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Life Cycle & Sustainability

Sustainability assessment of denim fabric made of PET fiber and recycled fiber from postconsumer PET bottles using LCA and LCC approach with the EDAS method

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Abstract

The textile industry is under pressure to adopt sustainable production methods because its contribution to global warming is expected to rise by 50% by 2030. One solution is to increase the use of recycled raw material. The use of recycled raw material must be considered holistically, including its environmental and economic impacts. This study examined eight scenarios for sustainable denim fabric made from recycled polyethylene terephthalate (PET) fiber, conventional PET fiber, and cotton fiber. The evaluation based on the distance from average solution (EDAS) multicriteria decision-making method was used to rank scenarios according to their environmental and economic impacts, which are assessed using life cycle assessment and life cycle costing. Allocation, a crucial part of evaluating the environmental impact of recycled products, was done using cut-off and waste value. Life cycle assessments reveal that recycled PET fiber has lower freshwater ecotoxicity and fewer eutrophication and acidification impacts. Cotton outperformed PET fibers in human toxicity. Only the cut-off method reduces potential global warming with recycled PET. These findings indicated that recycled raw-material life cycle assessment requires allocation. Life cycle cost analysis revealed that conventional PET is less economically damaging than cotton and recycled PET. The scenarios were ranked by environmental and economic impacts using EDAS. This ranking demonstrated that sustainable denim fabric production must consider both economic and environmental impacts. *Integr Environ Assess Manag* 2024;20:2347–2365. © 2024 The Author(s). *Integrated Environmental Assessment and Management* published by Wiley Periodicals LLC on behalf of Society of Environmental Toxicology & Chemistry (SETAC).

KEYWORDS: EDAS Method; Life cycle assessment; Life cycle costing; PET bottle; Recycled polyester fiber; Recycling

INTRODUCTION

The textile industry is responsible for a wide range of environmental impacts, including water pollution from chemicals and dyes, greenhouse gas emissions from excessive energy consumption, and water consumption and pesticide use from raw materials (Fidan et al., 2021a). According to the report *Pulse of the Fashion Industry 2017*, the global textile and apparel industry generated 1715 million tons of CO_2 emissions and 92 million tons of waste, and consumed 79 billion cubic meters of water in 2015. With the conventional business model, these figures would increase by at least 50% by 2030 (Eder-Hansen et al., 2017). Recently, the circular economy concept has become a popular way to reduce the textile industry's environmental impact and keep products that have reached the end of their useful life in the consumption and production cycles as long as possible by reusing them. With the increasing demand for textile products, there is a growing interest in the environmental impacts of textile production. According to the literature, most environmental impacts of textile production were attributed to raw material production (Fidan et al., 2021a). This industry consumes various raw material such as cotton, polyester, and jute. However, polyester, the world's most widely used raw material in the making of fiber, accounts for roughly half of the general market and 80% of the synthetic fiber market, according to the Textile Exchange's 2017 *Preferred Fiber and Materials Report* (Textile Exchange, 2017). Additionally, since 2000, the use of polyester has grown by 157% (Gina-Marie Cheeseman, 2016). Because polyester does not dissolve naturally, it remains a waste product for many years, enters the food chains, pollutes seawater, and has adverse environmental impacts because of its toxicity (Monteiro et al., 2018). Therefore, recycling polyester waste is essential for preventing environmental

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pollution (Naguib & Zhang, 2018). According to the Textile Exchange's 2017 report, the global production of recycled polyester reached 2.5 million tons in 2019, up from 0.3 million tons in 2008 (Textile Exchange, 2017). The most common source of polyester waste is polyethylene terephthalate (PET) bottles. Studies of recycled PET polyester in the literature have focused on recycling processes and technologies (Naguib & Zhang, 2018), various properties of recycled polyester fibers (He et al., 2015; Muslim & Basuki, 2016; Silva, 2012), and socioeconomic benefits (Leal Filho et al., 2019). Approximately 72% of the goods derived from recycling PET bottles are manufactured specifically as fiber (r-PET) and are used mostly in the textile industry (Aizenshtein, 2016; Sarıoğlu, 2017). Moreover, the industry is interested in the expected environmental and economic benefits of recycling PET fibers.

Life cycle assessment (LCA) is a powerful tool for assessing the environmental impacts of products from a cradle to grave perspective. It is standardized with ISO 14040 and ISO 14044 and is a widely used method that allows process development by identifying environmental hotspots in products throughout their life cycle (ISO, 2006a, 2006b). Recycled PET polyester was employed to reduce environmental impact by promoting product reuse. Nevertheless, few studies of recycled PET polyester using the LCA methodology have been reported. This methodology is valuable for assessing environmental impacts (Chilton et al., 2010; Nakatani et al., 2010; Schmidt et al., n.d.; Valentino, 2017). Moreover, although polyester is the most widely used raw material in the textile industry, studies examining the environmental impact of recycled PET polyester use in the textile industry with LCA are also very limited. Recycled PET polyester in garment and fabric production was included in a few studies such as those on fiber and clothing and fabric production (Qian et al., 2021; Shen et al., 2010; Subramanian et al., 2020). Braun et al. (2021) conducted an LCA analysis of a circular polyester jacket (Braun et al., 2021). Zhang et al. (2020) investigated the environmental impacts of blanket production using 100% recycled PET bottles (Zhang et al., 2020). They found that the use of recycled PET offers several advantages in terms of environmental impacts. Denim is one of the largest textile subsectors, and polyester is a major raw material, but there is no LCA study comparing conventional and recycled polyester use in denim. Denim LCA studies have typically concentrated on conventional cotton and recycled cotton (Akı et al., 2020; Åslund Hedman, 2018; Cundubey & Azgin, 2024). Polyester must be examined to reduce the environmental impacts of the textile industry, which is the second largest emitter of greenhouse gases. In addition to environmental impacts, when extending the use of recyclable materials, it is crucial to consider their economic consequences. The most common economic impact calculation method is life cycle cost (LCC).

Multicriteria decision-making (MCDM) is frequently employed to select or rank the best choice when numerous criteria are present. In this study, one of the most modern MCDM approaches, evaluation based on distance from average solution (EDAS), was used to analyze the environmental and economic consequences of recycled PET polyester on denim fabric. Keshavarz Ghorabaee et al. (2015) conceived the EDAS approach (Keshavarz Ghorabaee et al., 2016). Although it is a relatively new technique, it has already been implemented in several fields, including supplier selection, building project and housing selection, and waste disposal site selection (Ghorabaee et al., 2016; Juodagalvienė et al., 2017; Kahraman et al., 2017; Stanujkic et al., 2017).

This study used the EDAS method to conduct an integrated and comprehensive sustainability assessment of denim fabric. The fabric was produced using both virgin PET fiber and recycled fiber from postconsumer PET bottles. Multiple scenarios were used in the assessment process. The assessment used LCA and LCC methodologies to thoroughly assess the environmental and economic effects, thus providing a strong framework for decision-making. We believe that this is the first to assess the use of PET fiber in the manufacture of denim fabric. The MCDM method was used to evaluate the scenarios because it integrates multiple criteria into a single framework, allowing decision-makers to compare and evaluate various alternatives more effectively. As far as we know, we were the first to use the EDAS approach to investigate the production of sustainable denim fabric. The LCA and LCC methods were used to assess the environmental and economic impact, respectively. This study is the first to evaluate PET fiber LCC in denim fabric production and apply allocation methods to LCA.

METHODS

Scenarios

This study examined the sustainability of denim fabrics produced using conventional PET, cotton, and recycled PET fibers in eight scenarios. This evaluation considered the economic and environmental sustainability dimensions using MCDM (Gulcimen et al., 2021). Polyethylene terephthalate polyester can be recycled using different methods such as open-loop and closed-loop recycling systems. Closed-loop recycling maintains the characteristics of the original material and creates a process in which monomers are recovered and used to produce new PET, resulting in a closed-loop plastic recycling process with minimal greenhouse gas emissions (Sonnendecker et al., 2022). Although closed-loop recycling aims to maintain the quality of the initial material, it can be expensive. Open-loop recycling transforms the material into a different product (Mwanza et al., 2022). This process alters the inherent characteristics of the original material but can hinder its functionality, thereby complicating the recycling process (Nakatani et al., 2010). Similarly, PET breaks down after a few cycles in quasi-open recycling, limiting its recyclability and functionality (Wei et al., 2019). However, although not as much as closed-loop recycling, open-loop recycling methods provide secondary use, albeit limited, by converting waste into various products. Polyethylene terephthalate fiber is referred to as open-loop recycling because it is recycled from

PET bottles. After the useful life of used goods, open-loop recycling transforms manufactured goods into new products for their second life.

