Advancing life cycle sustainability of textiles through technological innovations

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Preface

Throughout their life cycle, textiles produce 5–10% of global greenhouse gas emissions and consume the second-largest amount of the world's water with polluting microplastics and chemical agents released to waterways. Here we examine the state-of-the-art technology developments meant to solve these problems in a cradle-to-grave fashion. We analyse their impacts with respect to the Sustainable Development Goals in the United Nations Agenda 2030, particularly those concerning the deployment of natural resources, energy and environmental impacts. We follow a systematic analytical framework that identifies and elucidates impactful technologies. We further discuss future directions along which the green transformation of textiles could be accelerated.

Textile products have a global market valued at US$961.5 billion, with major sectors in apparel (~75%), technical textiles (~12%) and household goods (~9%)[1]. Approximately 90 billion articles of clothing, or 62 Mt, are manufactured and sold each year[2]. Apart from meeting essential clothing needs, the textile supplier chain provides ample employment opportunities, fuels economic and social developments, and improves well-being and life quality, especially in developing countries.

The life cycle of textile and apparel products involves different stages and players because the product supply chain is long, highly branched and globalized, as shown in Fig. 1. The life cycle begins with making or harvesting raw materials for textile fibres, originating from plants, animals and petroleum, among other sources, thus involving the agriculture and chemical industries. Fibre production routes vary greatly, from harvesting from plants or animals to fibre forming through methods such as melt spinning, dry spinning and wet spinning. At the textile conversion stage, fibres or fibre blends are used to make yarns and fabrics with the desired tenacity, durability, colour, pattern and hand feel. Products such as garments require further processing to realize the final forms to be used by consumers. The distribution stage involves logistics, wholesalers and retailers. Product cleaning and care are normally conducted at home as laundry at the usage stage. The disposal stage has several branches; the used products may be sent to landfills or incinerators or alternatively recycled or reused. Since the suppliers of raw materials; manufacturers of fibres, yarns, fabrics and apparel products; distributors; consumers; and waste disposal/treatment sites are situated in different regions, the various stages are connected by the transportation of physical goods.

While the textile industry remains a prominent and even necessary global entity, it poses many threats to the environment and humans. The textile life cycle represents one of the most wasteful and polluting cycles on Earth, second only to oil and gas[3] and exceeding international aviation and maritime shipping combined[4]. An estimated 17 $tCO_2\,t^{-1}$ tex-tiles are released versus 3.5 $tCO_2\,t^{-1}$ plastics and 1 $tCO_2\,t^{-1}$ paper[5]. Textile consumption is projected to reach 102 Mt and the related greenhouse gas (GHG) emissions to increase 30% by 2030[4]. The textile industry is also the second-largest consumer of the world's water supply and greatly pollutes waterways with microplastics and colourants. Water pollution occurs primarily during textile conversion, with 20% of pollution resulting from wet colouration/finishing processes, but also during the garments' use stage. In addition, 1 billion detergent jugs per year, as used for washing, contribute to terrestrial and marine eutrophication.

Hence, we attempt to review the state-of-the-art technologies developed to solve these problems across the life cycle of textiles using the methodology described in Supplementary Information. We start with the first stage of natural and synthetic materials before moving on to focus on fibre production. Following that is the textile conversion, and finally we discuss distribution, consumption and care and examine the stage of disposal, reuse and recycling. We endeavour to quantitatively analyse technology impacts on sustainability in terms of natural resource deployment, energy and environmental impacts.

In estimation of the energy consumption and waste emission/diffusion in manufacturing, transporting, using and caring, recycling and disposing, we are confined by several important assumptions made by previous studies in the literature. For example, the electrical energy was generated mainly from the consumption of fossil fuel, and the geographical differences are ignored, assuming similar levels for the pollution, toxicity and eutrophication caused by the effluents discharged into natural water bodies, landfills and so on. We conclude by pointing out the limitations of the study and suggesting promising directions for future developments.

Raw materials and fibre production

Among many types of textile fibres, synthetic fibres typically rely on petroleum resources for their production. Without considering other stages, the production of synthetic fibres alone is fairly energy and water efficient, resulting, counterintuitively, in small environmental footprints on multiple metrics, including CO_2 emissions, water scarcity, eutrophication and the depletion of abiotic resources[1]. Currently, more than half of the fibres produced in the world are made of poly(ethylene terephthalate) (PET)[6], followed by polyamide (PA) fibres. Despite high fibre production efficiency, synthetic fibres require an extremely energy-intensive process of polycondensation, making them carbon-intensive fibre materials. The degradation of PET fibres may also take over 2,500 years[7], and they are the major source of marine microfibre pollution[2,3].

Mechanical recycling is the first and most used among three sustainable production approaches, built mainly for the synthetic fibres and their fibre blends as shown on Fig. 2a. At present, 14.7% of PET fibres (~8.4 Mt) are made from mechanically recycled materials, which are derived mainly from used PET bottles that were cut, ground, washed and melt spun. Compared with virgin PET materials, producing textiles with recycled PET uses ~50–85% less energy and can reduce GHG emissions by 72%[8]. This assessment, however, is limited to fibre production and does not consider disposal, as recycled PET may have higher global warming potential than virgin fibre production.

The second recycling approach is the chemical recycling of fibre-forming polymers, which requires re-engineering their chemistry to reduce the pyrolysis activation barrier. Petroleum-based biodegradable polymers, such as polycaprolactone, polybutylene adipate terephthalate and polybutylene succinate, are good candidates for chemical recycling. Inserting low-density in-chain functional groups as break points in a polyethylene (PE) chain enables chemical PE recycling via solvolysis, with a recovery rate over 96% (ref. [9]). Similarly, by inserting a small number of cleavable bonds inside thermoset polymers, they can be engineered to undergo triggered, mild degradation to yield soluble, recyclable products of controlled size and functionality[10].

The third approach uses degradable biopolymers, such as bio-based PET and bio-poly(trimethylene terephthalate) (bio-PTT) produced using bioethanol production;[11] bio-based polyethylene derived from sugar-cane biomass;[1] thermoplastic biodegradable bio-polyesters such as polylactide (PLA); polyhydroxyalkanoates (PHAs); and materials based on furan dicarboxylic acid[5]. Braskem's green PE has been certified as carbon negative, and other new bio-polyesters can potentially achieve the same status[1]. The energy and GHG emissions of producing bio-PTT fibres are reduced by ~30–40% and ~56–63%, respectively, compared with those for PA fibres[11]. PLA and PHAs had the top share of the bio-based fibres by nearly 70% in 2020[12]. PLA is environmentally friendly due to its solvent-free polymerization and low-temperature processability, as its glass transition and melting temperatures are ~55–60 °C and 165 °C, respectively[13]. Its derivation from raw corn and sugar cane is still debatable, however, as this requires water, agrichemicals and farmland. Even so, the raw materials may be replaced by organic waste from seed oil extraction, potato processing waste, bagasse or recycled PLA. Similarly, degradable PHAs can be produced via the bacterial fermentation of carbohydrates. Poly(hydroxybutyrate co-hydroxyvalerate) blended with PLA has been used for textile production, but these bio-based fibres have lower thermal stability and mechanical properties than PET and PA fibres, causing production and care difficulties that may limit their product range. Solution spinning of PLA and PHAs is sometimes preferred to reduce thermal degradation where solvent usage is unavoidable[14,15].

