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EFFECTIVE WASTE MANAGEMENT WITH EMPHASIS ON CIRCULAR ECONOMY

The impact of organic cotton use and consumer habits in the sustainability of jean production using the LCA approach

Fatma Şener Fidan[1] · Emel Kızılkaya Aydoğan[2] · Niğmet Uzal[3]

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Abstract

Due to the rise in clothing consumption per person and growing consumer awareness of environmental issues with products, the textile industry must adopt new practices for improving sustainability. The current study thoroughly investigates the benefits of using organic cotton fiber instead of conventional cotton fiber. Because of the extensive use of natural resources in the production of cotton, the primary raw material for textiles, which accounts for the environmental effects of a pair of jeans, a life cycle assessment methodology was used to examine these effects in four different scenarios. The additional scenarios were chosen based on the user preferences for washing temperatures, drying methods, and the type of cotton fiber used in the product. The environmental impact categories of global warming potential, eutrophication potential terrestrial ecotoxicity potential, acidification potential, and freshwater ecotoxicity potential were analyzed by the CML-IA method. The life cycle assessment results revealed that the lowest environmental impacts were obtained for scenario 4 with 100% organic cotton fiber with an improvement of 87% in terrestrial ecotoxicity potential and 59% in freshwater ecotoxicity potential. All of the selected environmental impacts of a pair of jeans are reduced in all scenarios when organic cotton is used. Additionally, consumer habits had a significant impact on all impact categories. Using a drying machine instead of a line dryer during the use phase is just as important as the washing temperature. The environmental impact hotspots for a pair of jeans were revealed to be the eutrophication potential, acidification potential, and global warming potential categories during the use phase, and the terrestrial ecotoxicity potential and freshwater ecotoxicity potential categories during the fabric manufacturing including cotton cultivation. The use of organic cotton as a raw material in manufacturing processes, as well as consumer preferences for washing temperature and drying methods, appears to have significant environmental impacts on a pair of jeans' further sustainable life cycle.

Keywords Life cycle assessment · Environmental impacts · Jean · Organic cotton · Use phase · Consumer maintenance habits

Introduction

Textile production emitted 1.2 billion tons of CO_2 equivalent in 2015, more than all international flights and maritime shipping combined (Kalliala and Nousiainen 1999; van der Velden et al. 2014). With increased awareness among both producers and customers, there is a growing trend in sustainable jean production in the modern world. Although a variety of methodologies have been used to evaluate the environmental performance of goods with this tendency, life cycle assessment (LCA) is unquestionably the most often utilized method today. With a cradle-to-grave approach, LCA is a thorough and scientific methodology for defining the probable environmental impacts of a system or product over its life cycle (Baumann and Tillman 2004). ISO 14040 and

Responsible Editor: Philippe Loubet

✉ Fatma Şener Fidan
fatmasener@gmail.com; fatma.senerfidan@agu.edu.tr

1 Department of Technology Transfer Office, Abdullah Gul University, Kayseri 38170, Turkey

2 Department of Industrial Engineering, Erciyes University, Kayseri 38060, Turkey

3 Department of Civil Engineering, Abdullah Gul University, Kayseri 38170, Turkey

14,044 provide this useful methodology, which identifies hotspots across the life cycle and shows potential improvement possibilities (ISO 2006a, 2006b). Because the textile and garment industry has such significant environmental implications, there are several LCA papers on the subject in the literature (Ibrahim and Eid 2018). T-shirts have been the subject of most LCA research in the apparel industry (Baydar et al. 2015; Esteve-Turrillas and de La Guardia 2017; Hackett 2015; Kazan et al. 2020; Moazzem et al. 2018; Roos et al. 2015; Zhang et al. 2015). On a limited basis, studies on clothes such as pants and briefs were also offered (Collins and Aumônier 2002). Furthermore, LCA analyses for dynamic textile applications of technical textiles, different phases of textile products such as the end of life (EOL), and dyeing contributed significantly to the literature (F. Ş. Fidan et al. 2021a, b; Koligkioni et al. 2018; Samani and van der Meer 2020; Wiedemann et al. 2020; Yasin et al. 2016a, b; Yasin et al. 2016a, b; Yasin et al. 2018; Yasin and Sun 2019). Despite the widespread use of jean clothing, studies are uncommon and limited to LCA reports issued by well-known brands. The LCA studies and system bounds for a pair of jeans in the literature are given in Table 1.

Current research looking into the environmental impact of a pair of jeans has focused on the stages of the life cycle from cotton cultivation to retailing (Browne et al. 2005; F. Fidan et al. 2021a, b; Hackett 2015; Levänen et al. 2021; Levi Strauss 2015; Morita et al. 2020; Nellström and Sarclca 2019; Zamani et al. 2017). One of the studies was a report prepared by Levi Strauss (2015) for the company's products (Levi Strauss 2015). The company performed a lifetime LCA to determine the environmental impact of the Levi jeans. The LCA focused on the product's use and EOL disposal, which were crucial stages of the product that were tied to customer behavior. The findings revealed that fiber production and consumer care activities utilize the majority of water, with 68% of fiber production and 23% of consumer care activities (such as cleaning and washing) over the course of the product's life cycle. In addition, the phase of product usage by consumers had the greatest impact, with equivalent carbon dioxide emissions accounting for 88% of overall emissions. Nellström and Sarclca (2019) compared a pair of Nudie Jeans' life cycles, taking into account circular and linear conditions. In the linear case, a pair of jeans was assumed to be discarded after their functional life, whereas in the circular case, the jeans were repaired and reused three times (Nellström and Sarclca 2019). Zamani et al. (2017) used the LCA technique to examine the environmental impact of clothes libraries and evaluated the benefits and drawbacks of standard business model methods (Zamani et al. 2017). They evaluated jeans, t-shirts, and dresses, demonstrating the benefits of using clothing libraries for apparel with long service life.

Aside from the variety of textile products that were subject to LCA studies, the system boundaries that these studies cover were also a significant factor in evaluating environmental impacts. Many studies, like the jean example, tend to leave out the use and EOL phases. However, one of the most significant environmental challenges during the life cycle of a pair of jeans was the maintenance conducted by consumers during the use phase (Allwood et al. 2006). The consumer's choices influence the use of a jean garment throughout its life cycle. Consumer behavior in daily activities, such as doing laundry and drying clothes, poses a hurdle to long-term consumption (Jack 2013). It was discovered that the energy consumed during the washing and drying processes for various clothes, such as t-shirts and polyester pants, was significantly higher than at any other stage of the manufacturing process (Collins and Aumônier 2002; Walser et al. 2011). Furthermore, energy expenditures at the consumer use phase were demonstrated to account for more than 65% of total energy expenses (Allwood et al. 2006; Collins and Aumônier 2002). Post-purchase consumer behavior, which demonstrates how clothing is preserved, is also important for long-term sustainability, and a thorough and rigorous examination of these environmental implications for a pair of jeans is required.

