sustainability

Article

Evaluating Environmental Impact of Natural and Synthetic Fibers: A Life Cycle Assessment Approach

Victoria Gonzalez, Xingqiu Lou * and Ting Chi

Department of Apparel, Merchandising, Design and Textiles, Washington State University, Pullman, WA 99164, USA; victoria.gonzalez@wsu.edu (V.G.); tchi@wsu.edu (T.C.)
* Correspondence: xingqiu.lou@wsu.edu

Abstract: This research aims to analyze the environmental impact of six fibers in the textile industry: conventional and organic cotton, silk, jute, flax, and polyester. The study used a life cycle assessment (LCA) methodology with a cradle-to-gate system boundary and analyzed the stages of agriculture, spinning, weaving, and dyeing. In agriculture production, five impact categories (i.e., fossil resource scarcity, global warming, land use, terrestrial ecotoxicity, and water consumption) have the most significant differences across these fibers. Polyester production significantly impacted the terrestrial ecotoxicity impact category, while stratospheric ozone depletion had a minor impact. In yarn preparation and spinning, silk has the most significant impact in most categories, followed by conventional cotton, while jute had the most minimal impact. In weaving, the most visible differences were in fossil resource scarcity, global warming, land use, terrestrial ecotoxicity, and water consumption. Conventional cotton dyeing showed significant impacts on global warming potential and terrestrial ecotoxicity. This study contributes to the limited literature on existing LCA research in the textile industry. Adding updated information will help increase the comprehension of LCA research and guide stakeholders in transitioning fashion supply chains more sustainably.

Keywords: life cycle assessments; natural fibers; synthetic fibers; textiles; environmental impact; sustainable fashion

check for updates

Citation: Gonzalez, V.; Lou, X.; Chi, T. Evaluating Environmental Impact of Natural and Synthetic Fibers: A Life Cycle Assessment Approach. *Sustainability* **2023**, *15*, 7670. https://doi.org/10.3390/su15097670

Academic Editor: Cinzia Buratti

Received: 29 March 2023
Revised: 4 May 2023
Accepted: 5 May 2023
Published: 7 May 2023

1. Introduction

Apparel products undergo a series of different stages in their lifecycle, including raw material extraction, processing, manufacturing, and end-of-life [1]. Each stage of the apparel lifecycle yields different environmental impacts due to different production and consumption practices. The substages of the apparel lifecycle include fiber and yarn production, textile and apparel manufacturing, packaging, transportation and distribution, consumer use, and end of life or disposal [2]. In the raw material extraction stage, conventional cotton cultivation generates a large number of ammonia emissions and requires extensive energy use [3,4]. The apparel and textile manufacturing stage consist of yarn spinning, dyeing, weaving, knitting, and fabric finishing [5]. Spinning alone creates significant environmental impacts. Gomez-Campos et al. [6] performed a life cycle assessment (LCA) on flax fiber and discovered that the spinning and weaving processes contributed more than 60% to all impact categories evaluated. Similarly, Dissanayake et al. [7] identified spinning as the leading provider of generated environmental impact. Moazzem et al. [8] found that the most significant impact created for climate change was caused by the textile processing stage of manufacturing a polyester jacket and the electricity consumed in this stage. The finishing processes in this stage also require abundant water and energy [2]. In addition, transporting textile and apparel products emits significant greenhouse gas emissions (GHG) [9]. The consumer use phase significantly contributed to the fossil fuel impact category [10]. Lastly, when garments reach their end-of-life stage, the majority are thrown away in landfills. There were 208 million pounds of textile waste generated in 2019, among which, only 14.7% were recycled [11]. The textile and apparel industry's waste and resource utilization make a clear case for implementing more sustainable innovation.

The type of fiber utilized for apparel products has different sources and production requirements and yields different environmental impacts across the product's lifecycle. The six fibers analyzed in this study include 100% conventional cotton, 100% organic cotton, 100% polyester, 100% jute, 100% flax, and 100% silk. Conventional cotton, polyester and flax were selected due to their significant market share size: cotton held 58% of the market in China, polyester held 54% of the global fiber output volume in 2021, and flax held 50% market share in China [12–14]. Jute was selected not only for its mechanical performance when utilized to reinforce polymer composites [15], but also because it holds the largest market share (50%) of all other plant-based fibers [16]. Organic cotton is expected to experience a compound annual growth rate of 6.8% from 2022–2029 [17]. A total of 342,265 tonnes of fiber were harvested in 2020–2021 [18]. In addition, Ellis, McCracken and Skuza [19] discovered that consumers would pay 25% more for organic cotton t-shirts. Companies such as Nudie Jeans went from creating their first organic cotton t-shirt in 2004 to convert to 100% organic cotton use in all of their cotton products in 2017 [20]. Although other fibers, such as silk, may take up smaller market shares, it is still a vital fiber type, as approximately 300,000 households are engaged in raw silk production [12,16].

Life Cycle Assessment (LCA) offers a comprehensive understanding of environmental implications by systematically compiling and quantifying inputs and outputs throughout the entire life cycle of a product or service. There are several LCA studies evaluating the environmental impacts of textile products. However, most of them focused on limited product life cycle stages [21]. Other LCAs concentrated on one specific type of fiber or a limited number of fibers (e.g., cotton/polyester, cotton/organic cotton). The diverse chemistry of natural plant fibers, which are mainly composed of lignin and cellulose [22], introduces a high level of complexity in estimating their LCA [23]. Additionally, limited data availability is not a new concept in LCAs, which lead to inaccurate results or data uncertainties, especially in developing countries. Since LCA results depend on the quality of inventory data [3], additional life cycle inventory studies need to be performed to advance the reliability and reduce the number of uncertainties [24,25]. Increasing the application of life cycle assessments in the fashion industry and collecting relevant life cycle inventory data is essential to maintain the consistency of life cycle assessments.

The purpose of this study is to analyze and quantify six commonly used fibers in the textile and apparel industry by comparing their potential environmental impacts created at each stage of the supply chain. This research enhances the understanding of LCA in the textile and apparel industry and provides new insights from underexplored angles. The findings of this research guide stakeholders when choosing which countries are the most sustainable and regulated to produce their products in, which processes of specific natural and synthetic fibers are the most environmentally damaging, and how to enhance these processes.

2. Literature Review

2.1. Life Cycle Assessment (LCA)

Life cycle assessment is a well-established method that has been widely applied to evaluate textile and apparel products in their lifecycle stages. These stages include raw material extraction, fiber processing, textile and apparel manufacturing, distribution, consumer use, and end-of-life [26]. LCA uses either a "cradle-to-gate" or "cradle-to-grave" analysis technique when assessing the potential environmental impacts of these products. Cradle-to-gate is an assessment of a partial product life cycle from raw material extraction to manufacturing, excluding the stages of transportation, retail sales, consumer use, and end-of-life. Cradle-to-grave covers the entire lifecycle of a product. Furthermore, LCA quantifies the amount of impact created by each stage of the supply chain and initiates a starting point for possible reductions, also referred to as "hotspots". These hotspots help supply chain stakeholders identify the most destructive processes in their value chain and evaluate opportunities when seeking to transition to a more sustainable supply chain.

The International Organization for Standardization (ISO) standard framework published a standard framework that outlines four stage of a life cycle assessment [27]. ISO 14040 describes the principles and framework for LCA, while ISO 14044 specifies requirements and provides guidelines for LCA. The goal identifies the objectives and the expected products of the LCA study. The scope identifies the system boundary, the functional unit, and the methodology used in the study. The functional unit quantifies a product or product system based on the performance it delivers [28]. The functional unit is a core characteristic of LCAs because it facilitates impartial comparisons across different products or systems [28]. The system boundary is the limit for which product life cycle processes will be included in the assessment [29]. The results from life cycle inventories of a product system are evaluated utilizing life cycle impact assessment (LCIA) [30]. The life cycle impact assessments combine consumed resources and generated output data (e.g., emissions), which are converted into environmental impact categories [31]. The most commonly used impact assessment methodologies include USEtox 2.01, ReCiPe, CML, Eco-indicator 99, and TRACI 2.1 [31]. Each of these methodologies investigates different impact categories. The final stage of a life cycle assessment is interpreting the assessment's results. After the modeling, quantified amounts are provided in a correlating unit for each impact category. The numbers are analyzed regarding their relevance to the given context or industry. These quantified amounts for each impact category highlight specific processes or materials that yield more significant environmental damage than others. The more detrimental processes emphasize good starting points that hold high reduction potential, also referred to as "hot spots" [8]. Life cycle assessment results are essential to communicate to critical stakeholders. They can demonstrate how to transition to a more sustainable supply chain.