Allocation is a crucial concern in open-loop recycling techniques. ISO 14044 specifies allocation methods; however, there is no widely accepted procedure (Shen et al., 2012; Valentino, 2017). After the primary product is consumed, the secondary product is produced. Allocation is hardest when dividing the environmental impacts of these two products. ISO 14044 emphasizes the recommendation to avoid allocation to ensure the accuracy and reliability of LCAs. However, dividing environmental impacts between primary and secondary products is challenging. This difficulty arises because the two products often have significantly different life cycles, environmental impacts, and functional purposes. When primary and secondary products serve different functions or are used in different contexts, it is difficult to determine how to fairly distribute the environmental burdens associated with their production and disposal. These processes involve different technologies, energy uses, and emissions, making direct comparisons and allocations complex and potentially inaccurate. When multiple products are produced from the same process, the allocation process becomes more complex, leading to the division of environmental burdens between the main products and by-products (Pierobon et al., 2018).

According to ISO 14044, to ensure a more accurate representation of environmental impacts, allocation should be avoided as much as possible by using system expansion or substitution. System expansion involves expanding the system boundaries to include the additional functions provided by secondary products (Heijungs et al., 2021). By evaluating the entire life cycle and all related processes in a single system, the need to allocate impacts between different products can be eliminated. The substitution approach, on the other hand, considers the secondary product as a replacement for an equivalent raw product, thereby crediting the system with the environmental benefits of avoiding the production of raw material. For example, if recycled plastic is used instead of new plastic, the impacts of producing new plastic are removed from the overall environmental impact assessment, and the benefits of recycling are effectively recognized.

Various methods, such considering as economic allocation and product- and process-related parameters, are also used to overcome the challenges associated with environmental assessments. Economic allocation is recommended as an appropriate approach to modeling multifunctional processes, especially when dealing with waste or recycling product flows (Milani et al., 2011). Researchers have also explored the creation of allocation factors based on product- and process-related parameters to evaluate the environmental impacts of producing value-added coproducts (Pradel et al., 2018).

In this study, scenarios were developed using literature-based methods to mitigate allocation challenges. These scenarios are designed to provide a more comprehensive and accurate assessment of the environmental impacts of open-loop recycling, ensuring that allocation is avoided when possible.

(1) Cut-off, a frequently employed method in the literature, considers primary and secondary products to be two distinct systems (Hopewell et al., 2009; Shen et al., 2010). The production of the primary product, including the raw material, is considered outside the system's boundaries. In contrast, the entire end-of-life phase of the product is designated as the secondary product (Frischknecht, 2010).
(2) Shen et al. (2010) proposed the waste valuation method, which focuses on the distribution of the environmental impact of the raw material used in the production of the primary product over its two life spans (Shen et al., 2010). Additionally, the environmental burden of the end-of-life phase is shared between the two life spans. ISO 14044 recommended using mass or economic value-based allocation procedures (ISO, 2006b; Shen et al., 2010). In accordance with the standard, the economic allocation procedure was used, as detailed below.

$$E_{wv} = E_{cut-off} + AF \times E_{vPET}. \tag{1}$$

E_{wv} represents the environmental impact of recycled PET fiber; $E_{cut\text{-}off}$ is the environmental impact of recycled PET fiber based on the cut-off approach; E_{vPET} is the environmental impact of virgin PET bottle grade resin, and AF is the separation factor. AF × E_{vPET} is the environmental load shifted from the first life to the second life. According to Shen et al. (2010), using the waste valuation technique, the assumed AF was 32% (Shen et al., 2010).

Using both cut-off and waste valuation techniques, as well as varying proportions of conventional PET and recycled PET fibers, including cotton, we developed eight scenarios. The reference scenario (S1) consisted of 85% conventional cotton fiber and 15% conventional PET fiber. This ratio was selected because it was a product manufactured by a denim fabric production company from which the data were obtained. Scenarios 2 and 3 are the two distinct allocation methods for this scenario, both of which contain the same proportion of recycled PET instead of conventional PET. Scenarios S4–S6 were manufactured by increasing the polyester content to 100% and substituting this ratio with recycled PET using two distinct allocation methodologies. To examine the effects of using the highest recycled PET ratio, we used 100% recycled polyester denim. Blending and sample comparison of proportions are used frequently in textile production (Sarıoğlu, 2017). In S7 and S8, the percentage of recycled PET was 50%, and the percentage of conventional PET was 50%. In the literature, 50:50 ratio is a prevalent ratio for textile product production. This ratio was selected because of its popularity in the market and literature (De Saxce et al., 2012; Fidan et al., 2021a; Roos et al., 2015; Zhang et al., 2020). Given that it is not technically feasible to produce denim fabric from 50% and 100%

recycled PET due to the lack of technology for desirable construction, appearance, and mechanical properties, as well as the impossibility of indigo rope dyeing, these hypothetical scenarios were developed to assess the sustainability options of denim fabric. The inclusion of hypothetical scenarios, such as the total production of denim textiles using 100% recycled PET, serves as a valuable thought experiment for assessing sustainability alternatives in the production of denim fabric. Although it is currently not feasible to achieve the desired structure, appearance, and mechanical properties due to technological limitations, studying these extreme scenarios aims to gain an understanding of the difficulties and possibilities associated with sustainable textile production. The identification of gaps in technology and innovation necessary for transitioning toward more sustainable practices in the future—as well as the resolution of challenges such as indigo dyeing that could impede the use of recycled PET in denim fabrics—will serve as a driving force. Given the significance of sustainability assessments in guiding decision-making toward more sustainable practices, the objective is to provide insight into the future of the sector through hypothetical scenarios (Safarpour et al., 2022).

In addition to the raw material used, the production of the denim fabric was identical to that of the scenario used as a reference. The environmental and economic effects of denim fabric manufactured using open-loop recycling PET fiber and conventional PET fiber, which were added at varying rates depending on the scenario, were thoroughly evaluated. Table 1 presents an overview of all denim fabric manufacturing scenarios investigated in this study.

Environmental impact assessment using LCA

Goal and scope definitions. This study used LCA to assess the environmental impact of eight scenarios on denim fabric using conventional PET, recycled PET, and cotton as fiber raw material. ISO 14040/44-compliant LCA was performed using SimaPro Software PhD 9.2.02 and the Ecoinvent (v. 3.7.1) database (ISO, 2006a, 2006b; Pré Consultants, 2016; Wernet et al., 2016). This study used 1 m of denim fabric weighing 365 g and measuring 1.35 m^2 as the functional unit (van der Velden et al., 2014). The selection of functional units was based on industry standards and literature. Although van der Velden et al. (2014) suggested using kilograms for textile LCAs, the use of a linear measurement (meter) is also relevant in the textile industry, where fabrics are often sold and processed by length (van der Velden et al., 2014). This choice aligns with how denim fabric is typically marketed and used in manufacturing, making our results more directly applicable to real-world scenarios. In addition, using a functional unit based on length facilitates easier comparison with other studies.

The production of primary materials, which includes cotton cultivation and PET production, is the initial step in the production of denim fabric. These fibers are subsequently processed and transformed into yarns. The weaving process transforms the yarns into fabric. Consumers use denim garments made from these fabrics. These products are recycled or discarded as waste at the end of their useful life (EOL). The cradle-to-factory-gate LCA in this study covers the stages from raw material production to the production of denim fabric. The system focuses on the raw material (PET, recycled PET, and cotton) and production stages of denim fabric (from cradle to factory gate with denim fabric as the final product). Additionally, due to a lack of data, the stages of clothing production, use, and disposal were excluded from the system boundary. The net emissions are zero as a result of the biogenic CO_2 captured during the growth of plants, which is released during the harvesting and use of biomass (Anil, 2014; Kouchaki Penchah et al., 2023). The assumption that cotton is carbon neutral at the disposal stage additionally indicates that this exclusion does not substantially affect the results of this study. The system boundaries of this study are illustrated in Figure 1.

Figure 1 shows the four subprocesses of open-loop recycling PET fiber production. First, postconsumer PET bottles are collected for recycling. Baling and compaction during the collection stage require little energy (Arena et al., 2003; Detzel et al., 2004). Transportation of used PET

TABLE 1 Summary of all scenarios

Scenario	Cotton (%)	PET (%)	Recycled PET content (%)	Allocation type
S1[a]	85	15	0	Cut-off
S2	85	0	15	Cut-off
S3	85	0	15	Waste valuation
S4	0	100	0	Cut-off
S5	0	0	100	Cut-off
S6	0	0	100	Waste valuation
S7	0	50	50	Cut-off
S8	0	50	50	Waste valuation

Abbreviation: PET, polyethylene terephthalate.
[a] Reference scenario.

