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COMPREHENSIVE LIFE CYCLE ASSESSMENT: THE CASE OF 100% COTTON BED SHEET

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Highlights

- The environmental impact of the use of the product is more.
- The washing process is the main factor in increasing the environmental impact.
- The use of the 'take-back system' is strongly recommended.

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ABSTRACT: Wastes generated during the production of textile products and the interaction of products with the environment throughout their life cycle significantly contribute to environmental pollution. In this study, the negative impacts during the production and usage stages of a 100% cotton single bed sheet were assessed through a field study conducted in Gaziantep and Bursa provinces. The study evaluated environmental impacts over a production and 7-year usage period, considering relevant impact categories identified through life cycle analysis. It was determined that water use and dye-based pollutants have significant effects, ranging from toxicity to global warming. Especially in the categories of aquatic ecotoxicity, eutrophication, global warming, and respirable organics, it has been observed that the use-based impact is higher and directly negatively affects the environment and public health. Accordingly, it was determined that the environmental impact of the product in the use phase is higher than in the production phase. Finishing and dyeing stages were determined to be the main processes in the formation of pollution, and various suggestions were made to reduce various negative impacts to protect the environment and public health, especially in the treatment of wastewater, and the reduction of water consumption.

Keywords: *Cotton Bed Sheet, LCA, SimaPro, Textile Industry*

1. INTRODUCTION

Today, industrial pollutant sources have the largest share of environmental pollution. One of the sources with a significant share in industrial pollution is the textile industry, whose life cycle stages (e.g., weaving, dyeing, garment, etc.) have significant environmental burdens [1-3]. The textile industry plays an important economic role not only in developed countries but also in developing countries [4]. Worldwide textile production and consumption have increased significantly, particularly in the 2000s. Over the last 20 years, global fibre production has almost doubled from 58 million tonnes in 2000 to 113 million tonnes in 2021 and is expected to reach 149 million tonnes in 2030 if business as usual continues [5]. The most widely used natural fiber in the world, cotton, is renowned for its versatility [6]. The amount of cotton produced worldwide is approximately 73.7 million tonnes. China is the largest producer with 17.4 million tonnes. Türkiye, which ranks seventh in the world, accounts for 3.1 per cent of the world's cotton production. [7]. The textile sector, which is the fourth largest sector with a share of 7.5% in industrial production, is one of the important branches of Turkish industry [8]. In recent years, developments in the textile industry, as in many sectors with developing technology, have played a major role in the increase of environmental problems. The main environmental impact in the textile industry is manifested by the discharge of water with high chemical loads to the receiving environments. In addition, intensified production also increases water use and causes the rapid depletion of water resources. The wastewater resulting from the production process has high COD (Chemical Oxygen Demand) and BOD (Biochemical Oxygen Demand) values, and due to various chemicals (sulphate, etc.), it also negatively affects the environment and public health affecting odor and colour parameters. Textile wastewater, which poses risks to aquatic ecotoxicity and eutrophication due to the high concentration of suspended solids, reduces water quality. Another important factor is air pollution resulting from the use of fossil fuels for energy consumption and energy recovery activities. The combined use of gas and coal for heating activities causes