2.2. Environmental Impact of Each LCA stage

2.2.1. Raw Materials Extraction

During raw material extraction, natural fibers are cultivated and harvested. Cotton, the most widely used natural fiber in apparel production, has a significant impact on various categories due to its heavy use of water, land, fertilizers, pesticides, and energy [12]. La Rosa and Grammatikos [3] found that 1 ton of cotton textile requires 1736 m^3 of water. Additionally, Moazzem et al. [12] reported that 0.63–0.95 MJ of electricity is required per production of 1 kg of cotton. Moreover, cotton utilizes 26% of global pesticide use [32].

Polyester is one of the world's most popular choices of synthetic material. Polyester depends on energy-intensive processes and non-renewable resource use such as petroleum. Polyester production involves extracting crude oil and refining it to create blocks for PET and other industrial uses [33]. The conversion of polyester from a chemical block to a textile is an energy-intensive process. Poly-condensation, which is a sub-process of the polymer synthesis phase, requires high temperatures of 290 °C (554 °F) and inputs of catalysts such as metal oxides and metal acetates [34]. These high temperatures result in enormous carbon dioxide (CO_2) burdens [33].

2.2.2. Textile Manufacturing

Textile manufacturing stage includes weaving, knitting, dyeing, finishing, bleaching, all of which require significant energy. During this stage, the natural and synthetic fibers are turned into yarns to create textile fabrics. Cotton spinning can take up to 3984 kWh of energy [35]. Moazzem et al. [12] discovered that the spinning process was most burdensome to climate change potential, abiotic depletion, and acidification categories. Knitting process requires 926 MJ of electricity, while weaving process demands 10,430 MJ energy [36]. Dyeing and finishing are significant drivers of environmental impact and emissions. For example, the dyeing stage of a cotton t-shirt causes the most significant portion of abiotic depletion damage due to the significant amounts of coal, steam, water, dyes, and auxiliaries required [37]. Additionally, dyeing and finishing is responsible for 20% of global water pollution [33]. For example, batch dyeing requires 150 L of water used per 1 kg of fabric dyed [33].

2.2.3. Transportation

Consumer goods are typically transported via sea and air freight because of the large distances between manufacturing and retail locations. Consumer transport activities constitute the second-largest carbon footprint provider, with emissions of almost 600,000 tonnes of CO_2 [12]. Van der Velden et al. [24] estimated that shipping textile products from China generates approximately 0.16 kg CO_2 eq per kg of textile. Limited data are available on transportation from different regions. In most cases, LCAs rely on outdated transport inventories or a small pool of existing sources, leading to less accuracy in impact calculations.

2.2.4. Consumer Use

The consumer use stage involves care activities performed on garments, such as washing, drying, and ironing. These activities vary by region. For example, washing clothes without changing the water temperature is standard in China, but not in the US and other countries [38]. Energy consumption and CO_2 emissions vary depending on the temperature and load size used during washing [39]. In addition, Zhang et al. [37] discovered that 45.4% of the total electricity consumed in the use stage is because of electric drying and ironing activities. The footprints generated in the use stage depend on user behavior, which is highly variable according to the country of origin, climate, age, and lifestyle [38]. The use phase accounts for only 7.3% of the total environmental impacts generated throughout the product life cycle in China, while in the U.S., this stage accounts for 84% of the lifecycle impact [37,40].

2.2.5. End of Life

Clothing disposal methods include landfilling, donation, give away, resale, swapping and reuse [41]. In the U.S. and Japan, 80% of apparel ends up in landfills, while in Australia, 35% is reused in charity shops, 40% is exported for overseas reuse, and 25% is landfilled [42]. Incineration methods are preferred in some countries. In the Netherlands, 67% of discarded clothes go into a municipal waste incinerator. However, incineration is an energy-intensive and highly emitting process. Some regions are trying to combat these unsustainable disposal processes. For example, the European Union mandated all residents to separate their textile waste into dedicated bins by 2025 [33]. While these are steps in a more sustainable direction, further change at a larger scale is necessary.

2.3. Different Fibers' Environmental Impacts

2.3.1. Conventional Cotton

Conventional cotton is one of the most widely chosen fibers amongst consumers, as they spent approximately $38.54 billion on this fiber from 2019–2020 [43]. However, its production entails substantial environmental impacts. Cotton cultivation requires substantial amounts of fertilizers, pesticides, and energy, resulting in adverse effects on the environment and human health [44]. Moazzem et al. [8] reported that 98.37% of the agricultural land occupation impact in textile production is contributed by the textile production stage, with cotton raw fiber production accounting for 96.53% of that impact. In China, 3.5×106 hectares of agricultural land were used for cotton planting in 2015 [44]. Comparing cotton with other natural fibers, La Rosa and Grammatikos [3] found that cotton cultivation and yarn production consumed the most energy. Irrigation and fertilizer use in cotton cultivation contribute to water depletion, further adding to its environmental impact [35]. Other heavy resource requirements for cotton include the amount of energy needed to spin cotton yarns. Liu et al. [35] found that 3984 kWh of electricity was required for the spinning stage. Similarly, Kazan, Akgul, and Kerc [45] found that the highest global warming potential impact (GWP) was created by electricity used in the cotton yarn production phase.

2.3.2. Organic Cotton

Organic cotton is a growing sustainable alternative to conventional cotton. According to Textile Exchange [46], demand for organic cotton products increased by 31% from the previous year. Organic cotton is grown without chemical inputs such as fertilizers, herbicides, insecticides, growth regulator or stimulators, boll openers, or defoliants [47]. Fidan et al. [48] conducted a comparative LCA study and found that denim fabric made with organic cotton scored lower in every environmental impact category than conventional cotton denim. For example, organic cotton cultivation caused a large decrease in the aquatic eutrophication potential category compared to conventional cotton cultivation [4]. Sener Fidan et al. [49] found that the overall GWP impact was reduced from 20.11 kg CO_2 eq. to 19.48 kg CO_2 eq. when switching from conventional to organic cotton. This reduction in GWP impact is mainly attributed to the limited use of fertilizers and pesticides when producing organic cotton [49]. In addition, the use of organic cotton led to a 47.6% increase in the freshwater aquatic ecotoxicity potential (FAEP) impact category [49].

2.3.3. Jute

Jute and other bast fibers such as hemp have been gaining attention in industrial applications [50,51] due to their superior mechanical properties compared to other natural fibers [15]. Understanding the interactions between plant fibers and other materials is crucial to effectively utilizing these fibers in various applications [52]. Additionally, jute has environmental advantages over cotton, as it requires much less water to grow and has lower impacts in impact categories such as human toxicity and acidification. Jute consistently scores lower than cotton in categories such as water resource depletion, cumulative energy demand, acidification, and eutrophication [3].

2.3.4. Flax

Flax is another sustainable alternative fiber that is growing in popularity. Garel [53] reported that 25% increase in its usage in 2020 compared to 2019. Flax has one of the lowest environmental impacts in its production processes compared to other virgin fibers [21]. When comparing flax with cotton, flax requires lower inputs but produce higher yields [3,12,54]. In terms of environmental impact, flax has significantly lower GHG emissions, energy use, and water usage compared to cotton [55]. Moazzem et al. [8] discovered that flax fiber significantly reduced acidification potential, agricultural land occupation, and water demand impacts. In this context, hemp and flax are suitable alternatives to other plant fibers, with annual productions in the United States of 1.0–5.0 tons per hectare (flax-hemp), much greater than the 0.8–0.9 tons per hectare produced in the case of conventional cotton [56]. Flax has also been found to have a smaller environmental impact in its raw material extraction phase compared to other fibers such as hemp, jute, polyester, and silk [21].