Finally, the raw materials investigated in LCA studies were a concern that should be considered when assessing

Table 1 System boundaries of LCA studies for a pair of jeans in the literature

Reference	Cotton cultivation	Fabric production	Jeans production	Retailing	Use phase	EOL
Browne et. al. (Browne et al. 2005)	x	x	x	x		
Hackett et. al. (Hackett 2015)	x	x	x	x		
Levi Strauss (Levi Strauss 2015)	x	x	x	x	x	x
Morita et. al. (Morita et al. 2020)	x	x	x	x		
Fidan et. al. (F. Fidan et al. 2021a, b)	x	x				
Nellström and Sariclca (Nellström and Sarclca 2019)	x	x	x	x	x	x
Zamani et. al. (Zamani et al. 2017)	x	x	x	x	x	x
Levanen et. al. (Levänen et al. 2021)	x	x	x	x	x	x

environmental implications. Cotton is the most frequently used natural fiber, accounting for more than 82% of global fiber use (Shui and Plastina 2013). Conventional cotton cultivation consumes a lot of water and energy, uses a lot of fertilizers and pesticides, and takes up a lot of areas, all of which are harmful to the environment and human health (Bevilacqua et al. 2014; Chapagain et al. 2006; La Rosa and Grammatikos 2019). Cotton cultivation has the most significant environmental impacts in terms of worldwide water use and pesticide consumption, which account for 2.6% and 11% of global consumption, respectively (Bevilacqua et al. 2014; Chapagain et al. 2006; Scheffer 2001). Alternative sustainable raw materials are gaining increasing attention in the textile industry every day, as conventional cotton has substantial environmental and health-related consequences.

One of the most important raw materials is organic cotton, which has strict regulations and limits (Bevilacqua et al. 2014; Textile Exchange 2014). In organic cotton farming, the use of genetically modified organisms is prohibited, and fertilizer usage with chemical synthetic pesticides is strictly regulated (Ingram 2002). Through these arrangements, organic cotton is expected to reduce the environmental impacts and enables textile production concerning nature.

Although there are several LCA studies on the usage of organic cotton in garments in the literature, they are still limited. Baydar et al. (2015) compared an eco-t-shirt made of organic cotton and colored with green dye to a typical cotton t-shirt (Baydar et al. 2015). In the categories of global warming potential (GWP), water use, terrestrial ecotoxicity potential (TEP), and acidification potential (AP), the eco t-shirt had a lower environmental impact. Cotton cultivation was discovered to be the second most common cause of GWP. Khan et al. (2018) conducted aN LCA study for organic and conventional cotton t-shirts with data acquired from the literature (Khan et al. 2018). They also investigated in great detail the hotspots of white cotton t-shirt production in Bangladesh, which added to the societal difficulties. Sipperly et al. (2019) used the LCA to examine the difference in the environmental impacts of a shirt when organic cotton was used instead of conventional cotton (Sipperly et al. 2019). Organic cotton, except for land use and water use, was much more environmentally benign, according to their study. Through the LCA, Kazan et al. (2020) assessed the environmental impacts of cotton-woven shirts using several raw material scenarios, including organic and conventional cotton (Kazan et al. 2020). They concluded that utilizing organic cotton improved the GWP, AP, and acidification potential (EP) categories due to pesticide and fertilizer elimination. None of these studies investigated the use of organic cotton as a raw material for a pair of jeans that are widely used and have a high environmental impact. To fill these gaps in the literature, this study explored deeply the environmental impacts of a pair of jeans produced with organic and conventional cotton.

Even though jeans account for a significant portion of the textile sector, existing LCA studies are confined to brand reports, and only a few studies examine the results for a single pair of jeans, including the use phase and EOL. Also, any research was done to see if using organic cotton as a raw material reduces the environmental impact of a pair of jeans from an LCA standpoint. Cotton is the most significant raw material in the life cycle of jeans and should be placed at the top of the sustainable jeans production agenda (Downey 2014). This research filled in the gaps by investigating the environmental impacts of a pair of jeans made using organic and conventional cotton raw materials, as well as varied consumer habit practices during the use phase. In comparison to prior studies, this study expanded the life cycle boundaries considered in the analysis of the environmental impact of a pair of jeans and presented a thorough sustainability assessment using a cradle-to-grave methodology. This research was carried out to give a full sustainability assessment of raw materials using a cradle-to-grave methodology for four alternative scenarios for a pair of jeans. The LCA approach was used to conduct the environmental impact analysis, which included the use of primary and secondary data as well as sensitivity analyses to assess the impact of uncertainty. This study encouraged the widespread adoption of organic cotton in the jean industry to reduce environmental impacts and highlighted the importance of customer maintenance habits in the lifespan of a pair of jeans.

Material and methods

Scenarios

The sustainability of a pair of jeans made with both conventional and organic cotton fibers and maintained under various consumer habits was evaluated using four scenarios. All of the scenarios are listed in Table 2.

The cotton type used is the first variable in the scenarios created. The conventional cotton used in the first and second scenarios was used as the raw material. Cotton cultivation was the hotspot of denim fabric used in jean production, so organic cotton was included in S3 and S4 to explore more sustainable options. The study's main goal was to determine the contribution of organic and conventional cotton use to the environmental impacts of a pair of jeans, and the blend ratios of the selected fabrics in the scenarios were set at 100% (F. Fidan et al. 2021a, b). The consumer washing and drying habits during the use phase were the second variables in the scenarios. The most important factor in the washing process was the temperature of the water (Daystar et al. 2019). The washing temperature preferences of different

Table 2 Summary of the scenarios (S: scenario)

Scenario	Raw Material	Use Phase	EOL
S1	Conventional cotton	Washing: % 70 consumers 40 °C and %30 consumers 60 °C Drying: % 70 consumers use a clothes dryer and %30 consumers apply line-dried outdoors	30% landfill and 70% incineration with energy recovery
S2	Conventional cotton	Washing: % 50 consumers 40 °C and %50 consumers 60 °C Drying: % 50 consumers use a clothes dryer and %50 consumers apply line-dried outdoors	30% landfill and 70% incineration with energy recovery
S3	Organic cotton	Washing: % 70 consumers 40 °C and %30 consumers 60 °C Drying: % 70 consumers use a clothes dryer and %30 consumers apply line-dried outdoors	30% landfill and 70% incineration with energy recovery
S4	Organic cotton	Washing: % 50 consumers 40 °C and %50 consumers 60 °C Drying: % 50 of consumers use a clothes dryer and %50 consumers apply line-dried outdoors	30% landfill and 70% incineration with energy recovery