Among natural fibres (originating from plants, animals and minerals), the most used is cotton, which makes up 24% of the current world fibre production. Cotton plants suppress CO_2 emissions via photosynthesis, although the use of chemical fertilizers, pesticides and plastic mulch to grow them means large environmental footprints in other metrics, including water consumption, eutrophication and the depletion of abiotic resources (Fig. 2b). To reduce the use of chemical fertilizers, several methods have emerged, most notably a urease inhibitor or a nitrification inhibitor with urea to effectively reduce N_2O (whose global warming potential is about 298 times greater than CO_2 (ref. [16])), zero or mulch tillage, and biochar to improve soil microclimate and structure and to store GHG in the soil. Moreover, planting genetically modified crops can reduce N_2O emissions, but their influences on humans and the environment must be more thoroughly examined first. To reduce synthetic pesticide use, some studies have proposed release of sterile insects and total pest management to disrupt mating[17]. Integrated pest management controls the pest population within an economic threshold using biological, chemical and physical control measures, including *Bacillus thuringiensis* (Bt) transgenic cotton planted with non-Bt crops, host plant resistance, mass trapping (pheromone and ultraviolet (UV)/visible light trapping), natural enemies, and viral and fungal agents. Of note, Bt cotton has no immediate effect on non-target insects[18]. Meanwhile, the decision support system is important and should address remote sensing, monitoring systems, action thresholds and predictive population models[19]. Beyond the plants themselves and pest management, biodegradable and liquid film improve soil properties and promote plant growth without harmful additives (for example, plasticizers, dyes, photo-stabilizers and pro-oxidants) in plastic mulch[20]. Degradable mulch made from waste materials, such as the gelatine extracted from scrap skin in leather processing or tex-tile mill waste, may also reduce costs. Some degradable PET paper is equipped with controlled release of the fertilizer infused in the paper[21]. The long-term influence of these methods on the ecosystem is not yet clear, however[20]. Other technologies include precise seeding, simplified plant pruning, rational high-density planting techniques, and water and fertilizer integration technology[22].

Regenerated fibres are those generated from natural materials other than fibres such as wood, soy bean and milk. Regenerated cellulose fibres (for example, lyocell, rayon/viscose and cupro) are becoming increasingly popular because of their controllable and excellent fibre properties, as well as their degradability. To avoid deforestation in particular, wood pulp can be replaced by various sources of natural cellulose fibres, including fast-growing plants (bamboo, mengkuang leaves), organic waste (plant residues, cotton linters leftover from ginning) and bacterial cellulose (*Komagataeibacter xylinus*)[23], as illustrated on Fig. 2c. Potential sustainability can be further achieved by avoiding logging, using rapidly renewable cellulose sources from non-agricultural land and recycling waste. Despite these benefits of regenerated cellulose fibres, some issues may arise from the unchecked commercial exploration of rapidly renewable plants (for example, the intensive application of fertilizers and pesticides) to increase yield and profit, or there may be detrimental effects for biodiversity due to substituting more economic plants for original forests[24,25].

The present mainstream production of regenerated cellulose fibres involves the heavy use of sodium hydroxide for swelling and toxic carbon disulfide for mercerizing, which leads to the emission of toxic sulfur (CS_2, H_2S, COS, SO_2, $ZnSO_4$) in exhaust gases and effluent and solid waste (only about half of produced CS_2 can be recovered)[26]. In turn, the eco-friendly direct dissolution of lyocell fibres employs non-toxic recyclable solvent technology and consumes only one-tenth of the chemicals, with the N-methylmorpholine-N-oxide solvent in particular having 99% recovery[23,26]. However, the market adaptation of lyocell fibres (only 4.3%) is hindered by the solvent's high cost and need for energy due to its high-temperature dissolution[23]. Other issues, such as strained feedstock supply, non-ideal feedstock characteristics and energy-intensive harvesting and pulping processes, severely limit any environmental benefits of regenerated cellulose fibres over widely used petroleum-derived fibres. This calls for the development of new energy-efficient and scalable plant cell culture techniques to selectively generate plant-based materials without involving whole-plant cultivation and harvesting. Cultured plant materials that yield cellulose fibres with improved uniformity and reduce the textile industry's environmental footprint can even revolutionize fibre production[27].

Textile conversion

The major challenges in the textile conversion portion of the textile life cycle are the reduction of energy and water consumption and the discharge of chemicals. Figure 3 outlines the various methods discussed in this section that are meant to address these concerns. Supplementary Table 1 illustrates the potential reduction of GHGs.

First, yarn spinning via ring frame consumes up to 72% of the total electricity for some combed yarns[28], while the spinning frame alone uses as much as 55.5% of the total amount. A significantly reduced yarn twist in ring spinning, meant to reduce energy consumption[29], normally yields useless, weak yarn. This dilemma has been overcome with low-twist spinning technology, which introduces false twisters between the front roller and the yarn guide[30,31]. This technology can achieve a twist reduction of 20~40%, raising productivity by the same amount, as the soft low-twist yarn has a similar strength to high-twist yarn. Electrospinning, a versatile solution-based technique for generating multi-functional ultrathin fibres from a wide range of materials, has been implemented for the industrial production of polymer nanofibres in large volumes, enabling downstream commercial applications, such as water and air filtration, and the creation of bio-medical products[32]. However, few studies have reported its sustain-ability impacts. Significant energy saving in air humidification can be achieved by using energy-efficient nozzles and variable-frequency drives based on the real-time humidity conditions in the spinning and weaving process[33].

Energy saving has been a major concern in fabric formation, yielding innovations such as nozzle technology in air-jet weaving looms, which account for ~27–38% of total manufacturing costs. High-volume, low-pressure nozzles can save up to 26% of energy[34] thanks to their optimized nozzle geometry. A weft insertion mechanism via magnetic actuation can also save 60% of energy[35]. Eliminating processing steps is another noticeable development in textile conversion[36–38]. Another example is the combination of spinning and knitting pro-cesses in a single machine that allows the direct input of fibre slivers or roving into a circular knitting machine, thus eliminating ring spinning and yarn storage and saving energy, space and operational costs; reducing CO_2 emissions; and improving product quality[39]. Moreover, a foam-laying technique has been studied as a replacement for the wet-laying non-woven process, using only one-fifth of the water and saving energy simultaneously[36]. The anionic surfactant for foaming can be recycled in large-scale applications of this technique as well. Braiding has also emerged as a means of fabricating net-to-shape industrial fabrics and composites. Optimized horn gears used in a rotary braiding machine have been reported to further improve pro-duction efficiency[37], although their impact on sustainability requires further investigation.

Supplementary Table 2 gives a summary of colouration and finishing technologies and their environmental impacts. These approaches can reduce processing temperature, GHG emissions and water consumption/discharge without compromising recyclability. First, for synthetic fibres, colourless polymers can be structurally coloured with nano-sized pigment inclusions (via spin dyeing)[40]. Recent life-cycle-analysis studies have indicated that this method yields 50% energy savings, a 60% lower carbon footprint, 50% water savings and the reduction of environmental impacts by ~40–60% compared with conventionally dyed modal fabrics[40]. Another way to colour synthetic fibres is by introducing structural periodicity[41]. These nanoscale features can be engineered to cause wavelength-selective light scattering and reflection, thus exhibiting visible colours.

For all fibre types, waterless or less-water colouration technologies include supercritical carbon dioxide (sc-CO_2) dyeing, aerosol dyeing, plasma dyeing, ultrasonic-assisted dyeing, spin dyeing of yarns, micelle dyeing, non-aqueous medium dyeing, foam dyeing, electrochemical dyeing, microwave-assisted dyeing, digital inkjet printing using dye nanosphere and ozone stripping, and structured colour via nanoscale coating. Sc-CO_2 dyeing was successfully scaled into bulk polyester dyeing in 2008, saving 40 l of water and 0.2 kg of chemicals per kg PET[42]. In addition, it can avoid effluent generation due to the CO_2 medium and unused dye's recyclability, eliminate energy-intensive drying steps and facilitate the dispersing agent[42]. This technology also uses CO_2 that is the recycled by-product of combustion, fermentation and ammonia synthesis, which contributes to the reduction of GHGs. For natural fibres, new functionalized reactive disperse dyes assisted with polar auxiliaries have been reported to mitigate the insolubility of polar dyes in non-polar sc-CO_2 fluid[42]. The energy consumption of sc-CO_2 dyeing still requires reduction, however, because its typical operation is con-ducted at 120 °C and 300 bar. Micelle dyeing consumes only one-third of the water used in conventional dyeing, which allows dyeing under a lower liquor ratio without dyestuff aggregation. Further, microwave radiation provides uniform and efficacious non-contact heating and amplifies the dispersion and penetration of dye molecules in swollen fibres, thus improving dye exhaustion rate and dye fixation. Recycling wastewater generated from spent dyeing and rinsing baths through catalytic ozonation with carbon aerogel is also a method to minimize water consumption[43,44]. Although digital inkjet printing adapts to the rapid changes in fashion trends due to easy colour matching, it faces challenges such as heavy dye and chemical usage, heavy effluent load and high energy demand. To solve these problems, new reactive dye@ copolymer nanospheres have been recommended to achieve high dye utilization efficiency and good colour shade, save chemicals in pre-treatment, shorten post-treatment, reduce dye residues by 45% in the printing effluent and save energy by 30%[45]. Other approaches have also been suggested, such as polyethylene glycol or diethylene glycol formulations that replace urea and synthesized reactive dyes in azo structures to improve fixation and attain urea-free printing. Ideally, these inks or pigments should be environmentally friendly and removable with heat, UV light and/or humidity and wetting.

