Chapter

Understanding Denim Recycling: A Quantitative Study with Lifecycle Assessment Methodology

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Abstract

Global denim jeans market size is over 70 billion dollars today, and it continues to grow with a compound annual growth rate (CAGR) of 2%. As a reflection of this annual growth, systems' waste generation also increases. Textile waste including denim accounts for nearly 5% of all landfill space, according to the Environmental Protection Agency (EPA). Today, efficient recycling technologies are essential to revive the waste generated. Recycling technologies potentially represent a new way to engineer products. This book chapter analyzes these different recycling technologies and their advantages and challenges and concentrates on denim fabrics produced with recycled content. Life cycle assessment (LCA) methodology is adopted to quantify and compare the environmental impact of recycled denim fabrics. The chapter concludes the challenges and the future of recycling, creating systems, and engineering of waste. The view of seeing waste as a raw material potentially represents a new opportunity to design circular systems.

Keywords: denim recycling, textile waste, life cycle assessment, design for sustainability, circularity

1. Introduction

Denim is one of the most prevalent fabrics worldwide, and therefore the environmental degradation associated with denim jean production is highly dangerous as the volume of jeans produced and used by consumers today is humongous. Also, as cotton is the fundamental building block for denim production, denim represents a mainspring for cotton consumption. Considering the fact that the textile and apparel industry in general is pressured to increase the recycling potential for cotton to cover contemporary and prospective market demands, the use of recycled materials (fiber, yarn, and fabric) in the production of new denim products has become an area of great interest. The decision to use recycled materials in products occurs during design and product development, and it continues throughout the manufacturing processes. The most important requirements for recyclable denim designs are monomaterials, elimination of toxic substances, modular manufacturing for ease of removal or exchange, easily compatible materials, and labels or codes that can be recycled.

The environmental impact of denim products, during manufacture, use, or disposal, can be evaluated by looking at the different phases of the product's life cycle and taking action at the phases where it will be most effective to reduce the impact. However, the lifecycle of a product is long and complicated, covering many areas with many people involved in each phase [1]. There is a variety of voluntary and mandatory tools which help achieve this objective. These include economic instruments, bans on certain substances, environmental labeling, voluntary agreements, product design guidelines, etc. Life cycle assessment (LCA) methodology is one of the aforementioned tools, and within the frame of this chapter, it is adopted to quantify and compare the environmental impact of recycled denim fabrics. But before that, the global denim market, environmental impacts of denim manufacturing, sources of denim waste, and recycling processes currently used in textiles and apparel today are also discussed in this chapter.

2. An overview of the global denim market

Denim is a type of sturdy cotton twill woven fabric with a characteristically diagonal ribbing known for its use in the form of jeans and other clothing all across the world. Originally used for workers' clothes, denim has entered the world of high fashion for a long time, and this has urged the industry to produce innovative denim with different fibers including lyocell, bamboo, viscose, rayon, polyethylene terephthalate, and elastane. Also, several types of washes have been introduced, such as stonewash and stoneless wash, acid wash, moon wash, monkey wash, and enzymes which have been used because of their environmental-friendly nature in comparison with hypochlorite and pumice stones [2].

Rising casualization of clothing all over the world, together with the availability of high-quality, cost-effective denim products, has contributed to the growth of the market over the years. E-commerce is the other factor which has a positive influence on the denim market's growth. In addition, brands have started to reinforce their commitments to responsible production efforts and launched more sustainable collections to the market, which has dramatically increased new retail products described as "sustainable" since 2017. Orta Anadolu, for example, introduced its organic cotton production of denim fabrics in 2006 and a capsule collection without virgin cotton in 2018. Similarly, Diesel launched a sustainable capsule collection with Coca-Cola [3].

The global denim market is segmented into North America (NA), Europe (EU), Asia-Pacific (APAC), the Middle East and Africa (MEA), and South America (SA). The major companies operating in the global denim market are Levi Strauss & Co., VF Corporation (with renowned brand names of Lee and Wrangler), Diesel SpA, Gap Inc., Hennes & Mauritz AB, Inditex, and PVH Corp., and Tommy Hilfiger Licensing LLC. The jean market is a highly fragmented market, with a strong presence of local and global players operating all over the world. Thus, to sustain their positions in the market, the active players are bringing innovation in their product offering, in order to cater to changing consumers' fashion lifestyle [4].

Also, they have been focusing on social media platforms as well as online distribution channels for their marketing and branding activities so as to attract more customers. Denim manufacturers, however, appear to focus on acquisitions, expansions, and collaborations with mostly startup companies to gain a significant market share [2–3].

In 2019, the global denim market was valued at approximately 90 billion US dollars and is expected to reach a value of around 107 billion US dollars by 2023 [5]. The global denim jean market size, on the other hand, was valued at USD 64.62 billion in 2018, and it is estimated to expand further at a compound annual growth rate (CAGR) of 6.81% from 2019 to 2025 [6]. The Asia-Pacific region led the market in 2019, which was followed by North America, Europe, South America, and the Middle East as a response to the introduction of global brands and an emphasis on premium denim. Japan, China and India are expected to lead the region through 2024 as a result of the countries' rise in promotional activities within the denim market [2, 4].

According to the World Denim Fabric Foreign Trade Report published by the Istanbul Textile and Raw Materials Exporters Association (ITHIB), global denim fabric exports increased by 5.1% in 2018 and reached approximately 5 billion US dollars. The top five countries performing most denim exports are China (42% share of total exports), Pakistan (11.7% share of total exports), India (8.2% share of total exports), Hong Kong (7.4% share of total exports), and Turkey (6.8% share of total exports). It is stated that there is a strong growth in the denim production in Bangladesh and Vietnam, although these countries are mostly importing denim fabric [7].

Europe, the United States, and Japan are the biggest consumers of denim, whereas China and India, being relatively younger economies, are witnessing a steady rise in demand for denim. In 2018, men's wear segment accounted for the largest market share of more than 55%. It is forecasted that the segment will retain its leading position over the upcoming years mainly because of the improved standards of living and demand for trendy fashion apparels. Women's wear segment is, on the other hand, expected to register the fastest compound annual growth rate (CAGR) of 7.25% from 2019 to 2025. This growth is attributed to the high product demand, especially in emerging countries. In addition to that, constant product innovation in this segment is also expected to drive the growth further [2, 6].

2.1 Environmental impacts of denim processing

It is estimated that producing a pair of jeans consumes around 2900 liters of water and large amounts of chemicals and energy. If this is multiplied by the number of jeans produced globally, one can get an idea of the enormous contribution of wastewater and harmful gases by denim industry to the environment [8, 9].