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high amounts of PM (particulate matter), CO (Carbon monoxide), CO_2 (Carbon dioxide), NOx (nitrogen oxides), and O_3 (ozone) emissions. In addition, finishing processes, drying processes, and the use of solvents cause volatile organic compounds (VOC) emissions [9]. Other important factors are energy consumption, air pollution, solid waste, and odor generation. Most of the growing amount of textile waste, according to multiple studies, ends up in landfills, making it a global problem [10-11]. Considering all these factors, it can be said that (i) the textile industry has many negative effects on flora and fauna, (ii) it causes acute and chronic diseases, especially due to the use of chemicals. Life cycle analysis is one of the tools to help understand, quantifying and solving environmental problems. Life cycle assessment (LCA) is a scientific analysis method used globally, defined in detail and standardized in the ISO 14040 and ISO 14044 series [12-13]. LCA is a tool that enables the systematic assessment of the environmental impacts of inputs and outputs at all stages of a product's life cycle, namely the acquisition of raw materials, production, transportation, use, recycling, or waste [14]. LCA studies are mainly categorized as “cradle to grave”, “cradle to gate”, and specific life cycle segments [15]. LCA is a scientific method that measures and evaluates the environmental burdens associated with a product or activity by systematically identifying and evaluating the energy and materials used and released into the environment throughout its life cycle [16-17]. LCA is an approach that aims to reveal the environmental impacts of products and services in detail [14]. Environmental analyses and LCA studies for the textile sector are generally focused on a product or process. De Saxce et al [18] conducted a life cycle assessment to analyze the environmental impact of the product’s life cycle and production of 8 bed sheets with different characteristics in terms of raw materials, ease of processing, quality, and weaving processes. It was determined by the researchers that a bed sheet containing 50% polyester resulted in lower water consumption (100% cotton consumes 800 kg of water, while 50% cotton-polyester consumes 475 kg) and has the lowest eutrophication potential. This result highlights the impact of cotton harvesting on water consumption. A life cycle assessment was carried out to identify the potential environmental impacts of the processes with a focus on ‘Traditional T-shirt’ and ‘Eco T-shirt’. The researchers found that the water and electricity consumption rate of the eco T-shirt scenario was 60% less compared to the conventional T-shirt. The water and electricity consumptions were reported as 21,276 L, 608 MJ, and 35,460 L, 407 MJ, respectively [19]. Another study on T-shirts was conducted by Zhang et al [20]. As a result of the LCA of cotton T-shirt production in China, it was found that cotton growing and dyeing processes were at the forefront in the impact categories, and 1.5 kWh was spent on a T-shirt in energy consumption scenarios. At the same time, it was reported that 12.9 kg of wastewater is generated as a result of the dyeing process (for 1 t-shirt), and this amount increases significantly depending on various parameters (hand washing, washing machine, etc.) in the use phase. Yacout et al [21] analyzed the environmental impacts of acrylic fibre production in Africa, the Middle East, and North Africa (MENA) regions, especially in developing countries, using SimaPro 7.1 and Eco indicator 99 methods. Accordingly, they emphasized that both resource consumption and aquatic ecotoxicity potential are significantly affected, with energy consumption of 133 MJ, and fossil fuel depletion identified as the largest impact area and water use of 3.6 m^3. According to Munasinghe et al [22], most LCA studies focus on the raw material extraction stage as an important step. They also identified research gaps in the areas of non-woven fabric production, fabric and garment production (smart textiles), retailing, dry cleaning, ironing, use phase (where there are significant differences in user behavior and brand standards), and landfill. The review article compared the percentage of selected papers reporting each impact category and found that greenhouse gas emissions (GHG) and renewable and non-renewable energy use were reported in an average of 84% of the selected papers. Fidan et al. [3] investigated the life cycle impacts of using mechanically recycled cotton fibre instead of cotton fibre and a combined heat and power (CHP) plant instead of grid energy on the denim fabric product. According to the results of the study, there are improvements in the relevant categories between 54% and 98% and the use of mechanically recycled cotton as raw material and CHP plant as energy source in denim production processes will facilitate the transition to the circular economy. The study by Chen et al. [23] also discusses key issues such as data collection, carbon storage, allocation methods, and the environmental benefits of recycling when assessing the environmental impacts of cotton textiles.

The waste generated during the production of textile products and the interaction of the products with the environment throughout their life cycle are important factors in preventing environmental pollution. LCA is used to determine how much raw material and energy are used in the production, use, and after-use of the product, how much waste is created, and the impact on the environment at every stage. In this study, the production processes of a 100% cotton single bed sheet, a common home textile product manufactured in Bursa province, were explained. Life Cycle Assessment (LCA) was then conducted using the Impact2002+ method of SimaPro 8.0.4 software, encompassing the entire process from the arrival of cotton yarn at the company to the sheet's end-of-life waste scenarios.

2. MATERIAL AND METHODS

2.1. Location and Transport Route

The textile company selected as an example was established in Bursa province in 1936 and carries out weaving, dyeing, and apparel activities on 23 thousand square meters of land. The company manufactures home textiles such as bedspreads, piques, tablecloths, kitchen sets, duvet covers, bed sheets, and peshtemals. Considering the product's preparation and usage time, the chosen company, known for producing durable products, offers researchers the opportunity to observe the long-term effects through usage-based evaluations. In this respect, the relevant company was preferred. The transport route (Gaziantep-Bursa/Kestel) representing the transport process of the study is shown on Google maps. 100% cotton yarn is sent directly to the factory in Bursa after production in Gaziantep.