2.3.5. Silk

Silk is a luxurious, biodegradable natural fiber that has significant environmental impacts in its production [57]. Munasinghe, Druckman, and Dissanayake [21] stated that silk created in India has the highest environmental impact during the raw material extraction phase, with GHG emissions of 52.5 kg CO_2 eq/kg, energy usage of 1467.3 MJ/kg, and water usage of 26,700 L/kg [58]. Astudillo et al. [58] discovered that silk possesses the highest energy usage. Previous research has identified mulberry production as an environmental hotspot in the silk supply chain, particularly in the categories of freshwater ecotoxicity, human toxicity, and terrestrial ecotoxicity [57–59]. These impacts were primarily due to soil maintenance, which involved the use of phosphorous or organic fertilizers that generated metal emissions to water and soil [57]. Water depletion was also identified as a significant impact of mulberry production [57]. While silk is valued for its luxurious feel and longevity [60], further research is needed to fully understand the environmental impacts of silk production.

2.3.6. Polyester

Polyester is a dominant synthetic fiber, accounting for more than half of global annual fiber production [18]. The market size for synthetic fibers reached $59.95 billion USD in 2020, with an expected CAGR of 6.6% from 2021–2028 [61]. Despite its widespread use, polyester has significant environmental impacts. Moazzem et al. [8] found that the electricity used in the textile-processing phase for a polyester knit jacket contributed the highest impact to the climate change potential (CCP) category, followed by the fiber-processing phase. The dyeing and finishing stage of polyester was ranked as the most unsustainable stage, followed by the yarn-preparation and fiber-production stages [33]. The production stage was found to be the most detrimental to all impact categories, requiring up to 125 MJ/kg polyester fiber [33,62].

3. Methodology

The study utilized data from the Ecoinvent v3.8 database for input and output data in LCI results. All the production processes referenced in the Ecoinvent v3.8 database were filtered with a "rest of world (RoW)" location variable. The RoW location signifies the world, excluding all local geographies where a process occurs in the database [63]. The functional units for the agricultural phase are as follows: flax (1 kg flax green matter), jute (1 kg of jute plant), conventional cotton (1 kg of seed-cotton), organic cotton (1 kg organic seed-cotton), and silk (1 kg cocoons). A cradle-to-gate system boundary was utilized in this research. The agricultural stage includes field activities such as cultivation, soil preparation, inputs of all required materials (e.g., seeds, water, fertilizers, etc.), egg incubation, and other relevant upstream processes. The functional unit for the spinning stage is 1 kg of yarn of the fibers analyzed in this stage (e.g., jute, silk, and cotton), starting from the cradle and including all upstream processes. The dyeing dataset encompasses all upstream processes that produce 1 kg of dyed conventional cotton fabric.

The LCI results were then assigned to impact categories based on the ReCiPe (2016) methodology. The ReCiPe Midpoint (I) (2016) methodology is one of the most commonly utilized methodologies in LCA academic research [5,26,64,65]. Midpoints represent an environmental mechanism in the cause-effect chain of a particular impact category prior to the endpoint, at which, characterization factors can be calculated to reflect the relative importance of emission or extraction in a Life Cycle Inventory (LCI) (e.g., global warming potentials defined in terms of radiative forcing and atmospheric half-life differences) [66]. The impact categories include climate change, ozone depletion, terrestrial acidification, freshwater eutrophication, marine eutrophication, human toxicity, photochemical oxidant formation, particulate matter formation, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, ionizing radiation, agricultural land occupation, urban land occupation, natural land transformation, depletion of fossil fuel resources, depletion of minerals, and depletion of freshwater resources.

4. Results and Discussion

4.1. Agricultural Production

Natural fibers require different agricultural practices. For cotton varieties, these practices include sowing, harvesting, washing, ginning, spinning, and distribution. In contrast, for other bast fibers such as jute and flax, although the harvesting phases are similar, these fibers undergo different processing than cotton. Silk is a unique natural fiber that is developed through a distinct process. The production of silk fiber involves harvesting mulberry trees, which serve as the only food source for silkworms [57]. These worms are then allowed to cocoon, after which, the cocoons are boiled to extract the fiber. The resulting fibers are then further processed to be spun into fibers. In contrast, polyester fiber is a synthetic fiber that is produced in a chemical lab rather than on a farm. Despite this difference, the outcomes of its processing are still compared to the five natural fibers analyzed in this study to enhance the amount of LCAs comparing natural and synthetic fibers. Given the vast range of agriculture activities required to create different natural fibers, evaluating the sustainability footprint behind these practices is critical. Table 1 compares agricultural and production procedures for the six fibers analyzed in this study. The results indicate that five impact categories (i.e., fossil resource scarcity, land use, global warming, water consumption, and terrestrial ecotoxicity) have the most significant differences across these fibers (Figure 1).

Table 1. Environmental Impact in Agriculture Production Processes.

Impact Category	Silk	Conventional Cotton	Organic Cotton	Flax	Jute
Fine particulate matter formation (kg PM2.5 eq)	0.01216	0.00068	4.69950×10^{-5}	0.00015	0.00014
Fossil resource scarcity (kg oil eq)	2.59640	0.21201	0.01708	0.02071	0.00943
Freshwater ecotoxicity (kg 1,4-DCB)	0.77849	0.17624	0.03973	0.00743	0.00491
Freshwater eutrophication (kg P eq)	0.00676	0.00097	0.00611	3.00837×10^{-5}	0.00013
Global warming (kg CO_2 eq)	18.66263	1.35726	0.46731	0.17942	0.14672
Human carcinogenic toxicity (kg 1,4-DCB)	0.05845	0.00028	0.00019	0.00051	0.00056
Human non-carcinogenic toxicity (kg 1,4-DCB)	0.38301	1.98380	0.00892	0.00341	0.00421
Ionizing radiation (kBq Co-60 eq)	0.57408	0.02449	0.02011	0.00253	0.00146
Land use (m2a crop eq)	12.30352	1.91413	7.39269	0.09064	0.18001
Marine ecotoxicity (kg 1,4-DCB)	0.22382	0.04104	0.01228	0.00182	0.00120
Marine eutrophication (kg N eq)	0.01411	0.00582	0.01194	0.00068	0.00034
Mineral resource scarcity (kg Cu eq)	0.05903	0.00464	0.00035	0.00068	0.00027
Ozone formation, Human health (kg NOx eq)	0.06708	0.00563	0.00304	0.00070	0.00031
Ozone formation, Terrestrial ecosystem (kg NOx eq)	0.06816	0.00570	0.00361	0.00071	0.00031
Stratospheric ozone depletion (kg CFC11 eq)	6.87856×10^{-5}	7.21148×10^{-6}	8.28099×10^{-6}	1.27404×10^{-6}	4.93978×10^{-7}
Terrestrial acidification (kg SO_2 eq)	0.18559	0.01514	0.01048	0.00275	0.00105
Terrestrial ecotoxicity (kg 1,4-DCB)	26.47910	2.57065	0.20721	0.20165	0.10487
Water consumption (m^3)	3.90515	0.36277	0.00668	0.06240	0.05661

Note: DCB: Dichlorobenzidine; CFC: Chlorofluorocarbon.

Silk has the highest impacts across all impact categories, except for human non-carcinogenic toxicity (0.38301 kg 1,4-DCB), compared to other natural fibers analyzed. Terrestrial ecotoxicity is one of the impact categories where silk production generates the largest impact (26.47910 kg 1,4-DCB). Previous silk studies have identified hotspots for terrestrial ecotoxicity as being caused by soil maintenance activities, such as the emissions of phosphorous to water and soil, the transport of organic fertilizers, and the emission of metals to soil [57]. The global warming category was another leading impact for silk production, with a value of 18.66263 kg CO_2 eq, which is significantly higher than the global warming values for all other fibers analyzed (excluding polyester), which ranged from 0.4–1.3 kg CO_2 eq. Barcelos et al. [57] identified transportation of mulberry leaves, production of Kraft paper used for covering silkworms, and electricity production as significant contributors to this category. These activities generated significant emissions of CO_2, CH_4, and N_2O into the air. Land use generated a value of 12.30352 m2a crop eq, and stratospheric ozone depletion created a value of 6.87856×10^{-5} kg CFC11 eq.