Indigo dye is one of the organic colorants used to color textiles, paper, leather, and plastic and for many applications such as cosmetic and photochemical production. Unfortunately, textile effluents containing indigo dye and other dye types make water toxic and harmful for human and animal consumption, which causes an imbalance in different aquatic ecosystem food chains [10]. The use of synthetic indigo and sulfur dyes also presents serious effluent problem. Bearing in mind that majority of warp dyeing for denim uses indigo and sulfur dyes, the environmental impacts of denim processing can be classified into three main categories:

- Water pollution: dyeing and finishing effluent discharge in water bodies
- Air pollution: cotton dust, abrasives, and chemicals found in air
- Solid waste (sludge)

As is well-known, denim washing is imparted to fabric to improve the softness, comfort, and most importantly achieving a variety of looks such as a faded or worn-out appearance. Pumice stone is used to stonewash denim garments. The stone gets abraded during the process and becomes powdered; part of it remains in the liquor, and part of it sticks to the garment. A sizeable amount of water is required for repeated washing cycles to remove the deposited pumice from the denim. The effluent and pumice dust lead to environmental pollution. Sandblasting is a mechanical finish which uses sand containing silica. The minute silica dust spreads in air, it poses serious respiratory disease such as silicosis [10].

Micro sanding is another finish which pollutes the environment. In the case of chemical washing involving the use of sodium hypochlorite or potassium permanganate, the effluent contains chlorinated organic substances which cause severe impacts to the environment, and the bleaching chemicals are harmful to human health. Acid wash uses both pumice stone and chemicals, namely, sodium hypochlorite or potassium permanganate, and it does not require water but leads to pollution through the effluent having pumice dust and residual manganese which are hazardous [11–12].

Despite all these setbacks of the denim processes summarized above, various suitable treatment processes have been developed and employed for the dyeing effluent on the basis of the nature and complexity of the dyes and chemicals present in denim. Fortunately, many denim companies and their suppliers have been striving hard to embrace greener methods such as laser processing and nano bubble ozone washing machines and are also making effort to develop new techniques of producing jeans, as a part of their business strategies to preserve the environment. They have also understood the importance and the need to build a sustainable business [12–14].

2.2 Sources of denim waste

It is considered that sustainable material management is a precursor of circular economy, which promotes recycling, reuse, and remanufacturing. It was estimated that around 65 billion tons of raw materials were processed by the industrial system at the end of the first decade of the twenty-first century, and this quantity is expected to reach about 82 billion tons by the end of 2020. Therefore, in the last two decades, circular economy (CE) is gaining growing global consideration as the new development model which is capable of influencing the existing production and consumption model [15]. Within that concept, waste is classified on the basis of generation as pre-consumer textile waste, post-consumer textile waste, and industrial textile waste. Pre-consumer waste is the remaining production processes in the industry which includes raw material to finished products ready for market. This may include offcuts, shearing, selvedges, b-grade garments, export surplus, etc. which are homogenous and clean in nature to be used for other purposes. The waste under this class has great potential for reuse and recycling. The post-consumer textile waste can include any product that has completed its life cycle and is no longer useful to the consumer in both function and esthetics. Industrial textile waste is, however, the result of the manufacturing processes and is termed as dirty waste [13, 16].

The textile and apparel industry, which generates a substantial environmental footprint from cultivation, fabric and garment manufacturing, to the landfill disposal of post-consumer items, faces tremendous environmental and resource challenges [17]. In order to tackle such challenges to some extent, several fashion companies offer their customers to take care of their worn-out clothes including denim jeans. However, studies have concluded that less than 1% of these collected clothes are being recycled while nearly 80% of them are mainly sold on the second-hand market in poor countries around the world or used as blankets or isolation material. The remaining 20% of the clothes are either sold on the second-hand market within the EU or is sent to landfill or incineration [18].

Being the largest fraction of apparel, waste jeans (or waste denim fabric from tailoring operations) are composed mainly of "cotton" and "cotton/polyester" fabric with different weight ratios [19]. Although this may lead to the understanding that denim made with 100% cotton, in particular, will readily deteriorate in the environment, in practice a pair of such jeans can stay alive in the environment for a very long time, and therefore the negative environmental impact is very high. The literature reveals that the amount of waste jeans generated annually is estimated as 2.16 million tons and only 35–50% of this amount is collected in Western Europe in order to reuse or recycle it after sorting [13, 20–21].

As one of the sources of solid waste, the cutting waste during denim jean production—which has relatively a homogeneous nature—is between 10% and 15%, and most of the waste is recycled by unraveling and reusing the fibers in the production of insert yarns (weft direction), which is a good example of "recycling in design (RiD)." Most jeans' producers recycle denim waste in their own manufacturing plants or have contracts with textile waste recyclers to reuse the waste material in the spinning of new yarns. There is also substantial trade of denim waste all over the world [13, 21–22].

Another source of denim waste is the post-consumer denim jeans. Color, quality of fabric, and garment accessories like rivets, buttons, zippers, and labels are the main components of the heterogeneous nature of this very denim waste. The main problem is the collection of post-consumer jeans. Although in many countries collection systems are in place, many consumers discard their jeans as solid municipal waste. Jeans that are collected are mostly sold to textile sorting companies which manually/automatically sort the rewearable jeans for sale to second-hand shops and in Third World countries. Nonwearable jeans are, however, shredded and used for the development of various types of products such as thermal and acoustic insulators and/or textile-based composites for certain structural and other specialized applications [13, 21, 23–28].

Finally, as a different approach to decreasing the denim waste regarding post-consumer denim jeans, the leasing of jeans was introduced several years ago by MUD Jeans. In this concept, the producer or distributor of the jeans stays the owner. The user of the jeans only "buys" the right to the use the jeans for a period of 1 year. If the jeans need to be repaired, it is at the cost of the lease company [22]. The same company, together with several of others, has also focused on "design for recycling (D4R)" for facilitating the recycling of denim jeans, such that they do not use leather labels but printed ones at the waistband, employ rivets and buttons that are made from 100% stainless steel and no finishing (electroplating), and have utilized buttons made out of recycled jeans on their denim shirts and sweaters, etc. [13, 29–30].

3. An overview of recycling in textiles and apparel

An average person buys 60% more clothing items every year and keeps them for half as long as they used to keep about 15 years ago. It is assumed that overall consumption of textiles will have reached to 102 million tons by 2030 and that the textile industry's waste will have increased by about 60% between 2015 and 2030. That means the total level of fashion waste will reach to 148 million tons in 2030. As is known, the majority of clothing waste ends up in landfills or is incinerated, and once in landfills, it takes hundreds of years for natural fibers to decompose and may release methane and CO_2 into the atmosphere. Synthetic materials, on the other hand, are not designed to decompose and may release toxic substances into groundwater and the surrounding soil. If the average life of clothing could be extended by only 3 months, it would reduce waste generation as well as their carbon and water footprints, by 5–10% [19, 31–34].

The textile industry's linear model of "make, use, and dispose of" represents an apparent pressure on scarce natural resources. Circular economy, on the other hand, aims to move away from the unsustainable linear model by decoupling economic activity from the consumption of finite resources and designing waste out of the system. When the recycling component is included, it helps to absorb the residuals of industrial and consumer use [35–36]. Accordingly, circular economy's principles may be given as follows:

- Put an end to waste generation and pollution during the design stage.
- Keep products and materials in use.
- Restore and regenerate natural systems.