countries varied greatly. Studies from Europe were used because this study used input from Turkish consumers and there was no existing consumer maintenance habit study for Turkey. The current European laundry temperature is 41 °C, with approximately 68% of European loads washed at or above 40 °C (A.I.S.E 2013). Moreover, 40 °C and 60 °C temperatures are the test program according to EU regulation EU/2019/2014 and EN 60,456:2016/prA:2020 standard (CLC EN 2020; European Commission 2019). In this study, it was assumed that 70% of consumers choose a washing temperature of 40 °C and 30% of them 60 °C in S1 and S3. Two additional scenarios (S2 and S4) were created to see the contribution of washing temperature to the environmental impact of a pair of jeans. In these scenarios, 50% of consumers choose a washing temperature of 40 °C and 50% of them 60 °C. Another choice that affects the environmental impacts in the use phase is the washing method. The most used washing methods are machine washing, hand washing, and dry cleaning. Due to the near-100% ownership rate of washing machines in Turkey and the fact that they are an essential component of every home, only the machine washing option was thoroughly investigated for all scenarios and the other options were left out (Vakıf Investment 2018). The resource usage and environmental effects of washing clothes vary greatly because there are many different washing applications and different types of washing machines (Pakula and Stamminger 2010). In this study, a washing machine with the labeled A energy efficiency class was chosen because less energy-consuming devices are now preferred more. Since the eco-program is a test program following EU regulation EU/2019/2014 and EN 60,456:2016/prA:2020 standard, it was chosen as the washing machine program (CLC EN 2020; European Commission 2019). The two most popular ways to dry clothes are on a line or in a dryer. In this study, there were two methods used in each scenario. A drying machine with the labeled A + + energy efficiency class was chosen due to the rising demand for energy-efficient products. To identify the relation between washing and drying habits, the ratio of consumers choosing the two drying methods was calculated using the same criteria as the choice of washing temperature. At the EOL phase, it is decided what will happen to a pair of jeans when their life expires. In the literature, several approaches—including recycling, landfilling, and incineration—were examined. In this study, it was assumed that 70% of a pair of jeans moved to a landfill and that the remaining 30% was burned for energy recovery during the end-of-life phase.

Environmental impact assessment with LCA

In the study, the LCA approach was applied to determine the environmental impacts of determined scenarios for a pair of jeans. LCA performed obeying ISO 14040 and ISO 14044 standards (ISO 2006a, 2006b). According to ISO standards, goal and scope, LCI, LCIA, and interpretation are the steps of an LCA study. The aforementioned steps are detailed below.

Goal and scope

The main purpose of this LCA research was to determine the environmental impacts of a pair of average-size jeans (0.67 kg) vie four scenarios. Organic cotton use instead of conventional cotton as raw material and the consumer maintenance preferences in the use phase were included in the scenarios to analyze environmental impacts deeply. To reveal the change in environmental impacts with the use of different types of cotton as input, jeans with a blending ratio of 100% were selected. The remaining manufacturing processes for the pair of jeans were the same. The functional unit was a pair of average-size jeans manufactured in Turkey with a lifespan of 45.5 cycles. In the LCA studies including the use phase of the clothes carried out in the literature, lifespan is required used to express the functional unit (Åslund Hedman 2018; Braun et al. 2021).

The LCA was conducted using the "cradle-to-grave" approach, including all life cycle stages. The system boundaries and life cycle diagram for a pair of jeans are given in Fig. 1.

Jean production is a complex system that includes many processes from farming to EOL. The production stages are divided into 3 parts: downstream, core, and upstream processes. The downstream processes for a pair of jean production include the cultivation of natural fibers such as cotton and hemp, ginning, and fiber production. Although cotton fibers are the main ingredient of jean production, today jeans may also contain man-made fibers. However, cotton is the most used raw material for a pair of jeans, the use of other fibers was not mentioned in this study. Core processes of a pair of jeans are respectively spinning, indigo rope dyeing, sizing, weaving, and finishing. Lastly, upstream processes include garment production, use phase, and the EOL. This study investigated the environmental impacts of a pair of jeans with the scenarios created in downstream and upstream processes.

Life cycle inventory analyses and assumptions

The LCA methodology requires a large amount of data from primary or secondary sources. In this study, primary data was process-specific and obtained from a denim mill and one-to-one interviews. For the remaining process, the Ecoinvent V.3.7.1 Database and literature were used as secondary data (Wernet et al. 2016). The detailed description of the data used and the assumptions are given explained in detail in the following subsections.

a) *Textile Production*

In Turkey, system boundaries have been defined, including conventional and organic cotton fiber production, fabric production, use phase, and EOL. For this study, spinning and fabric production data for 2019 was provided by a denim mill in Turkey. One-on-one interviews were used to gather information on the production of organic cotton seeds in Turkey. Ecoinvent V.3.7.1 database was used for background data including materials, energy, resources, transportation, and waste management. All raw material transportations were included in the calculation, considering the distance between the place of production and the place of use. Capital goods (land, buildings, machinery) and intermediate packaging were excluded, assuming a 1% cut according to ISO

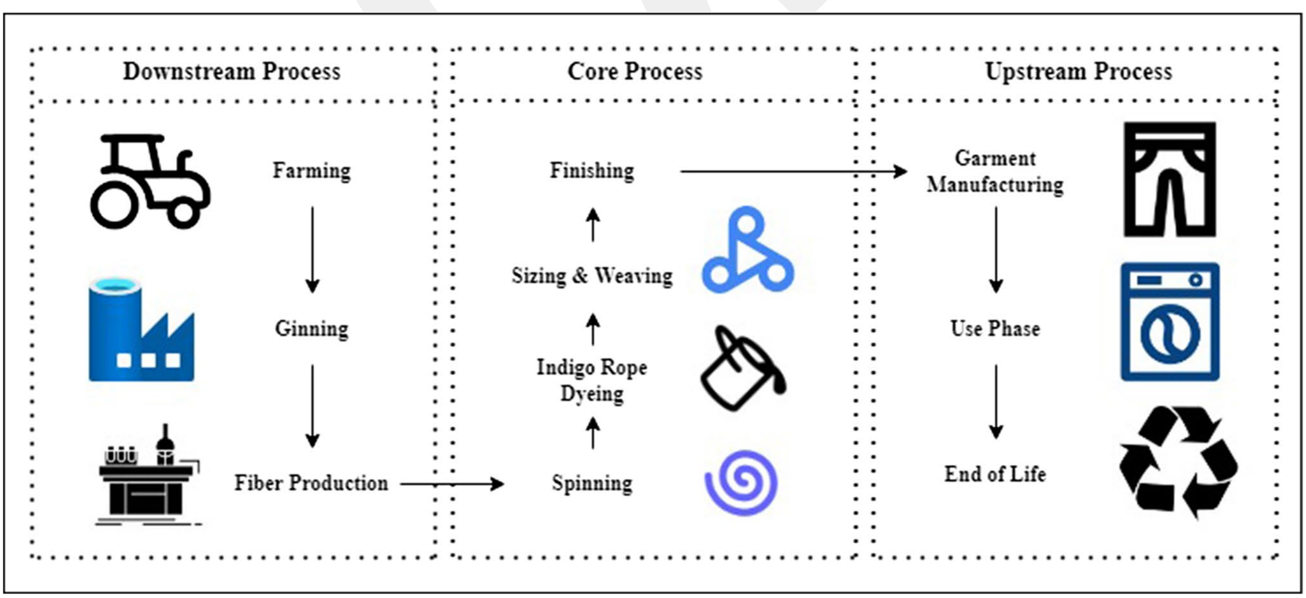

Fig. 1 System boundaries and life cycle diagram for a pair of jeans

14040. Textile processes were included in this study and data sources are given in Table 3.

b) Use Phase

Maintenance of garments by itself seems to have small and environmentally quite insignificant impacts. However, with the process being done by all people in the world, significant environmental impacts arise (Laitala et al. 2018). While the textile production phase is done once for a pair of jeans, the maintenance in the use phase continues regularly. The length of life of a garment plays a decisive role in the environmental impact of this phase (Laitala et al. 2018). The processes applied during the use phase are washing, drying, and ironing. In this study, the washing and drying processes were considered. Since it is known that jeans are generally used without ironing, it was assumed that the jeans were not ironed in this study.