Figure 1. Route from production (Gaziantep) to the factory (Bursa/Kestel)

2.2. Aims and Scope

In this study, a company engaged in the production of home textile products in Kestel district of Bursa province was contacted and information on (i) production process, (ii) transport process, and (iii) energy used for a 100% cotton single bed sheet was obtained. The data obtained from the company were integrated with data from SimaPro 8.0.4 software [24] and the Ecoinvent 3.0 database. Subsequently, a life cycle process tree for a 100% cotton single bed sheet was created, and impact analysis was performed. The study features (a) a field study based on original data, (b) a life cycle analysis of 100% cotton single sheets, which are commonly used in daily life, and (c) a cradle-to-grave life cycle analysis, including waste scenarios. In this way, a life cycle analysis of a product that is frequently used in daily life - within the scope of a case study - has been carried out, and it is aimed to accurately bring the possible environmental impacts to literature. The International Organization for Standardization's guidelines, ISO 14040: Environmental Management–Life Cycle Assessment–Principles and Framework and ISO 14044: Environmental Management–Life Cycle Assessment–Requirements and guidelines, were followed in this study's LCA evaluation and comparison of the environmental impacts [12-13].

2.3. Functional Unit and System Boundaries

In this study, a 1 kg 100% cotton single bed sheet is considered as the functional unit. With the obtained data, a 100% cotton single bed sheet was modeled using SimaPro 8.0.4 software, following the principles of ISO 14040 and ISO 14044 standards for LCA. The system boundaries include the system starting from the entry of 100% cotton yarn into the company until the final product is used and wasted. The production processes and system boundaries of a 100% cotton single bed sheet are given in Figure 2.

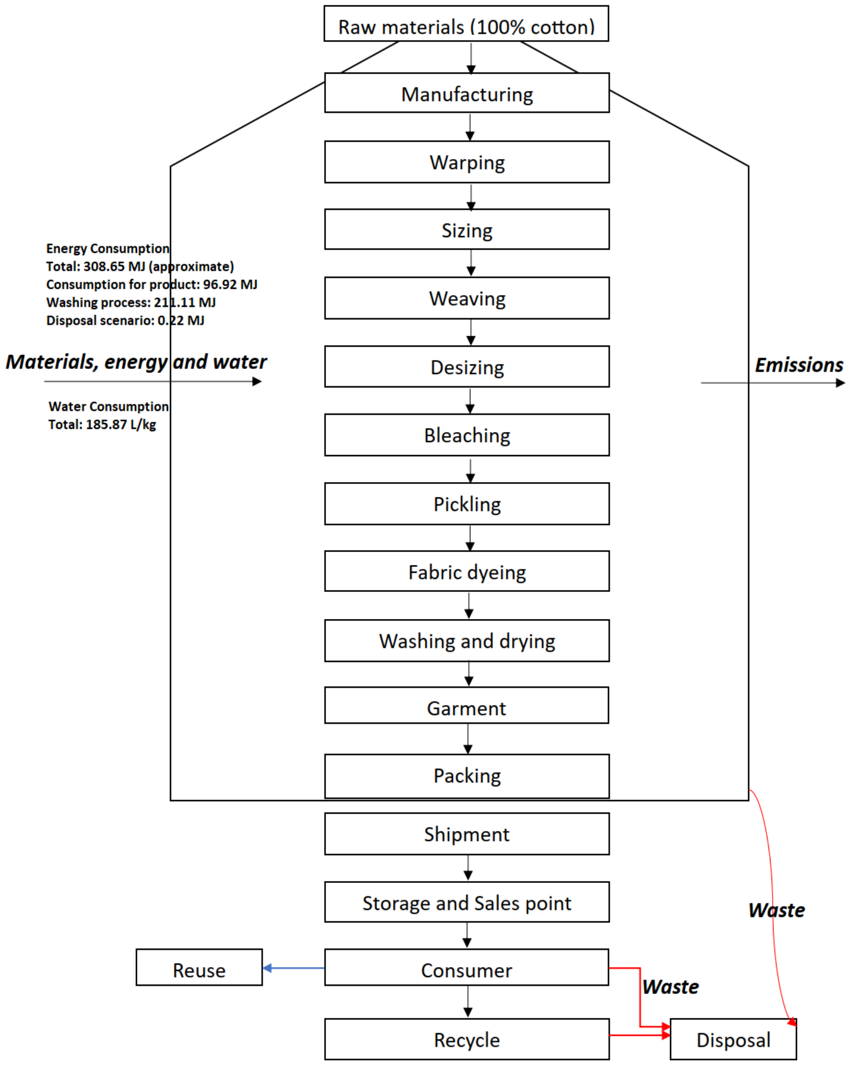

Figure 2. Production processes and system limits of 100% cotton bed sheet

Finishing process data of plain white sheet are given in Table 1. The product is designed for 100% reuse after washing, as is typical for textiles. It was observed that 60% of the users recycled the product as cleaning cloth and 40% disposed of the product as waste after use and the waste scenario was created considering this situation. All data provided were calculated to correspond to 1 kg. The transportation data were calculated in the "kg/km" unit, which is calculated by multiplying the weight value of the material and the distance traveled and entered SimaPro 8.0.4.

