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Environmental impacts of cotton and opportunities for improvement

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Abstract

Cotton—supplying approximately a quarter of global textile fibres—has various environmental impacts, including water use, toxicity, eutrophication, and greenhouse gas emissions. In this Review, we identify these global impacts across multiple life cycle stages. Environmental impacts at the cultivation stage depend on levels of irrigation, pesticide, and fertilizer applications. At the textile manufacturing stage, impacts depend on energy infrastructure and manufacturing technologies. At the use phase, consumer habits related to buying, washing, drying, and ironing play a role. Depending on the impact category and country, either cotton cultivation, manufacturing, or use can dominate such impacts. For example, the use phase dominates greenhouse gas emissions in countries with carbon-intensive energy grids. Use of alternative fibres has the potential to reduce these environmental impacts, particularly jute and flax, which have much lower water demands. Opportunities for farmers, manufacturers, and consumers to improve the environmental sustainability of cotton textiles include, among others, improving water use efficiency in agriculture, innovative recycling, and laundering less frequently. Future cotton sustainability assessments are needed to fill data gaps related to developing and emerging countries, the number of uses of a cotton garment, further environmental impacts like salinization, as well as socio-economic impacts.

Introduction

Cotton grows on over 30 million hectares of cropland in 85 countries and regions, and more than half of all countries and regions are involved in the international cotton textile trade[1]. Cotton comprised approximately a quarter of the global textile fibre market in 2017–2021[2] and also accounts for about 2.3% of global vegetable oil production[3]. The life cycle of the cotton commodity is complex and includes cultivation and several manufacturing steps (such as ginning, blowing, carding, drawing, roving, spinning, weaving, dyeing, cutting, sewing, and ironing) before it ends up in retail for consumers to purchase. Tens of millions of jobs, particularly in developing countries[4], are associated with cotton across these sectors.

While cotton and the cotton textile industry have greatly contributed to economic development, they also negatively impact the environment[5]. For example, inputs of chemical fertilizers and pesticides in cotton cultivation cause non-point source pollution. Cotton cultivation is also water intensive[7]. Furthermore, textile production is associated with high greenhouse gas (GHG) emissions[8] and releases numerous pollutants, such as dyes, wetting agents and softeners, into waterways[9]. These environmental impacts are compounded by escalating rates of cotton consumption, which has exploded owing to the promotion of fast fashion leading to over-consumption [9,10]. All these impacts vary regionally, depending on agricultural practices, manufacturing standards, and consumer behaviors, as measured through life cycle assessment.

In this Review, we assess the environmental impacts and mitigation options across cotton's life cycle. We begin by exploring variations in cotton cultivation, manufacture and use to identify the associated environmental impacts related to water use, toxicity, eutrophication, and greenhouse gas emissions. Subsequently, we compare the environmental impacts of cotton fibres with alternative plant, animal, and synthetic fibres. We also outline how improvements to the sustainability of cotton and cotton textiles could be gained through interventions in cotton cultivation, the production of cotton textiles, and consumer behaviour. Finally, we point to knowledge gaps and challenges that require further research, such as coverage of further cotton products, regions, and impact categories.

Cotton cultivation around the world

Around 85 countries or regions grow cotton[11], but the commodities resulting from cotton are consumed globally. Global and regional patterns of cotton agriculture, and its associated water, pesticide, and fertilizer requirements, are discussed in this section.

Production, consumption, and trade patterns

The global production of cotton fibre was estimated to be 25 million tonnes on average from 2018 to 2022 (ref[12]). The world's largest cotton producer is China, with production concentrated in the northwest Xinjiang region (FIG. 1a)[13]. Production in China accounts for 24% of global production, followed by India (23%), the United States (hereafter "US") (15%), Brazil (11%) and Pakistan (5%)[12]. Despite a downturn in production during the COVID-19 pandemic, production is anticipated to reach 31 million tonnes in 2031 (ref[2]). This growth reflects an expansion of harvested area in locations such as the US and Brazil and from the increase in average global yields[2]. The assumed yield increases reflect greater adoption of smart mechanization, development of new varieties, and improved pest management.

Overall, global use of cotton fibres by mills (hereafter, cotton consumption) increased from around 10 million tonnes at the beginning of the 1960s to 27 million tonnes in 2007. Cotton consumption stabilized at a lower level of around 25 million tonnes in the following years, mainly owing to competition from synthetic fibres such as polyester[2]. China, the world's largest cotton mill operator, accounts for 32% of the global cotton fibre consumption, followed by India (21%), Pakistan (9%), Bangladesh (7%) and Turkey (7%)[11].

Importantly, cotton cultivation, mill manufacturing, and purchase of a final cotton product (for example, jeans) often occur in different locations, connected by global trade patterns. For example, Malaysia does not grow cotton but imports raw cotton for processing in the textile industry and exports cotton clothes to the European market[2]. The product group "textiles, clothing apparel and leather" was estimated to account for as much as 24% of the water scarcity footprint of international trade due to the high water scarcity footprint of cotton lint[14]. US consumption of clothing, leather and furniture from China and other Asian countries drove the variation in marine eutrophication impacts embodied in global non-food trade [15]. Substantial amounts of the carbon footprint in the EU textile and clothing sector were 'outsourced' abroad to regions including China, India, Brazil and Turkey[16,17]. The globalization and fragmentation of the textile and fashion system have led to an uneven distribution of environmental consequences[18]. The projected increasing global trade of cotton[2] would exacerbate this trend by allowing countries to consume without bearing the environmental consequences of production.

Irrigation

Cotton is a water-intensive crop that is contributing to worsening water scarcity in many locations. The global average water consumption (including both rain and irrigation) of seed cotton (3588 m^3 $tonne^{-1}$) is substantially larger than food crops such as sugar, vegetables, roots and tubers, cereals and oil crops (ranging from 182 to 2243 m^3 $tonne^{-1}$), while being smaller than food crops such as pulses, spices, nuts, and stimulants (ranging from 3321 to 13983 m^3 $tonne^{-1}$) [19]. Cotton's water requirements vary from around 700 to 1200 mm per growing season, depending on factors such as season length, climate, and cultivar[20].

About half of the global cotton fields are irrigated with 'blue water' rather than being rainfed[21]. Globally, cotton's blue water consumption varies from 0 to 726 mm yr^{-1} (FIG. 1b). Cotton is one of the five crops which dominate the global unsustainable blue water footprint, contributing to 10% of the unsustainable global portion[22]. Approximately 50% of its unsustainable blue water footprint is located in five catchments (Indus, Aral, Syr-Darya, Tigris and Euphrates, and Mississippi) with a total population of 319 million people who experience severe water scarcity for some part of the year[22].