The parameters that are required to be assigned to include the use phase in LCA studies are as follows (Laitala, Klepp, and Henry 2017).

Cleaning method In this study, it was supposed that all washing operations were done in the washing machine since the ownership rate of the washing machine in Turkey is 100% (Vakıf Investment 2018). Hand washing or dry cleaning processes were excluded.

Features of the devices Since it determines water and energy consumption, it is necessary to consider the characteristics of the devices used. In this study, washing machines labeled as A, and drying machine labeled as A++ in terms of energy efficiency and manufactured by a company with more than half of the market share, were used.

The different temperatures examined are 40 °C and 60 °C while the setting for the load was kept constant at a full load of 9 kg. Quantitative data on energy and water consumption for temperatures of 40 °C and 60 °C during washing operations were taken from the Washing Machine User Manual prepared by the manufacturer (Arçelik 2021b). It was assumed that the effluent from the washing machines was the same amount as used (Moazzem et al. 2021). The capacity of the drying machine is 9 kg, and it was assumed to operate in the standard cotton program at full load (Arçelik 2021a). Quantitative data on consumption during washing and drying operations are presented in Table 4. All consumptions are given for 1 wash cycle. These values were converted to the number of washes per lifetime.

Detergent use The amount of detergent used is an important parameter in terms of environmental impacts (Giagnorio et al. 2017). In this study, the detergent consumption value was determined by following the literature and given in Table 5.

Consumer behavior and practices in the laundry These are the washing decision after use, the degree of filling of the

Table 3 Textile processes and data sources

Process	Description	Data source
Farming and ginning	Conventional cotton	Ecoinvent V.3.7.1
	Organic cotton	Collected data from institutions
Spinning	Electricity, materials	Collected data from a textile company Ecoinvent V.3.7.1
Fabric production	Electricity, heat, steam, water, materials, chemicals, and dyes	Collected data from a textile company Ecoinvent V.3.7.1
Garment production	Chemicals, brass, ribbons, woven fabric	(Åslund Hedman 2018)
Use Phase	All detail is given next section	Collected data from the literature Ecoinvent V.3.7.1
EOL	Electricity	Collected data from the literature Ecoinvent V.3.7.1

Table 4 Energy and water consumption according to the washing and drying machines

Machine type	Temperature	Energy (kWh/cycle)	Water (L/cycle)	Wastewater (M^3/cycle)	Reference
Washing Machine with label A	40 °C	0.95	80	0.080	User manual
	60 °C	1.08	55	0.055	User manual
Drying machines with label A++	NA	2.17	NA	NA	User manual

Table 5 Inputs and flows for washing machine and consumer habits

	Parameter	Unit	Amount	Reference
Washing and drying machine	load	%	100	User manual
	Capacity	Kg	9	User manual
	Detergent consumption	g/cycle	134	(Nellström and Sarclca 2019)
Consumer habits	Lifetime of a jean	Week	78	(Nellström and Sarclca 2019)
	Number of wearing before washing	Wears	6	(Nellström and Sarclca 2019)
	Frequency of wearing	Days/week	3.5	(Periyasamy and Militky 2017)

washing machine, the choice of the washing cycle, temperature, etc. These parameters that affect the environmental impact results should be taken into consideration (Laitala and Klepp 2016). Inputs and flows for washing machines and consumer habits used in this study are given in Table 5.

LCA results were calculated for a full load of machinery (9 kg). Therefore, the results were distributed to a pair of jeans. The equation used for this purpose is given below (Moazzem et al. 2021).

$$I = (100 \cdot A)/L \quad (1)$$

where I is the impact per kg jean based on machine load (%); A is the apparel weight (Kg); L is washing machine load (Kg).

The lifespan of the garment It is the information of how long the garment was used effectively. The number of washes per lifetime for a pair of jeans was calculated from the following equation:

$$\text{Number of washes per lifetime} = \text{Lifetime of } a \text{ jean} * \text{Frequency of wearing} / \text{Number of wearing before washing} \quad (2)$$

According to this formula number of washes per lifetime for a pair of jeans was calculated as 45.5.

Differences in the lifespan of different fibers also have a remarkable effect on the environmental impact of garment care, but the products in this study were assumed to be equal in the fabrics used, as they were both cotton.

a) EOL

There are several options for what to do when a piece of clothing reaches the end of its useful life. The hierarchy of waste treatment that is environmentally friendly is reuse, recycling, incineration, and the landfill (Dahlbo et al. 2017; Sandin and Peters 2018). However, because reuse and recycling in the textile industry are not yet at the desired level, these alternatives were left out of the scope of this study. According to the literature, 74% of the textile waste stream in the UK is disposed of in landfills, while 13% is incinerated (Allwood et al. 2015). According to EPA (2019) textile waste data, the landfill rate was 66%, while incineration was 19% (Patwary 2020). Lastly, the Global Fashion Agenda and the Boston Consulting Group reported that 30% of clothing waste was incinerated, while 70% of them went to landfills (Global Fashion Agenda and the Boston Consulting Group Report 2017). For these reasons, landfill and incineration methods were examined in this study as an EOL. In this study, both of these disposal scenarios were modeled according to the Global Fashion Agenda and the Boston Consulting Group Report (2017) data (i.e., landfill/incineration: 70% / 30%). Waste treatment was modeled according to Roos et al. (2015) and the transportation from consumer to incineration and landfill plant was modeled as 30 km for all garments (Roos et al. 2015). Since energy is produced by waste incineration, heat and electricity are obtained as by-products. In this study, the heat and electricity generation obtained with the system expansion approach was taken as a credit for the product and harmed the total emissions (Roos et al. 2015). In addition, the efficiency rate for garment use in waste-to-energy production was assumed to be 70% (Grosso et al. 2010). For renewable materials such as natural fibers, emissions from combustion were often neglected (Yasin and Sun 2019). CO_2 emissions from combustion have been followed in the literature and assumed to be none.

Other design features Identifying features that may affect durability or such as ease of cleaning and design features. Consumption during washing may be different for different textile materials. For this reason, the detergent dosage used in this study was taken from a jean LCA study available in the literature to minimize the effects (Nellström and Sarclca 2019).

Life cycle impact assessment

The environmental impacts of using organic cotton fiber as raw material and maintained specifications selected by consumers were investigated for sustainable jeans using the LCA methodology. The LCA was conducted from a cradle-to-grave perspective with Simapro 9.2.02 software-PhD version according to the guidelines of ISO 14040/44

(ISO 2006a, 2006b; Pré Consultants 2016; Wernet et al. 2016). The LCA method was CML-IA which is commonly used in previous LCA studies on the textile industry (De Saxce et al. 2012).

Five different environmental impact potentials were investigated (Guinée and Lindeijer 2002): freshwater ecotoxicity potential (FAEP), AP, GWP, TEP, and EP. The environmental impacts were chosen in consistency with the environmental concerns and the target of the study according to the literature.

