A review: life cycle assessment of cotton textiles

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ABSTRACT – REZUMAT

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A significant amount of research has been published on the environmental impact assessment of cotton textiles using the life cycle assessment (LCA) method. This review summarized and analysed the findings of these publications, and presented valuable insights for identifying the hotspots that have considerable potential for reducing the environmental burden of cotton textiles. The relevant papers were selected according to two criteria: life cycle assessment of cotton textiles or footprint of cotton textiles. Subsequently, key features were screened and critically analysed: functional unit, system boundary, data sources and geographic location, and impact assessment methods and impact categories. We found that there is an emerging market demand to transform conventional cotton to organic cotton. From the global perspective, a spatially explicit LCA of cotton textiles should be conducted. In addition, a comprehensive and holistic life cycle impact assessment containing more impact categories that are appropriate to cotton textiles is required. LCA is a well-justified approach among practitioners and researchers and has been widely applied to the topic of cotton textiles. This methodology should be studied and developed further to more precisely evaluate the environmental impacts of cotton textiles.

Keywords: *cotton, environmental impacts, footprint, life cycle assessment, review, textiles*

Studiu: evaluarea ciclului de viață al materialelor textile din bumbac

Multiple cercetări au fost publicate cu privire la evaluarea impactului asupra mediului al materialelor textile din bumbac, folosind metoda evaluării ciclului de viață (LCA). Acest studiu a identificat și a analizat rezultatele acestor publicații și a prezentat informații valoroase pentru identificarea punctelor importante, care au un potențial considerabil de reducere a presiunii asupra mediului create din producerea materialelor textile din bumbac. Lucrările relevante au fost selectate în conformitate cu două criterii: evaluarea ciclului de viață al materialelor textile din bumbac sau amprenta materialelor textile din bumbac. Ulterior, caracteristicile cheie au fost examinate și analizate critic: unitatea funcțională, limita sistemului, sursele de date și locația geografică, metodele de evaluare a impactului și categoriile de impact. S-a constatat că există o cerere pe piața emergentă pentru transformarea bumbacului convențional în bumbac organic. Din perspectiva globală, ar trebui implementată o metodă LCA explicită spațial pentru materialele textile din bumbac. În plus, este necesară o evaluare cuprinzătoare și holistică a impactului ciclului de viață, care conține mai multe categorii de impact, adecvate pentru materialele textile din bumbac. LCA este o abordare bine justificată în rândul practicienilor și cercetătorilor și a fost aplicată pe scară largă în ceea ce privește materialele textile din bumbac. Această metodologie ar trebui studiată și dezvoltată în continuare pentru a evalua mai precis impactul asupra mediului al materialelor textile din bumbac.

Cuvinte-cheie*: bumbac, impact asupra mediului, amprentă, evaluarea ciclului de viață, studiu, textile*

INTRODUCTION

Cotton is the most widely utilized natural fiber in the world, and has comprised approximately one third of the textile fibers market in 2000–2016 [1]. Cotton is grown in subtropical, seasonally dry tropical areas, primarily in the Northern Hemisphere. Approximately 32 million hectares of agricultural land is allocated for cotton plants in more than 75 countries, including India, China, the United States, Brazil, and Pakistan, which are the main producers of cotton and account for more than three-quarters of global cotton production. According to the Food and Agriculture Organization (FAO), global cotton consumption is ~31.8 million tonnes, with > 20 million tonnes of cotton being used for textile fibers. Approximately 8 million tonnes of cotton was traded in the global market during 2016/2017 [2].

The entire life cycle of cotton textiles is long and complex, and includes cotton cultivation and harvest, manufacture (ginning, spinning, weaving, dyeing, cutting and sewing, and ironing), consumption (retail and use), and disposal. Generally, cotton is considered to be an environmentally friendly fiber since it is grown and not manufactured. However, it consumes large quantities of water during the agricultural phase, and fertilizer and pesticides are also required, which can lead to eutrophication and toxicity. According to Cotton Inc. [3], global cotton accounts for 3% of land use, 3% of global agricultural water, and 5.2% of global pesticide sales. Previous life cycle assessment (LCA) studies have found that cotton cultivation has significant environmental impacts due to the use of pesticides, fertilizers, and water [4]. Dyeing is the most contaminative process in the life cycle of cotton textiles, the numerous inputs of chemicals such as dyes, wetting agents, and softener account for a huge environmental burden. Water usage for washing during the use phase of cotton textiles has also attracted attention. There have been many initiatives to reduce the environmental burden of cotton products, for example, by growing organic cotton and recycling cotton textiles. Over the past decades, the Better Cotton Initiative (BCI) and Cotton made in Africa (CmiA) as well as other programs have brought momentum to the movement for improving the environmental performance of cotton [5]. The long and complex supply chain of cotton in addition to the numerous associated environmental impacts requires a comprehensive methodology to evaluate the overall environmental burden.