The pre-treatments for conventional colouration have high chemical, water and energy consumption and yield effluent contaminants, including increased pH, biological oxygen demand, chemical oxygen demand and total dissolved solids in wastewater. Reduced water pollution can be achieved by replacing the chemicals with enzymes[46]. The one-step combination of enzymatic desizing, scouring and bleaching for starch-sized cotton fabric can save chemicals, water and energy, but its pH remains over 11, higher than that of a two-step process (~9) (ref. [47]). Ozone bleaching, plasma, cationization, UV and supercritical fluid are effective alternative pre-treatments. However, only a few environmental studies have compared these treatments with conventional methods.

As alternatives to their synthetic counterparts, natural colourants from plants and microorganisms have been attracting more attention as they are regarded as non-toxic, non-carcinogenic, degradable and renewable. For example, natural colourants such as anthocyanins, quinones and carotenoids can be extracted from fruit and vegetable residues as a valorization of agro-food wastes. Onion skin, turmeric, barberry, pomegranate and marigold are some sources of plant colour-ants applied in textiles. Colourants originating from bacteria, algae and fungi are more stable pigments and have been used for the colouration of both natural and synthetic fibres[48,49]. Natural dyestuffs are obtained via aqueous, acid, alkaline or organic solvent extraction[46]. Aqueous extraction does not change the water's pH value or discharge organic effluent, but it cannot extract water-insoluble colourants.

In addition, this extraction method yields water-soluble non-colourant compounds, necessitating further purification. The effluent from acid or alkaline extraction has to be neutralized as well before being discharged, and it cannot be applied to pH-sensitive colourants. Last, although natural colourants have many perceived advantages, the colours produced do not cover the whole spectrum and usually exhibit inferior stability, affinity, diffusivity, colourfastness and exhaustion to synthetic colourants[48,49].

Additive colouration is considered a competitor to traditional subtractive colouration methods. Recently, fully recyclable pho-tonic textiles have been engineered that use compact detachable light-emitting diodes and transparent synthetic polymer fibres as light guides[50,51]. Another approach is lustre manipulation, where perceived visual colour variations are achieved via local variations in the lustre of a mono-material yarn created from either knitting or jacquard weaving.

Apart from colouration, finishing may involve toxic or hazardous chemicals that can be replaced by eco-friendly biopolymers, enzymes and ozone, among other mediums, although their long-term stability and recyclability need to be further studied before their industrialization. Surface finishing, such as gas-phase plasma treatments, foam finishing and laser-assisted finishing, can substantially reduce water and energy consumption as well. Foam finishing in particular has been employed to impart functions such as water and oil repellence, crease resistance, fire retardant finishing, antibacterial properties, softening and denim easy-care finishing. Its water, energy and chemical savings are 80%, 65% and 84%, respectively[52]. In turn, fluorine-based finishing agents for textile water and oil repellence result in persistent pollution due to the emission of fluorine GHGs and the fluoride-containing water effluent[51]. Fluorine-free finishing methods such as silicone, hydrocarbon polymers, fat-modified resin, hyper-branched polymers and nano-micro-structured surfaces have been extensively studied as alternatives, but although they exhibit satisfactory water repellence, extremely poor oil repellence is still a great challenge[52,53].

Effluent treatments are necessary as typically ~70–250 l of water are used for every kilogram of finished textiles. These treatments are necessary before discharging into a drainage system, as shown in Supplementary Table 3. Textile effluents also show an undesirable colour due to ~1–20% dyestuff washing off and toxicity due to contained metals and chemicals[54]. In addition, the temperature and pH of textile effluents are in the range of ~21–62 °C and ~5.5–11.8, respectively[55]. Thus, the characteristics of textile effluents involve temperature, pH, colour, chemical parameters, sulfates, zinc, copper, chromium, iron, mercury, cobalt and lead[55]. Without treatment, the amounts of chemical parameters, sulfates and metals in textile effluents are generally several to hundreds times higher than permissible discharging limits[56] (see Supplementary Table 4 for explanations of the chemical parameters).

The effluent treatments include physical, chemical or biological, and hybrid methods. Physical methods are coagulation/flocculation, adsorption, ultrasonic degradation and filtration by membrane. As its discolouration efficiency is generally low, coagulation/flocculation is often paired with other methods. Ultrasonic degradation has a high energy consumption and a small active zone restricted near the transducers. Hydrodynamic cavitation is an emerging technology that can be applied on a large scale, with a power efficiency ~1–2 orders of magnitude higher than ultrasonic disinfection[57]. In addition, microfiltration, ultrafiltration, nanofiltration and reverse osmosis are efficient and stable, although the membranes face the major challenge of fouling (Supplementary Table 5).

The most used chemical methods are oxidation processes, in which most dyes composed of complex organic and inorganic chemicals are degraded. Chemical methods can effectively decolourize the effluent because the chemical bonds in chromophoric groups of dyes are broken down into non-chromophoric groups. However, the by-product may contain carcinogenic matter such as aromatic amines. These methods can non-selectively degrade many type of dissolved organic matter with high efficiency, but a large quantity of expensive reagent is normally required.

Biological methods involving algae, fungal or bacterial strains are known as bioremediation and are environmentally friendly. With fungal or bacterial strains, the decolourization of textile effluent via bioremediation is accomplished by enzymes breaking down the chemical bond in chromophoric groups, which is accompanied by reduced toxicity[58]. However, if the compounds are not totally degraded, the by-products may contain toxic matter such as aromatic amines. In some cases, bacterial strains cannot totally remediate the dyes, especially complex azo dyes, because of the dyes' non-permeability through cell membranes. Research on textile wastewater treatment with algae in particular has exponentially increased over the past 15 years as microalgae not only remediate the textile effluent but also produce biodiesel. Compared with physical or chemical methods, bioremediation is more easily influenced by textile effluents, such as oxygen, pH, dye structure, amount of nutrient and electron donor, and salt concentration. Thus, it requires case-by-case optimization to ensure the robustness and activity of microorganisms, which is a challenge in its applications on an industrial scale. Still, the maximum degradation efficiency of microorganisms is expected to be enhanced by genetic engineering. To obtain constant treatment results, hybrid methods are usually applied that combine physical, chemical and/or biological methods (Supplementary Table 6) with other technologies, such as sensor-enabled real-time monitoring systems, artificial intelligence and regression analysis.

From distribution to disposal of textiles

Most textile products are transported over varied distances between providers in the global supply chain and consumers located in different parts of the world. For example, a T-shirt sold in the United States may have travelled three times or more across the ocean (more than 25,000 miles) before reaching the consumer, as the cotton bales are shipped from the United States to, for example, Asia, where the textile and apparel conversion take place, then the products are sent back to the United States. If total transportation distance is reduced, so too is energy consumption, although the locations of sites in the supply chain are influenced by many factors other than sustainability alone. Container ships, which consume energy and generate GHG emissions, are the primary mode of transport between continents, so improvements to ships play an important role, too. For example, reducing the CO_2 that container ships produce can be achieved through several approaches, although liquefied natural gas is the most effective. This method reduces CO_2 emissions by over 60% and is already used as a secondary fuel in dual-fuel marine engines.

Care of products normally involves water, energy and detergents or solvents and is carried out mostly by institutional users or individual consumers at home when doing the laundry. The electricity consumed during domestic washing amounts to 2% of household usage, while tumble drying accounts for 4.5%[59]. Still, exact water and electricity consumption depend on the type of washing machine, the selected washing condition[60–63] and fibre type. In general, products made from hygroscopic fibres require higher energy in tumble drying and more water than their hydrophobic fast-drying synthetic counterparts.