Water consumption per unit of cotton production increased in locations with low agricultural intensification during 2000-2010 (REF.[23]). Conversely, water consumption is decreasing in locations with high or medium degrees of agricultural intensification[23]. These decreases are enabled by mechanization and technology adoption, such as drip irrigation, which is also reflected in increased water-use efficiency and water productivity (two similar concepts related to production-based water use). For example, water-use efficiency of Australian cotton increased by 40% from 1988 to 2010 while the cotton irrigation water productivity in the US increased from around 0.05 to 0.20 kg m^{-3} during 1980–2015. However, cotton water-use efficiency in Central Asia increased during 1960–1990 and then decreased again to the 1960s level because of a yield decrease probably caused by soil salinization and the decrease in mineral fertilizer application[24]. Under the background of climate change, future water consumption, yield, and water-use efficiency are expected to increase[25-27]. However, as climate change can also cause pressure on water availability, high water debts will make cotton unsustainable to produce in many regions[28,29].

Pesticide use

Pesticide (insecticide, herbicide, growth regulators, desiccant, defoliant and fungicide) use for global cotton cultivation accounted for about 6% of the world's total pesticide sales in 2014 (REF.[6]). Insecticide use specifically accounted for 16% of all insecticide sales, despite cotton using only 2.3% of arable land[11]. Globally, the average pesticide application rate was 1.57 kg ha^{-1} in 2015 (FIG. 1c). The total mass of the top 20 active ingredients used in pesticides applied in cotton cultivation was estimated to be 43.6 million kg[30]. The top five countries or regions in terms of pesticide application use about 90% of the global total. Among the top 10 cotton-producing locations, Brazil has the highest pesticide application rates, with almost four times the global average[30].

The fractions of overall agricultural pesticide use in cotton agriculture differ between insecticide and herbicide classes. The fraction of cotton's insecticide use out of total insecticide use declined from 19% in 2000 to 14.8% in 2010, but the use of herbicides stayed constant over this time period [6]. The relative reduction in insecticide use is attributed to the introduction of genetically modified *Bacillus thuringiensis* (*Bt*) cotton, integrated pest management, regulatory restrictions on some conventional pesticides, implementation of new pesticide technologies and changes in farming practices[31,32]. For example, Argentinian farmers growing *Bt* cotton used only half of the insecticides as those growing conventional cotton, with reductions especially in highly toxic chemicals, while achieving higher crop yields[33]. However, the trend also varies across countries, and some, like India and Pakistan, increased their insecticide uses owing to pressures from mealybugs and pink bollworms. In general, the downward trend of insecticide use did not last owing to a new surge in pests, leading to a higher value again in 2014 compared to 2010[6].

Pesticide use in cotton cultivation involves various environmental impacts, including toxicity to humans and ecosystems [34,35]. Several major cotton-production regions, including the Indus River valley in Pakistan, the Yellow River valley in China, and the Murray River catchment in Australia[34], are listed among the top five areas of concern for pesticide pollution. The particular chemical compounds used in the pesticides applied to cotton are more highly toxic to soil macrofauna (for example, earthworms)[36] than those applied to other crops. In addition, pesticide exposure harms agricultural workers in several ways, including skin injury, eye injury, headache, stomachache and fever[37,38].

Fertilizer use

The average global nitrogen and phosphorus fertilizer input to cotton is 150 kg ha^{-1}, which is a similar rate to maize, potato, canola, rice, sugarbeet and sugarcane[39]. However, nitrogen application rates vary globally (FIG. 1d), with higher rates in areas with irrigated and mechanized production [40] and lower rates in areas with capital- and water-constrained production. Generally, the level of agricultural mechanization is positively related to fertilizer use and its environmental impact, but the impact is constrained by natural conditions, farm income and potential yield-limiting fertilizer use[41].

In irrigated cotton systems on heavy clay soils, only 17-40% of the applied nitrogen fertilizer is taken up by the plant, with 47-55% lost to the atmosphere, and 7-10% stored in the soil[42]. Ideally, optimal fertilization practice should maximise uptake of nutrients into plant tissue and minimise losses into the broader environment. However, poor nitrogen and phosphorus use efficiency is a characteristic of 49% of cotton-growing countries or regions, which are over-fertilizing, while the other 40% of countries are under-fertilizing[38] (Supplementary Fig. 1). Over-fertilization causes excess nutrients to drain deeply into soils, resulting in increased groundwater and surface water nitrogen concentration[43]. Under-fertilization reduces soil quality by causing micronutrient[44] and/or macronutrient deficiencies[44], which reduce soil ecosystem services and agricultural sustainability.

Life cycle assessments of cotton textiles

Beyond the direct environmental impacts of cotton cultivation, cotton has other impacts associated with creating the inputs to cotton production and associated with how the raw cotton is processed and used. Life Cycle Assessment (LCA) is a technique used to assess the environmental impacts across a commodity's life cycle, from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal [45]. Numerous LCAs have been conducted to evaluate the impacts of cotton textiles, which are discussed in this section.

Life cycle of cotton textiles

The life cycle stages of cotton textiles include agricultural input production, cotton cultivation and production, yarn production, fabric production, manufacturing of final textile products, retailing, use phase, and end of life[46-49] (FIG. 2). Transportation is required between life cycle stages as individual textile production steps typically occur in different locations[50]. After cotton harvesting, the ginning process separates seeds and lint packaged to sell as bales[47]. Cotton yarn production includes a series of processes, such as blowing, carding, drawing, roving, and spinning[46]. Yarns are manufactured into fabrics using weaving or knitting[48], while nonwoven fabrics are made from bonded fibre webs. Fabric production includes wet processes, such as bleaching, dyeing, washing, and finishing. Fabrics are then cut, sewed, and assembled into final textile products with value-adding activities such as ironing and packaging[48]. Textile products are distributed to customers through online or conventional in-store retailing. The use phase of cotton textiles involves activities including washing, drying, and ironing, depending on individual customers[48]. Waste materials are generated in almost all stages of the life cycle of cotton; textile waste can be landfilled, incinerated, reused, or recycled for textiles (closed-loop recycling) or other products such as biochar (open-loop recycling)[51](Figure 2).

Published LCAs include different elements of the overall cotton life cycle within their system boundaries (the group of industrial activities connected with the cotton product under study – Supplementary Fig. 2). All LCAs considered here assess the impacts from raw material acquisition (that is, cotton cultivation) through wet treatment, and most consider the use phase. Consideration of recycling is rare (Supplementary Fig. 2). The most unusual inclusions are the transportation of the garment from the retailer to the user's home (which nevertheless cause a large proportion of GHG emissions in a Swedish assessment[52]) and the physical infrastructure of the garment user's laundry (a potentially important structure in garment life cycles when considering potential GHG emission reductions[53]). In addition to differences in Life Cycle Inventories (LCIs – the lists of environmental flows that enter and leave the system boundary in an LCA), differences between Life Cycle Impact Assessment (LCIA) methods (the quantitative environmental models used to translate emissions and resource use identified in the LCI into environmental impacts) also lead to different interpretations of LCAs on similar products. Accordingly, comparing published LCA estimates is problematic (FIG. 3).

Water use

Published LCAs differ in the ways that they measure and report water use. Some report raw water consumption, while others report a water use indicator weighted by water scarcity to consider water deprivation of other users where the water consumption takes place (refer to Figure 3a for examples of each).