Meanwhile, some practitioners are required to demonstrate how their cotton products or services reduce the environmental burden. LCA is an effective method for providing an interpretation of the entire life cycle of products. Since the introduction of the International Organization Standardization (ISO) 14040:2006 and ISO 14044:2006, LCA has been widely applied in the textile industry as a decision support tool for evaluating the environmental impacts of products and services [4]. The framework of LCA traditionally involves: 1) goal and scope definition; 2) inventory analysis; 3) impact assessment; 4) interpretation. The first step defines the purpose of the study, the product, system boundaries, and the function unit according to ISO 14040:2006 [6]. Inventory analysis is the foundation of impact assessment. The reliability of the results is partially dependent on the quality of the collected data. Many existing life cycle impact assessment (LCIA) databases provide convenience to practitioners. The impact assessment phase aims to evaluate the potential environmental impacts, transforming the life cycle inventory (LCI) into the potential environmental impacts through the use of characterization factors.

The aims of this review are to: i) explore and document the current state of LCA research with regards to the environmental burden of cotton textiles, ii) identify possibilities for reducing the environmental burden of cotton textiles, and iii) identify possible improvements for the existing LCA evaluation methods used in the cotton textile industry. By reviewing and comparing previous studies we further aim to illustrate the differences between methods and results, and in turn discuss their limitations as a means of providing an initial guide for data collection and method selection among practitioners.

IMPACT ANALYSIS OF COTTON PRODUCTS

Impact analysis of cotton fiber

Impact analyses of cotton fiber have focused on the impacts of the cultivation phase of cotton. The boundary has always been set as from cradle to gate (ginning). The functional unit is 1000 kg (or 1 kg) of cotton lint. Different studies have assessed the environmental performance of cotton in different regions, identified the potential to reduce the environmental burden, and compared the performance of different measures for reducing the environmental impacts.

Water use for cotton production differs considerably between countries due to the variations in climatic conditions and those that are required for cotton production. A report by Chapagain et al. aimed to assess the “water footprint” of worldwide cotton consumption by identifying the location and character of the related impacts [7]. The author analysed the largest 15 cotton producing countries, and found that climatic conditions were highly related to water use and cotton yields. The climatic conditions of Syria, Egypt, Turkmenistan, Uzbekistan, and Turkey – where the evaporative demand is high while effective rainfall is very low – are less appropriate for cotton cultivation because of the irrigation demand, which increases the environmental burden to local water resources. In addition, partial irrigation leads to low cotton yields. Optimal climatic conditions for cotton production are in the USA and Brazil, where evaporative demand is low and cotton can be grown without irrigation. The global cotton trade ensues that most of the cotton produced in a region is actually utilized in another, and countries that import cotton indirectly deprive water resources of the export countries through global trade. Approximately 84% of the water footprint of cotton consumption in the EU 25 region prior to 2005 was located outside Europe, with major impacts having affected India and Uzbekistan in particular. With regards to sustainable water management, it is feasible to hypothesize that improvements may be possible from the cotton consumption perspective if a degree of responsibility for the impacts is taken by consumers.

Cotton made in Africa (CmiA) is cultivated by small-scale famers under rain-fed conditions in crop rotation with other cash or subsistence crops. Agricultural inputs such as fertilizers or pesticides are low and the harvest is performed exclusively by hand. This extensive cultivation practice was found to have significant advantages over other methods in a report by CmiA., which evaluated the cradle to gate environmental impacts of cotton lint made in Africa (functional unit of 1000 kg cotton lint) [8]. Climate change, eutrophication, and acidification were assessed in the report using the Center voor Milieukunde at Leiden (CML) impact assessment methodology framework.

Additionally, water use and water consumption were investigated. Freshwater use includes the withdrawal from surface water, ground water and rainwater and water consumption means that the water removed from but not returned to the same basin. The impact on climate change was quantified as 1037 kg CO_2 eq., which was lower than the global average (1801 kg of CO_2 eq.) [9]. The freshwater used to produce 1000 kg CmiA was determined as ~3400 m^3, but the blue water (surface and ground water) consumed was found to be very small due to the precipitation in this region being sufficient to meet the water demand for growing cotton. The eutrophication impact was evaluated as 20.4 kg PO_4^{3-}, to which soil erosion made a significant contribution. In this report, the emission of N and P was modeled and it found that soil erosion and the nutrient content of the soil were determined to be sensitive parameters with regards to eutrophication, with the potential for eutrophication differing between regions. However, this regional difference of has not yet been considered in existing life cycle impact assessment of cotton.

Xinjiang, China, has become one of the most important cotton producing regions and has the highest yields worldwide. Günther et al. focused on the agricultural greenhouse gas emission and phosphorus consumption during the cultivation of cotton in Xinjiang, which measured as carbon footprint and phosphorus footprint, respectively [10]. Results showed that fertilizer production contributed 63.9% of the carbon footprint (total 4.43 kg CO_2 eq./kg fiber) due to the energy use during the fertilizer production phase. The phosphorus footprint of cotton was 101g P/kg fiber mainly from the high input of phosphorus fertilizer, which also indicated a high potential of eutrophication. Therefore, reduced fertilizer application and reuse of plant residues are the most probable ways to reduce the carbon and phosphorus footprints of cotton production. A limitation of this study was that it was carried out in a dryland area, hence, the findings should be combined with an analysis of the water footprint as a means of moving towards a more holistic picture of the environmental impacts of cotton.