Table 1. Finishing process data for white sheets

Process	Raw material	Amount (kg)
Desizing	Water	10
	Desizing agent	0.03
Bleaching	Water	10
	Wetting agent	0.01
	Sodium hydroxide	0.03
	Hydrogen peroxide	0.05
	Stabiliser	0.01
Pickling	Water	10
	Acetic acid	0.01
Bleaching	Water	10
	Whitening agent	0.004
	Soda	0.05
Washing (80 °C)	Water	10

2.4. Data Acquisition

Transport distribution, raw materials, chemicals, and energy data for the unit product were obtained from the textile company in the Kestel district of Bursa province. The data required for 1 kg of 100% cotton-dyed single-person product (bed sheet) are given in Table 2.

Table 2. Description of data used in the study

Life Cycle Phase	*Data Type*	*Source*
Transport and distribution	Bringing the raw material (cotton yarn) from Gaziantep to Bursa (1150 km) to the factory and distributing the produced sheets (see Figure 1)	Provided from Google map and company
Warping	Preparation of yarn for warping, energy and material utilization, waste yarn	Company
Sizing	The yarns from the warping process are sent to another sizing factory in Bursa, 11 km away from the company, for sizing.	Company
Weaving	Bringing the yarns back to the company after the sizing process and weaving, energy and material use, fabric waste	Company
Desizing, bleaching and pickling	Energy and material utilization	Company
Painting	Energy, water and material (paints, auxiliary chemicals) use, wastewater discharge, air emissions	Company
Washing	Energy, water and material use, wastewater discharge	Company
Usage	Consumer behavior: Lifetime of the sheet, frequency of use and habits (water, energy, detergent use per wash, drying, ironing), wastewater discharge, and pollutants	Estimation method/assumptions
Disposal	Textile, packaging waste (cardboard, plastic etc.)	Acceptance of packaging waste regulation and disposal scenario

Only usage-focused assumptions were made in the study; all other data were obtained from the company and through observations within the scope of the field study. In the study, only usage-oriented assumptions were made, and all other data were obtained because of company and observations within the scope of field study. The assumptions made are as follows: (i) A certain part of the product's packaging waste is assumed to be discarded, while some is assumed to be taken to a facility that collects packaging waste, (ii) The product is estimated to be used for an average of seven years, and it is assumed that two sheets are recycled, (iii) After seven years, it is assumed that some of the sheets are used as cleaning clothes (60%) and some of them are thrown away (40%), (iv) The user is assumed to change the sheets twice a month, the sheet selected as an example in the study is used once a month and washed at 30 °C in a 7 kg capacity washing machine (A+). The assumptions based on the amounts of energy, water, and detergent consumed during the washing of the unit product (1 kg) for 7 years are as follows: Water (596.4 L) [20], [22], Electrical Energy (12.1 kWh) [18-22], Natural Gas (19.5 kWh) [19], Detergent (2797 g) [19]. The relevant assumptions were prepared based on the averages in the literature [18-22].

2.5. Life Cycle Assessment

At this stage, the process input and output data required for the LCA study were obtained from the company and Ecoinvent 3.0 database. SimaPro 8.0.4 software Impact2002+ method was used for the LCA. Impact2002+ impact assessment includes sections such as characterization, damage assessment, normalization, and weighting. This method determines midpoint (human toxicity, respiratory effects, ionizing radiation, ozone layer depletion, photochemical oxidation, aquatic ecotoxicity, terrestrial ecotoxicity, terrestrial acidification/nutrification, aquatic acidification, aquatic eutrophication, land occupation, global warming, non-renewable energy, mineral extraction) and endpoint (damage impact) (Human health - Ecosystem quality – Resources - Climate change) impact categories (see Figure 3).