When scarcity weighting is considered, an estimated 97-98% of water use impacts are associated with the production of cotton fibre and only 2% associated with laundry activities[50,53]. Without scarcity weighting, considering only raw water use, water use is still dominated by irrigation of cotton (79%[54] in the only unweighted result in Figure 3) but is also high (14%, ref. 55) after garment retailing.

Human and ecotoxicity

The toxicity impacts of cotton garments can be dominated by the cotton cultivation or textile product manufacturing stages of the life cycle (Figure 3b). Such assessments of toxicity are relatively rare in LCA of textiles because analysts face a scarcity of both LCI and LCIA data [56]. Methods for the assessment of toxicity are changing relatively rapidly, so even the units used to express contributions to toxicity can differ, adding to the incomparability of those results. LCAs often include pesticide use data in toxicity assessments[1,52,57,58]. Excluding the effects of pesticides, the toxicity associated with garment life cycles is mainly attributed to the long-term effects of metallic pollutants resulting from combustion processes for energy production. Given that the emission of these toxicants is highly correlated with the emission of greenhouse gases, some LCAs instead include only the direct toxicity associated with fibre and textile production [52]. Similarly, other LCAs include only the chemical impacts of fabric production and wet treatment (excluding fibre and garment production) and focus on how to use quantitative structure activity models to complete LCIAs when information on textile chemicals used in wet treatment is scarce [59].

Eutrophication

LCAs reporting eutrophication impacts show several contributions from the cotton life cycle (Figure 3c), with the most impactful stages varying across LCAs. For example, the life cycle stage contributing the highest fraction of all eutrophying emissions was found to be either fertilizer use during cotton cultivation [57,60] (up to 83% of all emissions[1]), detergent use by consumers (91%, ref.[58]), or wet processing operations (ref.[55]). With the exception of important activities like these, the eutrophication profile in published LCAs of garments tends to follow the GHG emission profile on account of the contribution energy production makes to the emission of nitrogen oxides from combustion processes.

Greenhouse gas emissions

The carbon footprint is measured as CO_2-equivalents (CO_2-eq), referring to the equivalent mass of carbon dioxide emissions considering the combined effect of all the relevant climate-changing greenhouse gas emissions. Among the studies compared here, the carbon footprint over the full life cycle of a cotton product ranges from 3 to 62 kg CO_2-eq per product (Fig. 3d). In other words, a range of 50 to 872 g CO_2-eq is emitted at some point in the garment life cycle for each time the garment is used. Strikingly, this range indicates that, in most cases shown here, each garment use causes GHG emissions of the same order of magnitude as the mass of the garment.

Among published LCAs, either the garment production phase (including fibre spinning, fabric production and wet treatment) [52,57,60,61,62] or the consumer use phase [58,63] dominates the carbon footprint (Fig 3d). The underlying differences have much to do with the source of electrical energy in use by the household[52] and national variations in prevalent laundry technologies[57]. Moreover, garments are increasingly shipped by air cargo, which typically has higher GHG emissions than traditional ship cargo[9]. Identifying whether a higher share of the carbon footprint results from the production or the use phases is important to policy, in terms of identifying the best stage for a policy intervention to reduce emissions.

Comparison to cotton alternatives

The main alternatives to cotton textiles are those derived from natural plant fibres (jute and flax), animal fibres (silk and wool) and synthetic fibres (polyester, nylon, acrylic and viscose). While a growing number of LCAs individually consider these cotton fibre alternatives, direct comparisons of fibres are rare. The comparative LCAs discussed here consider differing environmental impacts up to the fibre or textile production phases but not during the use phase.

Plant fibres

Jute is the most common plant fibre produced after cotton, followed by flax[11]. Overall, across all impact categories investigated, jute and flax fibres have lower impacts than cotton fibres (Figure 4). Jute and flax require less fertilizer and water during their cultivation than cotton[61,64]. Terrestrial and marine ecotoxicities are lower for jute than for flax, while freshwater ecotoxicity is higher; human toxicity is similar for both plant fibre alternatives[65]. When extending the system boundaries from fibres to textiles, jute still outperforms cotton in all the impact categories under investigation[65,66].

Animal fibres

The environmental impacts of animal fibres are often higher than those of cotton in the production phase. Except for terrestrial ecotoxicity, silk generally has the highest impact in all impact categories under investigation compared to all the other fibres (Figure 4). Silk's impacts mainly arise from the high water and fertilizer inputs needed to cultivate mulberry trees, the host plant for the silkworms *Bombyx mori*[61,67,68]. Wool also has a relatively high carbon footprint, mainly owing to the methane emissions of sheep (56%), manure emissions of dinitrogen monoxide (16%), and the production of soybeans for feeding sheep (17%)[61]. Although the carbon footprint of wool is lower than that of silk, it still exceeds cotton's[61]. Water consumption is lower for wool compared to silk and cotton. There has been no quantitative comparison of the impacts of wool in terms of toxicity or eutrophication. The differences between animal fibres and cotton might change when considering the use phase. For instance, there are claims that silk garments, in general, have a longer lifespan and are washed less often than other fibres[57]. However, information on the wearing and laundry behaviour of garments made with different animal fibres is unavailable[64].

Synthetic fibres

Since synthetic fibres like polyester, nylon, and acrylic are based on fossil resources, water use and eutrophication impacts are very low [69]. Viscose is derived from cellulose extracted from wood; and process water is consumed in the production phases of viscose fibres (Figure 4A) [70,71]. The carbon footprint of nylon fibres is higher than that of cotton fibres, while other synthetic fibres show a similar level of GHG emissions as cotton fibres[61,62] during fibre production (Figure 4D). The difference between cotton and acrylic becomes more pronounced when considering textile production, with cotton exceeding the footprint of acrylic. Conversely, nylon textiles emit fewer GHGs than cotton textiles[62].

Opportunities for improvement

There are numerous opportunities for different stakeholders to reduce the environmental impacts of cotton across its life cycle. Potential interventions in cotton cultivation, the production of cotton textiles, and consumer behaviour (FIG. 5) are discussed in this section. However, we advise caution to avoid burden shifting among environmental impact categories or life cycle stages.

Cultivation improvements

Growers can use precision irrigation to optimize water application and reduce water use. Precision irrigation methods include technologies and decision support tools for irrigation scheduling, improved on-farm water delivery systems and reduced irrigation volumes. Irrigation scheduling offers particularly promising opportunities to improve water use efficiency[72]. Advances in irrigation scheduling include direct measurement technologies, such as wetting front detectors and soil capacitance probes; indirect measurement technologies, such as canopy temperature sensors, microwave and remote sensing; and the use of modelling and crop evapotranspiration coefficients[72].