As mentioned, cotton cultivation has considerable environmental impacts. Organic cotton that avoids the use of artificial fertilizers and pesticides has been encouraged by specialists [11]. A report published by Textile Exchange, a non-profit organization, addressed the LCA of organic cotton for the top five countries involved in organic cotton cultivation: India, China, Turkey, Tanzania, and the USA, which were found to collectively account for 97% of global cotton production [12]. The LCA of organic cotton were based on the CML impact assessment methodology framework. Comparison of organic and conventional cotton was made using the Cotton Inc. (2012) study of conventional cotton. The results indicated that organically grown cotton had the following potential impact savings over conventional cotton: 46% reduced global warming potential (GWP), 70% reduced acidification potential (AP), 26% reduced eutrophication potential (EP), 91% reduced blue water consumption, and 62% reduced primary energy demand (non-renewable). The lower agriculture inputs (e.g., mineral fertilizer, pesticides) as well as the practices required by the principles of organic agriculture accounted for the lower environmental impact of organic cotton. However, it should be noted that the low blue water consumption of the organic cotton cannot be attributed exclusively to the organic cultivation operations, since the irrigation requirements of a crop are mainly determined by climatic conditions, and the actual water usage is also influenced by irrigation techniques.

The recovery of cotton from discarded cotton presents a potentially wise strategy for reducing the environmental burden of cotton. A study undertaken by Esteve-Turrillas and Guardia [13] compared the environmental impacts of recovered cotton with virgin cotton. Findings showed that the use of recovered cotton avoided impacts related to cultivation and the dyeing process, although electricity consumption was relatively higher for recovering cotton (functional unit of 1 kg of colored cotton yarn). The results also illustrated a great advantage of recovered cotton because it was found to save 13.98 kg CO_2 eq. with respect to GWP, 0.32 kg SO_2 eq. for AP, 0.033 kg PO_4^{3-} eq. for EP, and 5594 kg water for the water use. However, the data of this study was taken from literature that was based on different regions and methods, hence, the advantages of recovering cotton may have been overestimated.

Many efforts have been made by the cotton industry in different countries to meet international obligations regarding emission reductions. The Australian cotton industry has made particular advances in this regard. Hedayati et al. assessed the effects of an array of on-farm mitigation options as a means of providing farm-level strategies for reducing emissions [14]. The climate change impact evaluation using the Intergovernmental Panel on Climate Change (IPCC) method of cotton lint on a cradle to port basis was determined as 1601 kg CO_2 eq. per tonne of cotton lint. The hotspots assessment found that the production and use of synthetic nitrogen fertilizers made the largest contribution to the emissions profile (46% of total). Farm level management options to minimize the life cycle of greenhouse gas (GHG) emissions were also compared. The results indicated that GHG emissions could be reduced by i) 5.9% through the controlled-release of stabilized N fertilizers, ii) 8.1% by changing from diesel to solar-powered irrigation pumps, iii) 3.4% by changing from diesel to biofuel-powered farm machinery, iv) 3.9% by changing from continuous cotton to a cotton-legume crop rotation, and v) 2.1% through the use of N fertigation. This study therefore demonstrated opportunities to reduce GHG emissions at the farm level.

Other strategies to reduce the environmental burden of cotton include the reuse of clothing (e.g., second-hand clothing) and cotton recycling to produce other products. A new technology has been reported recently for producing cellulose carbamate fibers using discarded cotton textiles as the raw material [15]. The authors compared the environmental impacts of two cellulose carbamate (CCA) fibers under different production scenarios with cotton fiber. The data for the reference cotton was taken from van der Velden, N. M., et al. and Shen and Patel, et al. [16–17]. Two CCA fiber production scenarios were modelled with Sustainability tool for Ecodesign, Footprints & LCA (SULCA). Assumed that CCA Intergrated fiber was produced in a factory integrated with a pulp mill, which included water circulation, recycling of chemicals and using renewable energy. CCA Standalone fiber was produced in a stand-alone factory, which represented a non-optimized process. 1 tonne of CCA Integrate fiber had a GWP value of 1979 kg CO_2 eq., which was ~30% lower than of that for the reference cotton fibers. However, CCA Standalone fiber generated twice of GWP of cotton fibers (6020.1 kg CO_2 eq.). The water use of CCA Integrated fiber and CCA Stand-alone fiber were 31 m^3 and 86 m^3 respectively, which is much lower than cotton (4342 m^3 per tonne of cotton fiber). Paunonen et al. concluded that the reuse of discarded cotton for CCA fiber can considerably reduce water use [18]. However, due to the huge contribution to GWP, it should be suggested to integrated spinning factory with pulp mill to optimized the production of CCA fiber.

In addition to an intensive water use, cotton production is also characterized by intensive land use during the cultivation phase. However, these two impacts are seldom addressed as impacts further down the cause-effect chain. Sandin et al. contributed to the developed of methods for characterizing the impacts of water and land use in the LCA, and assessed the impacts of water use and land use with respect to textile fibers [19]. The study used four indicators proposed by Pfister et al. to characterize the impact of water use: a midpoint indicator (water deprivation) and three endpoint indicators (human health, ecosystem quality impact, and resources) [20]. Sandin et al. also used the method proposed by Schmidt for characterizing the impact of land use on biodiversity [19, 21]. The results showed that the location of operations significantly influenced the impact of water use. The transformation of natural land had a greater impact on biodiversity than the occupation of land. Moreover, the study highlighted that the methodological aspects of both water and land use impact assessment require further research down the cause-effect chain.

