centres, followed by smaller retailers where clothing is purchased, often in the UK, EU and USA. Garments are traditionally transported by container boats, but increasing amounts are shipped through air cargo to save time, especially in online shopping. Air cargo has a substantially larger environmental impact, as it is estimated that moving just 1% of garment transportation from ship to air cargo could result in a 35% increase in carbon emissions[2]. Moreover, the long supply chains mean that garments can have travelled around the globe once or even several times during the many manufacturing steps in turning raw fibre cultivation into a ready outfit. At their end of life, many garments are incinerated or transported to landfills or developing countries, very often by ship to Africa[35,36], and few are recycled.

Environmental impacts

At each stage of the aforementioned supply chain, the fashion industry exerts environmental impacts, from water and chemical use during fibre, yarn and textile production to CO_2 emissions during the manufacture, distribution and consumption of clothing (FIG. 2).

The globalization of the textile and fashion system has resulted in an uneven distribution of these environmental consequences, with developing countries (who largely produce the textile and clothing) bearing the burden for developed countries[3] (who largely consume the products). Thus, western countries import the impacts (for example, water through cotton growth and CO_2 emissions associated with polyester production) when importing clothing (FIG. 3). However, the increased globalization and fragmentation of clothing manufacturing (FIG. 2) has also made it challenging to accurately assess these environmental impacts, for example, due to uncertainty in raw-material sourcing and processing[28]. Nevertheless, in the following sections we discuss current understanding of the impacts of the fashion industry on water resources, CO_2 emissions and environmental quality through chemical pollution.

Water use. The fashion industry uses large amounts of water, totalling 79 billion cubic metres in 2015 (REF.[4]) and averaging an estimated 200 tonnes of water usage during the production of one tonne of textile[9]. Most of fashion's global water usage is associated with cotton cultivation and the wet processes of textile manufacturing (bleaching, dyeing, printing and finishing). Current textile production uses an estimated 44 trillion litres of water annually for irrigation[37,38] (or about 3% of global irrigation water use), 95% of which is associated with cotton production[39]. In the production of a T-shirt and pair of jeans[40–42], for instance, cotton cultivation causes 88% and 92% of the total water footprint, respectively (BOX 1). Indeed, cotton has the highest water footprint of any fashion fibre[24] (FIG. 4) and, as 44% of cotton is grown for export[37], about half of the local-water-use

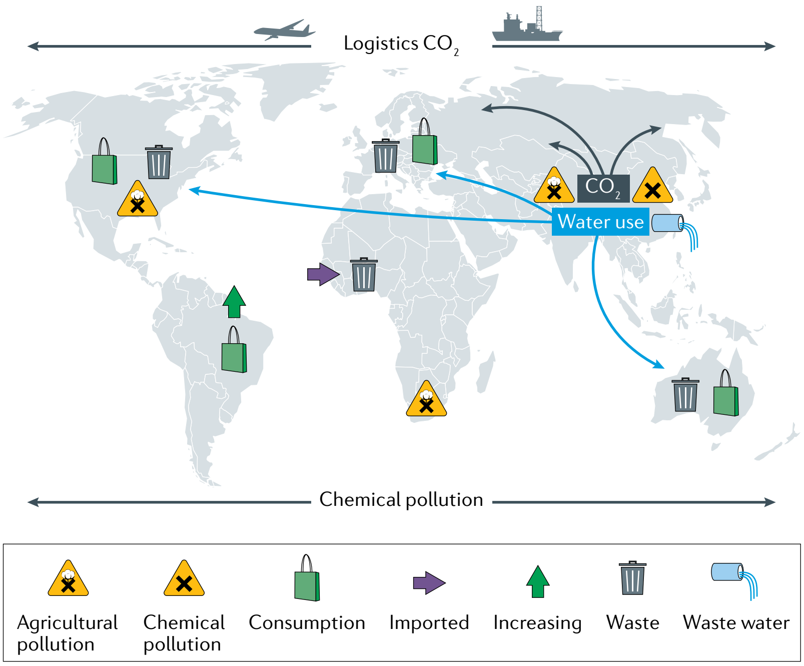


Fig. 3 | **Critical points in textile and fashion production.** The geographic distribution of key environmental impacts from the textile and fashion supply chains. High volumes of fashion production and consumption and the logic behind fast fashion increase the environmental impacts by promoting unsustainable manufacturing, distribution and use of garments. Chemical pollution is greatest in countries where cotton is cultivated, but also in countries where waste water from the textile industry is not purified properly. Moreover, chemicals spread around the globe and they enrich (bioaccumulate) in the food chain, causing a risk to organisms, ecosystems and biodiversity. Water and energy are exported as garments from countries where they are produced (such as some Asian countries) to countries where they are consumed (such as North America, Europe and Australia). Waste is generated during both production and consumption, where it is either disposed of locally or exported, for example to countries in Africa[63].

impacts of cotton cultivation are caused by foreign demand. For example, it was estimated from trade relations that 20% of the water loss suffered by the Aral Sea was caused by cotton consumption in the EU[41]. Recent reports use scarcity-based weighting to emphasize the impact of water use in arid regions[43], demonstrating that the textiles and fashion sector is associated with 7% of local groundwater and drinking water losses caused by water use globally, especially in the water-stressed manufacturing regions of China and India[44].