Within that concept, a five-step waste management hierarchy was introduced in order to direct toward a more sustainable behavior (**Figure 1**) [37].

Waste generation prevention has the highest significance followed by reuse. Reusing is the concept of using undamaged parts of used products for manufacturing activities. When textiles turn into waste and are disposed by their consumers, recycling offers the opportunity to save raw materials and energy as well as to reduce pollution. Product/material recovery includes the activities like repairing, refurbishing, and disassembling, performed to regain the product value at the end of its life cycle. To dispose generated waste is the last step of the hierarchy [17, 38–41].

Textile recycling routes can be categorized in different ways as follows:

1. Mechanical, chemical, thermal, and biological based on the nature of the process.

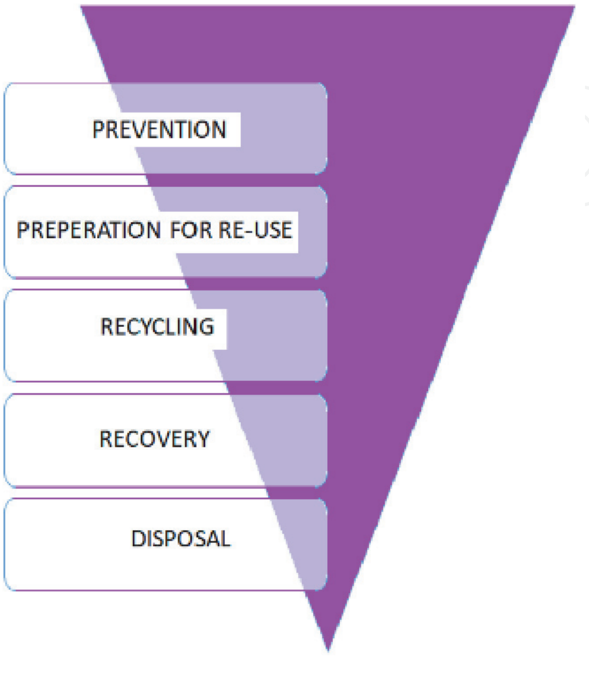

Figure 1.
Waste management hierarchy [38–39].

2. Downcycling where the product of the recycled material is of lower quality. As the length of fibers is shortened and the constituent of molecules is reduced by wear, laundry, and recycling process, the textile recycling is often in the way of downcycling.

3. Upcycling where the product of the recycled material is of higher quality.

4. Open-loop recycling covers a concept in which a product's raw material is separated to be utilized as a part of a randomly used item. Generally, the second item is not recycled and discarded toward the end of its life. Downcycling can be equalized with open-loop recycling system in which the reclaimed material is used to make a less valuable product than the disposed one. Therefore, it results in little economic value and low environmental benefits.

5. Closed-loop recycling refers to recycling techniques where the material recycled is a similar material which is being delivered. For example, the waste material reenters a piece of clothing production chain. Closed-loop recycling generates a greater impact on sustainability, and a product remains in a circular stream and retains its material quality. There are a number of ways to define closed-loop recycling approaches in the apparel industry. Three of them are [41]:

    - Recycling pre- or post-consumer textile waste.

    - Cradle-to-cradle (C2C) methodology in which waste is reclaimed and used again in the production of products of the same or higher value. Biological waste can be composted, while technical waste can be reused within industry to create the same products again.

    - Closed-loop reuse of existing garments: Although reuse of garments is not recycling in the sense of breaking down a product into its raw materials, the product may enter a new life cycle within the same production chain.

Textile recycling technologies are also categorized into four classes as primary, secondary, tertiary and, quaternary approaches [13, 40, 42–43]. Primary recycling involves recycling of material in its original form for recovery of equal value. Secondary recycling incorporates processing a post-consumer product into raw materials usually by mechanical means into a product with different physical and/or chemical properties (mechanical recycling). Tertiary includes processes like pyrolysis and hydrolysis, in which waste is converted to basic chemical constituents, monomers, or fuels (chemical recycling). Quaternary (recovery) covers waste-to-energy conversion processes such as incineration of solid waste or utilization of heat generated.

3.1 Textile recycling techniques

Recycling is the process of breaking down a product or material to make a material of a higher or equal value (upcycling) or of a lower value (downcycling), in which textiles are commonly mechanically or chemically broken down to their fiber constituents [41]. Biodegradation is another method used to recycle waste and to break down organic materials into compounds.

3.1.1 Mechanical recycling

The difference between mechanical and chemical recycling is that wet processing is eliminated or reduced in the mechanical recycling system [44]. Most of the current recycling systems for post-consumer waste textiles mainly include reuse and mechanical processes.

The method of mechanical recycling, which is categorized as a secondary recycling approach, is composed of two main processes: sorting of the waste material and the mechanical decomposition of the fabric. The material to be recycled is sorted according to fiber type, color, quality, etc. Sorting for post-industrial waste may be performed with a risk of uncertainty as the fiber content and properties of the fibers may not be always known. The in-house reprocessing of manufacturing-related waste represents recycling on the primary level [39].

The disintegration of textile material to a fibrous form through mechanical recycling is referred to as shredding or garneting [38, 40–41]. In mechanical recycling machines, the fabrics are cut into small pieces of 1 to 8 cm strips with a rotary blade and separated into single fibers through a process known as "picking," "pulling," or "tearing" by needle-equipped cylinders which have progressively smaller spiked surfaces. On such machines waste is fed through a conveyor belt of the front roller to be transferred to the spiked roller. Spiked roller rotates clockwise, and bottom roller, located under the spiked one, rotates anticlockwise. The distance between the rollers can be varied according to the type of input material, and the waste is opened while passing through rollers.

Mechanical recycling has some shortcomings since the process is too aggressive to retain fiber quality and can result in a 75% loss of value after the first cycle. The mechanical process breaks may cause a tremendous loss in fiber length and a significant decrease in the material quality. For the process, longer processing times are needed, and the production rate is lower. As a result, blending with virgin material (especially in the case of cotton and wool fibers) for spinning processes is inevitable [38, 42, 44]. Consistently, waste collected from the manufacturing supply chain produces higher-quality recycled fibers than those collected from post-consumer waste. The pre-consumer and post-industrial waste can be respun into yarns which are further woven or knitted into fabrics and then used in apparel, upholstery, etc. [13]. Heterogeneity of post-consumer waste worsens constant quality retention.

Nonetheless, despite the drawbacks of mechanical recycling, the technology has shown promising for the reprocessing of denim fabric and garments [45].