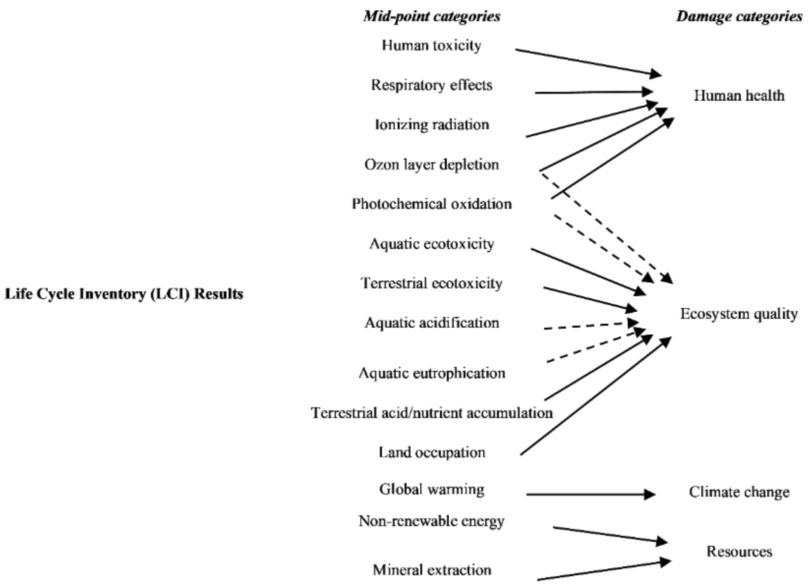

Figure 3. The Impact2002+ framework's overall design connects damage categories to LCI findings through the midpoint categories [25]

3. RESULTS AND DISCUSSION

The comparison of the endpoint impact categories for 100% cotton single-dyed bed sheets, determined by the Impact2002+ method, is presented in Figure 4.

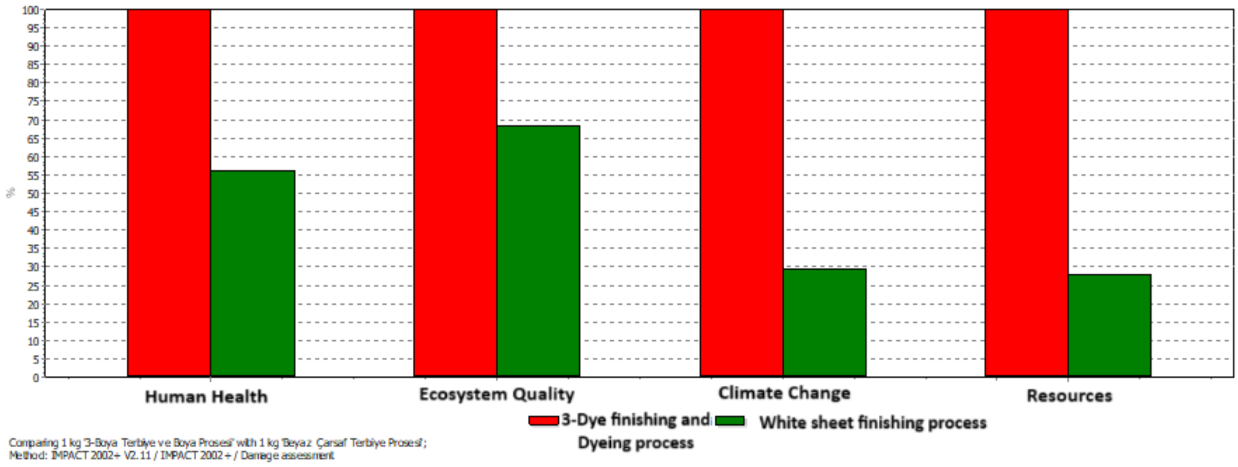

Figure 4. Endpoint impact categories for 100% cotton dyed single bed sheet product as determined by the Impact2002+ method

In all 4 main categories, the dyeing process emerges as the dominant contributor. The dyeing process creates hazards in terms of air, water, and soil with the dyestuffs and chemicals used. Especially in long-term exposures, living health is adversely affected. In addition, resource consumption - when considered from cradle to grave approach - plays a role in the significant increase of water and carbon footprint and the increase of pollution with various types of waste in air, water, and soil because of the production process.