Beyond exacerbating water scarcity, the fashion industry impacts local water supplies by producing waste water. As some chemicals used during manufacturing are toxic, improperly treated waste water that enters local groundwater might degrade the entire ecosystem[9]. In Cambodia, for example, the fashion industry, which is responsible for 88% of all industrial manufacturing (as of 2008), has caused an estimated 60% of water pollution and 34% of chemical pollution[9].

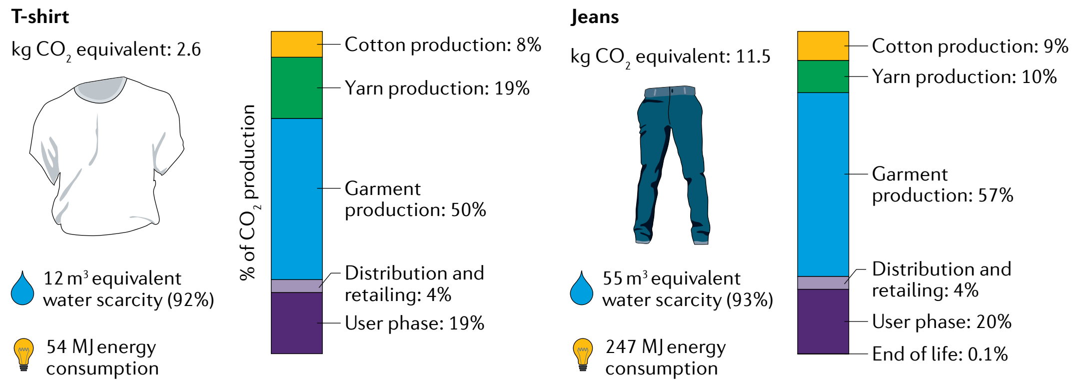
Carbon footprint. Textiles, alongside aluminium, generate the most greenhouse gases per unit of material[45]. The Intergovernmental Panel on Climate Change claims that the textile industry causes 10% of global greenhouse gas emissions[1], but the scope and method of this estimate are unclear. More conservative estimates have also been made — Quantis, for example, estimated that the fashion industry emitted approximately 4.0 gigatonnes (Gt) of CO_2 equivalent in 2016 (REF.[2]), or 8.1% of global CO_2 equivalent emissions. Approximately one-fifth (0.7 Gt CO_2 equivalent, or 1.4% of global emissions) of these CO_2 emissions were from footwear alone, with the rest from apparel[2] (3.3 Gt CO_2 equivalent, or 6.7% of global emissions), although none of these estimates includes emissions during the use phase of the life cycle, such as transport from retail environments and laundering. Estimates from the Carbon Trust are more conservative, approximating 0.33 Gt of CO_2 equivalent emitted in 2011 due to clothing production (omitting footwear), with a further 0.530 Gt of CO_2 added by the use phase of the life cycle[3]. Similarly, a study of Swedish textiles consumption[42] found that the use phase could contribute 14% of the total climate impacts of clothing consumption. We estimate global production of 2.9 Gt of CO_2 equivalent emissions, two-thirds of which is associated with synthetic materials during fibre production, textile manufacturing and garment construction. This estimate is based on the results obtained by Sandin et al.[42] for the Swedish consumption of textiles, scaled to the global consumption of textiles in 2018 and excluding the use phase for comparability with the Quantis[2] estimate.

The fashion industry's high carbon footprint comes from high energy use and is influenced by the source of the energy used. For example, in China, textile manufacturing depends on coal-based energy and, as a result, has a 40% larger carbon footprint than textiles made in Turkey or Europe[42,46]. High energy demands and CO_2 emissions are associated with textile manufacturing and consumer use[42,47,48] (namely, laundering), as well shipping when air freight is used[25,49]. However, in the garment life cycle, energy use and CO_2 emission is highest during initial fibre extraction, especially for synthetic fibres, such as acrylics[50], as they originate from fossil fuel[46] (FIG. 4). Polyamide production, for example, uses 160 kWh per kg of fibre[49].