Surfactants and builders in domestic detergents have been criticized for toxicity and water eutrophication. Surfactants often occupy ~15–40% of a detergent and builders ~6–55%[60]. Effluent detoxifying treatments have been studied. Green surfactants explored include synthetic biodegradable surfactants and biosurfactants (for example, synthesized amino acid–based surfactants with coconut oil–derived N-acyl prolinate)[61]. Coconut oil–based surfactants exhibit better antibacterial activity than traditional ones; those based on glycolipids and lipopeptides have similar biodegradability, biocompatibility and low toxicity to traditional surfactants. However, the price of biosurfactants is ~8–9 times that of synthetic surfactants such as sodium dodecyl sulfate and amino acid–based surfactants[62], with their recovery, purification and downstream manufacturing accounting for about ~60–80% of the total cost[63] and hindering their large-scale application. To reduce this cost, agro-industrial waste may be a potential alternative raw material.

Phosphate builders contribute to ~50–60% of phosphorous mate-rials in aquatic systems, which are responsible for the dynamic imbalance of aquatic ecosystems, the death of aquatic animals and drinking water shortages in some areas[60]. Although wastewater treatment plants can remove ~80–95% of phosphates, it is very expensive. Cheap natural materials, or zeolites, possess outstanding ion exchange properties in the hydrated state and have good prospects as inorganic builders as their high cation content results in high exchange capacities. Zeolites have been confirmed to have little toxicity in industrial and domestic usage[60], although they may cause skin irritation due to a pH of ~10–10.5.

Recycling and reusing post-consumer textile products form efforts to reduce resource waste and pollution rather than send them to land-fills or incinerators. Globally, 12% of textile materials are recycled, while paper, glass and plastic PET bottles have recycling rates of 66%, 27% and 29%, respectively, meaning the majority of textile products are des-tined for the landfill or incineration[64]. This take-makes-waste model[65] represents an irreversible loss of value from the material economy[66].

Figure 4 illustrates mechanical, chemical and enzymatic recycling technologies. Supplementary Table 7 provides a comparison of them. To start, the materials recycled via mechanical recycling (cutting and shredding) are used to produce insulating materials for cars and buildings, fibre-reinforced composites and disposable non-woven products such as sanitary wipes, napkins and diapers. Since 2015, the Spanish company Hilaturas Ferre has conducted industrial-scale recycling for the reproduction of yarns and garments[67]. Mechanically recycled fibres generally show weakened properties, however. For example, the viscosity and molecular weight of recycled PLA is reduced by 20% (ref. [68]) from virgin PLA. Moreover, its thermal stability is slightly weakened when exposed to temperatures above 250 °C. To alleviate the problem, fibre/polymer blends with virgin polymer/fibres or chain extender dicumyl peroxide can be added[69] to the recycled fibres.

The chemical recycling of polymers has been demonstrated. Inserting polycarbonates and PET with a low density of in-chain functional groups as break points in polymer chains enables solvolysis with an over 96% recovery rate[9]. Similarly, by inserting a small number of cleavable bonds inside thermoset polymers, they can be engineered to undergo triggered, mild degradation to yield soluble, recyclable products[10].

Most apparel products currently in use are fibre blends of multiple polymers, which are hard to separate at the end of their lifespan. Cotton/PET blends, the most used in apparel, are often recycled through this method. One pilot-scale recycling process used dimethyl sulfoxide to dissolve polyester then recover cotton[70]. However, this strategy is suitable only for fibre blends with a low PET content as the dissolution of PET is a long, energy-intensive process. Conversely, PET fibres can be recovered by using ionic-liquid 1,5-diazabicyclo non-5-enium acetate, although further improvements are required to ensure the recycled fibres' quality[71]. Enzymatic recycling removes just the target component, normally cellulose or protein fibres[72]. Chemical and enzymatic methods, however, may face the high consumption of energy, resources and chemicals. Another popular fibre blend includes spandex, often used in stretchy apparel. The spandex production involves toxic isocyanates. The blend is one of the hardest to recycle from post-consumer waste. Efforts are under way to chemically separate polyurethane-containing fibre blends[73] and to synthesize carbon-negative and degradable polyurethane replacements, such as poly(ester urea)s, from biomass and brine[74].

Except for mechanical recycling, chemical and enzymatic recycling do not seem to be ready for industrial-scale application, where the automatic sorting of collected textile products is crucial to effectively identifying fibre type and determining the appropriate recycling method. One approach is to embed radio-frequency identification chips or threads into garment tags that identify their composition[75]. Design for disassembly is another approach, in which the garment manufacturing stage uses heat-dissolvable threads, which facilitates the easy separation of textiles from trim such as zippers and buttons.

Outlook

We have critically examined major textile technology developments, in both industry and laboratories, and their impacts on sustainability in a cradle-to-grave fashion. Table 1 summarizes the impacts of various green technologies in terms of the 17 Sustainable Development Goals (SDGs) outlined by the United Nations Agenda 2030.

Note that there are some limitations in the existing sustainability studies and therefore in our review. Few systematic analyses of products or technologies exist in the literature, with most looking only at one or a few segments of the textile life cycle instead of the complete life cycle. The representation of our assessment data and our conclusion's applicability may therefore fall into question as the data either were not complete without error estimation or came from limited companies under specific conditions. To this end, we advocate an open, systematic and qualitative large-scale data analysis for future sustainability research, encouraged by the fact that more data will become available from environmental, social impact and governance reports disclosed by public-listed companies involved in the textile life cycle.

To solve the sustainability issue from its roots, we promote green sciences and processes based on high-throughput, data-driven discovery studies to identify and develop sustainable replacements for synthetic polyester and nylon fibres, similar to the processes already developed for the synthesis of green polyethylene. In addition, the discovery of biomass-based and degradable fibre-forming materials and the cultivation of insect- and disease-resistant plant seeds that require less water can be achieved through advancements in biological science. Physics also brings better understanding of the relationship between textiles' multi-scale structures and physical properties, thus guiding the development of new textiles. The green processes built on the advancement of science will ultimately address the roots of sustainability issues.

We also envisage continued technology development that will significantly reduce energy and water use in textile conversion processes. The reduction or elimination of production steps will continue as well. Waterless or less-water colouration and finishing technologies, such as inkjet printing, chip doping and foam and sc-CO_2 dyeing, will replace some traditional methods. Before natural colourants derived from plants and microorganisms can become mainstream, problems such as inferior stability, affinity, diffusivity, colourfastness, exhaustion and colour choices need to be overcome. Recycling, especially mechanical recycling, will become a major technology for single-material or some blend textiles.

We further explore the possible adaptation of mono-materiality in textiles, which has long been recognized for its great recycling efficiency without need for disassembly[76], making it one of the most effective design strategies for proactive material recovery and perhaps the basis for a new textile paradigm. The main idea of mono-material design is based on embedding new functionalities into textiles made from a single polymer via structural engineering (variations in fibre structure, packing density, surface texture and fibre configuration) rather than by blending chemically dis-similar materials. Mono-material apparel and footwear engineered for mechanical recycling may be fabricated from thermoplastic materials via a combination of existing machinery and processes. For example, bicomponent fibres and yarns can be composed of a single material with the same chemical composition but different molecular weight, orientation and crystallites[62]. Knitted fabrics can be engineered to be elastic and wrinkle free, enabling the fabrication of seamless garments that are comfortable and easier to maintain, and may significantly reduce the environmental footprint relative to woven fabrics[77].

The realization of mono-material textiles has to meet multiple challenges. First, the products are for human consumption, so the huge variation in consumer preference is not easily satisfied by a single material. Second, more evidence-based studies are required for new material science, multi-scale structural design and their manufacturing methods. Third, the cost of such products should not be inhibitive. It is expected that in the short term, mono-material-specialized products such as uniforms will be limited in uniforms collected and recycled in a centralized manner.

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Author Contributions

L.Z. and M.Y.L. collected the information, made all figures and tables, and revised the manuscript. S.B. contributed to the framework and material developments. X.T. conceived the framework and led the writing of the manuscript. All authors wrote the manuscript.