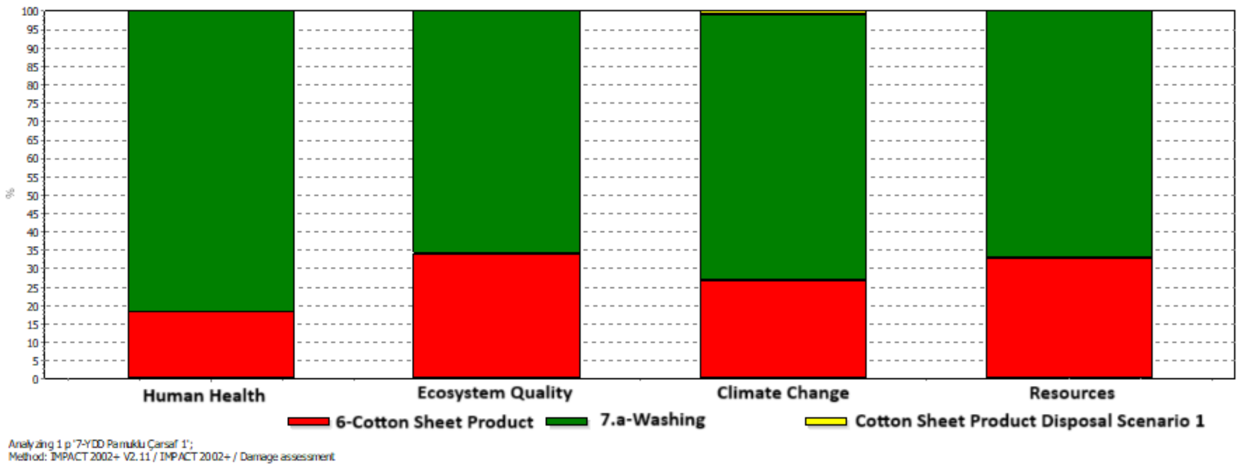

Figure 5. Endpoint impact categories for 100% cotton dyed single bed sheet as determined by the Impact2002+ method

Figure 5 shows the comparison results of the evaluation of the endpoint categories of the cotton-dyed bed sheet by Impact2002+ method according to the damage classes. According to the endpoint impact category, the washing stage was effective in all the impacts collected under 4 main headings. The reason for this is that the washing stage is effective in all categories except the "Ozone depletion" and "Soil occupation" sub-impact categories of the midpoint impact categories

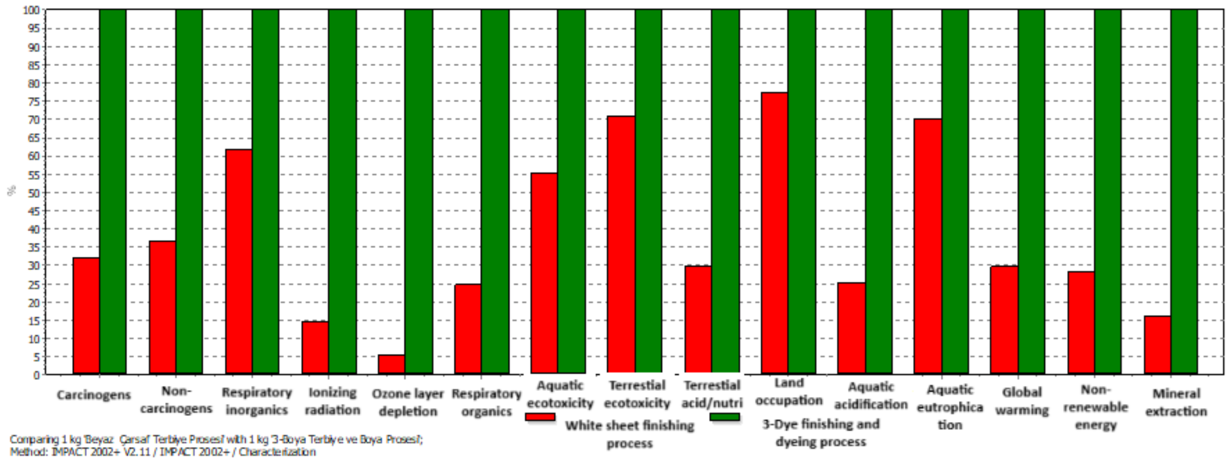

Figure 6. Comparison of midpoint impact categories determined by Impact2002+ method for 100% dyed cotton and undyed single bed sheet product

The midpoint comparison of the modeled white bed sheet finishing process and the dyed bed sheet dye finishing process to determine the net effect of the dyeing process on the production stage is given in Figure 6. In the production of white sheets, the dyeing process with vinyl sulfonyl group dyes used in the dyed sheets was not performed. The other steps in the white bed sheet production were the same as the dyed bed sheet, and only an extra finishing process was carried out with an optical bleaching agent (stilbenzene) after the bleaching process.