Beyond fibre type, the production method influences energy use and climate impacts, as highlighted by different modes of cotton production. For example, conventional cotton cultivation can emit 3.5 times more CO_2 than organic cotton cultivation, which, in India, produces double the CO_2 emissions of organic cotton cultivation in the USA[50]. However, organic cultivation can require more water than conventional management, presenting a drawback to organic cotton usage[9]. Nevertheless, as natural fibres have a lower carbon footprint than synthetic fibres (FIG. 4), the best way to decrease CO_2 emissions associated with fibre production would be to substitute the use of polyester with the use of natural fibres. Furthermore, plant-based fibres sequester atmospheric carbon and act as a carbon sink[50] — for instance, one tonne of dry jute is equivalent to the absorption of 2.4 tonnes of carbon. Linen and hemp production similarly have low carbon emissions (FIG. 4). However, the lower carbon footprint of the natural fibres during production can be offset during the use phase because of high energy requirements for washing, drying and ironing[50] compared with synthetics. One estimation of the life-cycle emissions of a cotton T-shirt

Box 1 | **The case of a cotton shirt and a pair of jeans**

To give an overview and an example of the environmental impact of fashion, two common garment items are examined to expose their impact: a T-shirt and a pair of jeans made in Asia (primarily China, Bangladesh and Turkey) and used in Sweden[42]. The water-scarcity impacts are dominated by the production of cotton fibre (see figure), as the water required for the use phase is relatively abundant in Scandinavia compared with cotton-growing regions. For example, estimates of the water use associated with the production of just one 250-g T-shirt range from 2.7 m^3 in the unweighted full-water footprint of Chapagain et al.[41] to 26 m^3 equivalent when weighted using the AWARE method[42] and scaled for this article. Most water use in cotton garment production is associated with cotton production (92% in the T-shirt example here, and 93% for the jeans). Since most of the energy for washing and drying the clothes during use in Sweden is provided by relatively climate-friendly nuclear and hydroelectric sources, the production processes in Asia for garments dominate the life-cycle climate impacts (kg CO_2 equivalent), representing about 80% of the total impact of Swedish clothing consumption. In a sensitivity analysis with average European electricity, the CO_2 emissions of washing and drying clothes in the user phase are considerably higher, but garment production is still the cause of 71% of the total impact.



shows that, based on 50 washes, 35% of CO_2 emissions are due to textile manufacturing, while 52% is produced during the use phase[3]. To decrease the greenhouse-gases impact of the fashion industry, production volumes and non-renewable energy use must be decreased, polyester production should be substituted with renewable plant-based textiles and sustainable shipping and garment usage must be considered.

Chemical use. The textile industry uses over 15,000 different chemicals during the manufacturing process[51], beginning during fibre production. Estimates suggest that, in terms of financial value, 6% of global pesticide production is applied to cotton crops[52], including 16% of insecticide use, 4% of herbicides, growth regulators, desiccants and defoliants, and 1% of fungicides. Heavy use of agrochemicals can cause nausea, diarrhoea, cancers and respiratory diseases[53,54], and acute pesticide poisoning is responsible for nearly 1,000 deaths a day and afflicts neurological and reproductive problems, such as infertility, miscarriage and birth defects[55]. In the environment, agrochemicals leach into the soil, where they cause a decrease in soil biodiversity and fertility, interrupt biological processes and destroy microorganisms, plants and insects[55]. Despite the substantial human and environmental impacts of pesticide application, non-target species have become increasingly problematic[56] (such as the whitefly *Bemisia tabaci*), leading to increased insecticide application. While the introduction of genetically modified cotton led to a reduction in external pesticide application, reduction appears to have been a temporary phenomenon in major cotton-producing countries such as India, Brazil, China and the USA[52]. Furthermore, the introduction of herbicide-resistant cotton has preceded major increases in herbicide application in recent years[52,57]. Thus, even with a lower energy footprint, cotton cultivation requires large amounts of chemicals, demonstrating another clear environmental impact caused by fibre production.

Many of the chemicals used during textile manufacturing are associated with spinning and weaving (lubricants, accelerators and solvents) and wet processing (bleaches, surfactants, softeners, dyestuffs, antifoaming agents and durable water repellents, among others). In one example, a single European textile-finishing company uses over 466 g of chemicals per kg of textile, including sizing agents, pretreatment auxiliaries, dyestuff, pigments, dyeing auxiliaries, final finishing auxiliaries and basic chemicals[48]. However, approximately 80% of EU-consumed finished textiles are manufactured outside of the EU, making it difficult to ascertain total chemical usage. Similarly, even some textiles labelled as being produced in the EU are actually imported as semi-finished textile materials from outside the EU and only finished locally. Hence, the majority of the chemicals use connected to producing textiles for the EU occurs outside the EU. The knowledge about chemical contents in textile articles should be made more readily available by increasing and improving the information exchange along the supply chain[58].