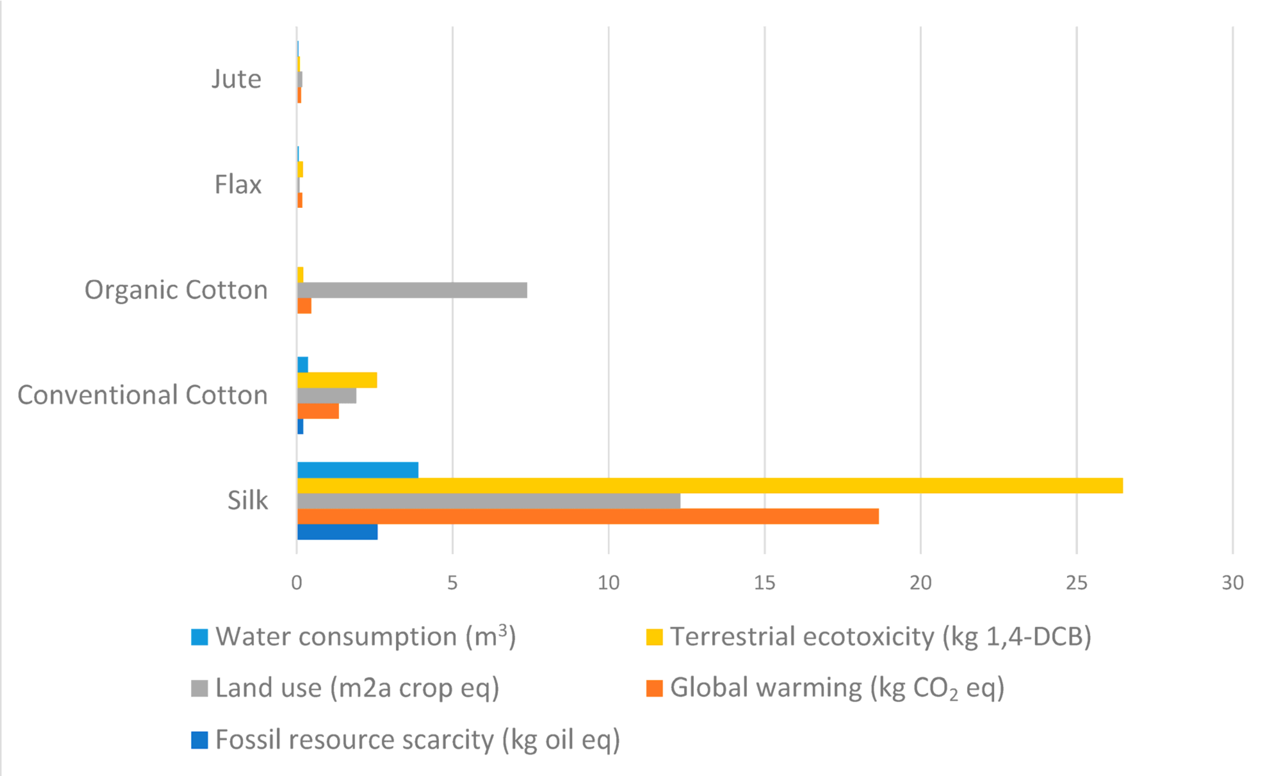

Figure 1. Different Environmental Impacts in Agricultural Process.

Conventional cotton has the most significant impact on human non-carcinogenic toxicity, which is characterized by the persistence, bioaccumulation, and toxicity of chemicals that do not pose a carcinogenic risk to humans [65]. One of the primary contributors to this impact is the use of pesticides in cotton farming. Papadakis et al. [67] detected traces of parathion methyl, a commonly used pesticide in cotton agronomy, in bodies of water in northern Greece, posing a low risk to humans if ingested via drinking water. Comparing conventional cotton with organic cotton, conventional cotton consistently generates more environmental except for freshwater eutrophication, land use, marine eutrophication, and stratospheric ozone depletion, which aligns with previous literature [3,49,68]. Notably, organic cotton seeds are not genetically modified. As a result, more land is needed to produce the same amount of fiber as conventional cotton, resulting in a significant difference in land use values between the two fibers, with organic cotton requiring 7.39269 m2a crop eq and conventional cotton requiring 1.91413 m2a crop eq [69]. In contrast, jute has the least significant impact in most categories, with a few exceptions, such as fine particulate matter formation, freshwater eutrophication, human non-carcinogenic and carcinogenic toxicity, land use, and water consumption. Flax consistently generated a higher impact than jute in most impact categories, except for human carcinogenic and non-carcinogenic toxicity, freshwater eutrophication, and land use. Since organic certification of both flax and jute is limited [18,70], this study assumes that fertilizers and insecticides are used in their agricultural production activities, contributing to emissions for this impact category. Moreover, the use of chemicals in agriculture production activities increase the soil phosphorous and nitrogen levels, leading to freshwater eutrophication, which damages the freshwater ecosystem and results in the loss of freshwater species [65]. Despite flax's higher impact than jute in the agriculture phase, its impact is minor compared to cotton varieties, which is consistent with previous literature [3].

Polyester was the only synthetic fiber analyzed in this study. As presented in Table 2, polyester production significantly impacted the terrestrial ecotoxicity impact category, while stratospheric ozone depletion had a minor impact. In contrast to natural fibers, which are impacted by anthropogenic activities during cultivation and harvesting, the synthetic origin of polyester contributes to its lower impact value in the ozone depletion category. Aside from agricultural emissions, sulfuric acid and steam are common factors that contribute to terrestrial ecotoxicity [71]. The surface of polyester fabric is sometimes treated with sulfuric acid and blended with petroleum products [72], which are significant contributors to its greater terrestrial ecotoxicity impact. The second-largest impact category for polyester was global warming, consistent with Moazzem et al.'s [8] finding that polyester apparel had a higher impact on the climate change potential category than apparel made of cotton, viscose, or flax. Polyester fiber creation depends on energy and heat-intensive processes, contributing to the global warming impact category. Khabbaz [73] also found that polyester requires more energy than flax, conventional cotton, wool, and polypropylene.

Table 2. Environmental Impact in Polyester Fiber Production Process.

Impact Category	Polyester
Fine particulate matter formation (kg PM2.5 eq)	0.00232
Fossil resource scarcity (kg oil eq)	1.91054
Freshwater ecotoxicity kg 1,4-DCB)	0.12778
Freshwater eutrophication (kg P eq)	0.00109
Global warming (kg CO_2 eq)	5.08799
Human carcinogenic toxicity (kg 1,4-DCB)	0.00133
Human non-carcinogenic toxicity (kg 1,4-DCB)	0.11459
Ionizing radiation (kBq Co-60 eq)	0.21618
Land use (m2a crop eq)	0.04253
Marine ecotoxicity (kg 1,4-DCB)	0.03775
Marine eutrophication (kg N eq)	0.00035
Mineral resource scarcity (kg Cu eq)	0.00983
Ozone formation, Human health (kg NOx eq)	0.00994
Ozone formation, Terrestrial ecosystems (kg NOx eq)	0.01099
Stratospheric ozone depletion (kg CFC11 eq)	4.48697×10^{-5}
Terrestrial acidification (kg SO_2 eq)	0.01253
Terrestrial ecotoxicity (kg 1,4-DCB)	6.28966
Water consumption (m^3)	0.05444

Note: DCB: Dichlorobenzidine; CFC: Chlorofluorocarbon.

4.2. Yarn Preparation and Spinning

Spinning is the process of converting fibers into yarn, and it involves various fiber-machine interactions [74,75]. The three fibers analyzed in the yarn preparation and spinning stage are conventional cotton, jute, and silk. Cotton spinning procedures include picking, carding, combing, drawing, and roving [35]. Silk, on the other hand, begins with removing and unwinding the filaments from water-softened cocoons, which are then combed and wound onto reels [76]. The cocoons are cooked in boiling water to remove the filament from the cocoon. As the cocoons wait to be converted into yarn, they are continuously heated in water at 33–40 °C (86–104 °F) [76]. Jute, due to its natural stiffness and harshness, requires conditioning with water and oil to improve its spin-ability [77].