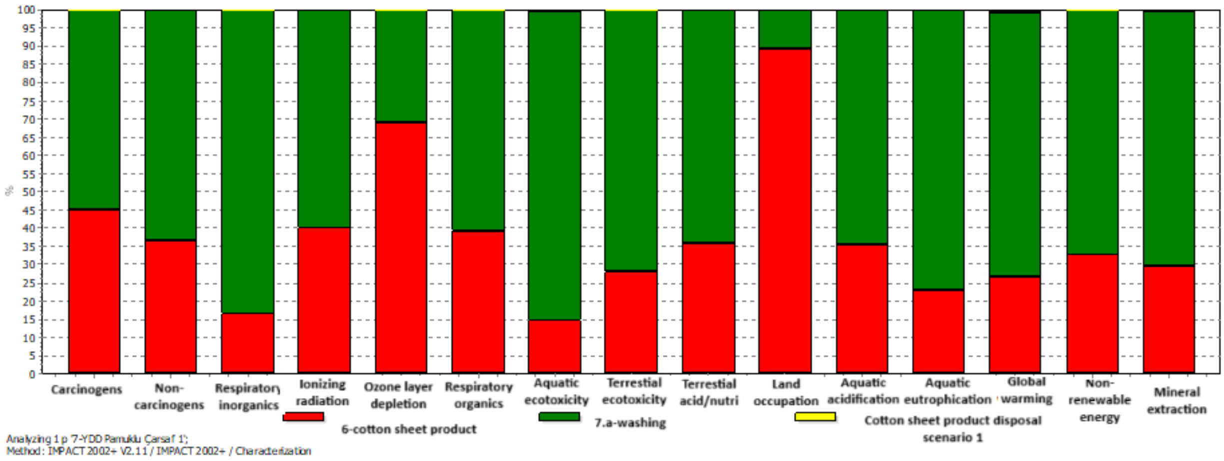

Figure 7. Impact categories determined by Impact2002+ method for 100% cotton dyed single bed sheet product

As can be seen in the impact categories determined in Figure 7, the washing stage is dominant in all categories except "Ozone depletion" and "Soil occupation" categories. The reason why the production stage contributes to the "Ozone depletion" category is the emission values caused by the dye finishing process and sizing process. The reason why the category of "soil occupation" is effective at the product stage is the soil occupied during the cultivation of cotton since the product is a cotton textile product. In this study, although the cotton production stage in the field is not taken as a basis, an impact calculation has been applied in SimaPro software.

The effect values of 100% cotton dyed single bed sheet are given in Table 3 in comparison with the literature.

Table 3. Comparison of study outputs with literature

Energy Usage (MJ/kg)	Water Usage (L/kg)	Relevant Study (based on cradle to grave approach)*
53.61	***185.87***	***This study***
51.84	621	[26]
54.00	1116.6	[27]
130.08	1770	[20]

*: There are different usage periods in related studies. For this reason, the relevant data are given on an annual basis for comparison purposes.

In the weaving process, approximately 4.7 g of fabric waste is generated to produce 1kg of product. In addition, 20 g of fabric waste is generated during the formation of the unit product (1 kg) in the garment stage. The production capacity and all wastage are included in the calculation, and the water consumption capacity in all stages is taken as 10 L per kilogram. The relevant assumption is also used in the literature [28]. Under all these conditions, the annual water use in the production and washing processes was 185.87 L. Calculations assume of 1 kg product production and utilization. The difference in water consumption compared to other studies in the table is due to the product's production process. When Figure 2 is analyzed, it is stated that the system limits of the study are designed based on the raw material coming to the factory.

Since the study covers a 7-year period of use and other studies generally calculate on an annual basis, the data of the study are given on an annual basis as indicated in the table. In the review study by Munasinghe et al [22], it is emphasized that the average impact ranges obtained in cotton-focused life cycle analysis studies are generally in the range of 10-80 MJ/kg for energy use and 250-3500 L/kg for water footprint. While the energy range obtained in this study is compatible with literature, the water consumption range (since the production stage of cotton raw material is not considered) is not compatible with the studies in the literature. In addition, the results showed that the environmental impact of the product in the utilization phase is higher than in the production phase. This result is also supported by the literature [29-31].