During chemical usage in textile manufacturing, the limited data on material safety data sheets are often the only source of information, increasing environmental risks from unsafe usage or disposal[48]. In one Swedish study, 2,450 chemicals related to textile manufacturing were investigated for their hazardous properties. 10% of these chemicals were identified to be of high potential concern for human health, including fragrances and

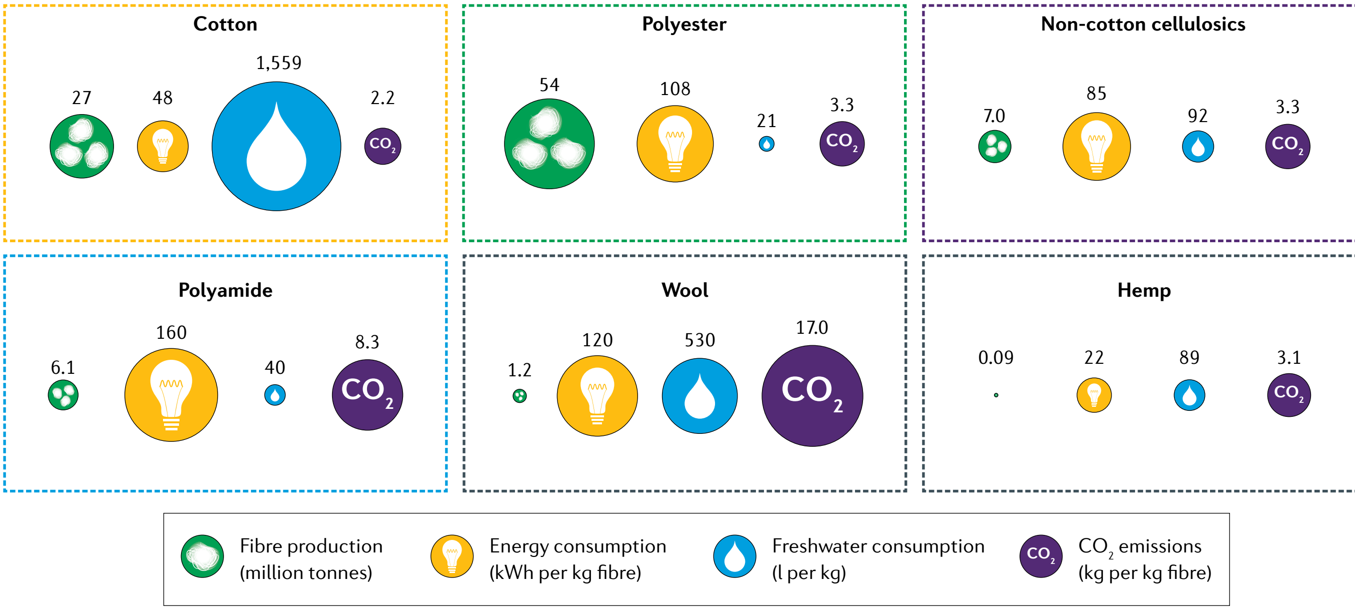


Fig. 4 | **Environmental impacts of six types of fibres.** Approximate fibre production, energy consumption, freshwater consumption and CO_2 emissions for cotton, polyester, non-cotton cellulosics, polyamide, wool and hemp. The environmental impact of production varies between fibre types — natural fibres (cotton, non-cotton cellulosics, wool and hemp) require less energy but more water during production than synthetics (polyester and polyamide). Total annual fibre production is from REF.[102]. Freshwater consumption for cotton, polyester, non-cotton cellulosics and polyamide are estimated using per-kg production data from ecoinvent[80] and thinkstep[38]. Freshwater consumption for wool and hemp are from REF.[40]. Energy-consumption and CO_2-production values are from REF.[40].

direct and acid-type azo dyes[58], as well as reproductive toxins such as brominated flame retardants, highly fluorinated water, stain repellents and phthalates[58]. Additionally, antibacterial agents are also added into textiles, which can lead to increased antibiotic resistance[58]. 5% of the chemicals investigated were of high potential concern for the environment, where they can spread globally and bioaccumulate (gradually increase in concentration in organisms), causing diseases, allergic reactions and increasing cancer risk[58]. For example, chemicals used to waterproof textiles, which are mostly chemically stable fluoropolymers, are found even in remote Arctic locations and in the bodies of polar bears and seals[59], demonstrating the global impact of chemical use during textile manufacturing. In some cases, substituting chemicals are developed to avoid the use of toxic chemicals, but problems arise when these are put into use before the safety of the new chemical is tested and proven. For instance, long-chain perfluoroalkyl and polyfluoroalkyl substances in manufacturing could be replaced with short-chain perfluoroalkyl and polyfluoroalkyl substances and perfluoropolyethers, but information on these fluorinated alternatives is insufficient for risk assessments. Even the alternatives that have low acute toxicity and are considered safe according to current regulations may still pose risks in the future. To improve the situation, communication among stakeholders (manufacturers of fluorinated materials, industrial users of these materials, regulators, scientists and the public) needs to be improved and intensified[60].