To balance the economic and environmental performances of cotton cropping systems, Ullah et al. performed an eco-efficiency analysis [21]. The authors assumed that farm size was a possible factor in the performance variation, and their results demonstrated that the use of pesticides and fertilizers, field emissions, field operations, and irrigation were the main sources of environmental impacts. Findings revealed that the production of 1 kg of seed cotton delivered at the farm gate could generate a GWP of 3–3.4 kg CO_2 eq. and could require 5–6 L of water, with no significant differences being observed with farm size. Small farms were found to have a potentially higher eutrophication impact in comparison to larger farms, but this could be counterbalanced by higher profits. Unfortunately, the study illustrated that the combination of high economic returns with low environmental impacts was seemingly impossible under the assumed conditions. However, the greatest potential for balancing economic and environmental performances was found to be through the reduction of pesticides and fertilizers with no effect on yield.

Impact analysis of cotton clothing

Cradle to grave LCA can be used to assess the advantages of recycling clothing, address environmental performance of garments, and identify the hotspot during the life cycle of a T-shirt or a pair of jeans, for example. The impact categories selected to address environmental burden of products are different from each study depending on the purpose and the chosen LCA methodology. The most utilized life cycle impact assessment (LCIA) methods in cotton textile are environmental design of industrial products (EDIP), ReCiPe and CML.

Woolridge et al. conducted a LCA for the reuse/recycling of donated waste textiles from an energy saving perspective [23]. To address the net energy saving from reused textiles, the authors used a case study of a charity bank, which recycled clothing and textiles by providing a collection and distribution infrastructure for donated second-hand clothing, textiles, shoes, and accessories. The energy use required for reuse and recycling was mostly attributed to the use of polyester packaging/bags and transportation. In comparison to virgin materials, 1 tonne of second-hand clothing was found to save 65 kwh energy (i.e., 97.4% of the energy used for virgin cotton clothing).

Many charity organizations collect used clothing and either resell or donate them. Not all clothes are suitable for reuse, and only ~60% may be recycled. The potential to reduce the environmental burden of recycled textiles was quantified by Farrant et al. [24]. The authors assessed the environmental benefits of reusing clothes by the EDIP method and a functional unit of 100 pieces of 100% cotton T-shirt. The concept of a “replacement rate” was introduced to evaluate the replacement of new clothes by second-hand clothing. Compared with directly discarded cotton T-shirts, reuse via second-hand shops in Estonia was found to decrease i) the GWP by 14%, ii) acidification impacts by 28%, and iii) nutrient enrichment impacts by 25%.

Baydar et al. used LCA to compare the environmental impacts of eco-T-shirts (produced from organically grown cotton and processed with green dyeing recipe) to those of conventional T-shirts [25]. Comparison was made of their contributions to global warming, acidification, aquatic and terrestrial eutrophication, and photochemical ozone formation using a functional unit of 1000 items of knitted and dyed cotton T-shirt (200 kg total weight). The environmental impacts over the period from cotton cultivation to disposal were assessed using EDIP 2003. The results revealed that the eco T-shirts had a lower impact potential across all of the observed categories. The most dramatic decrease in impact potential was observed for aquatic eutrophication potential (AEP) (up to 97% reduction), which related to the elimination of nitrogen and phosphorus containing chemical fertilizers during the cotton cultivation stage. GWP was by far the largest environmental impact for both conventional and eco T-shirts, with the main impact coming from the use phase (evaluated as 4140.4 kg CO_2 eq.), and this was followed by the cultivation and harvesting phase and then the fabric processing phase. In terms of AP, the use stage was found to make a considerable contribution to acidification that resulted mainly from wastewater treatment (51%), soap production (25.3%) and electricity consumption (22.4%). The elimination of certain chemicals during wet processing resulted in a significant reduction across all impact categories. Although the authors concluded that the use of organic cotton can significantly reduce environmental impacts, any immediate transition to organic cotton cultivation was considered to be challenging. Gradual reductions in the application of fertilizer and pesticides were determined as being more feasible for reducing the environmental impacts.

The LCA of a product includes the challenges of globalized production and consumption, and requires a spatial LCI to be developed. Steinberger et al. established a cradle to grave spatially explicit LCI for a cotton T-shirt and a jacket at the country level [26]. The cotton T-shirt was produced in India and the polyester jacket was manufactured in China, and both were consumed in Germany. The LCI included CO_2, SO_2, NO_x and particulate emissions, as well as energy use, which were disaggregated by country. The LCI of the T-shirt and jacket showed striking differences, > 70% of the CO_2 emissions and energy use associated with the T-shirt occurred in the consumption country, whereas > 70% CO_2 of emissions associated with the jacket occurred in the producing country. This striking difference of the CO_2 emission was related to the different washing frequency of two apparels (50 times and 6 times for the jacket). For SO_2, > 60% of emissions occurred in the production country for both the T-shirt and the jacket due to the combustion of fossil fuel in production phase. The difference in the emission of CO_2 and SO_2 of two garments was mainly depended on the location energy infrastructure. Analysis of the use-phase indicated the importance of consumer behaviour (e.g., washing machine temperature settings and air versus laundry drying) over equipment efficiency. In addition, the lifetime of a garment was also found to play a significant role in the contribution to environmental impacts, a longer lifetime increased the environmental impacts of the use phase, whereas the daily environmental burden of a garment being worn decreased. These findings indicate the necessity of a functional unit that provides the lifetime of a garment when conducting a LCA of clothing.