As shown in Table 3, silk has the highest impact in most categories, except for human non-carcinogenic and marine eutrophication. This is consistent with the findings of Astudillo et al. [58], who also identified silk as having the largest environmental impact across most of the categories analyzed. The maintenance of a constant temperature 33–40 °C (86–104 °F) required in the silk spinning process to remove the filament from the cocoon could be one potential catalyst for silk's significant impact in this stage. The silk fiber is transferred to reels to be spun into yarns in an energy-intensive process that also contributes to the global warming potential impact category (GWP). Astudillo et al. [58] mention that drying is known to have positive effects on the reeling process but is not used widely in India, making the reeling process more intensive and potentially contributing to the significant GWP value.

Table 3. Environmental Impact in Yarn Preparation and Spinning Processes.

Impact Category	Silk	Conventional Cotton	Jute
Fine particulate matter formation (kg PM2.5 eq)	0.04508	0.00390	0.00219
Fossil resource scarcity (kg oil eq)	8.35746	1.06841	0.27824
Freshwater ecotoxicity (kg 1,4-DCB)	2.45208	0.50770	0.06128
Freshwater eutrophication (kg P eq)	0.02071	0.00493	0.00337
Global warming (kg CO_2 eq)	58.73085	6.10840	1.43662
Human carcinogenic toxicity (kg 1,4-DCB)	0.16822	0.00172	0.00841
Human non-carcinogenic toxicity (kg 1,4-DCB)	1.20376	3.29710	0.04166
ionizing radiation (kBq Co-60 eq)	1.92351	0.31969	0.07269
Land use (m2a crop eq)	39.19282	6.14138	1.23939
Marine ecotoxicity (kg 1,4-DCB)	0.71172	0.12500	0.01758
Marine eutrophication (kg N eq)	0.04029	0.04535	0.00264
Mineral resource scarcity (kg Cu eq)	0.19043	0.01542	0.00354
Ozone formation, Human health (kg NOx eq)	0.21466	0.02178	0.00591
Ozone formation, Terrestrial ecosystems (kg NOx eq)	0.21871	0.02236	0.00614
Stratospheric ozone depletion (kg CFC11 eq)	0.00021	3.47452×10^{-5}	4.78876×10^{-6}
Terrestrial acidification (kg SO_2 eq)	0.54505	0.06535	0.01284
Terrestrial ecotoxicity (kg 1,4-DCB)	85.33574	8.00630	1.86305
Water consumption (m^3)	10.92839	4.68017	0.26624

Note: DCB: Dichlorobenzidine; CFC: Chlorofluorocarbon.

Additionally, conventional cotton has the second most leading significant impact in most categories, which is in line with the previous research [8]. According to Liu et al. [35] fiber acquisition is a primary contributor to the climate change category, primarily due to the electricity and water use required at this stage. Laursen et al. [78] further highlighted that spinning cotton yarn for a 100% cotton t-shirt accounted for 56% of the electricity consumption in yarn production. Additionally, conventional cotton's impact on the ionizing radiation stage could be attributed to coal burning for the machinery required to turn the fiber into a yarn [65]. The heavy reliance and increasing demand for fossil fuels in yarn production further contribute to the fossil resource scarcity category.

Jute had the least significant impact in all impact categories. Although jute's impact on most impact categories is minor, it generated the second most significant impact in the human carcinogenic toxicity category. This result is consistent with Alves et al.'s [79] study, which found that jute composites created more impact than glass composites in human health-related categories due to heightened respiratory inorganic impacts from energy consumption associated with fabric production of fibers and bonnets. Additionally, one potential explanation for jute's minor impact in the ionizing radiation category is the utilization of updated machinery in jute spinning that does not rely on coal burning for its energy source.

4.3. Weaving

Table 4 presents the impact category values for the weaving sub-stage, with available data for silk, jute, and conventional cotton. Silk had the highest impact across most categories, while jute had the lowest impact, except for freshwater eutrophication. The categories with the most significant differences are fossil resource scarcity, global warming, land use, terrestrial ecotoxicity, and water consumption. According to Babu [76], the modern silk weaving process involves the use of advanced shuttle-less looms such as Rapier and Air jet, which have replaced the traditional handloom method. However, this transition to an industrialized process is one of the factors contributing to the significant impact of silk production on global warming and fossil resource scarcity. Notably, conventional cotton had the lowest impact in the freshwater eutrophication category, which is surprising, given its high impact in the same category for 100% cotton jeans in Luo et al.'s [80] LCA.

Table 4. Environmental Impact in Weaving Process.

Impact Category	Silk	Conventional Cotton	Jute
Fine particulate matter formation (kg PM2.5 eq)	0.05115	0.00892	0.00267
Fossil resource scarcity (kg oil eq)	9.77103	2.30443	0.41688
Freshwater ecotoxicity (kg 1,4-DCB)	2.84419	0.69504	0.07891
Freshwater eutrophication (kg P eq)	0.02384	0.00744	0.00354
Global warming (kg CO_2 eq)	65.92711	12.43288	1.92720
Human carcinogenic toxicity (kg 1,4-DCB)	0.17942	0.00325	0.00878
Human non-carcinogenic toxicity (kg 1,4-DCB)	1.36387	3.96103	0.05134
Ionizing radiation (kBq Co60 eq)	2.72661	0.59590	0.09226
Land use (m2a crop eq)	41.39808	7.34410	1.24967
Marine ecotoxicity (kg 1,4-DCB)	0.82466	0.17629	0.02278
Marine eutrophication(kg N eq)	0.04259	0.05371	0.00266
Mineral resource scarcity (kg Cu eq)	0.21933	0.02043	0.00424
Ozone formation, Human health (kg NOx eq)	0.23444	0.03490	0.00738
Ozone formation, Terrestrial ecosystems (kg NOx eq)	0.23891	0.03569	0.00763
Stratospheric ozone depletion (kg CFC11 eq)	0.00022	4.21589×10^{-5}	4.92586×10^{-6}
Terrestrial acidification (kg SO_2 eq)	0.59007	0.9110	0.01465
Terrestrial ecotoxicity (kg 1,4-DCB)	94.59827	11.70685	2.59627
Water consumption (m^3)	11.52624	5.54420	0.26847

Note: DCB: Dichlorobenzidine; CFC: Chlorofluorocarbon.

4.4. Dyeing

The dyeing stage only had data available for conventional cotton batch dyeing techniques, with all other fibers excluded. Table 5 shows the impact category values for conventional cotton in this sub-stage. One of the most substantial impacts created during the dyeing stage was global warming, which is consistent with Zhang et al.'s [37] finding that the dyeing process accounts for 34.79% of GWP. Zhang et al. [37] attributed this immense impact contribution to direct CO_2 emissions resulting from the burning of hard coal to generate steam for this stage. Terrestrial ecotoxicity is another high impact category in cotton batch dyeing. According to Yacout et al. [81], the release of nickel and zinc from dyes has an impact on the terrestrial ecotoxicity category. Water consumption had a relatively smaller impact compared to other impact categories. This aligns with Cotton Inc.'s [36] report, which highlighted that water use for knit fabric accounts for only 19% of the water consumption in the dyeing process. The textile industry is known to utilize toxic substances into their industrial processes, often leading to the release of metals, solvents, and dyes into numerous environmental categories [81].

Table 5. Conventional Cotton Batch Dyeing Environmental Impact.

Impact Categories	Result
Fine particulate matter formation (kg PM2.5 eq)	0.00127
Fossil resource scarcity (kg oil eq)	1.18711
Freshwater ecotoxicity (kg 1,4-DCB)	0.11466
Freshwater eutrophication (kg P eq)	0.00090
Global warming (kg CO_2 eq)	4.53564
Human carcinogenic toxicity (kg 1,4-DCB)	0.00156
Human non-carcinogenic toxicity (kg 1,4-DCB)	0.07088
Ionizing radiation (kBq Co60 eq)	0.16172
Land use (m2a crop eq)	0.02878
Marine ecotoxicity (kg 1,4-DCB)	0.03497
Marine eutrophication(kg N eq)	0.00051
Mineral resource scarcity (kg Cu eq)	0.00404

Table 5. *Cont.*

Impact Categories	Result
Ozone formation, Human health (kg NOx eq)	0.00566
Ozone formation, Terrestrial ecosystems (kg NOx eq)	0.00581
Stratospheric ozone depletion (kg CFC11 eq)	9.61629×10^{-7}
Terrestrial acidification (kg SO_2 eq)	0.01037
Terrestrial ecotoxicity (kg 1,4-DCB)	5.13493
Water consumption (m^3)	0.11402

Note: DCB: Dichlorobenzidine; CFC: Chlorofluorocarbon.