As there is a wide variety of chemical pollutants emanating from the fashion and textile industries, life-cycle analysts have attempted to aggregate their impacts into an indicator that reflects both the relative rate of emission of the chemicals and their potential for harm[61]. The latest European approach to aggregate impacts is based on the USEtox model, a nested, multicompartment transport and fate model that has been applied to over 4,000 substances[42]. The USEtox model uses 'comparative toxicity units' (CTU) to estimate the impact of chemical pollution on human health (calculated as the incidence of disease per kg of chemical emitted) and the environment[42] (the potentially affected fraction of species integrated over time and area or volume per kg of chemical emitted). Based on scaling the total burden of toxic chemicals used during the production of fashion consumed in Sweden[40], the annual impacts of global textile consumption are 5,100 CTU for non-cancerous effects, 4,200 CTU for cancerous effects and 4.0×10^{13} CTU for ecotoxic effects. However, it is difficult to reliably compare these data with benchmarks due to the relative infancy of these aggregated-toxicity-assessment methods and the exclusion of supply-chain emissions, such as solid waste from coal combustion[62]. In general, though, it is clear and known that fashion companies look to save production costs through manufacturing in locations with lax environmental regulation and where pollution-mitigating technologies are not needed. This mode of manufacturing leads not only to high environmental impacts from chemical usage[9] but increased health risks for factory workers, cotton farmers and fashion consumers.

Textile waste

The dramatic increases in (fast) fashion production and consumption volumes have resulted in increasing textile waste. Western countries traditionally handled textile waste by exporting old garments to developing countries, such as those in Africa[63] (FIG. 3). However, with higher waste production, this practice cannot continue, as many developing countries are banning the import of textile waste, either to protect domestic textile production (as in Turkey and China) or because markets are oversaturated by second-hand garments and second-hand clothing has replaced local production[9,36,63] (as in parts of Africa). In the following sections, both pre-consumer and post-consumer waste are discussed.

Pre-consumer textile waste. Pre-consumer waste in fashion, also referred to as production waste, is produced during the manufacturing of textiles and garments, and includes fibre, yarn and fabric waste, the last of which is the greatest waste of resources. One study estimated that 15% of fabric used in garment manufacturing is wasted[64]; in other studies, the figure is ~10% for pants and jeans and >10% for blouses, jackets and underwear[65], and some estimates even place textile waste during garment manufacturing at 25–30% (REF.[66]). This waste percentage is impacted by many variables, from garment type and design to fabric width and fabric-surface design (for instance, greater waste is associated with one-directional prints). The fabric waste is produced during the cutting phase of garment construction and is influenced by how well the flat patterns are designed to be fitted on the fabric and by the garment design in general. Moreover, mistakes in garment assembly cause garments to be wasted[66]. As the output of the global fashion system has grown, so have all forms of production waste. To decrease the amount of pre-production waste, manufacturing rates should be decreased and production should be made more accurate through better communication between design and manufacturing[67].

In recent years, substantial attention has also been given to a type of pre-consumer waste called deadstock, which are new, unworn garments that are unsold (or returned, especially after being bought online) and 'designated as waste'. In 2016, for instance, Ecotextile News reported that only a third of all imported clothing in the EU is sold at full retail price, a third is sold at a discounted price and a third is not sold at all[68], although these figures remain unverified. In the Netherlands, however, it was confidently estimated that 21 million garments were unsold in 2015, representing 6.5% of garments[69], and two cases in 2018 shed additional light on deadstock. Swedish fast-fashion brand H&M was reported to hold $4.3 billion worth of unsold inventory in warehouses[70], following reports of the company incinerating brand new clothing at a waste-to-energy plant in Denmark[71,72]. Similarly, British luxury brand Burberry was reported to have incinerated £90 million worth of unsold inventory over five years as of June 2018 (REF.[73]), of which it admitted £28.6 million worth was incinerated in 2017 (REF.[74]). Although the incineration of deadstock 'recovers' some energy from the products, it also generates more emissions and air pollutants than reuse or recycling[26]. Relative to the total garment life cycle, however, carbon emissions associated with the incineration of clothing are of very low levels[24], whereas the biggest carbon emissions are produced in textile-manufacturing processes and during the use phase[3]. However, the bigger concern is the environmental impact of energy, material, water and chemicals that have gone into manufacturing unsold garments[67], which represents a substantial waste of resources.

Post-consumer textile waste. Post-production waste comprises garments discarded by consumers, including almost 60% (REF.[8]) of the ~150 billion garments produced globally in 2012 (REF.[75]) that were discarded within several years after production. The turnaround from consumption to post-production waste is rapid — the use lives of three garment types (T-shirts, knit collared shirts and woven pants) in six countries (China, Germany, Italy, Japan, the UK and the USA) averaged only 3.1 to 3.5 years per garment, albeit with significant variation between countries[76]. The short garment lifetimes, alongside increased consumption, has led to a 40% increase in landfilled textile waste in the USA between 1999 and 2009 (REF.[77]), and, globally, textiles account for up to 22% of mixed waste worldwide[78]. For fibre produced in 2015, 73% (39 Gt) was landfilled at their end of life. Per capita, both the USA and the UK waste an average of 30 kg of textiles per person annually[79], which is similar to Australia (27 kg annually[80]) and more than in Finland[5] (13 kg) and Denmark[81] (16 kg).