3.1.2 Chemical recycling

The method of chemical recycling, which is categorized as a tertiary recycling approach, involves chemical processing of the fiber polymers, e.g., depolymerizing or dissolving. Chemical recycling depends on the quality of the processed waste to a limited degree and decomposes fibers down to the polymeric level [39]. Various chemical recycling processes have been demonstrated and developed. Chemical recycling of synthetic polymers and feedstock recycling depolymerize waste plastics into base chemical molecule called monomers with high purity [38]. The presence of additives and chemicals used in the polymerization process affects the purity and quality of the monomers obtained after recycling. The thermochemical process used to decompose polymers is referred to as pyrolysis, sometimes thermolysis. Pyrolysis is conducted at various temperatures and pressure levels and with the presence of catalysts or reactive gases. Pyrolysis processes are only economically viable for certain manufactured fibers including polyesters, polyamides, and polyolefins [13, 40].

Mechanical recycling	Chemical recycling
Categorized as a secondary recycling approach	Categorized as a tertiary recycling approach
Wet processing is eliminated	Involves chemical processing
It is not as energy-intensive as chemical recycling	The biggest challenge is that chemical recycling is very energy-intensive
Mechanical recycling process is too aggressive to retain fiber quality	Chemical recycling allows a more valuable product in comparison to the products recycled by mechanical processes
Heterogeneity of post-consumer waste worsens constant quality retention	Chemical recycling depends on the quality of the processed waste to a limited degree
Mechanical recycling has been efficiently adopted by industry for recycling of single fiber materials	Chemical recycling is expected to be more suitable for large-scale recycling of blended materials

Table 1.
Comparison of mechanical and chemical textile recycling techniques.

Chemical recycling for polyester also includes glycolysis, hydrolysis, and metanolysis processes.

Chemical recycling is a promising process since it allows the recovery of a more valuable product in comparison to the products recycled by mechanical processes [34, 38, 42, 44]. As it uses a selective degradation method, chemical recycling is expected to be more suitable for large-scale recycling of blended materials, while mechanical recycling has been efficiently adopted by industry for recycling of single fiber materials. In products of cotton and polyester, the fibers can be chemically separated and then reformed into new fibers [13]. On the other hand, although chemical textile recycling has broader use than do the mechanical method, chemical and water consumption (70% lower in case of mechanical processing) for wet processing is high. Barriers to the widespread adoption of chemical recycling also include high costs, multiple processing steps requiring high operational knowledge, and energy requirement for heating and scouring processes [42, 44].

A comparison of mechanical and chemical textile recycling techniques are given in **Table 1** [38, 44].

3.1.3 Bioconversion processes

Biodegradation can be featured as a method used by nature to recycle waste and to break down organic materials into compounds by microorganisms such as bacteria, fungi, insects, worms, and others. Through biodegradation processes, it is possible for nature to clean up wastes, to provide nutrients for the growth of new lives, and to produce the energy necessary for various biological processes [46]. Biochemical transformation via fermentation is an attractive way for utilizing recycling textile waste. Cotton is typically composed of 88–96% cellulose, and it is possible to hydrolyze waste cotton by enzymatic or chemical methods to obtain glucose and then ferment it into value-added products. Biogas production from textile waste via anaerobic digestion is an alternative route to utilize solid waste from textile industry. Organic compounds in solid waste can be used as a raw material to produce desired products via bioconversion processes. On the contrary, thermal and chemical processes can convert both organic and inorganic compounds to value-added products [47].

3.1.4 Thermal and thermochemical conversion processes

Conventional thermal processing refers to the combustion of solid waste and its conversion into energy. Since solid waste from the textile industry contains a high energy content, it can be used as a raw material to generate heat energy [47]. Solid waste from the textile industry can be used as a raw material to produce briquette. The thermal processes that are performed at high temperature with inadequate oxygen could generate carbon monoxide, which is a greenhouse gas. Therefore, a thermochemical conversion process, such as pyrolysis, is applied. Pyrolysis is referred to the decompositional process with high temperature in the absence of oxygen condition [47]. Products from pyrolysis are various, such as activated carbon fiber, char, bio-oil, and syngas. The variation of product is related to pyrolysis condition.

3.2 Challenges in recycling denim

Despite its growing popularity, there are numerous obstacles to textile recycling [47–48]. The major ones to the optimization of textile recycling are:

1. Economic viability: Due to the widespread production of lower-grade products (downcycling) from textile recycling, many recycled textile wastes are unsuitable for multiple recirculation and use. Limited recirculation and reuse are not economically viable and discourages investment in textile recycling.

2. Composition of textile products: The base components of many textile products make them unsuitable for recycling. The presence of plastics and metals in textile products hinders their recyclability.

3. Nonavailability of recyclable textile materials: A limited quantity of used textiles and textile waste are collected and sorted for recycling, and the quantity that is suitable and accessible for recycling is insufficient.

4. Technological limitations: One of the main reasons for the limited quantity of recyclable materials is the lack of technologies for sorting textile waste in preparation for recycling. Dyes and other contaminants cannot be separated from the original fibers by most of the existing methods.

5. Lack of information and limited public participation: Limited public awareness on the merits of recycling contributes immensely to the low recycling rate, causing market inefficiency.

6. Poor coordination, weak policies, and standards: Uncoordinated collection of waste and absence of an integrated and well-coordinated framework and policies to enhance the overall efficiency of the textile recycling are identified as barriers to efficient recycling.

There are also some constraints and challenges faced specific to denim recycling processes [29, 49]. Collection and sorting of worn-out jeans is time-consuming and laborious. Labels; metal parts like rivets, zippers, and buttons; and leather patches have to be removed manually from the jean before shredding. Generally, the metal and leather parts are removed, but it is more difficult to remove the labels, and therefore jeans are sent along with them. The consequence is that the labels contaminate the recycled denim material as they are made of other materials. Any metal parts present on the jean to be recycled may cause problems to the machinery and process. It is easier to remove buttons and zippers by using gravitation but since rivets are too small and too light, special care is needed to remove them.

Denim jeans are characterized by thick lapped seams that create problems during shredding and carding processes. The presence of elastane is another problem. It is more convenient to separate it before shredding and cutting, but this can only be done by chemical recycling. Recycling different colored jeans together results in a multicolored yarn that can create problems in dyeing. Recycled fibers might not meet the quality of virgin ones and could not be spun or woven properly.

4. Life cycle assessment of a denim fabric

Life cycle assessment (LCA) is a methodology where the environmental performance of a product or service is assessed starting from the raw material extraction point to the end of life of that product/service, i.e., from "cradle to grave." The methodology of LCA is defined under the ISO 14040/44 Standard [50].

For a pair of denim jeans, the life cycle (**Figure 2**) starts with the production of raw materials such as fibers and chemicals. These materials are then transported to fabric manufacturer and processed to become a fabric. During fabric production, energy and water are consumed in addition to raw materials while emission to air and to water and production waste are generated. The following process for the fabric is garment manufacturing in which the fabric is cut, sewn, washed, and accessorized (rivets, buttons, etc.) according to the design. Finally, the finished garment is sent to a warehouse or directly stores to be sold. After it is bought, the garment is washed and dried (or dry-cleaned depending on its nature) many times throughout its use phase. When it completes its life span, the garment has various "end of life" scenarios such as recycling, reused, refurbished, and disposed in landfill or incinerated, etc., which were discussed in the previous sections.