The findings of the study show that water use and dye-based pollutants have significant impacts ranging from toxicity to global warming. In this context, the findings are supported by the existing literature and measures to prevent and/or reduce environmental pollution are suggested. In common accommodation areas such as dormitories and hotels, where bed sheet use and change are intensive, it is recommended that continuous washing machines capable of reusing rinse water be preferred, and regular maintenance of these machines must be ensured. In addition, it would be an important step to provide incentives for the reuse of wastewater, treated with advanced systems (e.g., membrane bioreactors), for purposes such as garden irrigation and toilet cleaning. The importance of wastewater and waste management is highlighted by the LCA. In particular (i) recovery and reuse of sizing agents by ultrafiltration, (ii) application of techniques developed to minimize the use of hydrogen peroxide stabilizers, (iii) caustic recovery, (iv) use of automated systems for dosing and dispensing of dyes, (v) the use of high fixing, low salt reactive dyes and treatment of wastewater by membrane filtration and (vi) the use of advanced oxidation processes such as Fenton processes for color removal are recommended for the textile industry. The importance of water has increased especially due to global warming and climate crisis. Accordingly, it is recommended to use and develop waterless dyeing processes (such as dyeing with ultrasonic energy [32] and supercritical carbon-dioxide assisted dyeing [33] specifically for the textile industry. At the same time, since ultrasonic energy is used in the treatment and color removal of wastewater, it is expected to provide high efficiency for the production phase and beyond. The dyeing process is a process that involves a high pollution load and waste generation [34]. In this regard, it is necessary to ensure process optimization for the use of water, chemicals, energy, and raw materials and to integrate artificial intelligence-supported software or systems with developing technology. Coupled with artificial intelligence, advanced technologies can change the world. AI-powered solutions facilitate smart manufacturing that maximize resource utilization through real-time monitoring and parameter adjustments throughout production. The integration of predictive analytics can also help reduce waste and improve productivity overall. The adoption of sustainable practices in combination with these technological breakthroughs has a synergistic effect, driving the industry towards a more ecologically conscious and commercially viable (circular economic model) future. In addition to addressing current environmental issues, the textile sector's commitment to sustainability, circularity, and technical innovation is preparing the way for a more resilient and responsible industry in the years to come. Another important issue is to ensure the recycling of the product after the end of its life. In addition, there are studies on the "take-back" system in the literature [35-36] and it is emphasized that the consumption of resources (such as water, energy, and raw materials) can be reduced if the relevant system is implemented. Therefore, recycling and reuse of textile products whose life cycle has not ended is an important step for natural resource conservation, sustainability, and prevention of some environmental problems (such as water, soil, and air pollution).

4. CONCLUSIONS

The textile industry, which is an important industry branch in Türkiye and the world, plays an important role in the economic development process. The main environmental problem in the production phase of the textile industry is identified as the chemical loads caused by the chemicals used and the significant amount of wastewater generated due to high water consumption. Today, life cycle assessment helps improve the resource, energy efficiency, and environmental performance of companies.

In this study, 100% cotton dyed single bed sheet and 100% cotton white single bed sheet production processes were selected as an example from a company producing home textile products operating in Bursa province, and a life cycle assessment was carried out from the arrival of the yarn to the end of use. The impact categories of the life cycle assessment for the product variants were evaluated using the Impact2002+ method. The results showed that the environmental impact of the product in the utilization phase is higher than in the production phase. Especially in the evaluations made based on the 1-year usage period, it was determined that (i) chemical-containing wastewater generated as a result of the washing process causes various negative effects on the aquatic ecosystem (such as eutrophication, aquatic ecotoxicity), (ii) when the midpoint hazard class of the LCA in the production stage is considered, the greatest impact is seen in the dyeing and finishing stages, (iii) aquatic ecotoxicity, carcinogenic effect and respirable organic hazard are high due to the use of chemicals. The related outputs reveal that natural resources are rapidly consumed, polluted, and their quality is adversely affected due to chemical and water consumption. For the sake of environmental and public health, it is urgently recommended to reduce chemical and water consumption, and to establish a sustainable production chain and logistics. Furthermore, implementing control mechanisms such as smart flow meters (for loss and leakage detection and consumption optimization), determining process and pollution profiles, and establishing and operating appropriate treatment systems (preferably membrane filtration, ceramic filtration processes, or advanced oxidation processes) are crucial.

Declaration of Ethical Standards

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Credit Authorship Contribution Statement

CRediT (Contributor Roles Taxonomy) was introduced with the intention of recognizing individual author contributions, reducing authorship disputes and facilitating collaboration.

Declaration of Competing Interest

The authors have no relevant financial or non-financial interests to disclose.

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Data Availability

There is no any data from a data repository.

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