Despite the high waste, textile-recycling rates remain low — only 15% of post-consumer textile waste was collected separately for recycling purposes in 2015, and less than 1% (0.5 million tonnes) of total production was recycled in closed loop[14] (recycled into the same or similar quality applications). Most of the recycled textiles (6.4 million tonnes) were recycled into other, lower-value applications, such as insulation material, wiping cloths and mattress stuffing, and 1.1 million tonnes were lost during collection and processing[6]. Post-consumer textile collection rates varies widely between countries, for instance, 11% of annual textile waste in Italy and 75% in Germany, and some have no textile-recycling system at all[17]. The UK's reported collection amount of 11 kg per capita is second only to Germany, but this recycling rate is partly due to the UK's far higher consumption of clothing and textiles than any other EU country. To reflect these differences, the European Clothing Action Plan report on textile collection in European cities proposed that recycling-collection rates should be viewed in relation to consumption rates[17]. Thus, to close the material loop and create an effective recycling system for all textile waste, not only must garment recycling become more widely adopted but the production and consumption of garments must be slowed.

Changing the paradigm

The current business logic in the fashion sector is based on ever-increasing production and sales, fast manufacturing, low product quality and short product life cycles, all of which lead to unsustainable consumption, fast material throughput, substantial waste and vast environmental impacts. Both production processes and consumption attitudes must, therefore, be changed. Doing so, however, requires involvement for all stakeholders: the textile industry to invest in clean technology, fashion businesses to construct new business models, consumers to change their consumption habits and policymakers to modify legislation and global business rules (FIG. 5). Here, we highlight key approaches to create a new paradigm for sustainable fashion, including limiting growth, reducing waste and promoting a circular economy.

Limits to growth. Despite actions by the fashion industry to reduce environmental impact, current efforts to improve sustainability are often outpaced by increasing consumption[11]. Sustainability potential, for example, has been constrained by consumer culture (that is, increased consumption) and the tightly related output growth (that is, increased production), both of which are factors that the fashion industry is slow, or unwilling, to mitigate for economic reasons[4,11,82]. Indeed, future projections of the fashion industry presently rely on assumptions of limitless resource use and economic growth. However, such unlimited-growth models do not take into consideration planetary boundaries, specifically, finite resources and waste generation associated with new or continued unsustainable practices[82,83]. Instead of pursuing unlimited growth and, thereby, promoting unsustainable practices, degrowth of the global fashion industry — that is, a planned economic contraction associated with reduced production volume — is desperately needed[79].

However, degrowth in the face of improved sustainability is a complex challenge, with many cultural, psychological and social factors that require consideration to accomplish 'post-growth fashion' (REFS[83–85]). For example, one difficulty is in determining 'fair share', even if a complete extent of a planetary boundary is defined. Moreover, it is problematic to define the individual share of a company or even a country in a global and open business environment. If the degrowth means ending manufacturing in many developing countries, there would be social and economic problems for those countries that are currently dependent on their textile-manufacturing or garment-manufacturing industry. For example, half of Pakistan's exports are from textiles and the apparel industry, and 55% of all exports from India are associated with the garment industry[9]. Furthermore, these changes cannot come solely from the industry — consumer culture in which fashion is cheap entertainment with no consumer consequences must change[10].

The industry needs to improve sustainability and business needs to create alternative models for fast fashion to lower its environmental impact. Degrowth could lead to better balance in the industry through slowing down production and creating stable businesses focused on better garment quality, longer product lifetimes and smaller production amounts. Extended producer responsibility, in which producers and importers are responsible for product disposal and recycling (FIG. 5), promotes more environmentally friendly business practices by making waste a cost for the industry and encouraging it to reduce overproduction.

Closing the loop. Further to limiting the growth of the fashion industry, promoting a circular economy (keeping materials in the system for as long as possible) is an additional approach to improve environmental sustainability. The extended use of a product can be achieved through various means, often falling on the consumer via improved product satisfaction and person–product attachments[9]. Achieving extended product lifetimes, however, can also require the decoupling of fashion ownership and use, necessitating new approaches for profit baselines, from single sale to extended use and grounding into new business models[86].

Access-based consumption models offer one such approach towards circularity[86]. These models are centred on rentals and peer-to-peer sharing systems, which currently exist in occasion, formal and designer wear. However, rentals have not traditionally been a viable alternative to fast fashion for many consumers, related to barriers in price, availability and hygiene[86,87]. Nevertheless, in recent years, collaborative consumption and sharing economy[88] (exchanges, swapping and sharing between parties) has started to emerge[89], with leasing and renting of clothing becoming more accepted and commonplace, especially amongst younger consumers[86–88]. In Europe alone, the sharing economy (including swapping and renting) is worth an estimated 28 billion Euros in transactions[104]. As a result, increasing numbers of companies have started to explore such collaborative business models to extend garment use, including repair services and second-hand sales, especially in the luxury market[67,90–93]. It must be noted, however, that the environmental benefits of collaborative consumption might be outweighed by additional transportation efforts[89].