Life cycle assessment (LCA) helps us analyze the environmental performance of denim production in a transparent and systematic way and identify the hot spots.

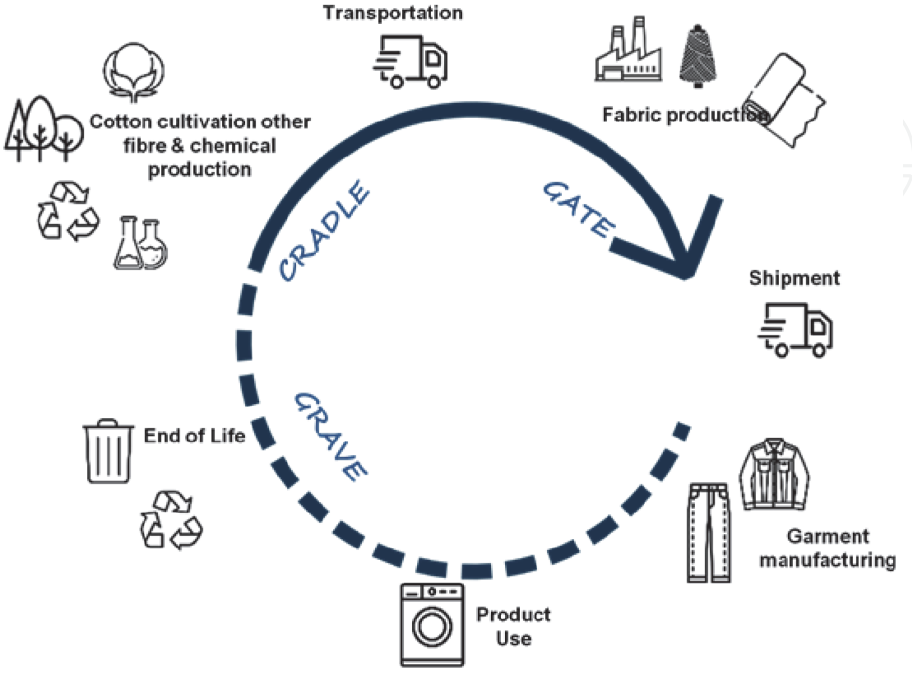

Figure 2.
Lifecycle of a jean.

4.1 Methodology used for assessing the lifecycle impacts

The methodology behind life cycle assessment (LCA) is to accumulate all the impacts originated from the inputs and outputs of a system starting from the "cradle to grave" and to give a total impact number for the system under discussion. Accordingly, in an attempt to exemplify the importance of recycling of denim from the perspective of its environmental impact, an experimental work regarding the life cycle assessment of a denim fabric with and without recycled fiber content was conducted. For the work, the inventory was based on the 2019 denim production figures of a Turkish denim manufacturer in their manufacturing plant in Turkey. As assessment tool, SimaPro software developed by the Pré Sustainability, was used. SimaPro is the leading life cycle assessment (LCA) software that has been used for more than 25 years by the industry and academics in more than 80 countries [51]. SimaPro uses two types of data: primary and secondary. The primary data involves the basics of a denim production such as the amount of cotton used to manufacture 1 m of denim, i.e., 0.5 kg cotton. This data is exclusive to the fabric production practices of the factory. The secondary data, however, comes from the database, and it includes the impacts originated from producing that much raw material (in our case cotton fiber) and all other inputs such as chemicals at every stage. For secondary data, Ecoinvent database that is embedded into the software and is the most common life cycle inventory (LCI) database worldwide is used [52].

To be able to perform life cycle assessment of a specific good or service, one needs to have inventory data for the complete supply chain. Due to the amount of data needed in order to be able to perform a life cycle assessment (LCA) study for a full supply chain, it is practically impossible to collect and organize the data of the complete background system. In that respect, the Ecoinvent database provides this very background system fulfilling the data required for the assessment. The Ecoinvent v3 database contains life cycle inventory (LCI) data taken from various sectors such as energy supply, agriculture, transport, building materials, production of chemicals, and metal production and consists of around 17,000 datasets, each of which describes a life cycle inventory (LCI) on a process level [52–53].

SimaPro software provides six libraries that each contain all the processes that are found in the Ecoinvent database but uses different system models and contains either unit or system processes. The three Ecoinvent system models are "allocation at point of substitution," "cutoff by classification," and "consequential." The system model "allocation at the point of substitution" follows the attributional approach in which burdens are attributed proportionally to specific processes. "Allocation, cut-off by classification" system model is based on the recycled content or cutoff approach in which the primary production of materials is always allocated to the primary user of a material. In this approach, if a material is recycled, the primary producer does not receive any credit for the provision of any recyclable materials available and burden-free to recycling processes; therefore recycled materials bear only the impacts of the recycling processes. The system model "substitution, consequential, long-term" uses different basic assumptions to assess the consequences of a change in an existing system and can be used for perspective studies and prediction of future changes [54]. In this study, for recycled materials "cutoff by classification" system model and for all other data "allocation at point of substitution" system model are used.

For life cycle assessment (LCA) of a product, the production of an item (e.g., denim fabric) is simulated, using both consumption and production data (primary) of a factory and the corresponding secondary data from the Ecoinvent database. The next step is to choose the environmental impacts to be calculated. The whole process is given in **Figure 3**.

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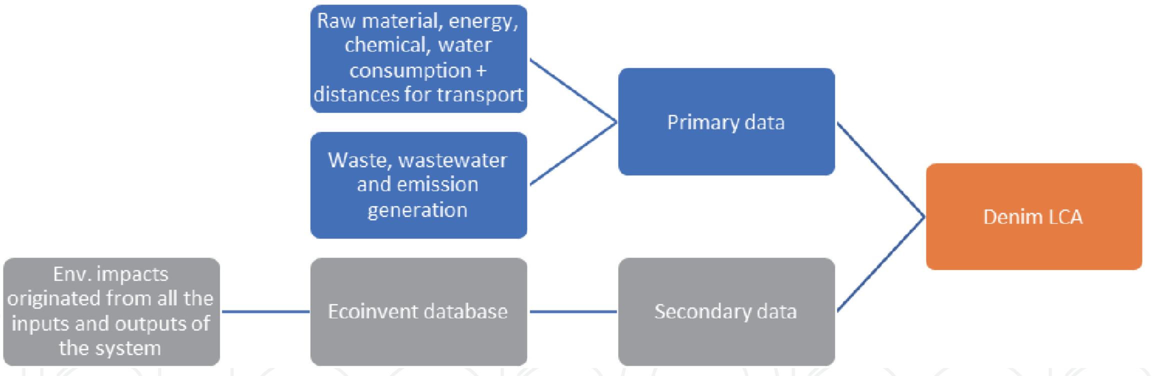

Figure 3.
LCA calculation process.