5. Conclusions

5.1. Implications

This study adds to the limited body of existing LCA research in the context of the textile and apparel industry. Adding relevant and updated information will increase the understanding of LCA research in this discipline. By comparing natural and synthetic fibers, this research identifies hotspots in the supply chain of each fiber and recognizes which fibers require further attention. However, missing inventory data is a consistent problem within LCA research. Expanding the amount of LCA research is one potential solution to address this problem, which can contribute to improving the reliability of life cycle assessments in the textile and apparel context.

LCA research will help stakeholders identify more sustainable fibers and exclude those that are less environmentally friendly, thereby facilitating the transition towards more sustainable fashion supply chains. This research can also assist consumers in making more informed decisions when purchasing textile and apparel products and in disposing of them once they are no longer viable for human use. Additionally, this research helps workers at different stages of the supply chain to recognize practices that contribute to higher environmental impacts and to learn how to reduce these emissions. Ultimately, quantifying the environmental footprint of commonly used textiles can guide the industry in making more sustainable choices when selecting materials for future products.

5.2. Limitations and Future Research Directions

One limitation of the present study is its limited scope regarding the analyzed fibers, as it mostly focuses on natural fibers, with only one synthetic fiber included. It is suggested to expand the fiber mix to include more synthetic fibers and fiber blends, considering their substantial market share in the textile and apparel industry. Another limitation is that the values for the impact categories presented in this study only reflect the aggregated elementary flows and do not consider upstream flows that lead to the impact of the entire process. Future research can build an entire process model for each analyzed fiber and utilize the values generated from the process model, rather than only reviewing aggregated elementary flows. Furthermore, this study only focused on agriculture and textile production. Future research can increase the number of life cycle stages to and further advance the impact comparison across different fibers. Data availability is a consistent limitation in conducting LCA studies, as not all fibers have data for various sub-stages of textile manufacturing such as spinning, weaving, and dyeing. This can be addressed by utilizing multiple LCA databases or retrieving missing data from previously published literature.

Author Contributions: Conceptualization, V.G., X.L. and T.C.; Methodology, V.G. and X.L.; Formal analysis, V.G. and X.L.; Investigation, V.G. and X.L.; Writing—original draft, V.G. and X.L.; Writing—review & editing, X.L. and T.C.; Project administration, X.L. and T.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Mu, D.; Xin, C.; Zhou, W. Life Cycle Assessment and Techno-Economic Analysis of Algal Biofuel Production. In *Microalgae Cultivation for Biofuels Production*; Yousuf, A., Ed.; Woodhead Publishing Series in Energy: Sawston, UK, 2020; p. 281. [CrossRef]
2. Khan, M.M.R.; Islam, M.M. Materials and manufacturing environmental sustainability evaluation of apparel product: Knitted T-shirt case study. *Text. Cloth. Sustain.* **2015**, *1*, 8. [CrossRef]
3. La Rosa, A.D.; Grammatikos, S.A. Comparative Life Cycle Assessment of Cotton and Other Natural Fibers for Textile Applications. *Fibers* **2019**, *7*, 101. [CrossRef]
4. Baydar, G.; Ciliz, N.; Mammadov, A. Life cycle assessment of cotton textile products in Turkey. *Resour. Conserv. Recycl.* **2015**, *104*, 213–223. [CrossRef]
5. Hackett, T. A Comparative Life Cycle Assessment of Denim Jeans and a Cotton T-Shirt: The Production of Fast Fashion Essential Items From Cradle to Gate. Master's Thesis, University of Kentucky, Lexington, KY, USA, 2015.
6. Gomez-Campos, A.; Vialle, C.; Rouilly, A.; Sablayrolles, C.; Hamelin, L. Flax fiber for technical textile: A life cycle inventory. *J. Clean. Prod.* **2021**, *281*, 125177. [CrossRef]
7. Dissanayake, N.P.J.; Summerscales, J.; Grove, S.M.; Singh, M.M. Energy Use in the Production of Flax Fiber for the Reinforcement of Composites. *J. Nat. Fibers* **2009**, *6*, 331–346. [CrossRef]
8. Moazzem, S.; Crossin, E.; Daver, F.; Wang, L. Life Cycle Assessment of Apparel Consumption in Australia. *Environ. Clim. Technol.* **2021**, *25*, 71–111. [CrossRef]
9. Lou, X.; Cao, H. A comparison between consumer and industry perspectives on sustainable practices throughout the apparel product lifecycle. *Int. J. Fash. Des. Technol. Educ.* **2018**, *12*, 149–157. [CrossRef]
10. Wiedemann, S.; Biggs, L.; Nebel, B.; Bauch, K.; Laitala, K.; Klepp, I.; Swan, P.; Watson, K. Environmental impacts associated with the production, use, and end-of-life of a woollen garment. *Int. J. Life Cycle Assess.* **2020**, *25*, 1486–1499. [CrossRef]
11. Fashion Industry Environmental, Waste, and Recycle Statistics. Available online: https://edgexpo.com/fashion-industry-waste-statistics/ (accessed on 12 March 2023).
12. Moazzem, S.; Crossin, E.; Daver, F.; Wang, L. Assessing environmental impact reduction opportunities through life cycle assessment of apparel products. *Sustain. Prod. Consum.* **2021**, *28*, 663–674. [CrossRef]
13. Statista, & Fernandez. Textile Fiber Market Share Worldwide 2021, by Type. Available online: https://www.statista.com/statistics/1250812/global-fiber-production-share-type/ (accessed on 12 March 2023).
14. Deng, Y.; Tian, Y. Assessing the Environmental Impact of Flax Fibre Reinforced Polymer Composite from a Consequential Life Cycle Assessment Perspective. *Sustainability* **2015**, *7*, 11462–11483. [CrossRef]
15. Todor, M.P.; Bulei, C.; Kiss, I.; Alexa, V. Recycling of textile wastes into textile composites based on natural fibres: The valorisation potential. In Proceedings of the IOP Conference Series: Materials Science and Engineering, Banja Luke, Bosnia and Herzegovina, 9–11 May 2018. [CrossRef]
16. Discover Natural Fibres Initiative. Available online: https://dnfi.org/ (accessed on 12 March 2023).
17. Organic Cotton Market—Global Industry Trends and Forecast to 2029. Available online: https://www.databridgemarketresearch.com/reports/global-organic-cotton-market (accessed on 12 March 2023).
18. Textile Exchange. Preferred Fiber and Materials Market Report—Textile Exchange. Available online: https://textileexchange.org/knowledge-center/reports/preferred-fiber-and-materials/?psafe_param=1&gclid=Cj0KCQiAjbagBhD3ARIsANRrqEvsI7MFiFvhFXlKKGmRr4pjphaMzYOyadHe-gbJyMgzrsRUwWANzgUaAjt4EALw_wcB (accessed on 12 March 2023).
19. Ellis, J.L.; McCracken, V.A.; Skuza, N. Insights into willingness to pay for organic cotton apparel. *J. Fash. Mark. Manag. Int. J.* **2012**, *16*, 290–305. [CrossRef]
20. Nellström, M.; Saric, M. A Comparative Life Cycle Assessment of Nudie Jeans' Repair and Reuse Concept. Master's Thesis, Chalmers University of Technology, Gothenburg, Sweden, 2019.
21. Munasinghe, P.; Druckman, A.; Dissanayake, D. A systematic review of the life cycle inventory of clothing. *J. Clean. Prod.* **2021**, *320*, 128852. [CrossRef]
22. Gerbin, E.; Frapart, Y.M.; Marcuello, C.; Cottyn, B.; Foulon, L.; Pernes, M.; Crônier, D.; Molinari, M.; Chabbert, B.; Ducrot, P.H.; et al. Dual Antioxidant Properties and Organic Stabilization in Cellulose Nanocomposite Films functionalized by In Situ Polymerization of Coniferyl Alcohol. *Biomacromolecules* **2020**, *21*, 3163–3175. [CrossRef]
23. Moretti, C.; Corona, B.; Hoefnagels, R.; Vural-Gürsel, I.; Gosselink, R.; Junginger, M. Review of life cycle assessments of lignin and derived products: Lessons learned. *Sci. Total Environ.* **2021**, *20*, 144656. [CrossRef] [PubMed]
24. van der Velden, N.M.; Patel, M.K.; Vogtländer, J.G. LCA benchmarking study on textiles made of cotton, polyester, nylon, acryl, or elastane. *Int. J. Life Cycle Assess.* **2014**, *19*, 331–356. [CrossRef]
25. Peters, G.; Svanström, M.; Roos, S.; Sandin, G.; Zamani, B. *Handbook of Life Cycle Assessment (LCA) of Textiles and Clothing*, 1st ed.; Muthu, S.S., Ed.; Woodhead Publishing Series in Textiles; Elsevier: Amsterdam, The Netherlands, 2015.
26. Muthukumarana, T.; Karunathilake, H.; Punchihewa, H.; Manthilake, M.; Hewage, K. Life cycle environmental impacts of the apparel industry in Sri Lanka: Analysis of the energy sources. *J. Clean. Prod.* **2018**, *172*, 1346–1357. [CrossRef]