Competing interests

The authors declare no competing interests.

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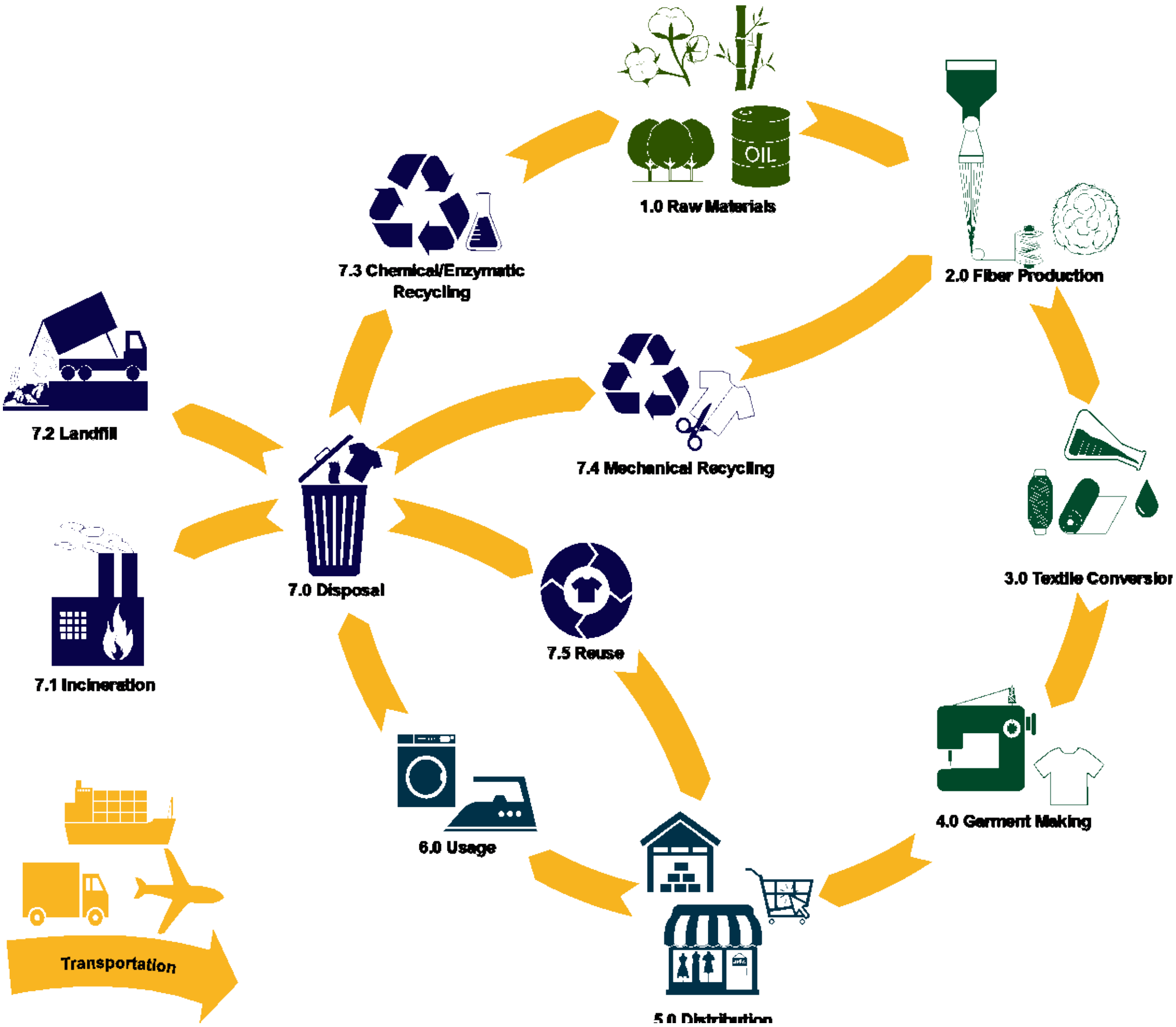

Fig. 1 The complete life cycle of apparel textile products from raw materials to landfill/incineration or recycling/reuse.

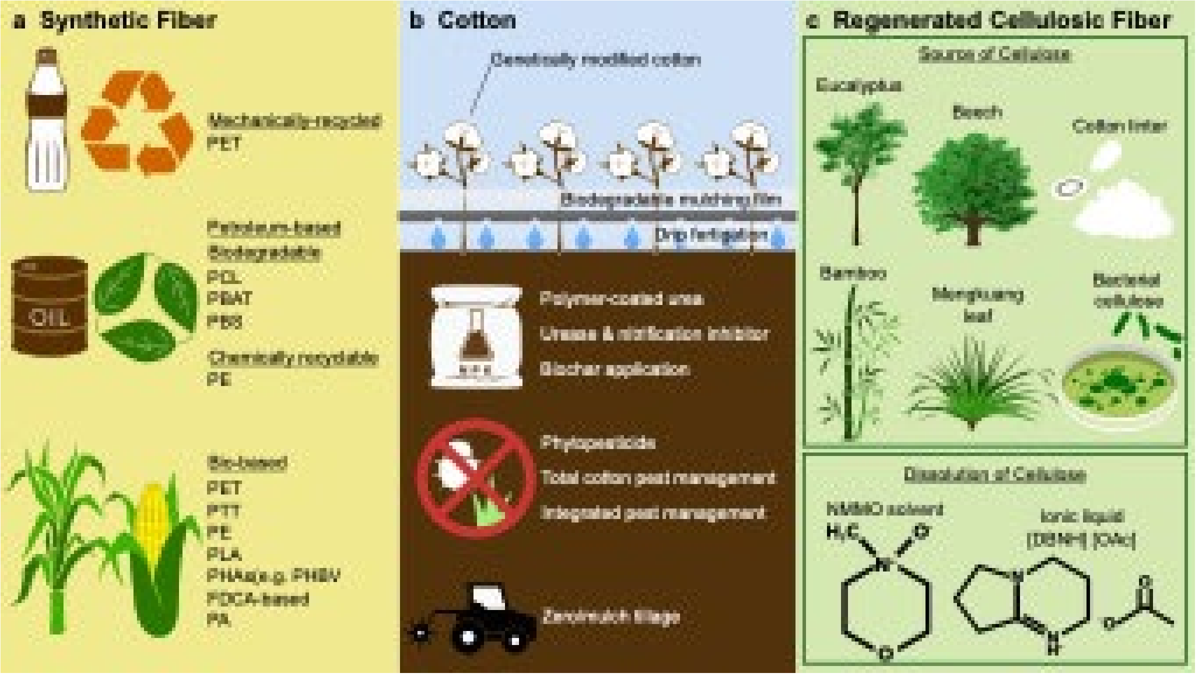

Fig. 2 Sustainability through fibre material innovations**.** a, Bio-based synthetics, biodegradable or chemically recyclable polymers, and recycled materials that are used in or potentially developed as textile fibres. b, Methods to reduce the negative impacts of cotton cultivation. c, Different sources of cellulose and alternative dissolution technologies used in synthetic cellulosic fibre production. FDCA, 2,5-furandicarboxylic acid; NMMO, *N*-methylmorpholine-*N*-oxide; PBAT, polybutylene adipate terephthalate; PBS, polybutylene succinate; PCL, polycaprolactone; PHBV, poly(3-hydroxybutyrate-co-3-hydroxyvalerate).