Large environmental impacts for cotton textiles are caused during the use phase, especially with respect to energy consumption for washing and ironing clothes. Cartwright et al. assessed the cradle to grave environmental impacts of a shirt using a functional unit of a button-up, short-sleeved, uniform work shirt made of 65% polyester and 35% cotton [27]. The shirt was washed 52 times over a 2-year lifespan. The environmental impacts (energy, water use, and GWP) were analysed for four distinct phases: material acquisition, shirt manufacturing, use and disposal. The total life-cycle energy use of the shirt was 102 MJ, the cumulative water use was 2728 l, and the GWP was 5.7 kg CO_2 eq. The results showed that the amount of resources used and the GWP were highest during the shirt's use phase, which accounted for 64% of total energy use, 72% of total water use, and 76% of the overall GWP. This was due to four main processes in: water heating, washing, drying, and transportation. The study concluded that more effort should be made to improve the environmental performance of the use phase, for example, by increasing equipment efficacy.

Hackett et al. addressed the cradle to gate phases of the life cycle assessment of a pair of denim jeans and a T-shirt [28]. The system boundaries that were assessed included: raw material production, fabric production, garment manufacturing, and transportation and distribution. The study showed that cotton fiber cultivation and harvesting made the most significant contributions to the overall environmental impacts, and that these originated from the use of fertilizers, pesticides, and irrigation water. The authors suggested that initiatives could therefore encourage the cultivation and harvesting of organic cotton that remove the use of artificial fertilizers and pesticides. However, due to concerns over low yields and finances, the transformation from conventional cotton to organic cotton was considered as having a long way to go. Limitations of the study included that the data came from existing LCAs, and that the comparison between the selected apparel was less meaningful because the environmental impacts of the cotton apparel varied from countries and the results are highly dependent on chosen methodology, hence, we suggested that the comparison of environmental impacts between two type different apparel (e.g. T-shirt versus jeans) should be based on LCIA results that evaluated under similar systems.

Zhang et al. aimed to identify hotspots in the life cycle of cotton textiles for the purpose of improving their sustainability [29]. The functional unit was one 100% cotton long-sleeved T-shirt and the scope was from cradle to grave. The data were obtained from a representative mill and from questionnaires for the use phase in China. Abiotic depletion, AP, GWP, photochemical ozone creation potential, EP, water use, and toxicity were assessed using CML 2001 and USEtox model. From a life cycle perspective, the study showed that cotton cultivation, dyeing, making-up, and the use phase were the main contributors to the environmental impacts. The author concluded that improving a product's environmental sustainability is not only a matter for the government and suppliers, but also for consumers.

In 2015, Levi Strauss and Co. conducted an LCA to assess the environmental impact of a pair of Levi jeans. The functional unit was one pair of women's Levi's 501 medium stonewash-jeans (340 g) that were made of cotton [30]. The LCA analysed the environmental impact of the denim during the entire life span, which encompassed the production of the raw materials, the manufacturing process, logistics, garment use, reuse of the denim, recycling, and disposal. The LCA focused on the product's use phase and end-of-life disposal phase because these are critical stages in a product's life cycle, which depend on consumer behaviours. ReCiPe 2008 was used to assess climate change potential, water consumption, EP, land occupation, and abiotic depletion. One pair of Levi's 501 denim jeans were found to emit 33.4 kg CO_2, to consume 3781 kg water and 48.9 g PO_4^{3-}, and to occupy 12 m^2/year of land. The study demonstrated that fiber production and consumer care activities consumed most of the water during the entire life cycle (91%), whereas fiber production consumed 68% and consumer care activities (e.g., cleaning and washing) consumed 23%. The results showed that consumer care contributed the largest impact (37%) to climate change over the life cycle. Moreover, processing factors such a washing frequency, washing water temperature, and the use of a washing machine were found to influence GHG emissions. The fabric product had the second largest impact on climate change (27%). Fiber cultivation had the highest impact on eutrophication due to the use of fertilizer and pesticides (Levi Strauss & CO, 2015). This study provided a comprehensive assessment of the environmental burden of a pair of cotton jeans, which could be used for improving the performance of jean.

The textile industry uses chemicals intensively in production phase. Toxicity assessments are therefore performed, and it is important that the results are both relevant and representative because it is crucial that there is confidence in the results. Three methods for strategic product toxicity assessment were compared by Roos and Peters as a means of disclosing the inherent characteristics of chemicals used in cotton manufacturing [31]. The differences resulting from the choice of toxicity assessment method were illustrated and compared using the wet treatment of a cotton T-shirt. The results showed that three different toxicity assessment methods did not give a consistent evaluation of the different chemicals used in the wet treatment. For example, optical brightener received a high score in the score system method but a very low score from USEtox. This was considered to mainly relate to the environmental persistence of organic chemicals, a property that is handled differently in these toxicity assessment methods.

Roos et al. calculated the GWP using ReCiPe and toxicity using USEtox, and used the score system as a supporting method [32]. The study addressed the importance of the life-cycle perspective as a means of avoiding improving part of a system in a manner that negatively affects other parts of the system. The environmental impacts of two white nightgowns were compared, whereby one was bleached and one was not. The results showed that, contrary to expectations, the environmental burden associated with the bleached nightgown over its life cycle was lower than that of the unbleached gown, owning to a shorter lifespan for the unbleached gown. A shortcoming was identified during the impact assessment step, many textile chemicals lacked character factors CFs and could not therefore be included in the LCA calculations. This represents an aspect for further study in the methodology of chemical assessments. From this study, we proposed that the operational lifespan of products should be determined when conducted LCA, which significantly influence by consumer behaviours. Assuming that consumers dispose of clothes when they are worn out, a long-life span ensures a lower replacement rate for consumers, which may be more environmentally friendly from a comprehensive perspective.