Further water use efficiency gains can be made through improved water delivery methods such as the replacement of furrow irrigation with precision drip and overhead irrigation systems[72-74]. Low-energy precision water application via an overhead irrigation system can be used to improve yields by 16% relative to sprinkler methods[75]. Water productivity in drip irrigation practice can be improved using plastic mulches (1.35 kg lint m^{-3} water) or biodegradable films (1.29 kg lint m^{-3} water) relative to the control (0.98 kg lint m^{-3} water)[76]. Alternatively, deeper drip tape placement with an optimized irrigation volume can achieve similar yields without creating plastic pollution or resulting in increased soil respiration[77]. Additionally, deficit irrigation, where irrigation volume is reduced at specific plant stages, or early irrigation termination has been shown to improve water productivity but can affect crop productivity[74,78]. Importantly, although precision irrigation in agriculture systems can increase crop yield and reduce water use, these methods may entail an increased carbon footprint[79]; further work is necessary to investigate this trade-off.

Growers can also adjust strategies to reduce toxicity and eutrophication. Newly developed cultivars and improved management have reduced yield gaps and pesticide use in some locations[80] and can potentially provide options for climate change adaptation strategies[81]. The use of *Bt* cotton[82] and/or the application of an ecologically Integrated Pest Management (IPM) approach can reduce the use of pesticides and promote biological control within cropping environments[83]. In Australia, applications of pesticides against the cotton bollworm (*Helicoverpa armigera*) have declined from 10-14 to 0-3 applications per season through the use of *Bt* cotton[84]. However, in some locations, *Bt* cotton has actually increased long-term pesticide use owing to resistance in pink bollworms and surging populations of non-target pests [82]. Finally, integrated approaches, such as intercropping[85], crop rotations, and increasing landscape biodiversity[86], reduce cotton's impact on the environment by reducing mono-cropping and increasing farm ecosystem functioning.

In many cotton-growing areas, sustainability gains in terms of reduced GHG emissions (3-20%) and off-site eutrophication can be made through the optimization of nitrogen and phosphorus synthetic or organic fertilizer input[87-89]. Optimized inputs must meet the cropping system nutrient requirement and soil fertility maintenance. It is critical that nutrient availability synchronize with plant growth requirements[82]. Potential solutions to improved synchronization include controlled-release fertilizers[90], split application[91], fertigation[92] and precision fertilization[93]. It is also important for growers to determine site-specific nutrient budgets and efficiency targets. Advances in portable near-infrared spectroscopy will enable near real-time in-situ crop nutrient analysis and empower the grower to make informed fertilizer application decisions in cotton production systems[94].

Several aspects of environmental impacts can be reduced by converting from conventional to other cultivation approaches. Organic cotton cultivation approaches, for example, can reduce terrestrial ecotoxicity during the production stage by 87% and freshwater ecotoxicity by 59% relative to conventional cotton[58]. Moreover, organic cotton can have 3.5 times fewer CO_2 emissions and reduced fertilizer inputs than conventional cotton but can require more water[9] and labour inputs[95]. While organic cotton systems are a minor component of the global supply, the systems could be used as benchmarks for assessing the sustainability of conventional cotton systems. Growers can apply other approaches, such as climate-smart agriculture, where the cropping system is aimed at adapting to - and mitigating - climate change to improve resource use efficiency, farming system resilience, and sustainability[96]. Also, controlled traffic farming (GPS-guided) approaches coupled with minimum or no-tillage practice reduce GHG emissions, soil erosion, and nutrient loss in runoff[97]. Other field practices include the modification of the cropping calendar and/or spatial distribution to align crop response to climate and landscape biophysical variations, thereby improving cotton sustainability[98,99]. Optimized cotton farming system management can mitigate the carbon footprint by 30-57%[100]. There are many cultivation approaches that can be combined and used by growers to improve sustainability of the cotton farming system.

Textile manufacturing improvements

Cleaner production of cotton textiles should aim to reduce resource consumption (for example, energy, water, and chemicals) and mitigate environmental emissions (for example, GHGs and wastewater discharges). Energy use is one of the main contributors to the life cycle environmental impacts of cotton textiles [57,101]. Improving energy efficiency[102] and using renewable energy[103] offer emission-saving opportunities. For example, an approach called Combined Heat and Power, which co-generate electricity and thermal energy at high efficiencies, can reduce the cost, GHG emissions, energy and water consumption of cotton denim fabrics[104].

Individual textile production processes can also be improved. Spinning is the most energy-intensive process in yarn production, and changing spinning technology could reduce energy consumption (for example, 6-10.6 GJ $tonne^{-1}$ for open-ended rotor spinning, and 11.6-13.5 GJ $tonne^{-1}$ for ring spinning)[50]. However, the benefit of this change depends on yarn type and count[62]. Manual spinning, used in some locations such as India, does not consume energy but is labour-intensive[48]. In fabric production, cotton knitting (4.9-18.2 GJ $tonne^{-1}$) is often less energy-intensive than weaving (17.7-118.4 GJ $tonne^{-1}$)[50,62]. One energy-saving strategy is combining spinning and knitting in one machine that eliminates the need for ring spinning and yarn storage [105]. The energy consumption of conventional wet processes is about 26-108 GJ $tonne^{-1}$ (REF.[50]), but this energy usage could be reduced through emerging technologies such as the ultrasonic-assisted wet process. These emerging technologies can potentially also reduce water and chemical consumption, but more information is needed on their large-scale performance[106].

Dyeing and washing-off steps are the most water-intensive processes in cotton textile manufacturing[48]; they also generate large amounts of coloured effluents with adverse environmental impacts[107]. Using naturally coloured cotton instead of white cotton avoids the dyeing steps, although current colour choices are limited to green and earth tones[108]. This limitation can be addressed by future research for more colour options (for example, using natural, non-earth tone dye)[109] or shifts in consumer preferences. One improvement is to replace water with alternative, non-aqueous media, such as silicone oil which was estimated to consume 20% less water and 41% fewer dyes and other chemicals than traditional water-based dyeing[107]. Other green solvents have also been explored[110], but these methods still need improvement[105]. Bio-based chemicals and natural dyes offer new opportunities for sustainable cotton dyeing. For instance, using bio-based materials such as natural indigo dye, nano-fibrillated cellulose, and chitosan reduced dyeing water consumption by a factor of 25 and eliminated reducing agents and alkali [111]. Many alternative dyeing technologies are still in early-stage development; their economic feasibility and effectiveness in reducing the environmental burdens of cotton dyeing need more comprehensive assessment.

Improving wastewater treatment reduces water consumption and environmental impacts by enhancing water reuse and pollutant degradation in factory effluents. Physical, chemical, and biological methods are common[105] and can be combined (as hybrid methods) with real-time monitoring and analytical techniques[112]. One example is an integrated ultraviolet and H_2O_2 treatment for effluents from textile companies in Brazil, which reduced 92.9% of water use and removed over 90% of the total organic carbon and salt[113]. Combined approaches of reusing wastewater, avoiding overflow washing, monitoring water systems, and using water-saving faucets have been found to reduce water use by 13.8-25.6%, wastewater by 18.2-32.9%, and chemical oxygen demand by 15.9-35.7% through a whole-plant water-use efficiency analysis for an integrated textile company in the western Marmara region of Turkey[114].More efforts are needed to identify cost-effective, best-available technologies and suitable hybrid methods for cotton textile mills.