Results and discussion

The selected environmental impacts of a pair of jeans made with organic cotton instead of conventional cotton and maintenance with different consumer habits were assessed via four scenarios with the LCA methodology. The environmental impacts for a pair of jeans in four scenarios and percentage improvement of environmental impacts of all tested scenarios for a pair of jeans are given in Table S1 in Supplementary Information (SI) and Fig. 2, respectively. As seen from the results in Fig. 2, a pair of jeans produced with organic cotton instead of conventional cotton and maintained with different laundry specifications significant improvements in TEP (0–85.10%), FAEP (0–48.91%), GWP (0–9%), AP (0–12.40%), and EP (0–7.96%) were obtained via scenarios.

For each scenario, the contribution of the jean production phases to the selected environmental impact categories throughout their life cycle is given in Fig. 3. Detailed LCA results according to the life cycle phase are given in Table S2 in SI.

For GWP, per pair of jeans was a 20.11 kg CO_2 eq. in the reference scenario (Table S1 in SI). The washing machine at 40 °C temperature and the dryer machine were used by 70% of consumers in the reference scenario (S1), which employed conventional cotton as the raw material. The remaining 30% of consumers utilized line dryers and 60 °C during the drying and washing phases, respectively. In S2, 20% of consumers increased the washing machine's temperature by 20 °C from 40 to 60 °C and preferred line dried outdoor instead of the dryer machine. With these changes, GWP decreased by 5.9% to 18.92 kg CO_2 eq. in S2. Although 20% of consumers in S2 increased the washing temperature from 40 to 60 °C, the 20% reduction in the proportion of consumers using dryers provided this improvement. The most important factor in this reduction was the decreasing number of consumers using dryers, which accounted for 73%. Also, the change in washing temperature provided 27% of this improvement. Despite raising the washing temperature, the improvement was achieved by using less water at a high temperature according to the washing machine's technical specifications. According to these findings, using a dryer was far more crucial than adjusting the washing machine's temperature, and water consumption was also a significant input. Since GWP is proportional to energy consumption, these results were expected with the increase in the rate of consumers who did not use dryer machines (Åslund Hedman 2018).

S3 was created for the production of a pair of jeans using organic cotton instead of conventional cotton. According to the S3, GWP was improved for the entire life cycle by

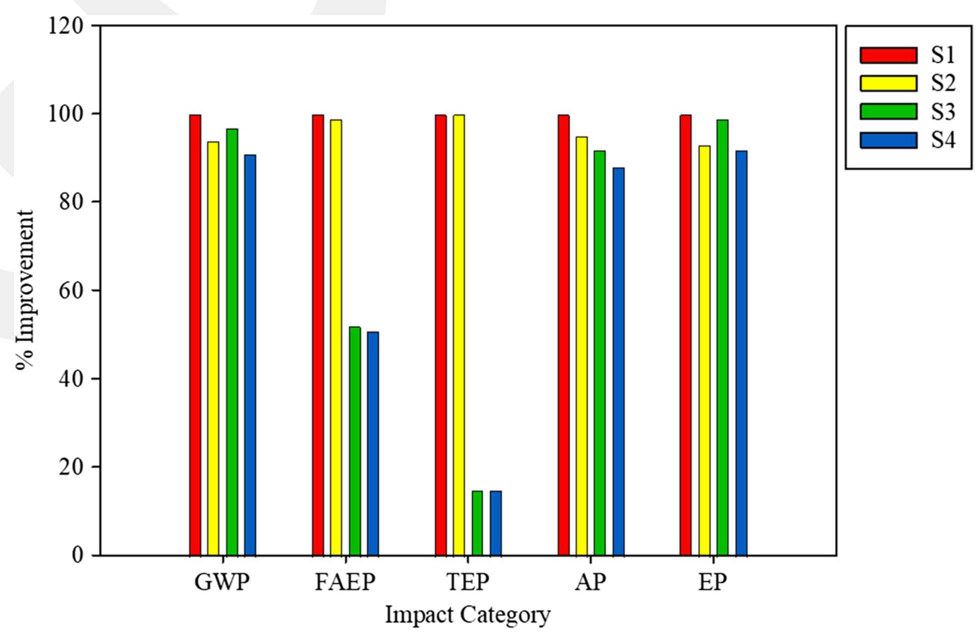

Fig. 2 Percentage improvement of environmental impacts of all tested scenarios for a pair of jeans (*S: scenario, S1, was the reference scenario, the reference scenario was accepted as 100%.)

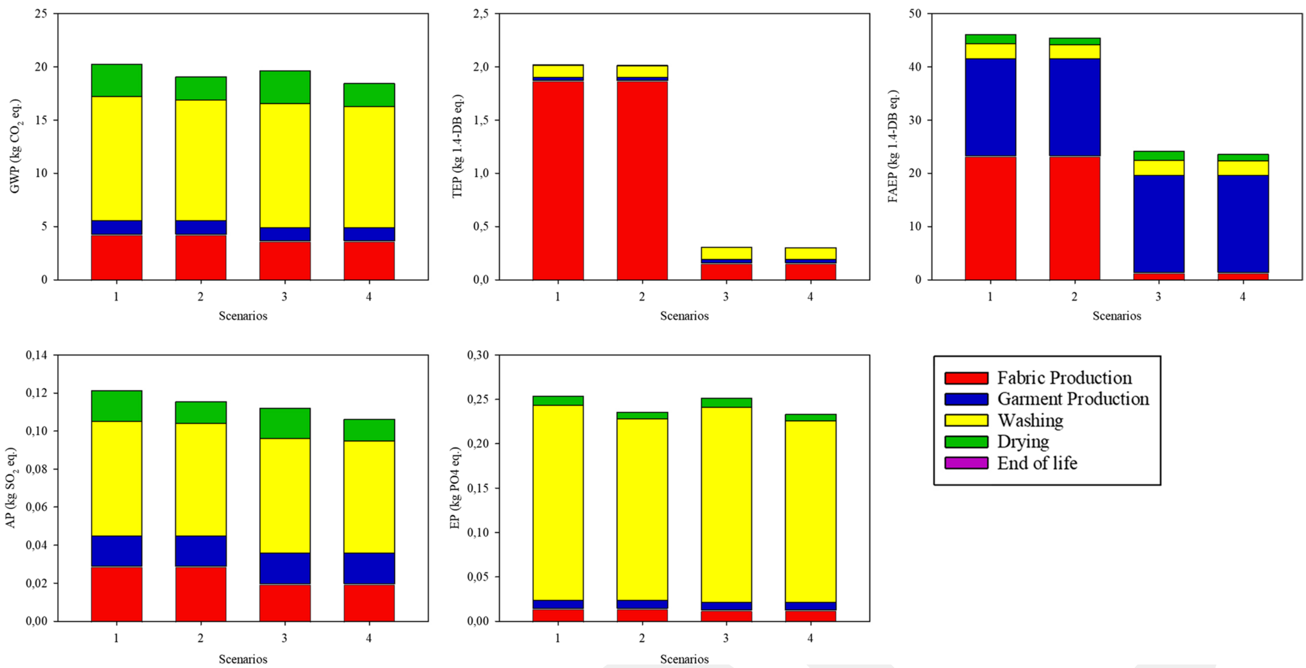

Fig. 3 Contribution of the jean production phases to the environmental impact categories