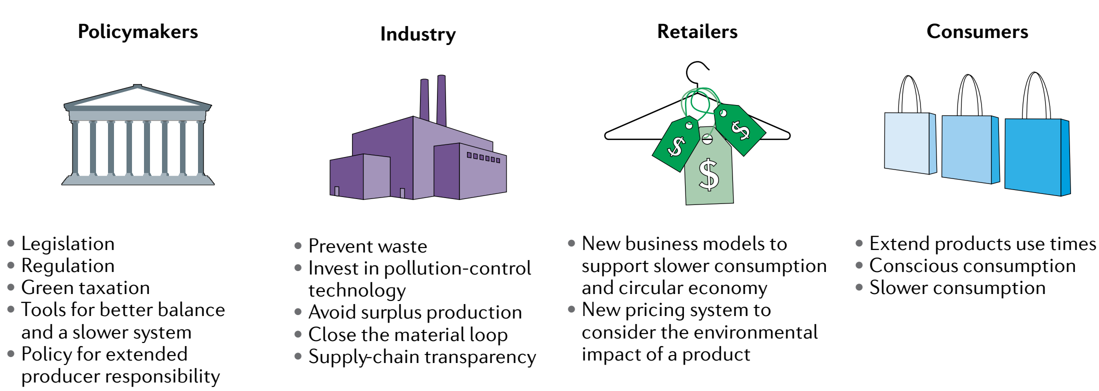


Fig. 5 | **Stakeholders and actions for a more sustainable fashion industry.** Recommendations for policymakers, industry, retailers and consumers to create a more environmentally friendly fashion business model.

Material recycling at the end of a product's lifetime also provides opportunities to promote a circular fashion industry[94] and minimize waste. Many forms of textile recycling exist for both pre-consumer and post-consumer waste[14,35], based on mechanical and/or chemical and thermal recycling processes. Recycling, however, is complicated by garments being constructed of fibre blends, which require separation. The heterogeneous composition of post-consumer waste, therefore, has high technical requirements for sorting, often achieved through automated solutions based on near-infrared technology[95]. Robotic technology has also been able to separate four different textile material classes with an average accuracy of over 90% (REF.[95]).

Mechanical fibre recycling works through simply shredding the textile waste into short fibres, lowering their quality, before they are manufactured into new materials. Given the shredding-related deterioration in fibres, it has been suggested that a maximum of 20% post-consumer mechanically recovered cotton fibres can be blended with virgin cotton before strength is compromised, although high percentages can be achieved when using pre-consumer cotton waste and/or other virgin fibres[96] (which are longer). The shredded fibre can then be used, for example, in composite materials, nonwovens and filling materials, materials with lower monetary value than the original product[95].

Other recycling processes are more efficient than mechanical recycling. For example, chemical recycling works by fractionating fibres through a chemical dissolving process into a polymer level and it is suitable for cellulose fibres[95]. The process preserves fibres better than mechanical recycling and is, therefore, anticipated to enable garments to be produced with higher percentages of recycled fibres, promoting upcycling — even 100% recycled yarn can be produced[95]. Thermal recycling is used for thermoplastics, like polyester, and, in this process, fibres are melt-spun through the same process as the original thermoplastic fibres[95]. New technologies further allow even greater improvements in textile return. The cellulose carbamate process, for example, creates viscose-grade staple fibres from cotton-rich textile waste[97], which can subsequently be used for the same applications as viscose fibres, namely, nonwovens, wovens and knits, or mixed with different fibres, such as cotton or polyester[95]. Moreover, other techniques[98], such as the Ioncell-F process, uses dissolution and spinning of cellulosic fibres to create an alternative to virgin cotton or viscose production[99]. As both Ioncell-F and cellulose carbamate rely on fibre-presorting technology, other chemical-recycling processes have focused on blended textiles (such as polycotton) to enable unsortable recycling using inexpensive chemicals[7]. Additionally, chemical processes can remove contaminants, such as hazardous substances included in textile waste[14].

Collectively, mechanical, chemical and thermal recycling of textile materials offers the potential to reduce environmental impacts when compared with processing virgin fibres[60]. For example, polyester (mainly through recycled polyethylene terephthalate bottles) and cotton recycling uses only 1.8% and 2.6% of the energy to process virgin fibres, respectively[24]. However, recycled polyester accounts for only 14% of the total polyester market share, and cotton recycling remains limited[34]. Moreover, in some situations, textile incineration with energy recovery can be more sustainable than recycling materials[100], as textiles might include chemicals that are not recyclable or recycling might be impossible, owing to inseparable fibre materials. Thus, further innovations in textile recycling are needed to promote circularity. With the EU proposing that all textile waste will be collected, sorted and recycled in each of its member states by 2025 (REF.[12]), developments in waste systems and recycling technologies may be on the horizon. Moreover, a policy of extended producer responsibility will exert stronger pressure on businesses and ensure that all apparel items are collected and put back into the system, closing the material loop. The understanding that waste is part of the fashion business that must be taken responsibility for pushes the business paradigm away from fast and environmentally harmful fashion towards cleaner, slower and more sustainable fashion. In the future, garments must be designed to be suitable for recycling and closing the material loop must be the norm, requiring systematic changes in the industry. Furthermore, extending the use time of garments and their waste should be integrated for a holistic garment life cycle model, thus, fostering a sustainable fashion industry.