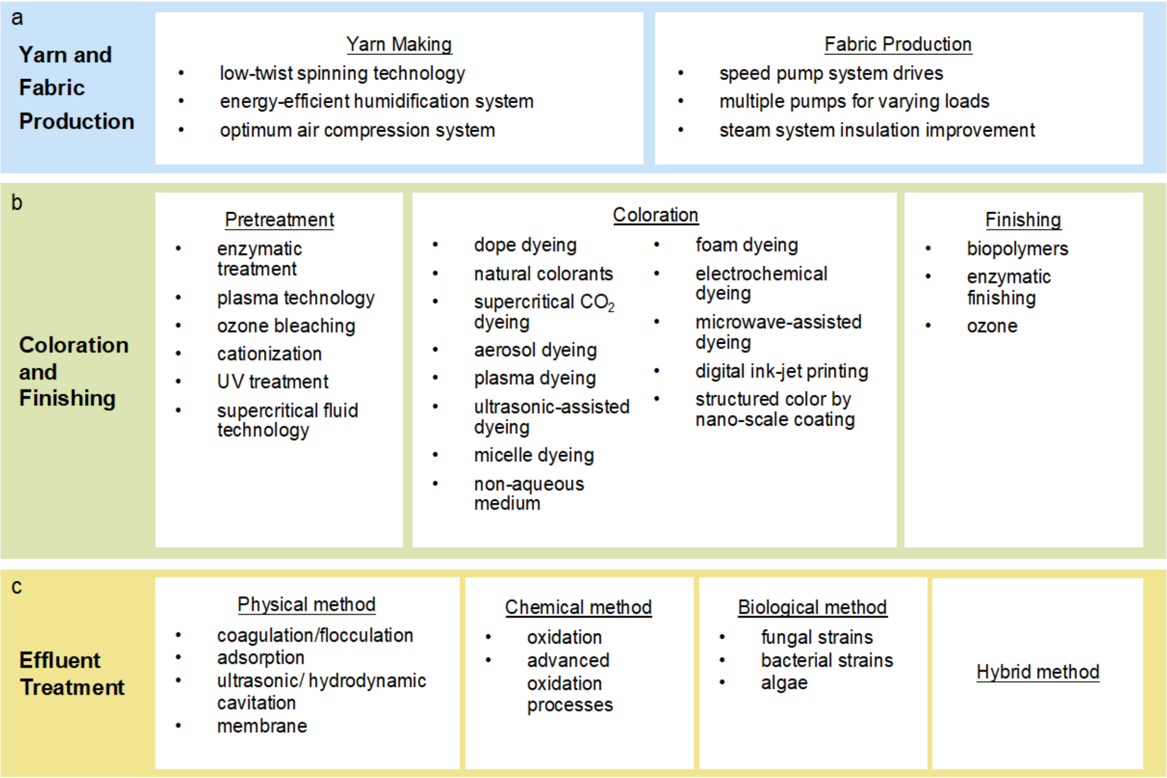

Fig. 3 Sustainability through the innovation of manufacturing technologies. a, Yarn and fabric production. b, Colouration and finishing. c, Effluent treatment.

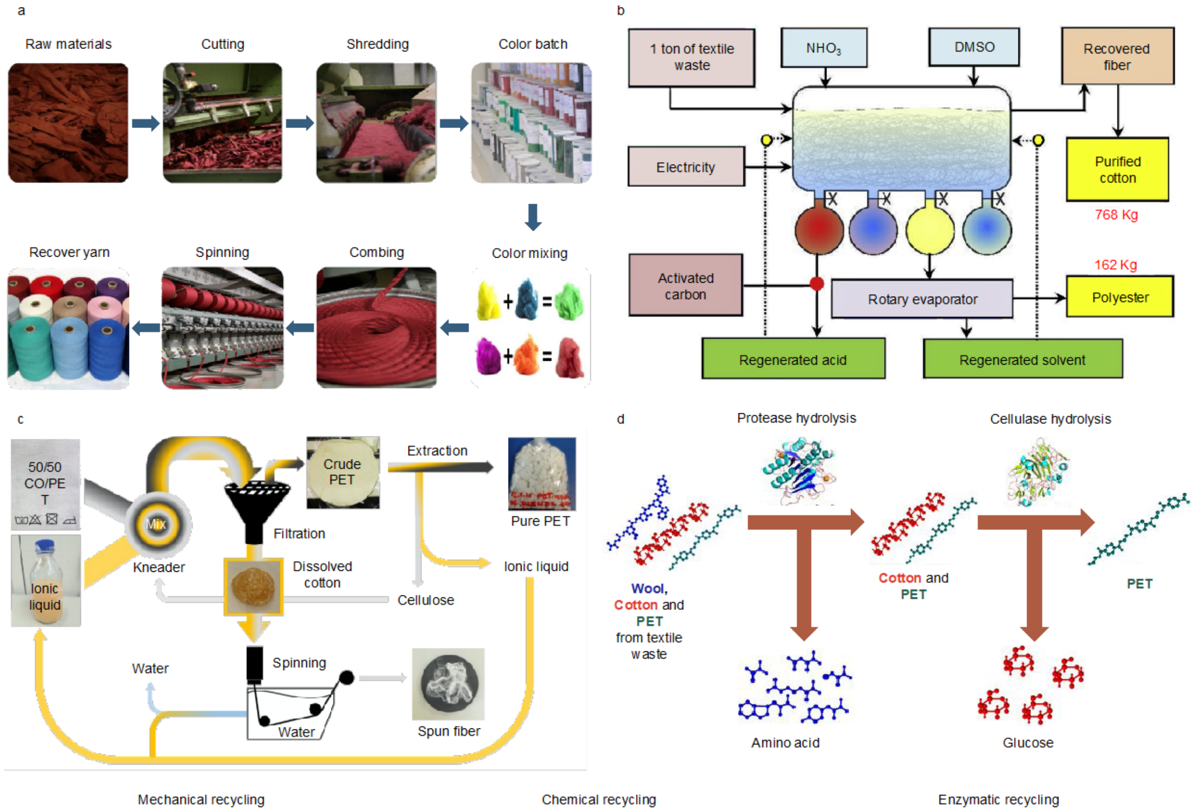

Fig. 4 Sustainability through textile recycling innovations. a, Mechanical recycling: cotton fibre recovery technology. b, Chemical recycling: selective dissolution of polyester using solvent for the recycling of cotton/polyester-blended wastes. c, Chemical recycling: selective dissolution of cellulose using ionic liquid for the recycling of cotton/polyester-blended wastes. d, Enzymatic approach for the recycling of wool/cotton/polyester-blended textiles. DMSO, dimethyl sulfoxide. Panels adapted with permission from: a, ref. [68], Elsevier; b, ref. [71], Elsevier; c, ref. [72], Elsevier; d, ref. [73] under a Creative Commons license CC BY 4.0.

Table 1 Indicative examples of textile industry technologies' impacts on each sustainability development goals (SDG) of United Nations Agenda 2030

No.	SDG	Exemplary impacts of technologies on the SDG
1	No poverty	Harvesting natural fibres from fast-growing plants, such as bamboo, on infertile and non-agricultural land in poor and remote areas may help create job opportunities and raise farmers' income.
2	Zero hunger	Growing crops for fibre production (corn- and sugarcane-derived) may cause arable land and agriculture resources to compete with food crops. Extracting natural dyes from vegetables or fruits also leads to food security concerns.
3	Good health and well-being	Zero net carbon emission fibre production alleviates global warming, and thus reduces health risks related to rising temperatures.
4	Quality education	Clothing that favours body thermoregulation can prevent decreased learning productivity caused by heat.
5	Gender equality	Digitalization, automation and artificial intelligence provide more opportunities for female workers to get involved in decision making and management.
6	Clean water and sanitation	Advanced textile effluent treatments and less detergent use when washing can reduce the release of hazardous chemicals into bodies of water, and thus help ensure the availability of freshwater and quality drinking water.
7	Affordable and clean energy	The incorporation of renewable energy and eco-friendly fuel in transportation and mills, and the development of energy-saving production technologies substantially increase the share of renewable energy in the global energy mix and double the global rate of improved energy efficiency.
8	Decent work and economic growth	Achieving cleaner production and care of textile products helps avoid or reduce pollution (e.g. remediation of contaminated water), hence decoupling economic growth and environmental degradation.
9	Sustainable industrialization	Resource (e.g. energy, water, chemicals) savings brought by waterless technologies incentivize the textile industry to adopt cleaner processes for greater sustainability, with increased resource use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes.
10	Reduced inequalities	The creation and implementation of sustainable technology provides job opportunities for various sectors within a country or among countries in the complete textile lifecycle.
11	Sustainable cities and communities	Recycling technologies reduces pressure on landfills and incineration facilities, and reduces the adverse per capita environmental impact of cities through better municipal waste management.
12	Responsible consumption and production	Replacing petroleum-based fibres with bio-based/regenerated/new fibres might slow the depletion of fossil resources, and harvesting fibres from fast-growing plants lowers irrigation demands.
13	Combat climate change	Improved farming practices using green energy and that save energy reduce greenhouse gas emissions.
14	Conserve the oceans and seas	Effluent treatments, reducing microplastics and using eco-friendly laundry detergents (with green surfactants and inorganic builders) can reduce eutrophication and water toxicity. Waterless colouration eliminates or reduces water use and effluent discharge.
15	Sustainably manage forests	Seeking alternative sources of raw textile materials, like cellulose from oceans or fast-growing plants, may reduce the demand for wood and thus promote sustainable forest management.
16	Peace, justice and strong instructions	The successful implementation of sustainable technology in the textile industry strengthens the management of corporations for improved environmental and social contributions and governance.
17	Partnerships for the goals	The systematic management of technologies in the complete textile lifecycle facilitates international cooperation among various parties and access to science, technology and innovation, as well as enhances knowledge sharing.