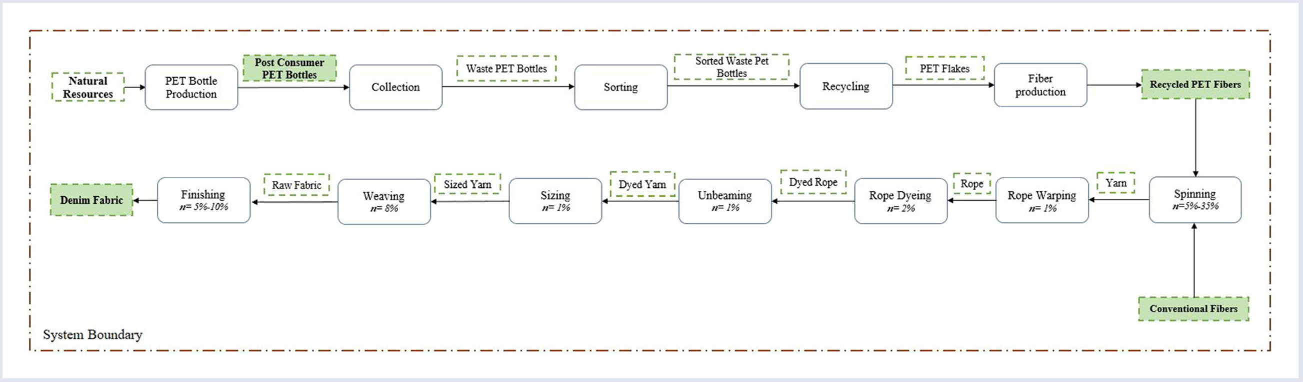

FIGURE 1 System boundary of the study. PET, polyethylene terephthalate

bottles to recycling facilities is the main environmental impact. Second, the plastic bottles are sorted to remove unwanted labels (Valentino, 2017). Sorting can be done manually or automatically. This study considered that sorting was conducted automatically. Recycling separates PET bottle components with washing, draining, and dehydrating processes (Shen et al., 2010). The PET recycling phase consumes material and energy inputs. Melt extrusion turns recycled particles into fibers in the mechanical recycling process.

Life cycle inventory. The life cycle impact (LCI) phase is the most important phase of an LCA. At this stage, data were collected from a well-known denim manufacturing company in Turkey. The secondary data were obtained from the Ecoinvent Database (v. 3.7.1) and publications. All data were acquired for the functional unit at each stage of the production. All primary data pertain to 2019. Table 2 presents the data used in this study of recycled PET fiber.

Cotton, conventional PET, and recycled PET fibers are the primary inputs for the spinning process. Literature and the company provided the production efficiency ratios for recycled PET fiber and denim fabric (*n* value in Figure 1). Transport was factored into the LCA for each raw material. Vehicles and ships were used as appropriate vehicles to calculate the distances between the production and consumption locations. According to ISO 14040, a 1% deduction was permitted, and fixed assets (land, buildings, and equipment) were excluded from the analysis.

Life cycle impact assessment. A life cycle impact assessment (LCIA) was conducted using the ReCiPe 2016 Midpoint (*H*) V1 method (Ekener-Petersen & Finnveden, 2013; Goedkoop et al., 2013; Roos et al., 2015). The textile industry has detrimental impacts on soil, water, and atmospheric systems by employing hazardous substances during dyeing and finishing procedures (Leal Filho et al., 2019). Given the release of toxic pollutants by these substances, it is imperative to consider the impact categories associated with human toxicity and ecotoxicity. The geographical scope of the ReCiPe Method is extensive, whereas other methods, for example, Bees+ and TRACI, belong to North America, focus on specific regions, and do not concentrate on a singular impact category such as the IPCC and USEtox methods.

Global warming (GWP), stratospheric ozone depletion (SOD), ionizing radiation (IR), ozone formation, human health (OFHH), fine particulate matter formation (FPMF), ozone formation, terrestrial ecosystems (OFTE), terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME), terrestrial ecotoxicity (TE), freshwater ecotoxicity (FET), marine ecotoxicity (MET), human carcinogenic toxicity (HCT), human noncarcinogenic toxicity (HNCT), land use (LU), mineral resource scarcity (MRS), fossil resource scarcity (FRS), and water consumption (WC) were the impact categories.

Life cycle cost assessment

The traditional economy is changing because of the need for environmentally friendly product alternatives. Although consumer interest in eco-friendly products has increased, price remains a significant factor. To develop sustainable products, it is crucial to consider the economic aspects (Hertenstein & Platt, 1998). The LCC method is frequently used in the literature to study economic implications. The method determines a product's cost by factoring in all production-related expenses.

In this study's LCC analysis, the Ciroth et al. (2009) method was applied with SimaPro software to determine the economic dimension of the scenarios (Ciroth et al., 2009). For this procedure, a method had to be devised that combines the steps of characterization, damage assessment, normalization, and weighting. The LCC is completed by inputting unit costs into this model. This study applied LCC to the scenarios, but the same expenses were not considered. An economic evaluation was conducted by simply considering the variable costs of the different scenarios. Regarding the price per kilogram, recycled PET fiber was approximately 36% more expensive than conventional polyester fiber in 2019. This information was collected from experts on the site.

EDAS method

In this study, the EDAS method was used as the MCDM approach to an integrated and holistic evaluation of the sustainability of denim fabric made from PET fiber and recycled fiber from postconsumer PET bottles, incorporating

TABLE 2 Life cycle impact (LCI) summary recycled PET fiber

Process	Outputs	Inputs	Dataset	Data	Efficiency	Reference
Cotton fiber production	1 kg cotton fiber	Cotton crops	Cotton fiber {RoW}| cotton production | APOS, U	1 kg	88%	Company data
PET fiber production	1 kg PET fiber	PET flakes	Fiber, polyester {RoW}| polyester fiber production, finished | APOS, U	1 kg	90%	Company data
PET bottle production	1 kg of PET bottles	Raw material (RM)	Polyethylene terephthalate, granulate, bottle grade [RER] | production | alloc Def, U	1 kg	100%	Europe (2017)
		Process	Stretch blow molding {RER}| production | Alloc Def, U	1.02 kg	98%	Kuczenski and Geyer (2011)
		Transport of RM	Transport, freight, lorry 16–32 metric ton, EURO4 {RER}| Alloc Def, U	0.933 tkm	NA	Valentino (2017)
Collection waste PET bottles	1 kg of waste PET bottles	Transport	Transport, freight, lorry 16–32 metric ton, EURO4 {RER}| Alloc Def, U	0.00000234 tkm	NA	Valentino (2017)
Sorting of waste PET bottles	1 kg sorted waste PET bottles	Collected waste PET bottle	Collection waste PET bottles	2.56 kg	39%	
		Electricity	Electricity, medium voltage {IT}| market for | Alloc Def, U	0.0266 kWh	NA	Intini and Kühtz (2011); Valentino (2017)
		Diesel	Diesel, burned in diesel-electric generating set {GLO}| market for | Alloc Def, U	0.084 MJ	NA	Intini and Kühtz (2011); Valentino (2017)
		Transport	Transport, freight, lorry >32 metric ton, EURO4 {RER}| Alloc Def, U	0.01 tkm	NA	Intini and Kühtz (2011); Valentino (2017)
		Sorted waste PET bottle	Sorting of waste PET bottles	1.278 kg	78.25%	Intini and Kühtz (2011)
Recycling of waste PET bottles	1 kg recycled PET flake	Electricity	Electricity, medium voltage {IT}| market for | Alloc Def, U	0.32 kWh	NA	Rigamonti et al. (2013)
		Methane consumption	Methane, 96% by volume, from biogas, high pressure, at user {GLO}| market for | Alloc Def, U	2.56 MJ	NA	Rigamonti et al. (2013)
		Water	Tap water {RER}| market group for | Alloc Def, U	2.96 kg	NA	Rigamonti et al. (2013)
		Sodium hydroxide	Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Alloc Def, U	0.003 kg	NA	Rigamonti et al. (2013)

(*Continued*)

TABLE 2 (*Continued*)

Process	Outputs	Inputs	Dataset	Data	Efficiency	Reference
		Treatment of residuals	Municipal solid waste {IT}| treatment of incineration | Alloc Def, U	0.099 kg	NA	Valentino (2017)
		Transport	Transport, freight, lorry >32 metric ton, EURO4 {RER}| transport, freight, lorry >32 metric ton, EURO4 | Alloc Def, U	0.05 tkm	NA	Valentino (2017)
PET fiber production	1 kg of recycled PET fiber	Flakes	Recycling of waste PET Bottles	1.008 kg	99%	Intini and Kühtz (2011)
		Water	Water, completely softened, from decarbonized water, at user {GLO}| market for | APOS, S	0.419 kg	NA	Intini and Kühtz (2011)
		Heat	Heat, district or industrial, natural gas {RER}| market group for | APOS, U	0.334 kwh	NA	Intini and Kühtz (2011)
		Electricity	Electricity, medium voltage {IT}| market for | Alloc Def, U	0.922 kwh	NA	Intini and Kühtz (2011)
		Natural gas	Heat, district or industrial, natural gas {CA-QC}| market for | APOS, U	0.031 m^3	NA	Intini and Kühtz (2011)
		Finish oil	Chemical, organic {GLO}| production | APOS, U	0.004 kg	NA	Intini and Kühtz (2011)
		Waste	Municipal solid waste (waste treatment) {TR}| treatment of municipal solid waste, incineration | APOS, U	0.018 kg	NA	Intini and Kühtz (2011)
		Transport	Transport, freight, lorry >32 metric ton, EURO4 {RER} | Alloc Def, U	1 tkm	NA	Fidan et al. (2021a)

Abbreviations: APOS, allocation at the point of substitution; CA-QC, Canada-Quebec; GLO, global; IT, Italy; NA, nonapplicable; PET, polyethylene terephthalate; RER, Europe; RoW, rest of the world; tkm, tons kilometer; TR, Turkiye.

both LCA and LCC approaches. The following steps outlined the application of the EDAS methodology to the subject of this study. The EDAS method was based on the outputs of the LCA and LCC methodologies.