Recycling waste cotton supports resource conservation and waste minimization [102]. Cotton garment production generated an estimated 11.6 million tonnes of pre-consumer cotton waste per year in 2018-2019[51], but it is unclear how much of that waste is disposed of versus recycled in some form. The way that textiles or fibres are reused or recycled varies (Figure 2). Waste cotton fibres can be recycled through mechanical processes such as cutting, shredding, and re-spinning[51]; recycled cotton yarn produced in this way has lower environmental impacts than virgin cotton yarn, mostly owing to the elimination of cotton cultivation and dyeing[102,115]. Mechanical fibre recycling processes usually produce short fibres that need to be spun with virgin cotton to maintain desirable properties[51]. Improvement opportunities include pre-treatment with lubricant[116], blending waste cotton fibres[117], or mixing waste cotton with other materials for thermal and acoustic insulations as open-loop recycling applications[118]. Limited by fibre quality, it is challenging to rely on mechanical recycling alone to supply raw materials for the textile industry[119].

Another form of recycling is polymeric recycling, which dissolves cotton fibres and regenerates them, maintaining or enhancing fibre properties[120]. The dominant commercial regenerated fibre is viscose, which is mainly made from wood. Cotton linters, short fibre leftover from cotton ginning, are also used to produce viscose-grade dissolving pulp, a common material for making textiles[51]. There are new processes to convert waste cotton to dissolving pulp, for example, SaXcell™ (REF.[121]), but these processes are water-intensive; for example, SaXcell™ needs 1500 litres of water to produce 100 kg pulp[121], and chemicals used during manufacture have large impacts on the environment[122].

A central problem limiting recycling is that waste cotton is often blended with other materials. In some cases when separating mixed materials or recycling chemicals is difficult, incinerating blended materials with energy recovery might have lower overall impacts than recycling [9]. Alkaline hydrolysis is another environmentally promising pathway to treat mixed textile waste [119].

Only 25% of global garments are reused or recycled[123]. The collection rate for reuse or recycling varies by country; for example, 75% in Germany and 10-15% in the US and China[123]. The 'fast fashion' business model, which maximizes the sale of cheap, short-lived garments designed with planned obsolescence, is associated with increased garment waste during sale and after consumer use. In contrast, a sustainable consumption style called 'slow fashion' aimed at more durable textiles in terms of both style and quality[124], can reduce such waste.

Consumer behaviour improvements

Consumer behaviour is decisive for the sustainability of textiles, as the use phase can dominate the environmental impacts, depending on the impact category and consumer habits. This dominance especially applies to countries with carbon-intensive energy grids affecting the carbon footprint[125,126] and poor wastewater treatment affecting eutrophication[57]. Consumers, especially middle-class and wealthy consumers, can influence sustainability at the point of purchase. They can reduce emissions by shopping at local stores and by walking or cycling rather than driving or by making the purchases jointly with other daily tasks to avoid special trips by motor vehicle exclusively for shopping textiles [126] Although LCAs of textiles generally exclude consumer transport from the calculations, it can constitute a considerable share of the environmental impacts: 3-12% of the carbon footprint of a t-shirt or jeans when special trips are made to a store at 5 km distance, also depending on the country[126]. Consumers can also think critically about a garment's material, opting for more sustainable fibres such as cotton with a recognized sustainability label, a blend of cotton and a more sustainable alternative fibre, or entirely an alternative fibre[61].

Because production of new garments often dominates the environmental impacts (Figure 3), purchasing fewer cotton items and extending the service life of existing items is crucial. Depending on the proportion of impacts that occur in the use phase, a change in user behaviour changes environmental burdens considerably – for a garment that has 20% of its impacts in the use phase, a 20% reduction in the number of uses means a 20% increase in impacts per use (Supplementary Fig. 3). Ideally, consumers would wear clothing as long as possible[61]. The product's life expectancy can also be extended by purchasing textiles of high quality and durability, repairing rather than discarding damaged clothing, purchasing at second-hand stores, reselling clothing[61], and laundering and tumble-drying textiles less frequently to slow down degradation, such as thinning and colour loss[127]. Renting clothes, for example through clothing libraries, can be beneficial if the garments' service lives are extended substantially. However, it runs the risk that increased mobility to and from the store can offset or even outweigh such benefits in terms of the carbon footprint and toxicity[128].

Choices during laundering have considerable environmental impacts. Running washing machines at full capacity, much more than reducing the washing temperature[61], can reduce environmental impacts, such as those related to GHG emissions. Increasing the number of wears before washing also reduces the environmental impacts by reducing the laundering frequency[126]. More efficient appliances help to a smaller extent[126]. Washing by hand can save small amounts of water, but the potential to save energy is inconclusive[129]. It is also unlikely to be done at a large scale internationally due to the convenience of using a machine. Reducing the detergent dosage can minimize eutrophication through reduced discharge[57]. Machine-drying causes twice the GHG emissions per action than washing, and in countries with frequent use of dryers, such as the US, it is responsible for the bulk of the use-phase emissions[126]. Consequently, air-drying rather than machine-drying textiles greatly improves sustainability[61,126,130]. Finally, avoiding ironing is also important for environmental sustainability, as it uses large amounts of electricity, thereby causing GHG emissions and resulting in somewhat higher eutrophication[57].

Summary and future perspectives

Cotton has a relatively large impact on the environment compared with plant-based alternatives. The environmental impacts of cotton cultivation, manufacturing and consumer behaviour vary greatly among regions; depending on the impact category and country, either cotton cultivation, manufacturing, or use can dominate the environmental impacts. Consequently, solutions to improve cotton's sustainability are also manifold, and various stakeholders across different life cycle stages can contribute. Sometimes, the relationship between different stakeholders and stages is symbiotic. For example, longer use of garments requires changes in product design, marketing, and consumer behaviour. Trade-offs among environmental impacts can occur, and care must be taken so that solutions that solve one problem do not create another problem within cotton's life cycle.

Complex global supply chains and the site dependence of environmental impacts, for example, owing to different environmental conditions and energy infrastructure, complicate the data collection for assessing environmental impacts. Much of the cotton cultivation and manufacturing occurs in developing and emerging countries, which are underrepresented in existing life cycle inventory databases[131]. Moreover, most LCAs so far have focused only on t-shirts and jeans, neglecting the wide variety of clothing and other textiles[131]. Most LCAs have neglected consumer behaviour, particularly the length of the garment lifespan or the number of uses, although the use phase dominates the environmental impacts of some impact categories and countries and determines the scale of the production impacts necessary to meet demand. It should be noted that the published LCAs discussed here are not strictly comparable owing to differences in LCIs and LCIA methods.