The carbon footprint of a pure cotton shirt (average weight of 0.28 kg) from cultivation to use stage in China was evaluated by Wang et al. using the IPCC method. This study constructed an operable carbon footprint assessment method and framework at the product level to establish the provision of a carbon labelling system [33]. The calculated carbon footprint was 8.771 kg CO_2 eq., and the indirect carbon footprint accounted for most of the total carbon footprint over the shirt's life cycle (96%) owing to the use of energy and materials. The industrial production process contributed 57% of the total carbon footprint, 36% for raw materials, 11% for use phase. A limitation of the study was that it only assessed climate change. According to previous research, the consumption of water and land use are other hotspots for cotton textiles. The authors emphasized that a product should be assessed in a comprehensive manner to inform consumers sufficiently, when develop environmental impact polices making or management decision. We proposed that a comprehensive ecolabel will be an effective way to reduce the environmental burden of garments.

DISCUSSION

Goal and scope

LCA of cotton textile aims to assess the environmental impact of cotton textile during the life cycle. The entire life cycle of cotton textiles includes many processes, and is related to many regions and has a long time-span. It can be separated to four main processes: cotton cultivation, production, use phase, and disposal (figure 1).

From the reviewed LCA studies on cotton, the system boundaries were always either from cradle to gate (fiber) or from cradle to grave (textiles). However, the gate can refer to a farming gate, ginning gate, factory gate, or family gate. Many studies for cotton fibers have focused on the environmental contribution of cotton cultivation beginning with cotton cultivation and ending at ginning, and used a functional unit of 1 kg/tonne of cotton lint. Others investigations have

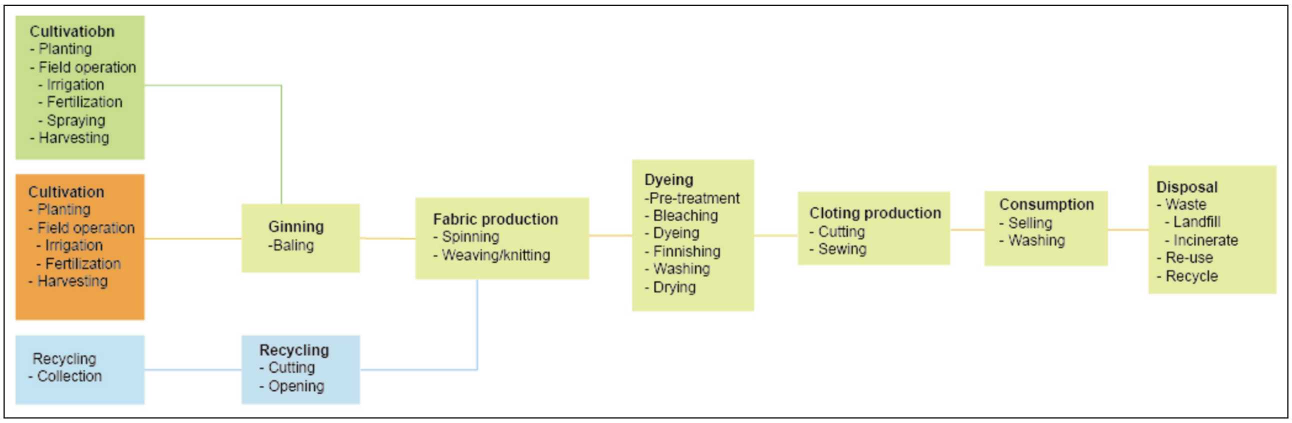

Fig. 1. Process of life cycle of cotton textiles

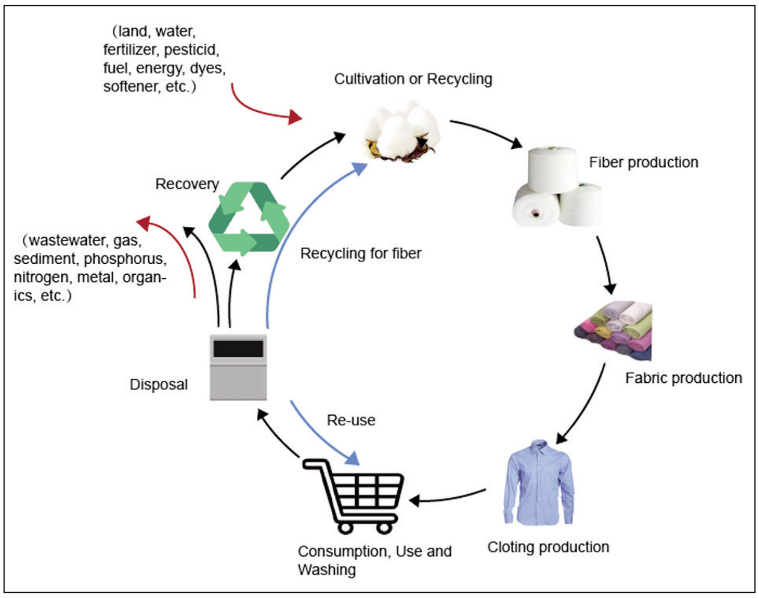

Fig. 2. The whole life cycle of cotton textile

aimed to evaluate the environmental burden from a holistic perspective that contains more processes. For cotton textiles, many researchers chose the functional unit as one piece of cotton garment, and ended at either the use phase or disposal stage. The inputs such as land use, water consumption, chemical inputs and output (e.g. wastewater, gas emission, metal and organics) will be documented and assessed (figure 2).