27. Vink, E.T.; Rábago, K.R.; Glassner, D.A.; Gruber, P. Applications of life cycle assessment to NatureWorksTM polylactide (PLA) production. *Polym. Degrad. Stab.* **2003**, *80*, 403–419. [CrossRef]
28. DOE Advanced Manufacturing Office (AMO). Defining Functional Units for LCA and TEA. Available online: https://www.energy.gov/sites/default/files/2022-06/2022-05-03%20-%20Functional%20Unit%20PDF_compliant.pdf (accessed on 12 March 2023).
29. What Is Included in a LCA? Available online: http://qpc.adm.slu.se/7_LCA/page_13.htm (accessed on 12 March 2023).
30. Lee, K.M.; Inaba, A. Life Cycle Assessment Best Practices of ISO 14040 Series. Available online: https://www.apec.org/docs/default-source/Publications/2004/2/Life-Cycle-Assessment-Best-Practices-of-International-Organization-for-Standardization-ISO-14040-Ser/04_cti_scsc_lca_rev.pdf (accessed on 12 March 2023).
31. Wu, Y.; Su, D. Review of Life Cycle Impact Assessment (LCIA) Methods and Inventory Databases. In *Sustainable Product Development*; Springer: Cham, Swizerland, 2020; pp. 39–55. [CrossRef]
32. Nayak, R.; Panwar, T.; Nguyen, L.V.T. Sustainability in fashion and textiles. In *Sustainable Technologies for Fashion and Textiles*; Nayak, R., Ed.; Woodhead Publishing: Sawston, UK, 2020; pp. 3–30, ISBN 9780081028674.
33. Palacios-Mateo, C.; van der Meer, Y.; Seide, G. Analysis of the polyester clothing value chain to identify key intervention points for sustainability. *Environ. Sci. Eur.* **2021**, *33*, 2. [CrossRef]
34. Mandal, S.; Dey, A. PET Chemistry. In *Recycling of Polyethylene Terephthalate Bottles*, 1st ed.; Thomas, S., Rane, A.V., Kanny, K., Abitha, V.K., Thomas, M.G., Eds.; William Andrew: Norwich, NY, USA, 2018; ISBN 9780323509671.
35. Liu, Y.; Huang, H.; Zhu, L.; Zhang, C.; Ren, F.; Liu, Z. Could the recycled yarns substitute for the virgin cotton yarns: A comparative LCA. *Int. J. Life Cycle Assess.* **2020**, *25*, 2050–2062. [CrossRef]
36. Cotton Incorporated. LCA Update of Cotton Fiber and Fabric Life Cycle Inventory. Available online: https://resource.cottoninc.com/LCA/2016-LCA-Full-Report-Update.pdf (accessed on 12 March 2023).
37. Zhang, Y.; Liu, X.; Xiao, R.; Yuan, Z. Life cycle assessment of cotton T-shirts in China. *Int. J. Life Cycle Assess.* **2015**, *20*, 994–1004. [CrossRef]
38. Pakula, C.; Stamminger, R. Electricity and water consumption for laundry washing by washing machine worldwide. *Energy Effic.* **2010**, *3*, 365–382. [CrossRef]
39. EnergyStar (2020) Laundry Best Practices. Available online: https://www.energystar.gov/products/laundry_best_practices (accessed on 12 March 2023).
40. Cotton Incorporated. The Life Cycle Inventory and Life Cycle Assessment of Cotton Fiber and Fabric. Available online: https://cottontoday.cottoninc.com/wp-content/uploads/2016/08/LCI-LCA-Handout.pdf (accessed on 12 March 2023).
41. Laitala, K. Clothing Consumption an Interdisciplinary Approach to Design for Environmental Improvement. Master's Thesis, Norwegian University of Science and Technology, Trondheim, Norway, 2014.
42. Caulfield, K. Sources of Textile Waste in Australia. Available online: https://studylib.net/doc/18791293/%20sources-of-textile-waste-in-australia (accessed on 12 March 2023).
43. Research and Markets. Global Cotton Market Report 2021–2027: $46.56 Billion Industry—Consumption, Production, Export, Imports. Available online: https://www.prnewswire.com/news-releases/global-cotton-market-report-2021-2027-46-56-billion-industry---consumption-production-export-imports-301241610.html (accessed on 12 March 2023).
44. Jin, S.Q.; Du, M.; Wei, X.; Sun, Y. Environmental impact assessment of cotton planting and suggestions for its sustainable development. *Rev. China Agric. Sci. Technol.* **2011**, *13*, 110–117.
45. Kazan, H.; Akgul, D.; Kerc, A. Life cycle assessment of cotton woven shirts and alternative manufacturing techniques. *Clean Technol. Environ. Policy* **2020**, *22*, 849–864. [CrossRef]
46. Textile Exchange. Organic Cotton Market Report. Available online: https://textileexchange.org/app/uploads/2022/10/Textile-Exchange_OCMR_2022.pdf (accessed on 12 March 2023).
47. Ingram, M. Producing the natural fiber naturally: Technological change and the US organic cotton industry. *Agric. Hum. Values* **2002**, *19*, 325–336. [CrossRef]
48. Fidan, F.S.; Aydoğan1, E.K.; Uzal, N. A Comparative Life Cycle Assessment of Conventional and Organic Cotton in Denim Fabric. Available online: http://uest.ntua.gr/thessaloniki2021/pdfs/THESSALONIKI_2021_Fidan_et_al.pdf (accessed on 12 March 2023).
49. Şener Fidan, F.; Kızılkaya Aydoğan, E.; Uzal, N. The impact of organic cotton use and consumer habits in the sustainability of jean production using the LCA approach. *Environ. Sci. Pollut. Res.* **2022**, *30*, 8853–8867. [CrossRef] [PubMed]
50. Ahmed, A.T.M.F.; Islam, M.Z.; Mahmud, M.S.; Sarker, M.E.; Islam, M.R. Hemp as a potential raw material toward a sustainable world: A review. *Heliyon* **2022**, *8*, e08753. [CrossRef] [PubMed]
51. Zampori, G.; Dotelli, V. Vernelli. Life cycle assessment of hemp cultivation and use of hemp- based thermal insulator materials in buildings. *Environ. Sci. Technol.* **2013**, *47*, 7413–7420. [CrossRef]
52. Marcuello, C.; Chabbert, B.; Berzin, F.; Bercu, N.B.; Molinari, M.; Aguié-Béghin, V. Influence of Surface Chemistry of Fiber and Lignocellulosic Materials on Adhesion Properties with Polybutylene Succinate at Nanoscale. *Materials* **2023**, *16*, 2440. [CrossRef]
53. Garel, J. Will Linen Conquer the Fashion Industry? Available online: https://fashionunited.com/news/fashion/will-linen-conquer-the-fashion-industry/2021012237617 (accessed on 12 March 2023).