3.1% when compared to the reference scenario, and the GWP value reduced from 20.11 kg CO_2 eq. to 19.48 kg CO_2 eq. The main reasons for the GWP of cotton cultivation are originated fertilizer and pesticide use with 57% and N fertilizer application to soil causes 22% of the GWP (Baydar et al. 2015). The GWP impact was reduced due to the restricted use of fertilizers and pesticides in the production of organic cotton. This improvement, however, was significantly less than the improvement attained by altering the consumer behaviors evaluated in S2. For this reason, the preferences of the users had an important place in the life cycle of a pair of jeans. Finally, S4 was designed as a combination of S2 and S3. S4 was produced with organic cotton in the fabric production phase and half of the consumers preferred 40 °C with a dryer machine while the remaining half preferred 60 °C with a line-dried in the use phase. S4 had the lowest GWP with a value of 18.30 kg CO_2 eq., showing an improvement of 9% compared to the reference scenario. The reason for this development was the rate of consumers using the dryer with 48%, the use of organic cotton with 35%, and the change in washing temperatures with 17%. These results showed that for the GWP category, consumer habits were the most important driver throughout the lifecycle. In addition, results demonstrated that processing factors such as washing frequency, washing water temperature, and drying machine use also affect greenhouse gas emissions.

In the literature, the GWP values for a pair of jeans vary greatly from 4.2 to 33.4 kg CO_2 eq. (Åslund Hedman 2018; Levänen et al. 2021; Levi Strauss 2015; Nellström and Sarclca 2019). This change was due to different assumptions in parameters throughout the jean's life cycle. While Levi Strauss (2015) and Levänen et al. (2021) accepted the number of washings as 20 during their lifespan, Nellström and Sarclca (2019) and Åslund Hedman (2018) used 38 and 200 washing cycles, respectively. Note that it was assumed that maintenance activities were performed 45.5 times during the lifespan of a pair of jeans in this study and relevant to the literature.

When the GWP results were analyzed by life cycle stages, in the reference scenario, the highest impacts were in the use phase at 73% and the fabric production phase including the cotton cultivation stages at 21%, respectively. In S2, the fabric production phase was 23% and the use phase was 71% in GWP. Garment production and EOL phases, which were the same in all scenarios, contributed 6–7% and – 1% to the GWP, respectively. The main reason for the negative impact of the EOL phase was the energy and heat credits obtained by the incineration process. Among the studies available in the literature, Levi Strauss (2015) reported a share of 37% for the use phase and a share of 27% for the fabric production phase in GWP. Also, Åslund Hedman (2018) found the contribution to GWP as 28.3% in the use phase and 45.5% in the fabric production phase (Åslund Hedman 2018; Levi Strauss 2015). According to the results of the study, the studies in the literature agreed that fabric productions including cotton cultivation and use phases were the two most important GWP sources for a pair of jeans.

For the reference scenario (S1), the AP for a pair of jeans was calculated as 0.12 kg SO_2 eq. In S2, 20% of the users increased the washing temperature selection by 20 °C from 40 to 60 °C and preferred line dried outdoor instead of a dryer, and the AP value decreased to 0.11 kg SO_2 eq., with an improvement of 4.8% compared to the S1. Eighty percent of this improvement was due to the temperature change during the washing phase and 20% was due to the decrease in the use of the dryer. The advantage of using organic cotton in S3 to the AP potential improved a 7.6% as compared with S1 (Fig. 2). Finally, S4, in which both organic cotton and consumer maintenance habits were examined together, showed an improvement of 12.4% compared to S1. These results showed that using organic cotton was the most important input in the fabric production phase than the use phase in AP for a pair of jeans.

The share of fabric production's environmental impact decreased to 14% with the use of organic cotton. Thus, 68% of the overall environmental impact was assigned to the use phase. These findings demonstrated the value of shifting to organic cotton from conventional cotton. In the literature, Kazan et al. (2020) showed that a t-shirt using organic cotton and consuming renewable energy decreased AP by 52% (Kazan et al. 2020). Similarly, La Rosa et al. (2019) showed that organic cotton has 80% lower AP than conventional cotton (La Rosa and Grammatikos 2019).

According to the results, the EP was 0.25 kg PO_4 eq. in the reference scenario. EP decreased to 0.24 kg PO_4 eq. with an improvement of 7.1% in the S2. Eighty-four percent of this reduction was due to the change in the washing temperature of the consumers and 16% to the change in the drying method. By using the organic version instead of conventional cotton in S3, an improvement of 0.9% was achieved compared to the reference scenario. These results were explained by the effect of high phosphorus, nitrogen, and chemical oxygen demand load in the wastewater resulting from the washing performed in the use phase, rather than the use of organic cotton (Zhang et al. 2015). S4, which dealt with the use of organic cotton and the changes in the preferences of the users during the maintenance phase, showed an 8% improvement with the EP value of 0.23 kg PO_4 eq. This development resulted; in 75% belonging to the washing and 15% to the drying phase, a total of 90% was from the use phase and the remaining 10% was from the organic cotton use. However, Sipperly et al. (2019) display that the EP category was improved by organic cotton use by 46% (Sipperly et al. 2019). Moreover, the EP value was found as 0.0051 kg PO_4 eq. by Nellström and Sariclca (2019) and 0.049 by Levi Strauss (2015) (Levi Strauss 2015; Nellström and Sarclca 2019). The results of the study were different from the results available in the literature due to both the system limits included in the LCA and the lifetime selected in the use phase.

The most important contribution to the EP of a pair of jeans was the use phase with 87% washing and 4% drying. These results revealed the importance of the detergent and energy used during the washing process for EP. Contributions to fabric production and garment-making stages were quite limited at 6% and 4%, respectively. Levi Strauss (2015) calculated the contribution of fabric production to the EP category as 48%, while Nellström Sarilca (2019) calculated it as 35% (Levi Strauss 2015; Nellström and Sarclca 2019). As a result, Levi Strauss (2015) and Nellström and Sarilca (2019) calculated the EP contribution of the usage phase as 16% and 23%, respectively. This difference was due to the number of washes during the lifespan of a pair of jeans identified as different functional units of the studies.

According to the results, the FAEP value for the reference scenario was found to be 45.96 kg 1.4-DB eq. With the change in consumer habits in S2, the FAEP impact showed an improvement of 1.3% and decreased to 45.35 kg 1.4-DB eq. In S3, where the use of organic cotton was evaluated, the FAEP showed a significant improvement with 47.6%. While 20% of the consumers gave up the use of dryers and increased the washing temperature to 60 °C, and S4, where organic cotton was used, showed an improvement of 48.9% and decreased to 22.48. These results were important because conventional cotton production consumes 2.6% of global water use and reduces freshwater reserves and causes drought problems in cultivation areas (Chapagain et al. 2006). The use of organic cotton had a significant effect on reducing FAEP. The impact of consumer preferences for the FAEP was limited throughout the lifespan. The sub-stages in the reference scenario that generated FAEP were fabric production (51%), followed by the stage of garment manufacturing (40%). Use phase contribution was just 10%; washing and drying sub-processes contributed 6% and 4%, respectively. Organic cotton dramatically reduced environmental impacts in FAEP.