Step 1: Creation of the decision matrix: In this step, the criteria and their weights in the decision matrix (*X*) are determined. In the decision matrix shown in Equation (2), x_{ij} represents the performance of option *i* according to criterion *j* (Keshavarz Ghorabaee et al., 2015).

$$X = [X_{ij}]_{mxn} = \begin{bmatrix} X_{11} & \cdots & X_{1n} \\ \vdots & \ddots & \vdots \\ X_{m1} & \cdots & X_{mn} \end{bmatrix}. \tag{2}$$

The study's decision matrix is shown in Supporting InformationTable S1. The weighting of criteria was set according to the opinions of subject matter experts.

Step 2: Development of the average solution matrix: Equations (3) and (4) calculated the average solution for all criteria. Supporting Information Table S2 displays the average solution matrix computed.

$$\mathrm{AV}_i = \frac{\sum_i^m X_{ij}}{\mathrm{m}}, \tag{3}$$

$$\mathrm{AV} = [\mathrm{AV}_j]_{1xn}. \tag{4}$$

Step 3: Construction of positive and negative distance matrices: The positive distance from the mean (PDA) and negative distance from the mean (NDA) matrices based on the kind of criterion (benefit and cost) are calculated in Equations (5) and (6):

$$\mathrm{PDA} = [\mathrm{PDA}_{ij}]_{nxm}, \tag{5}$$

$$\mathrm{NDA} = [\mathrm{NDA}_{ij}]_{nxm}. \tag{6}$$

If *j*th criterion is beneficial, Equations (7) and (8) are used.

$$\mathrm{PDA}_{ij} = \frac{\max(0, (X_{ij} - \mathrm{AV}_j))}{\mathrm{AV}_j}, \tag{7}$$

$$\mathrm{NDA}_{ij} = \frac{\max(0, (\mathrm{AV}_j - X_{ij}))}{\mathrm{AV}_j} \tag{8}$$

And if *j*th criterion is nonbeneficial, Equations (9) and (10) are used.

$$\mathrm{PDA}_{ij} = \frac{\max(0, (\mathrm{AV}_j - X_{ij}))}{\mathrm{AV}_j}, \tag{9}$$

$$\mathrm{NDA}_{ij} = \frac{\max(0, (X_{ij} - \mathrm{AV}_j))}{\mathrm{AV}_j}. \tag{10}$$

Supporting Information Tables S3 and S4 present the results of the distance negative and positive distance matrices, respectively.

Step 4: Calculation of the weighted sums of positive (SP_i) and negative (SN_i) distances: The weighted sums of PDA and NDA for all alternatives are calculated using Equations (11) and (12). The weighted sums of the positive and negative distances calculated for each scenario are given in Supporting Information Table S5.

$$\mathrm{SP}_i = \sum_{j=1}^{m} w_j \mathrm{PDA}_{ij}, \tag{11}$$

$$\mathrm{SN}_i = \sum_{j=1}^{m} w_j \mathrm{NDA}_{ij}. \tag{12}$$

Step 5: Normalization of SP and SN values: For each option, SP and SN values are normalized using Equations (13) and (14). The Normalized SP and SN values for each scenario are given in Supporting Information Table S6.

$$\mathrm{NS}P_i = \frac{\mathrm{SP}_i}{\max_i(\mathrm{SP}_i)}, \tag{13}$$

$$\mathrm{NS}N_i = 1 - \frac{\mathrm{SN}_i}{\max_i(\mathrm{SN}_i)}. \tag{14}$$

Step 6: Calculation of the appraisal score (AS): The appraisal score (AS) for all alternatives is calculated using Equation (15). The AS values for each scenario are given in Supporting Information Table S7.

$$\mathrm{AS}_i = \frac{1}{2}(\mathrm{NSP}_i + \mathrm{NSN}_i). \tag{15}$$

Step 7: Ranking of the options: To rank alternatives, the options are arranged in descending order according to the AS_i score. The first ranked option is considered the best option.

RESULTS

Life cycle assessment results

In this study, the LCA was used to investigate the environmental impacts of denim fabric made from conventional cotton, conventional PET, and recycled PET in variable proportions. Table 3 displays the results of the cradle-to-factory-gate analysis used in the production of 1 m denim fabrics.

Scenario 5 had the lowest GWP among the scenarios, 3.953 kg CO_2 eq., whereas S6 exhibited the highest, 6.385 kg CO_2 eq. Scenario 5 was calculated using the cut-off method and contained only PET fiber that had been recycled. In S6, the environmental impacts of PET bottle waste were factored in to the calculation. Åslund Hedman (2018) found 6.21 kg CO_2 eq. per meter; Morita et al. (2020) found 3.61 kg CO_2 eq.; and Fidan et al. (2021a) found 4.29 kg CO_2 eq. (Åslund Hedman, 2018; Fidan et al., 2021a; Morita et al., 2020). The findings of this study are consistent with those of previous studies. Table 4 illustrates the improvement ratio of environmental impacts for each scenario according to the reference scenario.

TABLE 3 Results of a cradle-to-factory-gate life cycle assessment (LCA) for the functional unit under various scenarios

Impact category	Unit	S1	S2	S3	S4	S5	S6	S7	S8
GWP	kg CO_2 eq.	4.880	4.630	4.995	5.619	3.953	6.385	4.786	6.002
SOD	kg CFC11 eq.	0.000014	0.000012	0.000014	0.000014	0.000002	0.000015	0.000008	0.000015
IR	kBq Co-60 eq.	0.139	0.123	0.182	0.165	0.062	0.456	0.114	0.311
OFHH	kg NOx eq.	0.011	0.011	0.011	0.012	0.008	0.013	0.010	0.012
FPMF	kg PM2.5 eq.	0.016	0.016	0.017	0.016	0.017	0.020	0.016	0.018
OFTE	kg NOx eq.	0.012	0.011	0.012	0.012	0.008	0.013	0.010	0.013
TA	kg SO_2 eq.	0.025	0.024	0.025	0.020	0.016	0.023	0.018	0.021
FE	kg P eq.	0.002	0.002	0.002	0.002	0.002	0.003	0.002	0.003
ME	kg N eq.	0.002	0.002	0.002	0.001	0.000	0.001	0.001	0.001
TE	kg 1,4-DCB	8.742	8.360	9.066	11.117	8.570	13.275	9.843	12.196
FET	kg 1,4-DCB	0.134	0.137	0.144	0.097	0.117	0.163	0.107	0.130
MET	kg 1,4-DCB	0.140	0.144	0.153	0.133	0.158	0.221	0.145	0.177
HCT	kg 1,4-DCB	0.150	0.146	0.158	0.179	0.151	0.234	0.165	0.207
HNCT	kg 1,4-DCB	1.362	1.226	1.395	2.039	1.130	2.258	1.584	2.148
LU	m^2a crop eq.	1.352	1.349	1.359	0.417	0.401	0.462	0.409	0.440
MRS	kg Cu eq.	4.880	4.630	4.995	5.619	3.953	6.385	4.786	6.002
FRS	kg oil eq.	0.000014	0.000012	0.000014	0.000014	0.000002	0.000015	0.000008	0.000015
WC	m^3	0.139	0.123	0.182	0.165	0.062	0.456	0.114	0.311

Abbreviations: FE, freshwater eutrophication; FET, freshwater ecotoxicity; FPMF, fine particulate matter formation; FRS, fossil resource scarcity; GWP, global warming; HCT, human carcinogenic toxicity; HNCT, human noncarcinogenic toxicity; IR, ionizing radiation; LU, land use; ME, marine eutrophication; MET, marine ecotoxicity; MRS, mineral resource scarcity; OFHH, ozone formation, human health; OFTE, ozone formation, terrestrial ecosystems; SOD, stratospheric ozone depletion; TA, terrestrial acidification; TE, terrestrial ecotoxicity; WC, water consumption.

Positive values indicate a decrease in environmental impact (enhancement), whereas negative values indicate an increase in environmental impact (deterioration).

By substituting 15% conventional PET fiber with recycled PET fiber, GWP, which is the most important environmental impact category, had a 5% improvement in S2. The production of S4 using only conventional PET fiber resulted in a 15% increase in GWP. This result indicates that PET fiber had a higher GWP than cotton fiber. Using 100% recycled PET fiber in the production of S5 reduced GWP by 19%. Recycled PET fiber has a smaller impact on the environment than both cotton and conventional PET fiber. In S7, the improvement attained by replacing 85% cotton fiber with 50% recycled PET fiber and 35% conventional PET was limited to 2%. Notably, these scenarios (S2, S4, S5, and S7) were calculated using the cut-off method, so it was presumed that the waste PET bottles used in the production of recycled PET fiber had no environmental impact because they had already been disposed of. Because used PET bottles are considered waste, they retain economic value. Therefore, it is essential to evaluate the effects from this perspective. In S3, S6, and S8 of the waste valuation method, the economic value of PET refuse bottles was also considered. Using the economic allocation method, 32% of the environmental impacts of the primary product are assigned to the secondary product, recycled PET fiber (Shen et al., 2010). Using the waste evaluation technique, the GWP of S3 containing 15% recycled PET fiber increased by 2%. The GWP of S6 containing 100% recycled PET fiber and S8 containing 50%–50% recycled PET fiber increased by 31% and 23%, respectively. These results indicate that there was no reduction in GWP when the environmental impacts of the PET bottle were included in the system boundaries. It should be noted that this value depends on the economic allocation prices.