Supplementary Information

Advancing life-cycle sustainability of textiles through technological innovations

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List of contents

Supplementary Table 1 Potential reduction of GHG emission in the textile conversion process[1]

Process	Energy saving measures	Emission reduction potential	Payback period (Year)
Yarn making	Energy-efficient spindle oil	3% ~ 7%	—
	Energy-efficient control system for humidification system	25% ~ 60%	2 ~ 3.5
	Speed motor drives	7% ~ 60%	<3
	Optimum air compression system	1% ~ 3%	2.4
	Heat recovery from flues and hot washing	2% ~ 3%	<1
Fabric production	Strengthen process equipment maintenance	2% ~30%	<1
	Speed pump system drives	20% ~ 50%	0.8 ~ 2.8
	Multiple pumps for varying loads	10% ~ 50%	<1
	Steam system insulation improvement	6% ~ 26%	0.3
	Replace mercury lights with metal halide or high pressure sodium lights	50% ~ 60%	0.08
Coloration and finishing	Counter-flow current for washing	41% ~ 62%	—
	Mechanical de-watering or contact drying stentering	13% ~ 50%	1.6
	Use of mixed drying system	25% ~ 40%	0.2 ~ 0.3
	Reduce re-processing in dyeing	10% ~ 12%	—
	Speed pump system drives	14% ~ 49%	<3

Supplementary Table 2 A summary of textile wet processing technologies and their environmental benefits

	Technology	Baseline scenario	Water reduction (%)	Energy reduction (%)	Salt reduction (%)	COD reduction (%)	BOD reduction (%)	TDS reduction (%)	Turbidity reduction (%)	Ref.
Pretreatment	pad-batch one-step enzymatic desizing, scouring, and bleaching	two-step bath pretreatment	80	—	—	76	76	7	78	2
	pad-steam one-step enzymatic desizing, scouring, and bleaching	two-step bath pretreatment	80	—	—	71	70	71	76	2
	Plasma and enzymatic pretreatment	one bath alkali peroxide pretreatment	67	—	—-	73	—	—	—	3
Coloration	Super critical carbon dioxide fluid dyeing	aqueous dyeing	(100-150 L per kg textile)	(8-18 MJ per kg textile)	—	—	—	—	—	4
	Aerosol dyeing	aqueous reactive dyeing	75	47	80	—	—	—	—	5
	Ultrasonic-assisted dyeing	reactive dyeing without ultrasonic	—	—	16.7 ~ 20	13	—	29	—	6
	Spun dyeing/dope dyeing/spin dyeing (using pigment)	jet dyeing of modal fabric using reactive dyes	50	50	—	—	—	—	—	7
	Micelle dyeing	conventional dyeing with 1:15 liquor ratio	60	—	—	—	—	—	—	8, 9
	Inkjet printing using Novel reactive dye@ copolymer nanospheres	Inkjet printing using commercial reactive dyes	-	30	—	—	—	—	—	10
	Ozone color stripping	conventional colour stripping utilising thiourea dioxide and soda ash	48	47	—	98	—	—	—	11
	Plasma as dyeing		100							12
Finishing	Ozone fading	sodium hypochlorite bleaching	85	—	—	26	—	—	—	13
	Foam finishing	—	80	65	—	—	—	—	—	14

Supplementary able 3 Constituents and environmental problems in wet processing of different fibers

Wet processing	Fiber			Constituents	Environmental problems
	Cotton	Polyester	Lyocell		
Sizing	✓	—	—	—	—
Desizing	✓	—	—	Sizing agents and its additives, enzymes, starch and waxes	BOD; TS; COD
Scouring	✓	✓	✓	Sodium hydroxide, surfactants, soaps, fats, pectin, oils, size and waxes	BOD; COD; TS; non-biodegradability
Bleaching	✓	—	—	H_2O_2, sodium silicate, organic stabilizer and alkaline conditions.	BOD; COD; TS; TSS; TDS; toxicity
Mercerizing	✓	—	—	Caustic soda, acid.	BOD; TS; TDS; COD; alkaline
Dyeing	✓	✓	✓	Metals, salts, surfactants, color and alkaline/acidic conditons	BOD, TS; TSS; COD
Printing	✓	✓	✓	Color, metals, urea, formaldehyde and solvents	BOD, TS; TSS; COD
Finishing	✓	✓	✓	Softeners, solvents, resins and waxes	Non-biodegradability; toxicity

Note: BOD= biological oxygen demand; COD= chemical oxygen demand; TS= total solid; TSS= total suspended solids; TDS=total dissolved solid. See Table S4 for more details.

Supplementary Table 4 Characteristics of textile effluent and their description[15, 16]

Characteristics	**Description**
Chemical oxygen demand (COD)	COD reflects the amount of consumed oxygen, when the organic matter is oxidized under strong oxidizing agents. Thus, higher COD indicates more organic matter[17].
Biological/biochemical oxygen demand (BOD)	BOD is the amount of oxygen that is required by microorganisms, when they degrade the organic matter in aquatic systems. Thus, BOD reflects the biodegradability of wastewater[17].
Total organic carbon (TOC)	TOC reflects the amount of carbon in a stream, which represents the organic character of the stream. Thus, higher TOC indicates larger oxygen consumption caused by microorganisms.
Total solids (TS)	TS includes all the suspended, colloidal, and dissolved solids in the water.
Total suspended solids (TSS)	TSS is the solids in water, which can be trapped by a filter[18].
Total dissolved solids (TDS)	TDS is the mass of residue, which is obtained if the filtered water sample is dried until no mass loss[19].

Supplementary Table 5 Different membranes, their operating pressure and corresponding particle size[20]

Membrane	Microfiltration	Ultrafiltration	Nanofiltration	Reverse osmosis
Operating pressure (kPa)	$150 \sim 600$	$150 \sim 600$	$600 \sim 2000$	> 2000
Particle size range (μm)	$1.5 \times 10^{-1} \sim 15$	$5 \times 10^{-2} \sim 1.5 \times 10^{-1}$	$5 \times 10^{-3} \sim 5 \times 10^{-2}$	$5 \times 10^{-4} \sim 5 \times 10^{-3}$
Possible usage of treated water	—	Rinsing, washing	Rinsing, washing, dyeing, finishing	Rinsing, washing, dyeing, finishing

Supplementary Table 6 Treatment results of textile effluent by hybrid methods: reduction of TS, BOD_5, COD and TOC