The reference scenario's TEP value was 2.02 kg 1.4-DB eq. S2 revealed a slight improvement of 0.2% when the preferences at the consumer stage were analyzed. Twenty-three percent of this improvement was due to the abandonment of the use of the dryer and 73% to the change in washing temperature. In S3, which investigated the use of organic cotton, a significant improvement was achieved with 84.9%, because EP is caused by wastewater, air pollution, and agricultural fertilization (Thinkstep Sustainability Solutions 2019). In S4, where both user habits and raw materials changed, the improvement was 85.1% and the TEP value decreased to 0.3 kg 1.4-DB eq. This improvement (99.77%) was due to the use of organic cotton and the remaining 0.23% was due to the use phase. The choice of cotton type for TEP was crucial, according to the results. The stage of fabric production contributed 93% of the total impact in the TEP according to the reference scenario. This ratio dropped to 52% in

S3, when organic cotton was utilized, lowering the impact on the lifespan of a pair of jeans. The percentages for the garment making and use phases in S3 were 10% and 38%, respectively.

Raw material effect

Because the raw material is the focal point of a pair of jeans and is important to creating sustainability, it was an intriguing research question to investigate how environmental impacts changed when other fibers were used instead of organic and conventional cotton fibers. Additional analyses were conducted to find an answer to this question. This comparison was made using the environmental impact values available in the literature for various fibers. For each fiber type, the environmental impact of the amount of fiber required for a pair of jeans was calculated first. The environmental impacts of the remaining phases were also added to the calculated impact values to provide the system boundaries. How the environmental impacts of a pair of jeans changed when selected fibers were used for the functional unit is given in Fig. 4. It was noted that substituting the fibers selected from the literature may not be possible as they provide different properties to the jean, and this supposition is only intended to provide a perspective to the decision-makers and designers. Additionally, although the production of a pair of jeans using these fibers may reveal different data such as waste rate and the consumption of energy, it was assumed that these values were the same since we investigated them in terms of raw materials.

The results show that when compared to the other fibers examined, conventional cotton jeans made from conventional cotton had an average environmental impact. However, except for recycled cotton, organic cotton jeans have a lower environmental impact than all other fibers examined. The environmental impact calculated using the values of another study on organic cotton in the literature, as shown in Fig. 4, supported the findings of this study (Textile Exchange 2014).

Sensitivity analysıs

Through scenarios, this study investigated both the use of organic cotton for a pair of jeans and the choices of consumers during the use phase. As a result, the first sensitivity analysis for organic cotton data was performed. Because this study looked at cotton use in terms of raw materials and included primary data on organic cotton. Instead of the primary organic cotton data used in the LCI phase, the calculations were repeated using the Ecoinvent database's organic cotton cultivation data (fiber, cotton, organic {GLO}| market for fiber, cotton, organic | APOS, U). Furthermore, the use phase was one of the phases that has the greatest impact on the environmental impact of a pair of jeans. Two sensitivity analyses were performed to investigate the use phase concerning the lifespan of a pair of jeans and detergent dosage.

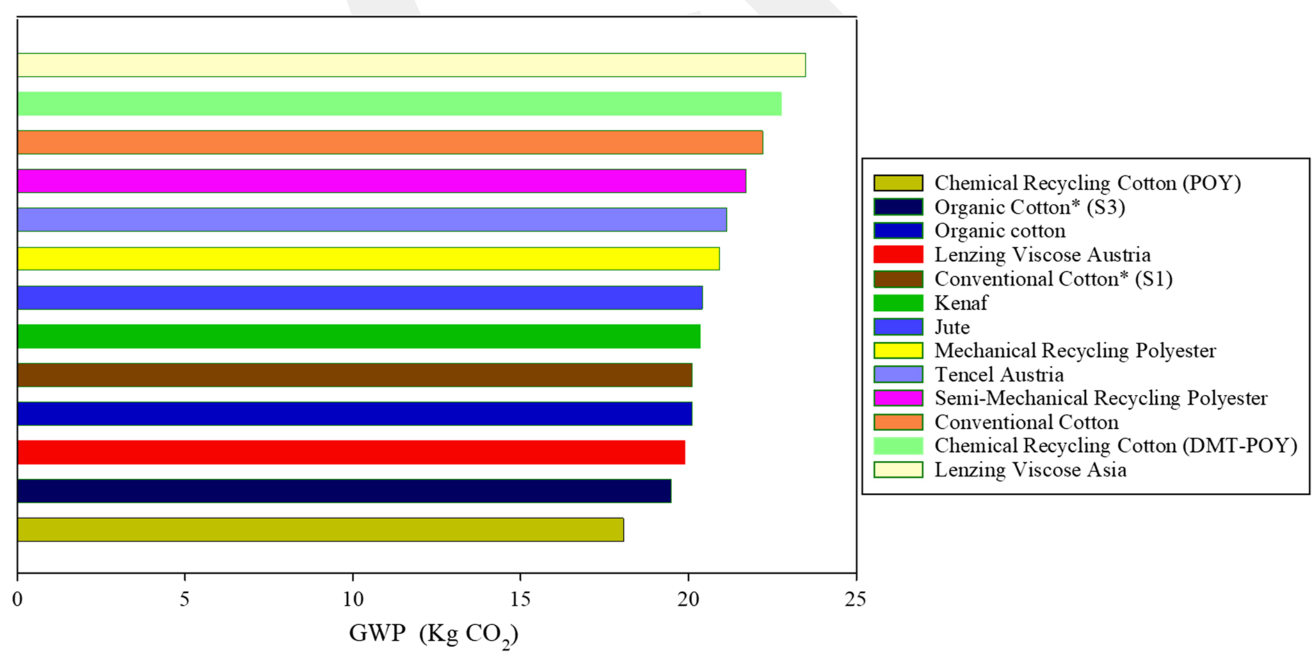

Fig. 4 Comparison of GWP (kg CO_2 eq.) for other fiber types for a pair of jeans. (*This Study) Data sources: (La Rosa and Grammatikos 2019; Shen and Patel 2010; Shen et al. 2010; Textile Exchange 2014)

These inputs were chosen since they were the main determinant of the use phase's environmental impacts. Each parameter was examined independently of the others, changing by ± 10% from its base value. The results of the sensitivity analysis are given in Fig. 5.

According to the results obtained, TEP and EP were the most sensitive categories to organic cotton data. Using the existing database, the TEP value decreased by 24.27% while the EP value increased by 24.36% in S4. The amount of change in GWP and FAEP was limited to − 3.16% and 7.05%, respectively. Also, the change was relatively low at 7.05% in AP. According to these results, it was revealed that TEP and EP are sensitive to organic cotton data, but the sensitivity level was still limited. Sensitivity analysis was performed separately for 40.95 washing cycles and 50.05 washing cycles (Table S3 in SI). According to the results obtained, a 10% change in the number of washing cycles did not lead to a more than 10% change in any environmental impact potential. The most important change for washing cycles was in EP with 8.8% in S3 and S4. The categories least sensitive to this input were FAEP and TEP with 0.6% and 0.5%, respectively. (S1 and S2). Moreover, the change percentage in S4 was quite low. Finally, the most important change in detergent dosage, which was the input parameter used for sensitivity analysis, occurred in AP with 4.1% and GWP with 3.9%. For FAEP and EP, the effect was less than 1%. As a result, a 10% change in the input variable did not affect the results significantly. These results revealed that the detergent dosage data did not have a significant effect on the LCA results.