4.2 Selected impact categories

One of the most important parts of life cycle assessment (LCA) is the outputs, in other words the environmental impacts of the product. With SimaPro software, it is possible to calculate over 100 environmental impact categories. For that reason, the academic- and industry-specific life cycle assessment (LCA) studies' guidelines and standards were surveyed to determine the environmental impacts for our study (**Table 2**).

With this taxonomy (**Table 2**), the commonly used environmental impact categories are listed for textiles. Consequently, based on the taxonomy given in **Table 1** and the raw material need for a denim fabric, five impact categories are selected. These impact categories, their definitions, and calculation methodologies within the SimaPro software are presented in **Table 3**.

4.3 Environmental impact as a rationale for denim fabric recycling

4.3.1 System perspective

As was mentioned above, the life cycle assessment (LCA) methodology is selected to calculate the environmental impacts of denim fabrics having different recycled contents in the same article so that the whole system can be taken into consideration. This means that we have to calculate the effect of every step in the life cycle to see the whole impact of our choices, including cultivation/production of the fiber, fabric production, garment manufacturing, distribution, consumer laundering, reuse, and final disposal [76–77]. One may think that using recycled cotton reduces the impact drastically, but parameters such as increased waste during production and increased energy usage should also be taken into account in a system perspective.

If only one process or only fabric production as a system were calculated, this would have represented a single framed approach which is generally not preferable as calculations for production of single frames may lead to unwanted and unforeseen effects elsewhere in the whole system.

4.3.2 Five environmental impact categories

The specifications of the denim article selected for the work is given in **Table 4**. Life cycle assessment (LCA) was conducted for 1 m of the article in accordance with the process steps including fiber cultivation, transportation, and all the production steps covered in the Turkish denim manufacturing company. The five environmental impacts are presented in **Figure 4**. For the comparative study, the results are

References	Global warming potential (GWP) climate change	Acidification	Eutrophication	Ozone layer depletion	Abiotic depletion	Photochemical oxidant formation	Freshwater use	Human toxicity	Water consumption	Terrestrial ecotoxicity	Greenhouse gases (GHG)	Nonrenewable energy use	Carcinogens	Land occupation	Aquatic eutrophication	Mineral extraction	Ecotoxicity	Freshwater eutrophication	Freshwater aquatic ecotoxicity	Ionizing radiation	Water depletion
[55]	1	1	1	1			1		1												
[56]	1	1			1			1										1			1
[57]		1	1	1	1	1		1		1											
[58]											1	1									
[59]	1			1						1		1	1	1	1	1				1	
[60]		1	1			1					1		1				1				
[61]	1	1				1									1						
[62]	1	1	1						1			1									
[63]	1					1												1			
[64]	1	1	1	1									1	1		1	1			1	
[65]	1	1	1	1	1		1	1		1									1		
[66]											1										
[9]	1		1		1		1		1					1							
[67]	1		1		1																1
Total	10	8	8	5	5	4	3	3	3	3	3	3	3	3	2	2	2	2	2	2	2

Table 2.
A taxonomy of environmental impact categories for textiles.

Indicator	Unit	Description	Example impact	Methodology
Global warning potential	kg CO_2 eq (kilogram carbon dioxide equivalent)	Emission of greenhouse gases (GHGs)	Climate change	IPCC 2013 GWP 100a [68–69]
Freshwater use	lt (liters)	Excessive freshwater taken from the environment	Water scarcity	Life cycle inventory
Land use	m^2 a (meter square per annum)	The amount of agricultural area ucccupied	Deforestation	ReCiPe 2016 Midpoint (H) [70–71]
Eutrophication potential (EP)	kg PO_4^{3-} eq (kilogram phosphate equivalent)	Emission of substances to water contributing to oxygen depletion	Nutrient loading to water stream-water pollution	CML-IA baseline [72–75]
Abiotic resource depletion	kg Sb eq (kilogram antimony equivalent)	Measure of mineral, metal, and fossil fuel resources used to produce a product	Mineral scarcity	CML-IA baseline [72]

Table 3.
Selected environmental impact categories.

Article Code	Width (cm)	Weight (oz/yd^2)	Composition
Article A	150	14.89	100% cotton

Table 4.
Article specifications.

given in terms of percentages (%) so that unit differences of the impact categories were eliminated.

In denim production, the hottest spot for the selected four categories is the fiber growth stage. In the fifth impact category, abiotic resource depletion, fiber stage has the second highest impact. This clearly shows the importance of raw material selection for denim fabric production.

4.3.3 Impact of recycled material content

This section aims to determine the impact of recycled cotton content in the denim fabric under discussion (**Table 4**). Accordingly, different recycled cotton contents are used in the life cycle assessment calculations of Article A. These are as follows:

- Article A-1: 100% cotton
- Article A-2: 80% cotton +20% recycled cotton
- Article A-3: 70% cotton +30% recycled cotton
- Article A-4: 60% cotton +40% recycled cotton
- Article A-5: 50% cotton +50% recycled cotton