Hybrid methods	Textile effluent	TS reduction (%)	BOD_5 reduction (%)	COD reduction (%)	TOC reduction (%)	Ref.
Electrocoagulation (pH = 7, 60 rpm, 10 min) + **Fenton** (pH = 4.3, $[Fe^{2+}]$ = 1.1 mM, $[H_2O_2]$ = 9.7 mM, 100 rpm, 60 min) + **activated carbon** (flow rate: 20 mL/min, 25 °C)	Wastewater from denim jeans factory (pH = 8.2, COD = 970 mg/L, TOC = 220 mg/L, BOD_5 = 206 mg/L)	100	45	73	79	21
Hydrodynamic cavitation (5 bar, 120 min) + **Fenton** ($FeSO_4 \cdot 7H_2O$:H_2O_2 = 1:5)	Textile dyeing industry (pH ≈ 6.9, COD = 2560 ~ 4640 mg/L, TOC = 556 ~ 1184 mg/L, TS = 5569 ~ 7553 mg/L)	64.4	—	38.1	48.4	22
Ultrasound (300 W/L) + **ultraviolet light** + **ZnO** (0.88 g/L) + **persulfate** (2.43 mmol/L)	Textile wastewater (pH = 8.3, COD = 1546.2 mg/L, TOC = 714 mg/L)	—	—	96.6	97.1	23
Coagulation + **sand filtration** + **ultrafiltration hollow fiber** + **ultrafiltration flat sheet membranes** (5 kDa) + **reverse osmosis**	Wastewater for dyeing cotton knitted fabric (pH = 7.91, TOC = 298 mg/L, COD = 1143 mg/L, BOD_5 = 617 mg/L)	—	95.4	94.6	88.5	24
Fungal strain (*Phanerochaete chrysosporium*) + **ultrafiltration** (13 kDa)	Textile factory (pH = 4.2 ~ 5.0, TS = 522 ~ 746 mg/L, COD = 3100 ~ 3800 mg/L)	31.2 ~ 60.9	—	90	—	25
Electron-Fenton (7 V) + **bacterial consortium**	Textile industry (COD = 1444 mg/L, TOC = 480 mg/L, pH = 6.52, TS = 25320 mg/L)	—	—	86	56	26

Note: TS= total solid; BOD= biological oxygen demand; COD= chemical oxygen demand; TOC= total organic carbon. See Table S4 for more details.

Supplementary Table 7 Comparison of various technologies for textile recycling

	Mechanical recycling	**Chemical recycling**		**Enzymatic recycling**			
Technology	Recovery Upcycled Textile System	Selective dissolution of cotton using ionic liquid	Selective dissolution of polyester using DMSO	Tex2Mat	Fungal cellulase for cotton digestion	Commercial cellulase for cotton digestion	Selective dissolution of wool using keratinase
Scale	Commercialized	Laboratory	Laboratory	Laboratory	Laboratory	Laboratory	Laboratory
Textile	Cotton garments	Cotton/PET	Cotton/PET (80/20)	Cotton/PET	Cotton/PET (80/20)	Cotton/PET (60/40)	Wool/PET (45/55; 70/30)
Processes	sorting wastes by colors, cutting and shredding to open fibers, open-end spinning to produce colored yarns	dissolving cotton by [DBNH] [OAc] in a kneader system, using cellulose solution as spinning dope, separating polyester by hydraulic pressure filtration	preparing substrates by dye leaching, dissolving PET by DMSO, bleaching residue cotton, recovering used chemicals	grinding in cutting mill, soaking in sodium hydroxide, enzymatic hydrolysis of cotton to glucose using commercial cellulase, recovering polyester for towel production	enzymatic hydrolysis of cotton using fungal cellulase produced from the solid state fermentation of textile waste	pretreatment of substrates by freezing NaOH/urea method, enzymatic hydrolysis of cotton using commercial cellulase	two-stage enzymatic dissolution of wool carried out in a pulveriser, keratin hydrolysate could be used for bio-fertilizers, microbial growth media, animal feed or cosmetic products
Chemicals used	-	[DBNH] [OAc], acetic acid	nitric acid, DMSO (liquor ratio 1:10 to 1:80), sodium hypochlorite, dilute hydrochloric acid	sodium hydroxide, citric acid, commercial cellulase	sodium citrate buffer, fungal cellulase (enzyme dosage of 25 FPU g−1 substrate)	NaOH, urea, sodium citrate buffer, commercial cellulase	trans-hydrochloride buffer, sodium thioglycolate, keratinase
Processing conditions	-	80ºC, 1 hour for dissolution; 70 °C, 1–8 Mpa for filtration	50ºC, 20 mins for dye leaching; 50ºC 9 hrs for PET dissolution; 40ºC 2 hrs cotton bleaching; 150ºC for chemicals recovery	room temp. 1 hr for NaOH soaking; 55ºC 24 hrs pH 5 for enzymatic hydrolysis	50ºC 96 hrs for hydrolysis of cotton	− 20 °C 6 h for freezing NaOH/urea pretreatment; 50ºC 96 hrs for hydrolysis of cotton	50ºC pH 10 total 20-22 hours 200 rpm of pulveriser
Yield	-	-	77% cotton; 16% PET; 99% regeneration of nitric acid and DMSO	-	70% glucose	98% glucose	90% degraded wool

Review Methodology

The information presented in this literature review is obtained through a three-step progress: collection, filtration and selection. At Step 1, according to the sub-topics related to the theme of this review, the information has been mainly collected with the keywords (**Table S8**) from the Scopus database. The 'Subject area' in Scopus has been applied. The reference types primarily include article, review and book chapter and some conference articles. The period is mainly from 2012 to 2022. For a rare sub-topic, earlier important references also attract our attention. The language of references is English. Although the collected references are the results from searching the keywords, some of their themes are not related to this review. Thus, at Step 2, the information filtration has been accomplished by reading the titles and abstracts of the collected references, to obtain the references directly related to this review. At Step 3, the information selection has been conducted through skimming the filtrated references and defining primary issues in each sub-topics. In Step 2~3, more attention has been paid on the references from 2017 to 2022 than before 2017. Based on the former steps, the manuscript is drafted and revised.

Supplementary Table 8 Summary of reviewed articles

Review Topic	Keywords	Subject area	No. Collected references	No. Filtrated references	No. Selected references
Raw materials and fiber production	Synthetic fibers, bio-based fiber, biodegradable fiber, textiles, sustainable, PET, PA, PLA, PHBV, PTT, PE, PBS	Materials science; engineering; chemistry; environmental science; chemcial engineering; agricultural and biological sciences; biochemistry, genetics and molecular biology	1,469	104	25
	Cotton, fertilizers, sustainable	Agricultural and biological sciences; environmental science; biochemistry genetics and molecular biology; engineering; immunology and microbiology; chemical engineering; chemistry; multidisciplinary; energy; materials science	549	74	12
	Cotton, pesticides, sustainable		409	79	14
	plastic mulch		1,488	98	11
	Regenerated cellulose fibers, cellulose-based textiles, lyocell, viscose rayon, ioncell, sustainability	Materials science, engineering, chemistry, chemical engineering, environmental science	159	20	15

Textile Conversion	Yarn spinning, sustainable	Materials science, engineering, chemistry, chemical engineering, energy ,environmental science, multidisciplinary	1.363	38	7
	Sustainable, textile, weaving, technology	Materials science, engineering, energy ,environmental science, multidisciplinary	1,366	26	10
	Sustainable, textile, knitting, technology		510	17	3
	Sustainable, textile, nonwoven, technology		2,645	39	3
	Textile, braiding, technology		47	14	1
	textile wet processing, pretreatment, coloration, dyeing, printing, finishing, waterless technology, plasma, enzyme	Materials science, environmental science, chemical engineering, engineering, chemistry, energy, agricultural and biological sciences, biochemistry, genetics and molecular biology	2,930	68	20
Effluent treatment	Coagulation, flocculation, adsorption, ultrasonic degradation, membrane, effluent, textile	Materials science, engineering, chemistry, chemical engineering, energy ,environmental science, multidisciplinary	2,952	94	12
	Ozon, hydrogen peroxide, photocalalytic degradation, electrochemical oxidation, fenton, sulfate radical, effluent, textile		1,369	36	7
	Algae, fungal strain, bacterial strain, effluent, textile		750	43	14
Distribution, Consumption and Disposal	shipping, sustainable	Materials science, engineering, chemistry, chemical engineering, energy ,environmental science, multidisciplinary	589	32	8
	detergent builder		57	12	5
	Surfactants	Materials science; engineering; chemistry; chemical engineering; energy; environmental science; multidisciplinary; biochemistry, genetics, and molecular biology;	2,807	82	25

		immunology and microbiology			
	Washing; drying; machine	Engineering; environmental science; energy; multidisciplinary	876	40	12
	textile waste management, sustainable, post-consumer recycling, mechanical, chemical, enzymatic, waste valorization	Environmental science; engineering; chemical engineering; chemical; biochemistry, genetics and molecular biology; materials science; energy	1752	24	11
Total			22724	940	215

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