Waste in focus. While the above-mentioned recycling technologies can help address textile and inventory waste (surplus production or deadstock), it is important to consider whether the fashion system could instead be redesigned so that waste and, in particular, surplus product (and, therefore, environmental impacts) are not created. Two approaches can be used to prevent clothing waste and implement more sustainable fashion practices: proactive (prevent, reduce) and reactive (reuse, recycle and dispose). The first priority when transforming the fashion industry is the proactive prevention of waste production, which requires novel design–production–marketing logic. A mix of proactive and reactive approaches to minimize waste production and reuse the product to extend its lifetime offers a feasible alternative. The least sustainable approach, however, is fully reactive, focused on efficient product disposal. All these approaches have challenges associated with their implementation.

When companies' design offices are located disparately to production, information sharing is made more difficult, inhibiting waste reduction. For example, designers and pattern cutters may not have full information on the width of fabric used in manufacturing and cannot, therefore, design to maximize fabric use and minimize waste. Instead, it is left to the planner at the manufacturing stage to try to cut a production lot as efficiently as possible. More recent design software bridges the gap between design and manufacture, providing real-time feedback between three-dimensional design and two-dimensional pattern layout[101]. Although the use of this software will not prevent all pre-consumer fabric waste, its capacity as a feedback mechanism for fabric wastage warrants further research.

Questioning current fashion design and manufacturing practices could indeed lead to more creative ways of producing garments. For instance, proactive methods have been developed to design garments that minimize cutting waste and put nearly all offcuts into production[66]. These strategies include: invisible remanufacturing, where fabrics are placed in invisible sections of the garment; visible remanufacturing, where they are placed in external visible places; and design-led manufacturing, where offcuts are used creatively to decorate the garment[66]. It has been estimated that this creative way of manufacturing garments could save as much as 17% of virgin material and 7,927 kg of CO_2 during the production of 10,000 garments[66]. Further consideration of small offcuts — which could later be used in mechanical fibre recycling — further offers opportunities to save more fabric and minimize CO_2 emissions. Creative manufacturing practices such as the example described here could be one solution to reduce the environmental impact of the fashion industry. Similarly, closer collaboration between design and manufacturing could create a new kind of low-waste-driven sustainable design–manufacturing–consumption model.

Summary and future perspectives

The cost pressure and level of competition in the fashion industry remain very high, making it difficult to change business practices. Yet, it is essential that the industry as a whole (from fibre production to retail) takes responsibility for its environmental impacts, including water, energy and chemical use, CO_2 emissions and waste production. Minimizing and mitigating these impacts, however, requires change, which businesses are often opposed to for a multitude of reasons, first and foremost being economic. For instance, investment in the latest pollution-control technology is an essential requirement for the short-term future of the textile industry, necessary to remove chemicals, heavy metals and other toxic substances from waste streams. Yet, using cleaner processes will increase production costs, a cost that is ultimately borne by the consumers, potentially ending cheap and fast fashion, leading to economic declines within the fashion industry.

However, streamlining industrial processes, including a reduction in the numbers of chemicals used, might also save costs in manufacture, providing economic incentives to implement more sustainable practices. Similarly, creative business models built on proactive design act to reduce waste, avoid surplus production and, thereby, creating a more stable business environment.

Ultimately, the long-term stability of the fashion industry relies on the total abandonment of the fast-fashion model, linked to a decline in overproduction and overconsumption, and a corresponding decrease in material throughput. Such transformations require international coordination and involve new mindsets being adopted at both the business and the consumer levels (FIG. 5). One approach to lowering fashion's environmental impact is to shift the system from linear (take, make, dispose) to circular with the following three approaches: narrowing (efficiency), closing (recycling) and slowing (reusing)[90]. Another is to consider new business models such as renting, leasing, updating, repairing and reselling, all of which enable longer product lifetimes while simultaneously proposing a new, slower lifestyle for consumers. Moreover, these models can result in eco-efficiency (intensifying the use, as in renting) or even sufficiency (less consumption). Successful changes in consumer behaviour, however, must be accompanied and supported by policies addressing the social organization of consumption at the social, cultural, economic and material levels.

Slow fashion is the future. However, we need a new system-wide understanding of how to transition towards such a model, requiring creativity and collaboration between designers and manufacturers, various stakeholders and end consumers. We need new system-level understanding on how to make the transition towards better sustainable balance in the fashion industry. Moreover, a functional system for textile recycling must be constructed. One of the most difficult challenges going forward will be to change consumer behaviour and the meaning of fashion. Consumers must understand fashion as more of a functional product rather than entertainment, and be ready to pay higher prices that account for the environmental impact of fashion.

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