In the MET category, S2 led to a 3% increase. Using the waste valuation method, the increase in MET reached 10% (S3). In S4, which was made with 100% conventional PET fiber, MET was reduced by 5%. Scenario 5 using the waste valuation method increased MET by 13% over the baseline scenario. Scenario 6 and S8 exhibited a strikingly similar pattern. These results demonstrated that the use of PET fiber in the MET category contributed to the enhancement compared with the use of cotton.

By substituting recycled PET fiber for 15% conventional PET fiber in the reference scenario, the TA and WC categories improved by 3% and 1%, respectively (S2). Terrestrial acidification and WC decreased by 38% and 70%, respectively, when the ratio of substitutes in S5 was increased

TABLE 4 Improvement ratio of environmental impacts of for 1 m denim fabric

Impact category	S1	S2	S3	S4	S5	S6	S7	S8
GWP	0	5%	−2%	−15%	19%	−31%	2%	−23%
SOD	0	12%	−1%	−1%	82%	−9%	40%	−5%
IR	0	11%	−32%	−19%	55%	−229%	18%	−124%
OFHH	0	5%	−1%	−3%	31%	−12%	14%	−7%
FPMF	0	−1%	−3%	0%	−3%	−22%	−1%	−11%
OFTE	0	6%	−1%	−7%	32%	−12%	13%	−9%
TA	0	3%	−2%	21%	38%	10%	29%	16%
FE	0	0%	−6%	3%	2%	−40%	2%	−19%
ME	0	1%	0%	76%	81%	77%	79%	77%
TE	0	4%	−4%	−27%	2%	−52%	−13%	−40%
FET	0	−2%	−7%	28%	13%	−22%	20%	3%
MET	0	−3%	−10%	5%	−13%	−58%	−4%	−26%
HCT	0	3%	−6%	−19%	−1%	−57%	−10%	−38%
HNCT	0	0%	−7%	11%	9%	−37%	10%	−13%
LU	0	0%	0%	99%	99%	98%	99%	99%
MRS	0	5%	−1%	9%	40%	−1%	25%	4%
FRS	0	10%	−2%	−50%	17%	−66%	−16%	−58%
WC	0	0%	−1%	69%	70%	66%	70%	67%

Abbreviations: FE, freshwater eutrophication; FET, freshwater ecotoxicity; FPMF, fine particulate matter formation; FRS, fossil resource scarcity; GWP, global warming; HCT, human carcinogenic toxicity; HNCT, human noncarcinogenic toxicity; IR, ionizing radiation; LU, land use; ME, marine eutrophication; MET, marine ecotoxicity; MRS, mineral resource scarcity; OFHH, ozone formation, human health; OFTE, ozone formation, terrestrial ecosystems; SOD, stratospheric ozone depletion; TA, terrestrial acidification; TE, terrestrial ecotoxicity; WC, water consumption.

to 50%. Environmental impacts in either category of S3 calculated using the waste valuation method did not improve. These results can be attributed to the energy-intensive processes involved in PET bottle manufacturing. The TA and WC of denim fabric made from 100% conventional PET fiber increased by 21% and 69%, respectively (S4). The best scenario for the TA category was S5, and the worst scenario was S3.

Although the FPMF did not change in S4, it deteriorated in all remaining scenarios when PET fiber was used. Scenario 6's environmental impact increased by 22%, particularly when using the waste valuation procedure. It was observed that 95% of this increase was caused by the production of PET bottles, which is the primary product. The most significant emission source in PET bottle production is the final product's chilling procedure (Baldowska-Witos et al., 2021).

Scenarios 5 and S7 reduced resource impact in the IR category significantly, with reductions of 55% and 18%, respectively. The values for S6 increased by 229%, and those for S8 increased by 124%. The use of the cut-off method (S5 and S7) in recycling PET significantly reduced the impact on resources, whereas the implementation of the waste valuation method (S6 and S8) resulted in substantial increases. The deterioration originated from the manufacture of PET bottles.

The SOD category revealed that S5 experienced the most substantial reduction at 82%, followed by S7 at 40%. The category experienced an increase of 9% in S6 and 5% in S8. Using the cut-off method (S5 and S7), PET recycling led to substantial decreases in SOD. On the other hand, the waste valuation method (S6 and S8) led to an increase.

Scenario 5 (32%) and S7 (13%) decreased significantly, whereas S6 (−12%) and S8 (−9%) increased in the OFTE category. These results demonstrate that the use of recycled PET fiber in the OFTE category contributed to the enhancement compared with the use of cotton in the cut-off method. For the OFTE, however, recycled PET fiber had greater environmental impacts than conventional PET fiber in the waste valuation method. This decline was attributable to the combustion of solid refuse during flake production (Shen et al., 2010).

Because all scenarios were evaluated based on the results of the LCA, S4's 99% improvement over the reference scenario was the greatest in the LU category. This improvement revealed that even traditional PET fiber has less environmental impact than cotton fiber in this category. Additionally, each PET fiber ratio had a lower LU value than cotton fiber.

Marine eutrophication was the third most diminished potential, with S5 improving by 81%. These findings indicate that recycled and conventional PET fibers are superior to cotton fiber. However, the proportion of recycled PET fiber added to the product had a nonnegligible impact on the environment in the ME. For instance, with 15% recycled PET fiber in S2, the improvement in this category was limited to 1%, whereas with 100% recycled PET fiber in S5, the improvement increased to 81%. Note that these enhancements were in accordance with the reference scenario. Additionally, the use of recycled PET fiber provided (S5) only a 5% improvement over conventional PET fiber for EP (S4).

According to the reference scenario, the use of conventional PET fiber and recycled PET fiber resulted in 2% and 7% deteriorations in the FET category, respectively. These results demonstrate that PET fibers are not superior to cotton fibers in the FET category. For the FET category, recycled PET fiber was not more desirable than conventional PET fiber.

In OFHH, another category that improved the most, the category S5 improved by 31%. Using recycled PET fiber (S5) as a source material resulted in 34% less environmental impact than using conventional PET fiber (S4). The results obtained using the waste valuation method did not yield the same improvement. When the environmental impact of the primary product was accounted for in the secondary product (S6), emission values increased by 9% over conventional PET fiber (S4). The use of recycled PET fiber (S1) was a 5% more environmentally favorable substitute for conventional PET fiber.

The use of recycled PET fiber at a low ratio (S2) did not affect HNCT and FE, but its emission values increased with the waste valuation method. Using the waste valuation method in S6, this deterioration reached 37% and 40% for HNCT and FE, respectively. In addition, using 100% recycled PET fiber in S5 resulted in 2% higher emission values than using 100% conventional PET fiber in S4 for HNCT. In the HNCT category, recycled PET fiber was not superior to conventional PET fiber.

Although studies of the production of recycled products are scarce in the scientific literature, evaluations of the environmental effects of using these raw materials as a product's basic materials are also scarce. In addition, because the functional units and objective scopes of these products are distinct, they cannot be compared explicitly.

TABLE 5 Comparative environmental impact assessment of raw materials

Impact category	PET instead of cotton	Recycled PET (cut-off) instead of cotton	Recycled PET (waste valuation) instead of cotton	Recycled PET (cut-off) instead of PET	Recycled PET (waste valuation) instead of PET	Recycled PET (waste valuation) instead of recycled PET (cut-off)
GWP	Negative	Positive	Negative	Positive	Negative	Negative
SOD	Negative	Positive	Negative	Positive	Negative	Negative
IR	Negative	Positive	Negative	Positive	Negative	Negative
OFHH	Negative	Positive	Negative	Positive	Negative	Negative
FPMF	Notr	Negative	Negative	Negative	Negative	Negative
OFTE	Negative	Positive	Negative	Positive	Negative	Negative
TA	Positive	Positive	Positive	Positive	Negative	Negative
FE	Positive	Positive	Negative	Notr	Negative	Negative
ME	Positive	Positive	Positive	Positive	Notr	Negative
TE	Negative	Positive	Negative	Positive	Negative	Negative
FET	Positive	Positive	Negative	Negative	Negative	Negative
MET	Positive	Negative	Negative	Negative	Negative	Negative
HCT	Negative	Negative	Negative	Positive	Negative	Negative
HNCT	Positive	Positive	Negative	Notr	Negative	Negative
LU	Positive	Positive	Positive	Notr	Notr	Notr
MRS	Positive	Positive	Negative	Positive	Negative	Negative
FRS	Negative	Positive	Negative	Positive	Negative	Negative
WC	Positive	Positive	Positive	Notr	Negative	Negative

Abbreviations: FE, freshwater eutrophication; FET, freshwater ecotoxicity; FPMF, fine particulate matter formation; FRS, fossil resource scarcity; GWP, global warming; HCT, human carcinogenic toxicity; HNCT, human noncarcinogenic toxicity; IR, ionizing radiation; LU, land use; ME, marine eutrophication; MET, marine ecotoxicity; MRS, mineral resource scarcity; OFHH, ozone formation, human health; OFTE, ozone formation, terrestrial ecosystems; PET, polyethylene terephthalate; SOD, stratospheric ozone depletion; TA, terrestrial acidification; TE, terrestrial ecotoxicity; WC, water consumption.