Impact assessment results

The most widely used LCA methods for cotton textiles have been EDIP, CML and ReCiPe, which are comprehensive methods that contain many environmental impact categories (table 1). The impact categories and their characterization as well as applicable locations vary between methods and studies. GWP, AP, EP, and water consumption are the most common impact categories in the LCA of cotton textiles (table 1). USEtox model focuses on the toxicity assessment that has been applied in the textile industry in recent years. The carbon footprint and water footprint are specialized parameters for evaluating the effects of GHG emissions and water consumption, which are concentrated on a smaller scope containing only one impact category. In the LCA assessment of cotton textiles, the selected impact category indicators for GWP, AP and EP are mid-point indicators, which evaluate the impact of the pollutants by using the equivalency of a reference substance. In terms of the impact assessment of acidification and eutrophication with respect to cotton textiles, the impact categories may include freshwater acidification/eutrophication or terrestrial acidification/eutrophication, depending on the characterization method used and issues being addressed. Water scarcity categories have been developed to address the different water stresses in various regions, and can report the water consumption effects in a location-specific way. There is a possibility that cotton industry areas may be affected by water stress. However, water consumption assessment of cotton textiles in an LCA is often reported in a loading assessment level by simply including the volume of water used. Few studies have applied water scarcity or assessed the water consumption effect down the cause-and-effect chain.

From the published LCA results for cotton textiles, it is difficult to form a consistent conclusion with regards to which factor contributes most to the overall environmental burden. This is due to the different assessment methods, locations, and production technologies amongst other reasons. However, it is possible to summarize the possibilities for reducing environmental impacts. A cradle to grave LCA of a piece of a cotton garment that contains comprehensive impact categories can support decision makers, although data quality is a high requirement. LCAs of a pair of jeans and a piece of T-shirt were reported in [25, 29, 30]. The most common impact categories in these studies were GWP, AP, EP, and water use.

The life span of cotton garments is separated into four phase cotton cultivation, production, use, and disposal. Cotton cultivation, wet processing during

Table 1

SUMMARY OF LIFE CYCLE ASSESSMENT OF COTTON TEXTILE

Textile products	Source	Method	Impact categories*
Cotton fiber	Chapagain et al., 2005 [7] Paunonen et al., 2019 [18] Günther et al., 2017 [10] Sandin et al., 2013 [19]	footprint	CF, EF, PF, WF
Organic cotton fiber	CmiA., 2014 [8] Textile Exchange, 2016 [5]	CML	AP, ADP, EP, FWAE, GWP, HTP, OLD, PED, TEP, WU, WC
Organic cotton fiber	Textile Exchange., 2016 [5]	USEtox	TP
Cotton lint	Hedayati et al., 2019 [14]	Australian impact method, Australian Indicator Set V3	GWP
Cotton fiber	Paunonen et al., 2019 [18]	ReCiPe	GWP
Seed cotton	Ullah et al., 2016 [22]	CML 2001	ADP, AP, EP, HTP, FWAE, GWP, OLD, TEP, WU
Recycled clothing	Woolridge et al., 2006	footprint	EF
Cotton T-shirt	Farrant et al., 2010 Baydar et al., 2015	EDIP	AP, AEP, GWP, OD, POFP, TEP
A work shirt	Cartwright et al., 2011	EDIP	GWP
Denim jean	Hackett et al., 2015 [28]	ReCiPe 2008	AD, EP, GWP, LO,WU,
Cotton T-shirt	Zhang et al., 2015 [29]	CML 2001	AD, AP, EP, GWP, POCP, WU
Cotton T-shirt	Zhang et al., 2015 [29] Roos and Peters, 2015 [31]	USEtox	EP, HTC, HTNC
A cotton nightgown and a cardigan	Roos et al., 2015 [31]	ReCiPe	GWP
A cotton nightgown and a cardigan	Roos et al., 2015 [31]	USEtox	TA
A pure cotton shirt	Wang et al., 2015 [33]	Footprint	CF

Note: * CF – carbon footprint; EF – energy footprint; PF – phosphorus footprint; WF – water footprint; AP – acidification potential; ADP – abiotic depletion potential; EP – eutrophication potential; FWAE – fresh water aquatic ecotoxicity; GWP – global warming potential; HTP – human toxicity potential; OLD – ozone layer depletion; PED – primary energy demand; TEP – terrestrial eutrophication potential; WU – water use; WC – water consumption; TP – toxicity potential; AEP – aquatic eutrophication potential; OD – ozone depletion; POFP – photochemical ozone formation potential; AD – Abiotic depletion; LO – Land occupation; POCP – photochemical ozone creation potential; HTC – human toxicity-cancer; HTNC – human toxicity-non cancer; TA – toxicity assessment.