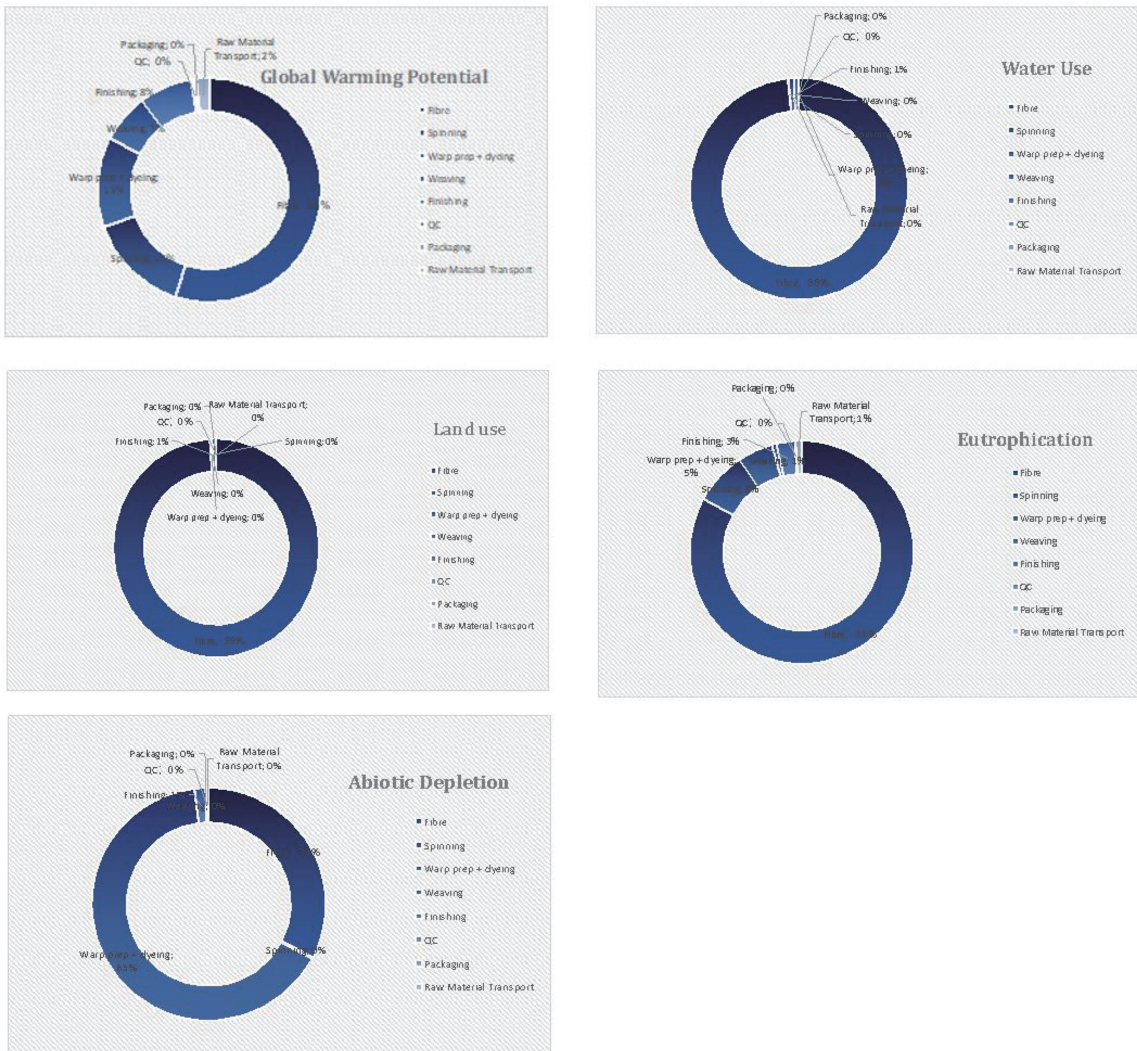

Figure 4.
Five environmental impacts of selected fabric according to process steps.

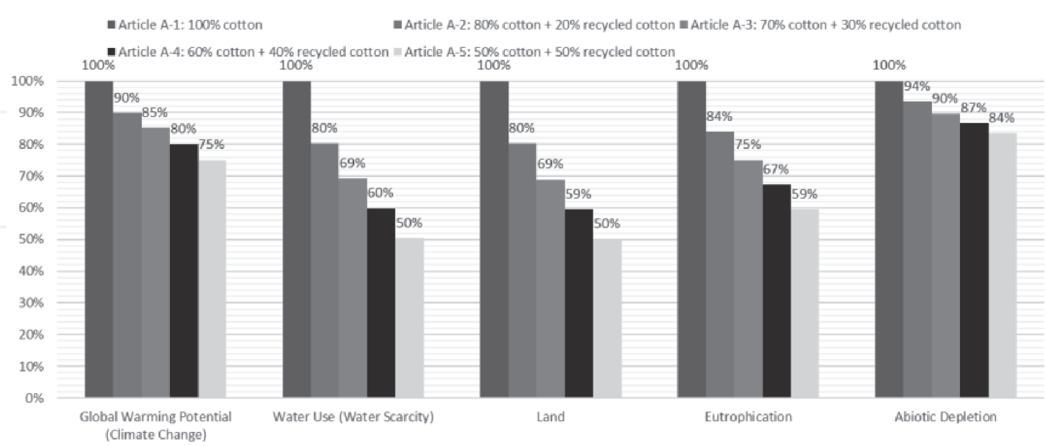

Figure 5.
Results of LCA calculations of virgin and post-consumer recycled cotton blends.

In each version, the recycled cotton content was increased by 10%. The recycled cotton used in the calculations is post-consumer recycled cotton, and its industrial data such as production and transportation data is obtained from a local supplier.

The results of the life cycle assessment (LCA) calculations are presented in **Figure 5**. As may be seen from these results, global warming potential decreases by

5%, eutrophication drops by 8%, and abiotic resource depletion drops by 3% with each addition of 10% recycled content in the blend.

Global warming potential, in other words climate change impact, is affected by two main stages: fiber cultivation and spinning. The energy usage in spinning increases when the recycled cotton content is increased, which implies a negative impact of the use of such fiber on global warming potential. However, since the percentage of the virgin cotton usage is decreased, this decline delivers a high positive impact for global warming potential, lessening the effect of energy usage.

In eutrophication calculation, the main effect derives from usage of fertilizers, pesticides, and insecticides at farm level. During irrigation of cotton, the probability of water pollution caused by these chemicals increases. Once the usage of virgin cotton decreases in the blend, the value of eutrophication decreases. Overall, the decrease results as 8% with a use of 10% recycled cotton.

Water use and land use impacts decrease by 10% with an addition of 10% recycled cotton. Since cotton uses land, and a high amount of water in the field during cultivation, avoiding the use of virgin cotton creates a high decrease in impact categories. If one can spin and weave a blend of 50% virgin and 50% recycled cotton, the overall impact on these two categories decreases 50%, which is a considerable figure when the amount of fabric produced reaches approximately 3 billion meters annually.

4.3.4 Impact of organic cotton and recycled cotton

This section aims to determine the impact of blending recycled cotton with organic cotton. Organic cotton data used in the calculations is generated from the literature [78–79]. The percentages used in the life cycle assessment (LCA) calculations are as follows:

- Article A-1: 100% cotton
- Article A-6: 100% organic cotton
- Article A-7: 80% organic cotton +20% recycled cotton

Once organic cotton is used, at least 25% decrease appears in three categories: namely, global warming potential, eutrophication, and abiotic resource depletion. The decrease in water use (11%) is comparably low. On the other hand, real decrease happens in the land use, nearly 40%. This is due to the data for Aegean Region organic cotton. The yield in Turkish organic cotton is comparably high. The land use for 1 kg of lint organic cotton is 4.65m^2 for Turkish organic cotton. The same figure appears to be 19.7 for global production and 20.9 for the US organic cotton (**Figure 6**).

The virgin cotton used in study for calculations is a blend of the US, Turkish, Greek, and Brazilian cotton.

The results of the life cycle assessment (LCA) calculations are presented in **Figure 7**. The data shows that diverting from 100% regular cotton to 100% organic cotton reduces global warming potential by 27%, eutrophication by 26%, abiotic depletion by 24%, and land use by 39%. In addition, as in Article A-7, blending organic cotton with 20% recycle cotton generates an additional 10% decrease in land use. With the aid of this blend, the comparably lowest impact in land use is achieved in this study. The same is true for global warming potential and abiotic depletion. Article A-7 has the lowest values compared to the rest of the articles in **Figures 5** and 7.