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Gaining insight into the environmental impacts of different raw materials is crucial when searching for sustainable sources for materials. Hence, a comprehensive assessment was done to compare the environmental impact of various materials and techniques used in textile manufacturing, with a specific emphasis on the effects of employing virgin PET, recycled PET (using cut and waste valuation allocation methods), and cotton. Table 5 provides a comparative analysis of raw materials. Positive values in this analysis signify a reduction in environmental impact, whereas negative values indicate an increase in environmental impact. This analysis offers a comprehensive understanding of the advantages and disadvantages associated with different materials by comparing their environmental impact across multiple categories. In the Table 5, positive results are colored orange, negative ones are colored green, and notr ones are colored blue. The purpose of this table is to enhance decision-making in material selection, with the goal of minimizing the environmental impact of textile products.

When evaluating the environmental impacts of the primary product using the waste valuation method, significant improvements in certain impact categories vanished. Both the energy consumed by the recycling process and the fact that the initial primary material is petroleum-based predicted these outcomes (Shen et al., 2012; Zhang et al., 2020).

To demonstrate the correlation between the acquired outcomes and the LCI, an analysis was conducted on the input procedures pertaining to polyester, cotton, and

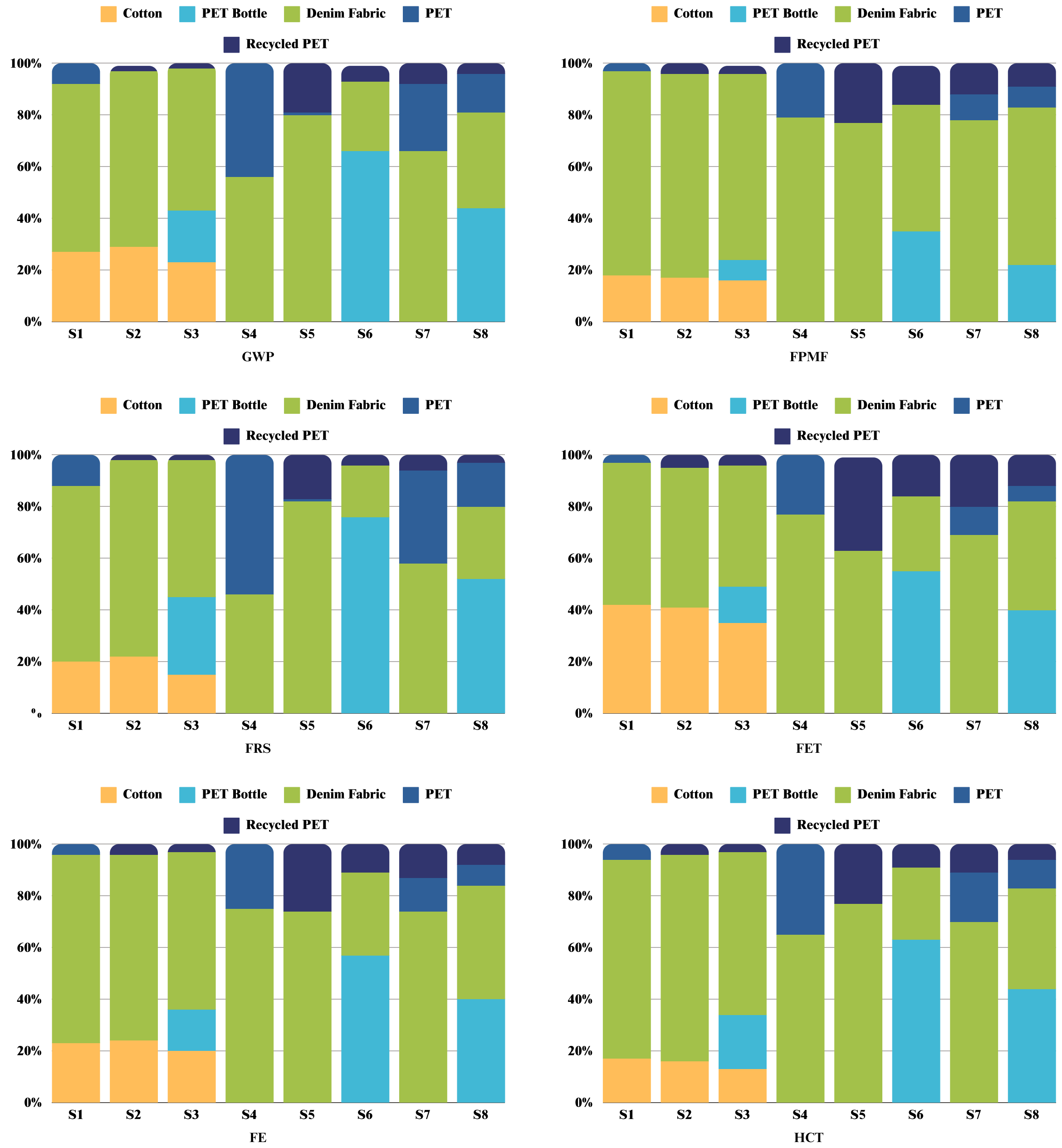

FIGURE 2 Share of inputs life cycle impact (LCI) in impact category results. PET, polyethylene terephthalate

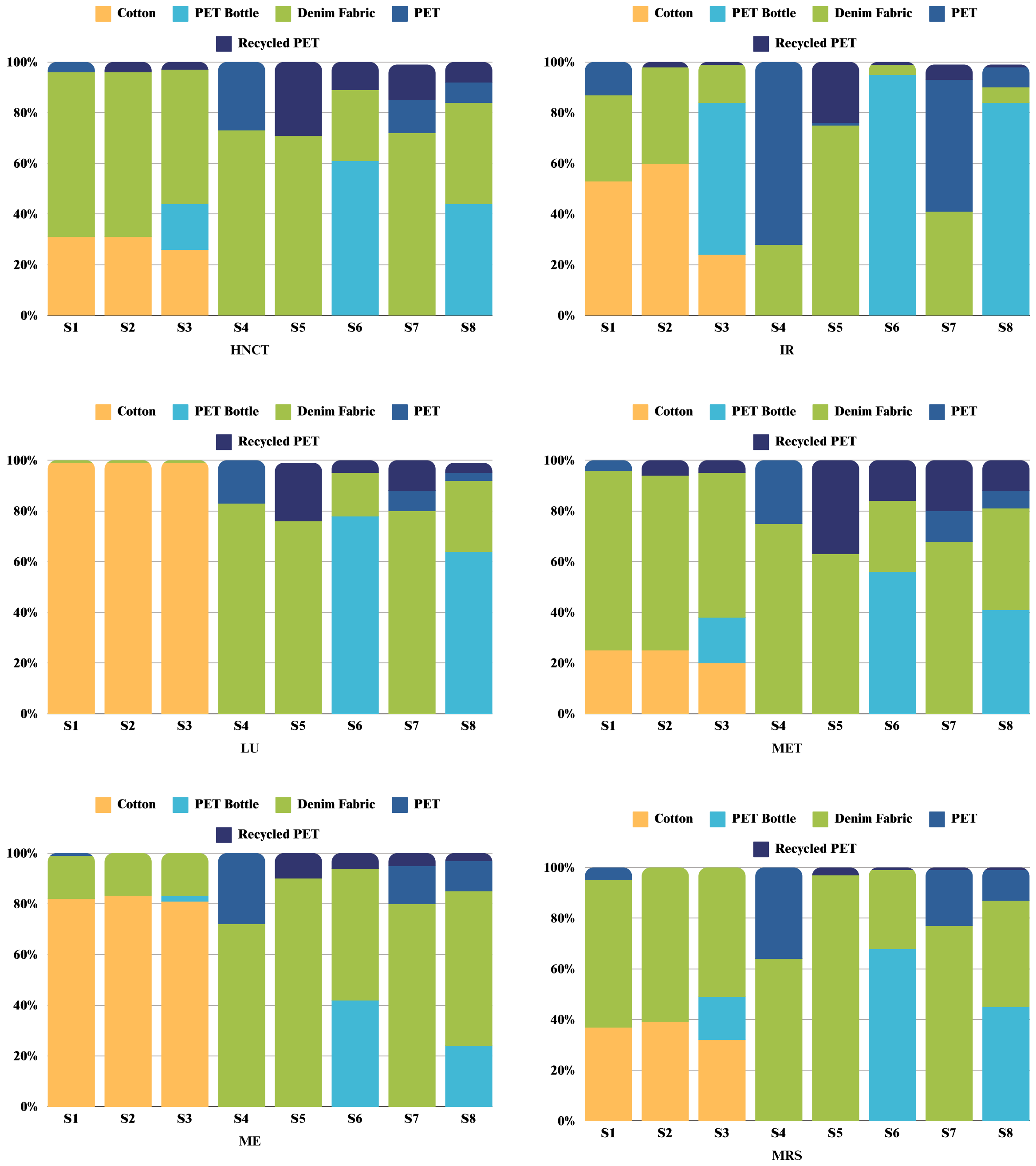

FIGURE 2 Continued.

recycled PET raw materials, as well as the processes involved in PET bottle production and denim fabric production. The share of inputs LCI in impact category results are presented in Figure 2 and Supporting Information S1.