Another limitation among prior LCAs is that often only a few impact categories have been investigated. Some non-traditional categories are especially in need of further analysis. For example, salt is used in the reactive dyeing of cotton textiles, which might lead to the salinization of local drinking and agricultural water, while growing cotton can reduce soil salinity[132], but salinization is not a traditional impact category of LCA[62,130]. While traditional LCAs focus on environmental impacts, socio-economic impacts can also be important. This importance applies especially to the textile industry, which is labour-intensive and plays a critical role in determining socio-economic outcomes in many developing countries[131]. For example, in some developing countries, workers' exposure to dangerous chemicals and emissions is much more prevalent and poses a serious social risk in the textile and clothing industry[133]. Socio-economic impacts can be considered together with environmental impacts within life cycle sustainability assessments, but these assessments come with their own challenges, such as a large number of stakeholder relationships along the supply chain[134] and a lack of harmonization of the methodology[135].

Although cotton textiles greatly impact the environment, some other uses of cotton have been largely ignored in the literature. Cotton is the world's fifth largest oil crop, providing about 5 million tonnes of oil every year[3]. Cottonseed meal is an important feed, providing 4.2% of protein every year[3]. In addition, the by-products cotton wool, raffinose, gossypol and so on can be of great value if further processed[4]. Therefore, it will be even more important to integrate the assessment of socio-economic benefits and environmental impacts of cotton textiles and by-products, which need further study in the future.

Making cotton sustainable requires not only technological and research breakthroughs but also training and education for farmers, manufacturers, and consumers[57]. Furthermore, it is not enough for some stakeholders just to have this knowledge; they might need additional motivation to reduce environmental impacts. For example, consumers might be more motivated to launder less frequently if they are aware that it also helps preserve their favourite garments[126]. Finally, it is important also to consider the socio-economic context, which might limit the opportunities for improvement in environmental sustainability for some stakeholders.

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Author contributions

L.S. conceived the idea for the work. L.S. and Z.Z. prepared the visualizations. All authors contributed to the writing of the article. L.S. coordinated and supervised the work.

Competing interests

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Figures

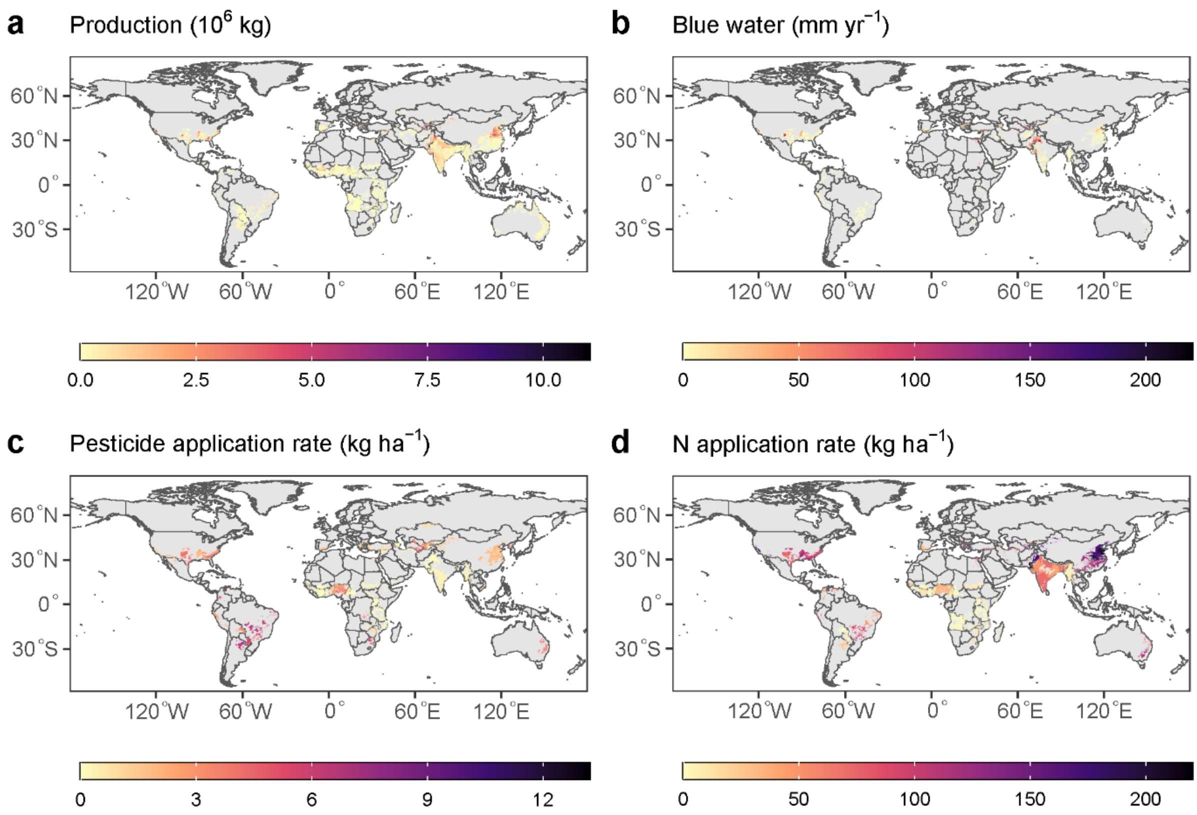

Fig. 1 | **Global maps of cotton production, blue water use, pesticide use, and nitrogen fertilizer use.** **A** | Cotton production distribution in 2015 (REF [13]). **B** | Blue water use distribution in 2000 (REF [19]). **C** | Pesticide use distribution in 2015 (REF [30]). **D** | Nitrogen fertilizer use distribution in 2000, shown only for production areas in **a** (REF [136]). In all panels, the grey area denotes regions with no cotton production or no data. The environmental pressures of cotton production show great spatial variability.