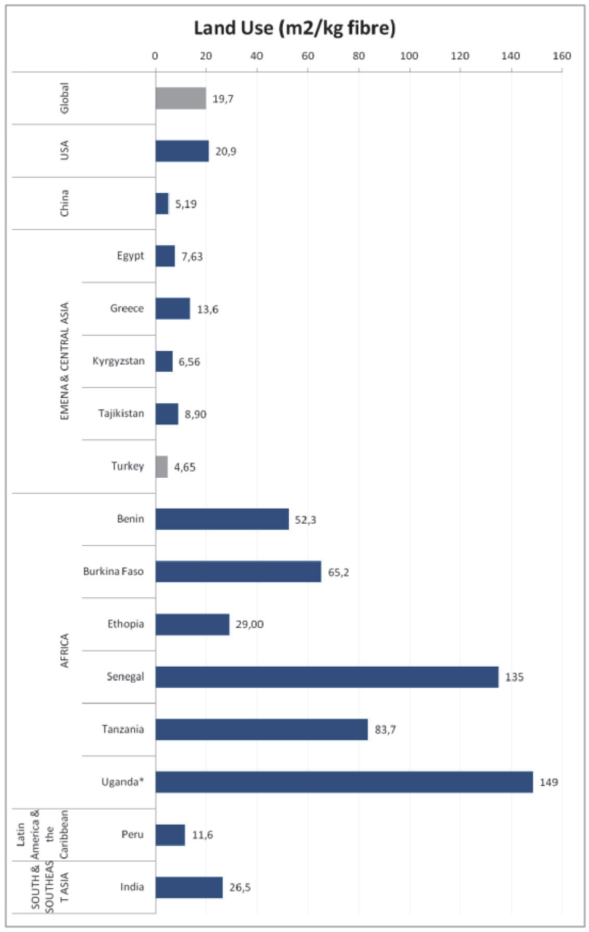

Figure 6.
Land needed for 1 kg lint organic cotton, m² [80].

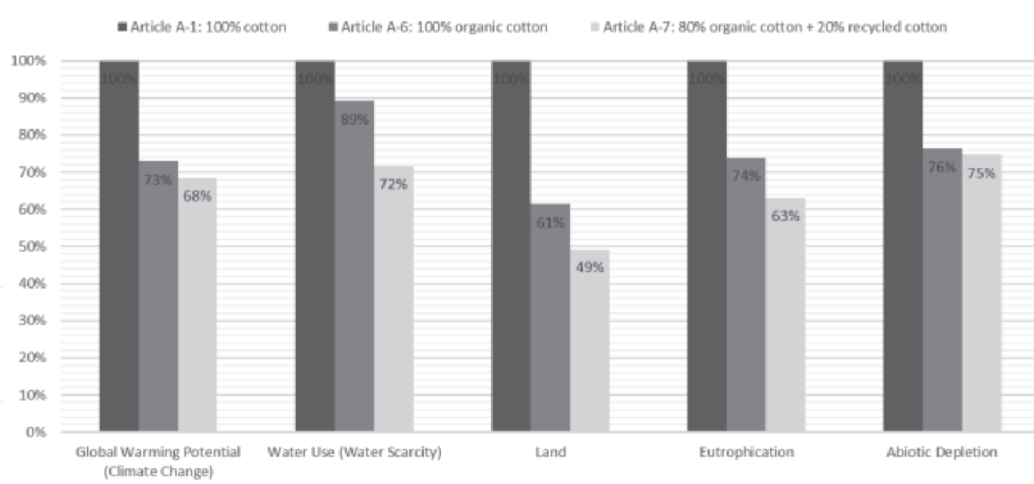

Figure 7.
Results of LCA calculations of organic and post-consumer recycled cotton blends.

On the other hand, eutrophication and water use remain higher than those of the articles in **Figure 5**. Organic cotton still uses a decent amount of water during cultivation. Therefore, Article A-7 could not result with the lowest impact on water use and eutrophication.

4.4 Discussion

Fiber selection stage—in this study fiber cultivation stage—has the main role in environmental impact of a denim fabric. Selected five impact categories are divided into the article's process steps starting from cradle, meaning cotton cultivation, to gate, the end of fabric production. When it is analyzed (Section 4.3.2), one can see that fiber has more than 50% of the total impact in four out of the five categories. Only in abiotic depletion, warp preparation and dyeing have a greater effect than that of the fiber itself. Since recycled cotton usage means eliminating the fiber growing stage or in other words not using virgin raw material that requires natural resource, the environmental impact decreases as the recycle content increases in the fabric. And this is mainly true for global warming potential, eutrophication, water use, and land use. Especially for water and land use, fiber growth stage has more than 90% impact on the overall score. Fifty percent recycled cotton use decreases both impacts by 50%. Therefore, it is better to use recycled content to decrease the environmental impact of water and land use mainly.

Organic cotton with recycled cotton combination has the lowest impact in land use. Using 100% organic cotton also helps reduce global warming potential and eutrophication more than using 50% recycled cotton. However, when it comes to water use and land use, recycled cotton always scores the best since it is not a grown raw material. Here, one can question the production of recycling. The data related to production and transportations are taken into account in the LCA calculations.

In conclusion, denim recycling is very crucial to reduce the water and land use impact of jeans. Combining recycled cotton with organic cotton also leads to reductions in other impact categories such as eutrophication, global warming potential, and abiotic depletion as well. As a future study, the impact of different fibers used in denim fabric production may also be analyzed with a combination of recycled cotton.

4.5 Challenges

Recycled cotton source appears to be the first challenge when whole textile system is considered. There are regulations in countries either limiting or declining the import of second-hand garments. This creates a limitation in source since the collection of second-hand garments is not organized in some countries.

The second challenge is the composition of jeans. Historically, the main composition was 100% cotton. Right now, more than half of the jeans include elastane fiber as well. Besides elastane, new compositions include man-made fibers and regenerated cellulosic fibers. The more complex the composition, the harder it gets to recycle jeans mechanically.

The most important challenge here is always the consumer mindset. Across the industry, only 13% of the total material input is in some way recycled after clothing use. Most of this recycling consists of cascading to other industries and is used in lower-value applications, for example, insulation materials, wiping cloths [81], Once discarded, over half the garments are not recycled but end up in mixed household waste and are subsequently sent to incinerators or landfill. According to a McKinsey analysis, as was mentioned before, an average consumer buys 60% more clothes per year than 15 years ago but keeps the clothes only half the time, and this really is shocking once the numbers become visible [82]. Consumer awareness should be increased via marketing channels and mainly in schools.

5. Future of denim recycling

Since mechanical recycling technique is a challenge in the process, recently, new techniques have emerged to use denim jeans and other cellulosic materials as a source/raw material. Companies like Re:newcell, Infinited Fibers, and Nanollose are taking second-hand garments, applying fiber separation and turning cellulosic part into liquid [83–85]. Some of them include fermentation, and as a last step, they turn the liquid into the material. The process resembles regenerated cellulosic fiber process. The use of fermentation appears to be a promising step into bio design for textiles, and this also eliminates all the negative sides of mechanical recycling.

Conflict of interest

The authors declare no conflict of interest.

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