The recycled PET processes exhibited the least significant impact across all scenarios in the GWP category. When considering the PET bottles, we observed that 80% of the environmental impact associated with the denim fabric made from 100% recycled PET fiber (S6) can be attributed to the recycled PET fiber itself, whereas the remaining portion is attributed to the production processes involved in manufacturing the denim fabric. The deterioration originated from the manufacture of PET bottles. When considering PET bottles using the waste valuation method, the proportion of recycled PET fiber in the overall GWP rose to 72%. These findings demonstrate the significance of the allocation method's impact on LCA study outcomes.

In LU category S6, denim fabric production accounted for 17% of the environmental impact, 78% was attributed to PET bottle production, and the remaining 5% was attributed to the use of recycled PET fiber. The use of recycled PET fiber in S5 accounted for 23% of the overall environmental impact, which decreased to 5% when employing the waste

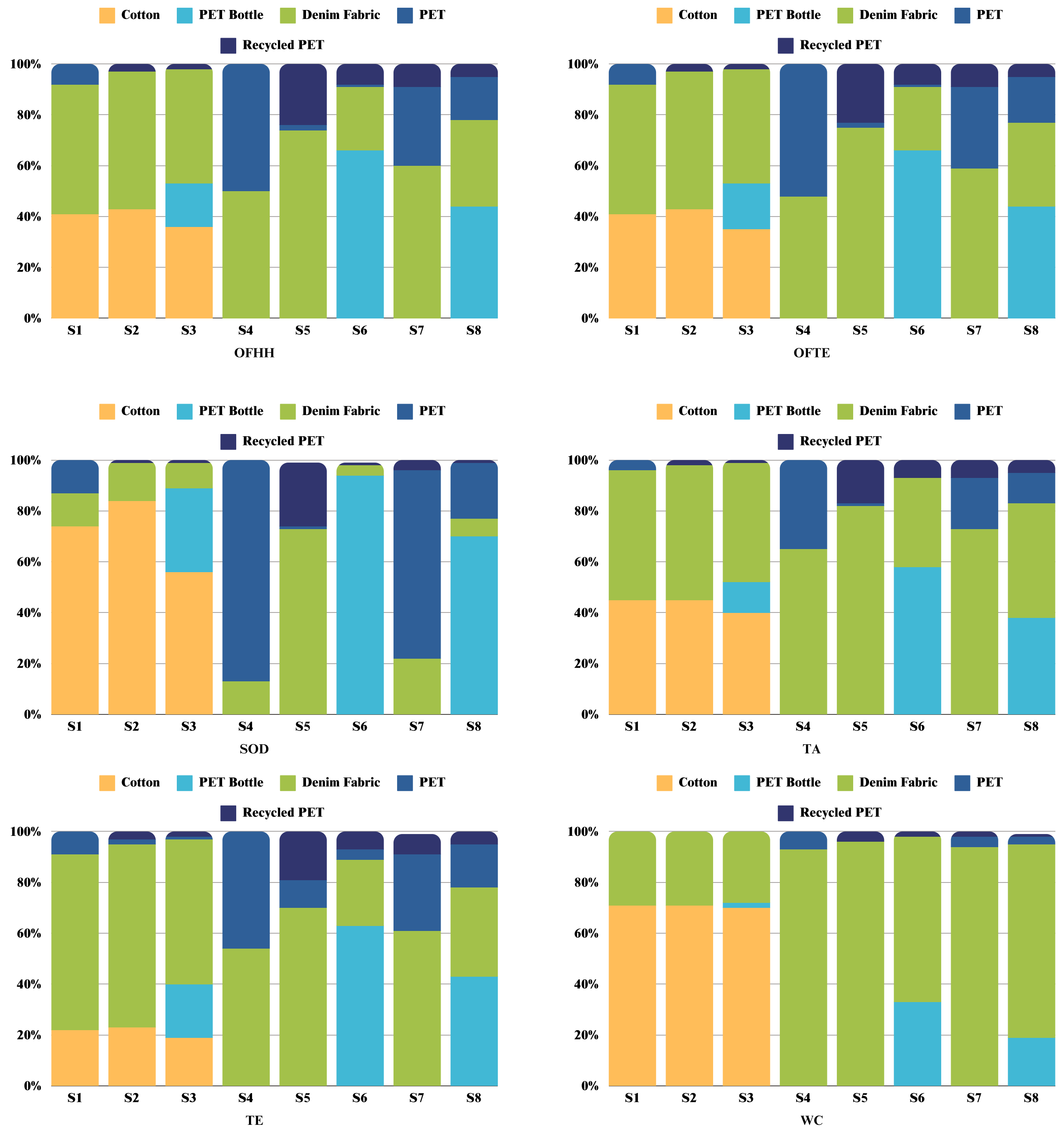

FIGURE 2 Continued.

valuation method. It is important to note that S6 was approximately 4.5 times greater than S5.

The environmental impact share of cotton varied between 24% and 60% in S1, S2, and S3, where cotton raw material was located. The primary factor that significantly influenced the environmental impact was the PET bottle, particularly in S6. Scenario 5 had the largest proportion of recycled PET fiber. The results for all impact categories are given in Figure 2 and Supporting Information S1.

This study's limitation is that it is unknown whether the same quality characteristics can be attained with various material contents. Nevertheless, numerous studies examining quality evaluations such as tensile strength and surface uniformity with the use of recycled raw materials indicate that it can at least reflect the expected quality values (Sadeghi et al., 2021; Saini et al., 2020; Telli & Özdil, 2015; Yuksekkaya et al., 2016). Furthermore, the absence of advanced technology hinders the production of products that incorporate a significant proportion of recycled materials. Although previous studies have considered the recycling of PET into textiles like denim, the mechanical and chemical properties of recycled PET fibers present significant challenges. Recycling processes, such as glycolysis, have been observed to result in a reduction in fiber strength (Peng et al., 2023). Moreover, the recycling process is complicated by the inclusion of blended materials, such as PET and/or cotton fabrics, which are characterized by unstable glycosidic bonds in cotton (Yang et al., 2023). Textiles composed entirely of recycled PET fibers exhibit a greater propensity for pilling than textiles made from virgin PET or blends (Telli & Özdil, 2015). Owing

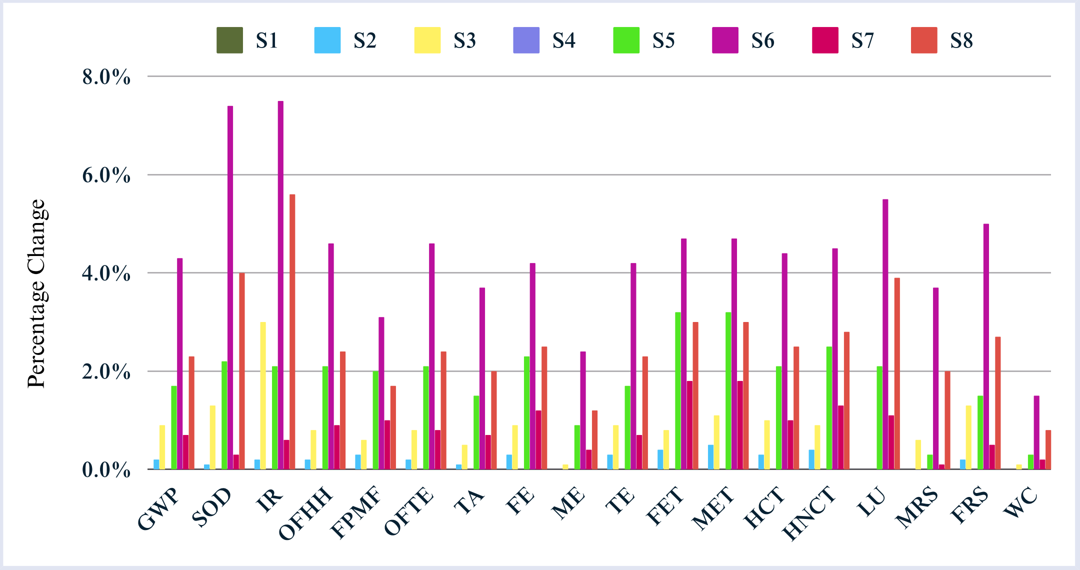

FIGURE 3 Sensitivity analysis results for recycled polyethylene terephthalate (PET) fiber waste ratio in the spinning process

to the variability in recycled PET properties based on the source of the material, achieving stability in large-scale production poses a challenge (Kijeńska-Gawrońska et al., 2022). The literature contains research on novel denim dyeing techniques (Fidan et al., 2021b; Masoudi et al., 2022; Sarafpour et al., 2022). These studies emphasize the progress made in implementing sustainable practices and enhancing materials in the denim and textile sectors. The restricted use of 100% recycled PET or polyester fiber in denim fabric stems from challenges in maintaining the mechanical characteristics of the fibers during recycling procedures, potential disparities in fabric properties compared with new materials, and variations in visual assessment. Progress in recycling technologies is expected to address these challenges and potentially enhance the use of recycled PET in denim manufacturing. Consequently, the recycle PET ratio is expected to increase (Sarıoğlu, 2017).