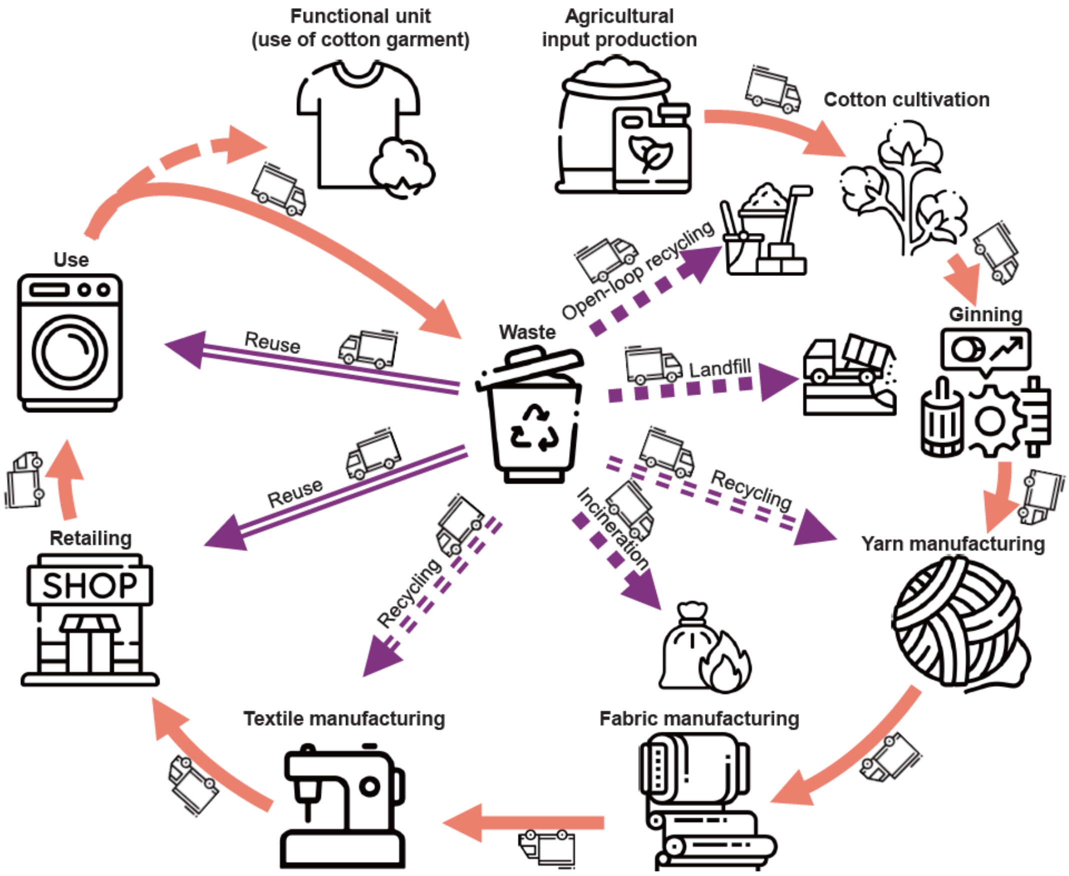

Fig. 2 | **Life cycle of cotton from cultivation to end of life.** Arrows among the life cycle stages denote flow, typically involving transportation to different locations. Cotton's life cycle is complex and globally fragmented.

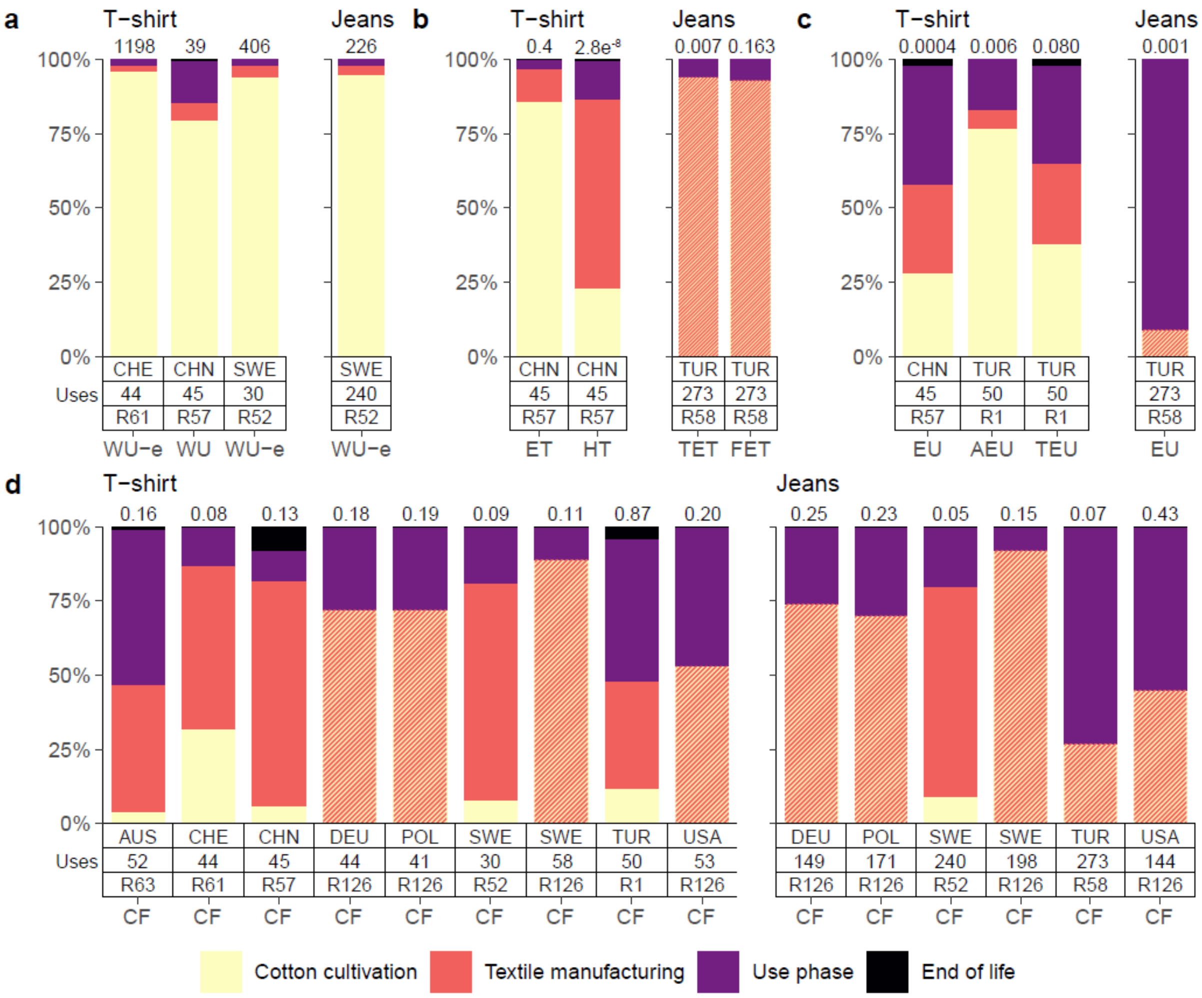

Fig. 3 | **Environmental impacts of cotton textiles at different life cycle stages. A** | Contribution of cotton cultivation (yellow), textile manufacturing (red), cotton cultivation and textile manuscfacturing combined (orange), garment use (purple), and end of life (black) to total water use (WU, L)[57] or scarcity-weighted water use (WU-e, L-eq)[52,61] for t-shirts and jeans produced in various countries. **b** | As in **a,** but for toxicity, encompassing human toxicity (HT, comparative toxic units CTUh)[57], ecotoxicity (ET, CTUe)[57], terrestrial ecotoxicity (TET, kg 1,4-DCB-eq)[58], or freshwater ecotoxicity (FET, kg 1,4-DCB-eq)[58]. **c** | As in **a,** but for eutrophication (EU, kg PO_4^{3-}-eq)[57,58], aquatic eutrophication (AEU, kg NO_3^--eq)[1], or terrestrial eutrophication (TEU, kg NO_3^--eq)[1]. **d** | As in **a,** but for the carbon footprint (kg CO_2-eq)[1,52,57,58,61,63,126]. In all panels, the table below the bars lists: the absolute values per use of a garment; the focal location where consumption takes place, the number of garment uses, and the reference number of the relevant LCA. Locations are denoted using ISO3 codes: AUS=Australia, CHE=Switzerland, CHN=China, DEU=Germany, POL=Poland, SWE=Sweden, TUR=Turkey, USA=United States of America. The dominance of either the production (cultivation and manufacturing) or use phase depends, among others, on the impact category and country of consumption.