54. van der Werf, H.M.G. Life Cycle Analysis of field production of fibre hemp, the effect of production practices on environmental impacts. *Euphytica* **2004**, *140*, 13–23. [CrossRef]
55. Bhalla, K.; Kumar, T.; Rangaswamy, J. An Integrated Rural Development Model based on Comprehensive Life-Cycle Assessment (LCA) of Khadi -Handloom Industry in Rural India. *Procedia CIRP* **2018**, *69*, 493–498. [CrossRef]
56. Schumacher, A.G.D.; Pequito, S.; Pazour, J. Industrial hemp fiber: A sustainable and economical alternative to cotton. *J. Clean. Prod.* **2020**, *268*, 122180. [CrossRef]
57. Barcelos, S.M.B.D.; Salvador, R.; Guedes, M.D.G.; de Francisco, A.C. Opportunities for Improving the Environmental Profile of Silk Cocoon Production under Brazilian Conditions. *Sustainability* **2020**, *12*, 3214. [CrossRef]
58. Astudillo, M.F.; Thalwitz, G.; Vollrath, F. Life cycle assessment of Indian silk. *J. Clean. Prod.* **2014**, *81*, 158–167. [CrossRef]
59. Bhalla, K.; Kumar, T.; Rangaswamy, J.; Siva, R.; Mishra, V. Life Cycle Assessment of Traditional Handloom Silk as Against Power-loom Silks: A Comparison of Socio-economic and Environmental Impacts. In *Green Buildings and Sustainable Engineering*; Drück, H., Mathur, J., Panthalookaran, V., Sreekumar, V.M., Eds.; Springer: Singapore, 2020. [CrossRef]
60. Ramchandani, M.; Coste-Maniere, I. Leather in the Age of Sustainability: A Norm or Merely a Cherry on Top? In *Leather and Footwear Sustainability*; Muthu, S., Ed.; Springer: Singapore, 2020; pp. 11–22. [CrossRef]
61. Grandview Research. Synthetic Fibers Market Growth Analysis Report, 2021–2028. Available online: https://www.grandviewresearch.com/industry-analysis/synthetic-fibers-market (accessed on 12 March 2023).
62. Muthu, S. *Assessing the Environmental Impact of Textiles and Clothing Supply Chain*, 2nd ed.; Woodhead Publishing: Sawston, UK, 2020; Chapter 10; pp. 181–186. ISBN 9780128197837.
63. Geographies. Available online: https://ecoinvent.org/the-ecoinventdatabase/geographies/#:~:text=RoW%20represents%20the%20world%20minus,or%20removed%20from%20the%20database (accessed on 12 March 2023).
64. Goedkoop, M.; Oele, M.; De Schryver, A.; Vieira, M. SimaPro 7: Database Manual. Available online: https://simapro.com/wp-content/uploads/2022/07/DatabaseManualMethods.pdf (accessed on 12 March 2023).
65. Huijbregts, M.A.J.; Steinmann, Z.J.N.; Elshout, P.M.F.; Stam, G.; Verones, F.; Vieira, M.D.M.; Hollander, A.; Zijp, M.; van Zelm, R. ReCiPe 2016 v1.1 A Harmonized Life Cycle Impact Assessment Method at Midpoint and Endpoint Level Report I: Characterization. Available online: https://pre-sustainability.com/legacy/download/Report_ReCiPe_2017.pdf (accessed on 12 March 2023).
66. Bare, J.C.; Hofstetter, P.; Pennington, D.W.; de Haes, H.A.U. Midpoints versus endpoints: The sacrifices and benefits. *Int. J. Life Cycle Assess.* **2000**, *5*, 319–326. [CrossRef]
67. Papadakis, E.N.; Rodríguez-Rodríguez, C.E.; Kotopoulou, A.; Kintzikoglou, K.; Makris, K.C.; Papadopoulou-Mourkidou, E. A pesticide monitoring survey in rivers and lakes of northern Greece and its human and ecotoxicological risk assessment. *Ecotoxicol. Environ. Saf.* **2015**, *116*, 1–9. [CrossRef] [PubMed]
68. Avadi, A.; Marcin, M.; Biard, Y.; Renou, A.; Gourlot, J.P.; Basset-Mens, C. Life cycle assessment of organic and conventional non-Bt cotton products from Mali. *J. Life Cycle Assess.* **2020**, *25*, 678–697. [CrossRef]
69. Bain, M.; Your Organic Cotton t-Shirt Might Be Worse for the Environment than Regular Cotton. Quartz. Available online: https://qz.com/990178/your-organic-cotton-t-shirt-might-be-worse-for-the-environment-than-regular-cotton (accessed on 12 March 2023).
70. Sewport. What Is Jute Fabric: Properties, How Its Made and Where. Available online: https://sewport.com/fabrics-directory/jute-fabric (accessed on 12 March 2023).
71. Borrion, A.; Khraisheh, M.; Benyahia, F. Environmental life cycle impact assessment of Gas-to-Liquid processes. In Proceedings of the 3rd International Gas Processing Symposium, Doha, Qatar, 5–7 March 2012; Aroussi, A., Benyahia, F., Eds.; Elsevier EBooks: Amsterdam, The Netherlands, 2012; Volume 3, pp. 71–77. [CrossRef]
72. Veolia. How Sulfuric Acid Regeneration Lowers Refinery Costs and Environmental Impact. Available online: https://blog.veolianorthamerica.com/how-sulfuric-acid-regeneration-lowers-refinery-costs-environmental-impact#:~:text=Sulfuric%20acid%20%E2%80%93%20In%20acid%20form,requires%20concentrated%2C%20pure%20sulfuric%20acid (accessed on 12 March 2023).
73. Khabbaz, B.G. Life Cycle Energy Use and Greenhouse Gas Emissions of Australian Cotton: Impact of Farming Systems. Master's Thesis, University of Southern Queensland, Toowoomba, Queensland, Australia, 2010.
74. Bevilacqua, M.; Ciarapica, F.E.; Mazzuto, G. Environmental analysis of a cotton yarn supply chain. *J. Clean. Prod.* **2014**, *82*, 154–165. [CrossRef]
75. Krifa, M.; Ethridge, M.D. Compact Spinning Effect on Cotton Yarn Quality: Interactions with Fiber Characteristics. *Text. Res. J.* **2006**, *76*, 388–399. [CrossRef]
76. Babu, K. Natural Textile Fibres. In *Textiles and Fashion Materials, Design and Technology*, 1st ed.; Sinclair, R., Ed.; Woodhead Publishing: Swaston, UK, 2015; ISBN 9781845699314.
77. Basu, G.; De, S.; Samanta, A. Effect of bio-friendly conditioning agents on jute fibre spinning. *Ind. Crops Prod.* **2009**, *29*, 281–288. [CrossRef]
78. Laursen, S.E.; Hansen, J.; Knudsen, H.H.; Wenzel, H.; Larsen, H.F.; Kristensen, F.M. EDIPTEX—Environmental Assessment of Textiles. Available online: https://mdpi-res.com/data/mdpi_references_guide_v5.pdf (accessed on 12 March 2023).

79. Alves, C.; Ferrão, P.; Silva, A.M.; Reis, L.; Freitas, M.D.C.D.; Rodrigues, L.R.; Alves, D. Ecodesign of automotive components making use of natural jute fiber composites. *Clean. Prod.* **2010**, *18*, 313–327. [CrossRef]
80. Luo, Y.; Wu, X.; Ding, X. Carbon and water footprints assessment of cotton jeans using the method based on modularity: A full life cycle perspective. *J. Clean. Prod.* **2021**, *332*, 130042. [CrossRef]
81. Yacout, D.M.M.; El-Kawi, M.A.A.; Hassouna, M.S. Cradle to gate environmental impact assessment of acrylic fiber manufacturing. *Int. J. Life Cycle Assess.* **2016**, *21*, 326–336. [CrossRef]