Sensitivity analysis. Because LCA is a data-intensive method, this study employed sensitivity analysis to determine the sensitivity of environmental impact potentials according to input data. The recycled PET fiber waste ratio in the spinning process was selected for sensitivity analysis because it was the primary input for this LCA assessment. In the literature, various ratios, such as 5%, 10%, and 20%, were cited for the waste ratio (Igos et al., 2019; IISBE, 2001; Liu et al., 2020). In this study, the value of the specified input was increased by 10%. The recycled PET fiber ratio, which was determined to be 10% during the spinning stage, was increased by 10% by keeping all other inputs constant. Figure 3 shows the results of the sensitivity analysis.

All environmental impact categories of the waste valuation and cut-off method were not sensitive to the waste ratio of recycled PET fiber, according to the results obtained. The category with the greatest sensitivity to this consumption was the IR category in S6 at 7.5%. Despite a 10% increase in inputs, no impact categories increased by that amount. Using this procedure to calculate S8 yielded similar results. Increases in response to the input ratios range from 1.2% to 5.6% in this scenario. Reducing the waste ratio of recycled PET fiber during the spinning process could result in environmental improvements, as demonstrated by these findings. In S3, all categories except LU showed a small sensitive ratio to the recycled PET fiber waste ratio. It should be noted that these results varied based on the proportion of recycled PET fiber in the product. In S5, FET and MET were the most sensitive categories on the waste ratio of recycled PET fiber according to the cut-off method, followed by HNCT. As a consequence, the data uncertainty in the cut-off method had no significant impact on the results of this study.

LCC results

In addition to the LCA for the environmental impacts of the scenarios, the LCC, which accounted for economic impacts, was also evaluated. In the LCC, the same costs in the scenarios were not considered. Figure 4 shows the LCC values for the scenarios in accordance with the LCC results.

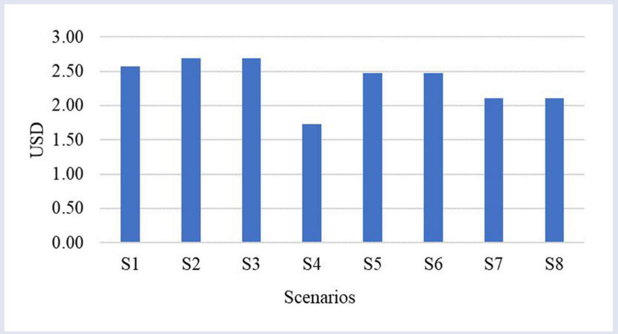

FIGURE 4 Life cycle cost (LCC) results for the functional unit (S: Scenario; S1: Reference Scenario)

TABLE 6 Ranking of the scenarios with the EDAS method

Scenario	S5	S7	S4	S8	S6	S2	S1	S3
AS_i	0.99	0.88	0.77	0.54	0.31	0.14	0.10	0.04

Abbreviation: EDAS, evaluation based on distance from average solution.

The scenario with the lowest LCC value was S4 with conventional PET fiber. The highest LCC values were found in S2 and S3, which contain recycled PET fiber and cotton. Scenario 2's LCC value increased by 4% after the incorporation of 15% recycled PET fiber. This increase was attributed to the fact that recycled PET fiber was 43% more expensive than regular PET fiber. By substituting PET fiber for cotton in S4, the LCC of denim fabric was reduced by 33%. With the use of recycled PET fiber (S5), the LCC value reduction was restricted to 4%. In S7 and S8, the LCC value increased by 18% due to the substitution of conventional PET fiber (35%) and recycled PET fiber (35%) for cotton fiber. Examining the scenarios revealed no economic differences between the waste valuation method and the cut-off method. Because cotton is more expensive than both conventional and recycled PET fibers, these values were expected. However, recycled PET fiber was an expensive primary material because it required more processing than conventional PET. To the best of our knowledge, the LCC of PET fiber in the production of denim fabric was conducted for the first time; therefore, these results cannot be compared with previous ones. Consequently, the contribution of the LCC analysis to the evaluation of sustainability was crucial for guiding decision-makers.

EDAS method results

In this study, the EDAS method was used to rank the eight scenarios, considering both LCA and LCC results. The ranking obtained is presented in Table 6. According to the results, the best scenario was S5, with an AS_i value of 0.99. This scenario (S5) contains 100% recycled PET fiber content. Like the GWP, SOD, and IR categories, S5 had the lowest environmental impact, but it ranked fourth for LCC. This result demonstrated that outcomes vary when economic and environmental criteria are evaluated together (Fidan et al., 2021b). The second-best scenario was S7, which ranked second for environmental impact results such as AP, EP, and LCC. Scenario 7 was created using the cut-off allocation method and contains 50% recycled PET fiber and 50% conventional PET fiber. The third-best scenario was S4 with an ASi value of 0.77 and 100% conventional PET fiber. Scenario had the best LCC and FET and MET results but ranked lower than the other scenarios for the remaining criteria such as GWP and HCT. According to EDAS, the ranking of all scenarios was S5 > S7 > S4 > S8 > S6 > S2 > S1 > S3. The worst-ranked scenario was S3, which contained 85% cotton and 15% recycled PET content and was calculated using the waste valuation method. Scenario 2 and S1 were second and third worst. Cotton content was common in the three worst-ranked scenarios, causing environmental and economic harm.

CONCLUSION

This study investigated denim fabric produced using recycled PET fiber instead of virgin cotton and conventional PET fiber in eight scenarios. The LCC and LCA methodologies were used for analysis, and a sensitivity analysis was performed to assess the LCA uncertainty. The scenarios were ranked by the EDAS method as a final step.

According to the LCA results obtained, the greatest improvement was attained with LU (99%), ME (82%), and SOD (81%) with the cut-off approach, compared with the reference scenario. The comparative analysis revealed several key findings regarding the environmental impacts of substituting cotton with PET or recycled PET. Using recycled PET with the cut-off method instead of cotton resulted in positive environmental outcomes across most categories, indicating a significant reduction in impacts such as GWP, SOD, and IR. Conversely, substituting cotton for PET generally increases environmental impacts in these categories. Furthermore, using recycled PET with the waste valuation method often leads to negative outcomes compared with the cut-off method, suggesting that the allocation method plays a crucial role in determining the environmental benefits of recycled materials. Overall, recycled PET, particularly with the cut-off allocation method, offers a more sustainable alternative to both virgin PET and cotton in many impact categories.

This result demonstrated the significance of the allocation method for the LCA of recycled materials. The scenario with the smallest economic impact, as determined by the LCC, is S4, which consists wholly of conventional PET fiber. Recycled PET and cotton fibers have the second and third lowest economic impact on denim fabric production, respectively. According to EDAS, the scenario with the best results was S5 with 100% recycled PET, followed by S7 and S4, respectively. These findings demonstrated that sustainable product development requires simultaneous economic and environmental evaluation.

Textile companies and decision makers benefited from the study's detailed analysis of recycled PET, conventional PET, and cotton fiber. This study informs scientists and policymakers about the environmental and economic impacts of recycled PET fibers and clothing, thus adding to the literature. Finally, there is room for more research on recycled PET fiber in clothing, PET fiber production from different raw materials, and allocation methods. In future research, EOL methods for cotton and PET fibers, particularly the biogenic carbon in cotton, considering its time-dependent impact on global warming should be explored more deeply. This approach can significantly improve our understanding of their environmental impacts.

Additionally, to reveal the economic effects of denim fabric, the techno-economic analysis method can be used, which is a valuable method used in decision-making processes such as launching a new technology or product.

AUTHOR CONTRIBUTION

Fatma Şener Fidan: Data curation; formal analysis; methodology; resources; visualization; writing—original draft. **Emel Kızılkaya Aydoğan:** Formal analysis; methodology. **Niğmet Uzal**: Conceptualization; investigation; validation; writing—review and editing.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data, associated metadata, and calculation tools are available from corresponding author Fatma Şener Fidan (fatmasener@gmail.com).

SUPPORTING INFORMATION

The supporting information provides evaluation based on distance from average solution (EDAS) method's calculation steps and Figure's data.

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