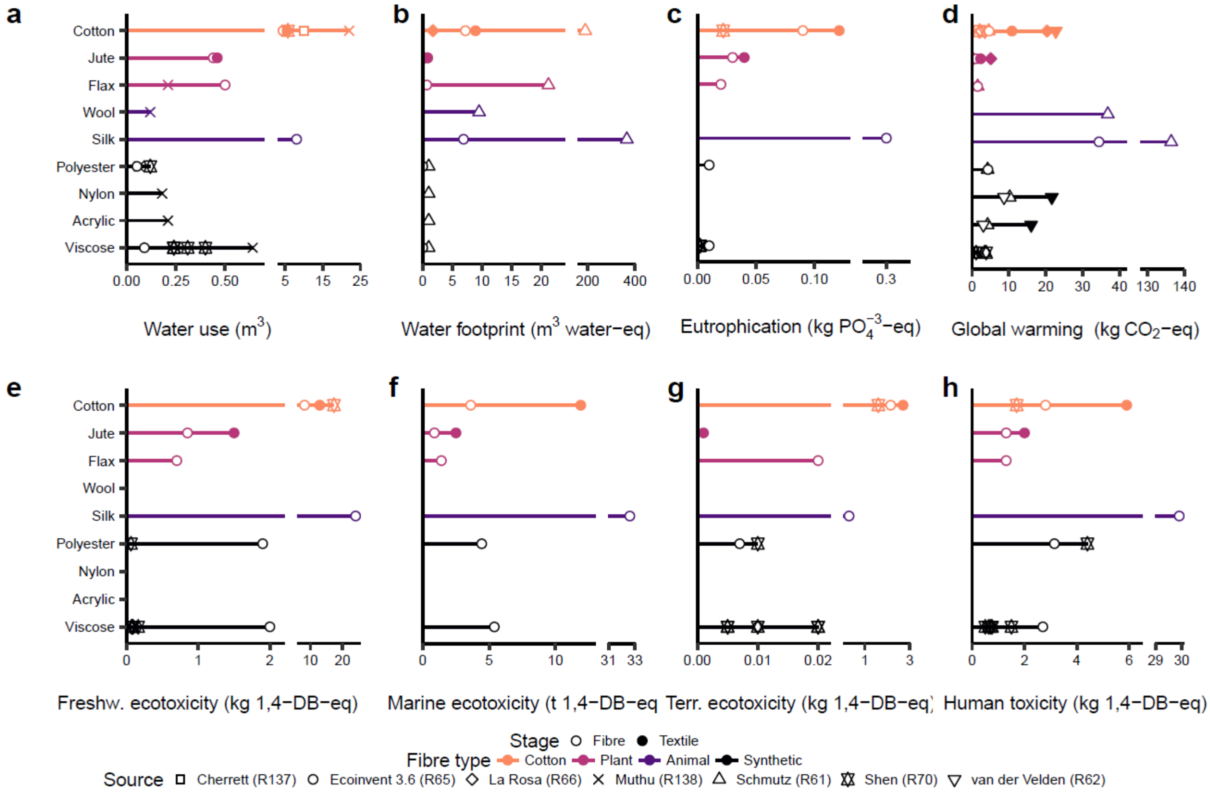

Fig. 4 | **Environmental impact comparison between cotton and alternatives. A** | Estimates of water use for production of 1 kg fibre or textile for different fibre types. **B** | As in **a,** but for scarcity-weighted water use. **C** | As in **a,** but for eutrophication. **D** | As in **a,** but for the carbon footprint. **e** | As in **a,** but for freshwater ecotoxicity. **f** | As in **a,** but for marine ecotoxicity. **g** | As in **a,** but for terrestrial ecotoxicity. **h** | As in **a,** **b**ut for human ecotoxicity. In all panels, circles represent estimates wherein additional LCAs are run with data from Ecoinvent 3.6 (REF [65]), assuming a global market for fibre, using CML-2001 impact assessment methods for eutrophication, human and ecotoxicity, ReCiPe 2016 midpoint (H) methods for water consumption, and ILCD 2011 midpoint+ methods for water resource depletion, as available within Simapro[139]. The environmental impacts of jute and flax are almost consistently lower than that of cotton, while the opposite applies to silk.

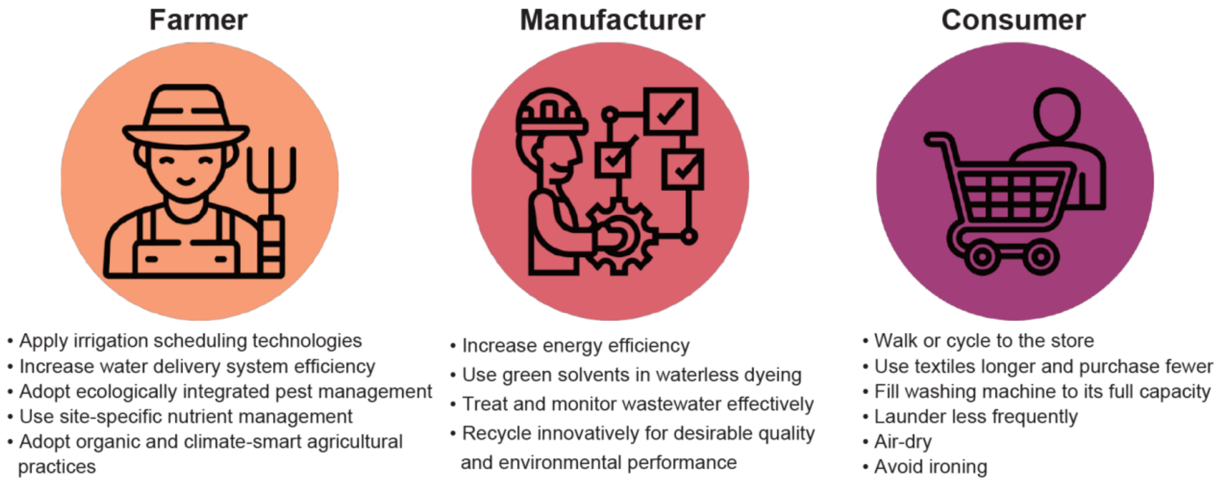

Fig. 5 | **Opportunities for improvements for different stakeholders.** A non-exhaustive range of promising options for famers, manufacturers and consumers to reduce the environmental impact of cotton.

TOC blurb:

Cotton is a water-hungry crop with many environmental impacts before and after it is processed into consumer goods. This Review summarises the environmental impacts across cotton's life cycle, compares the impacts to alternative fibres, and discusses options for mitigation.