production and the use phase have been found to be the main contributors to the overall environmental burden across all impact categories. In the cultivation phase, the intensively use of water, fertilizers, and pesticides have been reported as contributing most of the environmental impacts and can be considered as hotspots. Water consumption is highly related to the climatic conditions of a cotton growing region, and areas with a low evaporative demand but high effective rainfall are more attractive for cotton cultivation. Synthetic fertilizers have the potential to contribute considerably to eutrophication due to their nitrogen and phosphorus contents, whereas pesticides can negatively affect freshwater and terrestrial toxicity [17]. Wet processing during the production phase is another hotspot across the indicators of water consumption, GWP, AP, EP and toxicity. Most of the environmental burden has been found to originate from diverse chemical inputs (e.g., acids, alkalis, dyes, metals, and organic compounds) in the dyeing phase. An additional hotspot is the use phase, the high contribution of energy use to global warming during this phase is due to water heating, washing, drying, and ironing. Washing detergent has also been reported to account for high AEP. Furthermore, studies have illustrated that different consumer behaviours (e.g., life time span, frequency of use, and washing habits) can result in quite different environmental consequences related to energy and water use.

Strategies for reducing environmental impacts

Strategies for farm operations, organic cotton cultivation, to recycling of cotton textiles can all contribute to a reduction in environmental impacts. Opting for organic cotton versus conventional cotton is one strategy for reducing the environmental impacts of cotton cultivation, it avoids the use of artificial chemicals such that impacts related to the GWP and eutrophication are reduced. However, the cost and yields of organic cotton mean that there is still a long way to go to switch from conventional cotton to organic cotton. As mentioned previously, the various chemical inputs during wet processing can result in wastewater that contains high concentrations of pollutants. Feasible strategies include using substitute chemicals that have a lower environmental burden or recycling without dyeing. From a holistic life cycle perspective, cleaner consumption is more important than cleaner production due to its long-life span during the use phase. Lower water temperatures and hand washing have also been suggested by previous studies. However, the impacts related to detergent have seldomly been considered in the impact assessment of cotton textiles.

Limitations and potential improvements

As mentioned, LCA methods for cotton textiles contain many impact categories. However, many studies have only included a limited number of environmental indicators. Comprehensive impact categories that include eutrophication, acidification, and ecotoxicity could make cradle to grave studies more scientific and credible. This could also avoid missing potential hotspots, especially when new techniques are applied in the cotton textile industry. In addition, a more comprehensive water footprint that includes water scarcity would be more appropriate and relevant to current research.

The environmental impact assessment of cotton textiles in use phase was found to have high contributions to water consumption and energy use and results more uncertainties owing to various consumption behaviours. The results of LCIA are sensitive to parameters such as washing frequently, lifespan. Hence, the lifespan, washing frequency, washing temperature and other related operations in consumer care phase must be determined when assess the environmental impact of cotton garment in use phase. Moreover, the functional unit for use phase should be 1 mass of cotton garments per month or year.

Cotton textiles are characterized by a global circulation, moving between different regions through a long and complex chain. LCIA practitioners should recognize that the impacts of this movement depend on the array of locations involved [34]. Impact categories such as acidification, eutrophication, and water use are more site-specific. Site-dependent characterization models have rapidly developed in the past decade. Regionalized methods have included impact categories such as acidification [35, 36], eutrophication [37, 38], water scarcity, and their related impacts on human health and ecosystems [20, 39, 40]. Therefore, LCIA practitioners should chose appropriate methods to produce more accurate results as a scientific reference for decision makers.

Many sectors that use LCA require evaluation results to be of an increasingly high quality. Hence, there is a need for characterization models to include toxicity persistence and bioaccumulation assessments as well as generic exposure/effects assessment.

Furthermore, future LCAs of products such as cotton, which have long chains and are related to many regions during their entire life time, should involve a site-specific exposure/effects assessment.

CONCLUSIONS

We reviewed LCA research findings on the environmental burden of cotton fibers and textile products, which considered the degree to which eco-products or strategies can reduce the environmental impacts in comparison to convention cotton.

It can be concluded that cotton cultivation significantly contributes to the environmental burden of cotton due to the use of water, fertilizers, and pesticides. Cotton cultivation that is located in regions where precipitation can meet the water demand and evaporation is low is recommended if they do not increase the burden on local blue water resources.

Furthermore, the cultivation of organic cotton can significantly reduce the environmental burden of cotton fiber. During the manufacturing phase, the use of water, energy, and chemicals is traditionally high. Alternative chemicals that reduce the environmental burden should be encouraged. In addition, cleaner consumption is more important than cleaner production due to the significant contribution of the use phase to global warming and water scarcity. Consumption habits such lower water temperatures during clothes washing and the use of second-hand clothing should also be encouraged for consumers.

LCIA based on regional differences may be the next step for assessing the environmental burden of cotton due to the global consumption and production of cotton textiles. Regionalized LCIA is a credible method for i) determining the optimal locations for factories or suppliers, and ii) resource management and sustainable development. Moreover, comprehensive impact categories with a cradle to grave approach can disclose the environmental burden. The risk of simply shifting pollution and other environmental issues from one phase to another could be avoided by using more developed LCA methods that have the potential to cover the significant impacts in various categories. A credible LCA of cotton can support sustainable decision-making by providing a comprehensive and structured account of the potential environmental impacts.

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ADDITIONAL INFORMATION

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