Conclusion

The environmental impacts of using organic cotton rather than conventional cotton were examined in this study by using four LCA scenarios and examining consumer usage patterns for a pair of jeans. The CML-IA method was chosen to assess the environmental effects. Furthermore, the results of a pair of jeans made with organic cotton fiber were compared to those of other fibers found in the literature, demonstrating that the fiber type used had a significant impact on the development of sustainable products.

According to the LCA results obtained with the reference scenario, the hot spots of a pair of jeans varied depending on the environmental impact examined, including the GWP, AP, and EP for the use phase and the FAEP and TEP for the fabric production phase, which included the cotton cultivation phase. The most significant improvement was observed in the GWP category (5.9%), followed by the EP category (7.1%), as 20% of consumers eliminated the use of dryers and increased the washing temperature from 40 to 60 °C during the use phase (S2). In this study, the most significant improvements were achieved

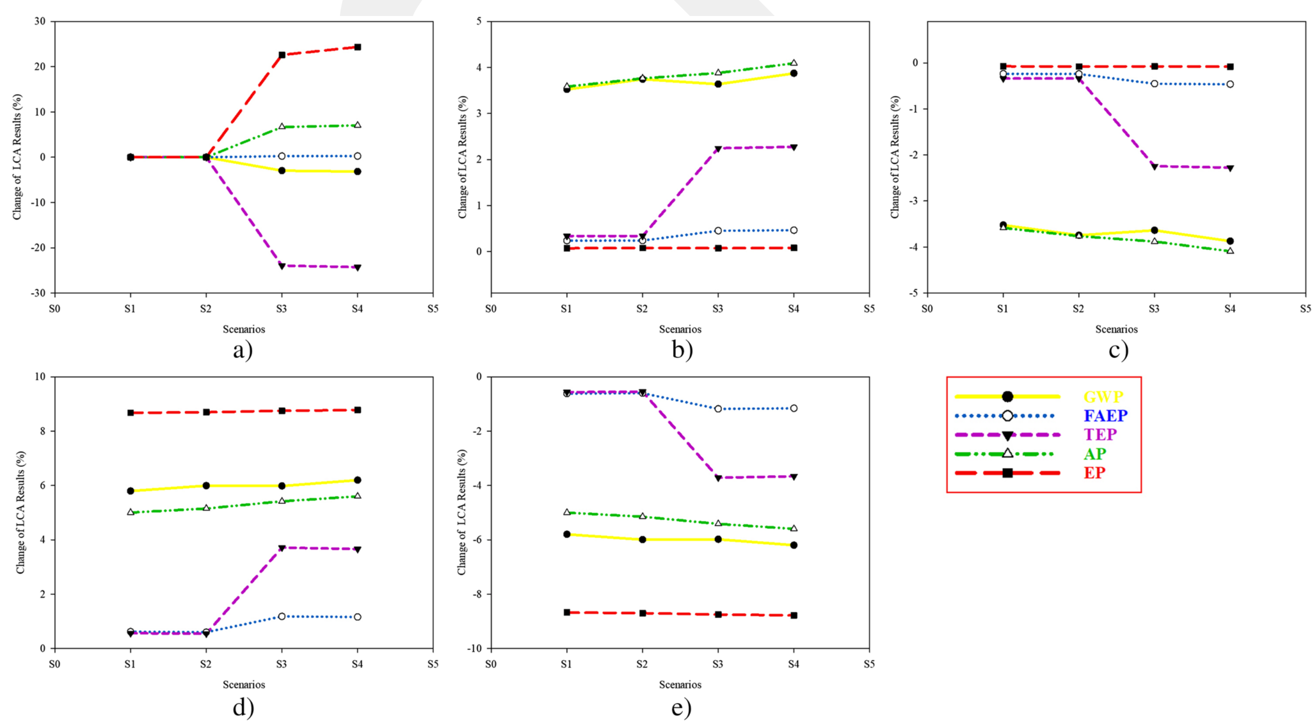

Fig. 5 Sensitivity analysis results for **a** organic cotton; **b** detergent dosage with + 10%; **c** detergent dosage with − 10%; **d** washing cycle with + 10%; **e** washing cycle with − 10%

at 47.6%, 84.9%, and 7.6% in the FAEP, TEP, and AP categories, respectively, according to the reference scenario, when the conventional cotton raw material was substituted with the organic version in the fabric production phase, in S3. Although the use of organic cotton improved the GWP and EP categories, the improvements were limited to 3.1% and 0.9%, respectively. As a result, it was clear that organic cotton jeans had a lower impact because they surpassed all other environmental impacts. Organic cotton was a better choice for the environment than conventional cotton. Finally, S4, which investigates both organic cotton use and consumer care habits, improved in all impact categories and became the scenario with the lowest values. Significant improvements were achieved with S4 with 85.1% in TEP and 48.9% in FAEP. Moreover, the most significant improvement was in the GWP category with 48%, as 20% of consumers eliminated the use of machinery during the drying in the use phase. In the washing process, because of the increase in the temperature of these consumers and the decrease in water consumption within the framework of machine consumption characteristics, the most important improvement occurred in the EP category with 74.5%. With the use of organic cotton, the most important effect was in the categories of TEP with 99.8% and FAEP with 97.3%. These findings revealed the significance of raw material selection in the life cycle of a jean. Furthermore, it was detailed in the literature that consumer clothing care habits have significant effects on environmental impacts.

The results of this study were helpful to a variety of parties, including consumers and business professionals. To produce products with less environmental impact in the sector, the use of cotton, the most widely used natural fiber, has been examined in terms of several environmental impact categories. Along with listing the benefits of organic cotton in terms of various environmental impact categories, it also thoroughly looked at the environmental effects of a pair of jeans over the course of their entire life cycle, including the production of the fabric, the creation of the garment, the use phase, and the EOL phase. By thoroughly examining the use phase, this study emphasized the importance of choosing more user-friendly methods at many decision points, from consumers' use of less detergent to the choice of washing temperatures, and from the consumption characteristics of the machine they use to their drying preferences. As a result, by raising consumer awareness, the study helped to reduce environmental impacts. The environmental impact of jeans, according to the findings, can be reduced by substituting more sustainable cotton options and changing consumer care habits. As a result, the scope of this research can be broadened to include other environmentally friendly raw material alternatives, such as recycled cotton fiber. Additionally, country-specific studies can be conducted to determine consumer behavior such as frequency of use, washing cycle, detergent type, and use during the use phase.

Abbreviations

***LCA*: Life cycle assessment; *LCI*: Life cycle inventory; *LCIA*: Life cycle impact assessment; *GWP*: Global warming potential; *EP*: Eutrophication potential; *TEP*: Terrestrial ecotoxicity potential; *AP*: Acidification potential; *FAEP*: Freshwater ecotoxicity potential**

Nomenclature

***CO2 eq.*: Carbon dioxide equivalent; *1.4-DB Eq.*: 1,4 Dichlorobenzene equivalent; *SO2 eq.*: Sulfur dioxide; *PO4 eq.*: Phosphate-equivalent**

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Data availability The datasets used during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

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