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An integrated life cycle assessment approach for denim fabric production using recycled cotton fibers and combined heat and power plant

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abstract

Due to the increase in consumption and awareness of environmental impacts, switching to new business models has become mandatory in the textile industry. The aim of this study is to investigate the contribution of using mechanically recycled cotton fiber instead of virgin cotton fiber, which is one of the most important raw materials in textiles and grown using a high amount of water and pesticides, and combined heat and power (CHP) plant instead of grid energy in terms of the environmental impacts, cost, and quality of denim fabric product via 8 scenarios using an integrated sustainability assessment approach. The scenarios were identified according to the use of the CHP plant in the manufacturing process and the ratio of recycled cotton fiber used in the product. Environmental impacts were analyzed using the life cycle assessment approach (LCA). Besides the environmental impact analyses, product quality and cost-savings of all scenarios were also examined using TODIM (an acronym in Portuguese for Interactive and Multicriteria Decision Making) method to apply an integrated approach for sustainable denim fabric production. Global warming potential (GWP), acidification potential(AP), eutrophication potential(EP), water use, and cumulative energy demand(CED) were investigated as environmental impact categories in the production of denim fabric. In addition to environmental impact categories washed weight, tear, tensile, and cost-saving were determined as the attributes of TODIM. According to the LCA results, the highest environmental impact improvements were obtained as 98% water use, 90% EP, 74% AP, 63% CED, and 54% GWP for scenario 8 with 100% recycled cotton and CHP plant use. Besides, the use of the CHP plant offered 4% GWP and 0.42% water usage saving regardless of the recycled cotton ratio. In addition, scenario 8 also showed the best performance for the integrated sustainability assessment by TODIM. It is obviously demonstrated that the use of the mechanically recycled cotton as a raw material and CHP plant as an energy source through the manufacturing processes of denim production will facilitate the transfer of traditional linear economy business models of companies to the circular economy.

1. Introduction

With an increase in awareness among consumers and stricter global legislations, the denim industry is shifting towards sustainable production methods and eco-friendly jeans (De Brito et al., 2008; Fletcher 2012). The key issues to achieving this change are rolling out using more sustainable raw materials, applying the circular economy, and energy technologies that significantly reduce environmental impact (Akı et al., 2020; Amutha 2017). Therefore, it is necessary to systematically evaluate the environmental impacts of the denim fabric from a life cycle perspective so as to identify the potential opportunities to improve the sustainability of the denim industry. Cotton is the main raw material for denim (Downey 2007) and one of the most important materials to be used in reducing environmental impacts in denim fabric production. Cotton production has important environmental impacts due to high water consumption, land occupation, energy, fertilizer, and pesticide use which can harm the environment and human health (Baydar et al., 2015; Zhang et al., 2015). The most important impact of cotton

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cultivation is in water consumption and causes drought with 2.6% global water use (Chapagain et al., 2006). As pesticide consumption is 11% of world consumption and about 50% in developing countries, it has harmful environmental impacts related to AP and EP (Bevilacqua et al., 2014). Moreover, cotton cultivation is a significant source of greenhouse gases, contributing between 0.3% and 1% of total global warming potential (Ton 2011) by including fuels or energy-intensive material inputs such as fertilizers, herbicides, seeds, diesel fuel, and electricity for irrigation, machinery, and labor used for agriculture. Besides, cotton has important land use potential as it is harvested in an area equivalent to approximately 2.3% of the world's arable land (FAO 2015). To avoid all these environmental impacts, the use of recycled cotton is significantly important towards a circular economy strategy. The uses of recovered cotton for denim fabric production include the added value from the environmental point of view by providing a second life for the textiles produced and avoiding cotton cultivation (Esteve-Turrillas and de La Guardia, 2017; Yousef et al., 2019). For decreasing environmental impacts in denim industry, using recycled cotton necessitates further evaluations. LCA is a very useful tool to analyze environmental impacts associated with life cycle stages, from cradle to grave, throughout the lifetime of products and services. It is a scientific and standardized methodology with ISO 14040 that helps decision making, which enables the development of processes by identifying hot spots throughout its life cycle (ISO 2006a). As discussed above, there are several LCA studies in the textile industry in the literature, as the textile industry has a major contribution to environmental pollution (Ibrahim and Eid 2018). LCA studies on recycled raw material mainly focused on chemical recycling of cotton waste to produce recycled fibers (Haslinger et al., 2019; Liu et al., 2019; Paunonen et al., 2019; Yousef et al. 2019, 2020), quality assessment of recycled fiber (Halimi et al., 2008; Ichim and Sava 2016; Utebay et al., 2019; Wanassi et al., 2016) and comparison of the virgin, organic and recycled cotton fibers including cultivation and production (La Rosa and Grammatikos 2019; Miljögiraff 2016; Murugesh and Selvadass 2013; Spathas 2017; Thinkstep 2018; van der Velden et al., 2014).

In addition to these studies on raw materials, several studies have been conducted on different garments, including hotel textile (Kalliala and Nousiainen 1999), T-shirt (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), bedsheets (De Saxce et al., 2012), towels (Blackburn and Payne 2004), tablecloth (Laursen et al., 2007), polyester trousers and a pack of men's cotton briefs (Collins and Aumônier 2002). Despite the huge consumption of denim garments, studies are few in numbers and limited with LCA reports prepared by famous brands (Hedman 2018; Levi 2015; Morita et al., 2020; Periyasamy and Duraisamy 2018; Roos et al., 2015). The studies carried out on garment generally reported environmental impacts only for the selected garments with a holistic perspective and also did not detailly analyze them for the fabric or fiber stages.

Energy is one of the prime cost factors and the second most important environmental issue to be evaluated in the textile industry (Hasanbeigi 2010). Besides the electricity, the high amount of fuels used to generate heat energy consumed in the sector resulted in a high ratio of emissions (McKenna and Norman 2010). For this reason, achieving sustainable production in the textile industry energy-efficient technologies must be used (Nayak et al., 2020). Recently, Hasanbeigi et al. (2010) have also listed the CHP as one of the most energy-efficient methods to be used for improving energy efficiency in the textile industry. Also, the CHP plant is one of the most advantageous tool for CO_2 reduction, as it demands less from energy sources (Gohul et al., 2012; Zarębska and Dzikuć 2013).

In addition to environmental impacts of fabric production and raw materials, studies on assessing environmental impacts of CHP plant use in energy production is also quite limited. While the studies in the literature generally examined the CHP plant using biomass fuel (Guerra et al., 2014; Guest et al., 2011; Kelly et al., 2014; Périlhon et al., 2012; Shen et al., 2015; Tagliaferri et al., 2018) and geothermal (Karlsdottir et al., 2010), there are only a few studies using natural gas (Banar and Cokaygil 2010; Bargigli et al., 2008; Turconi, 2014; Usubharatana and Phungrassami 2018). Besides, these studies were examined the environmental impacts of the CHP plant for generating a certain amount of electricity and not reported in the contribution of CHP plant use to the sustainability and cost of the product. As a result, providing information about how the use of CHP plant changes on environmental impact and cost-saving on a product basis is important for cleaner production.

As the denim industry is aggressive compared to other sectors, cost-saving and product quality are always significantly important criteria (Annapoorani 2017) and the first to be considered during the product design phase. For this reason in sustainable denim fabric design cost-effectiveness, meeting the customer's visual and physical expectations should also be considered. (Davila 2000). This creates major constraints on decision-makers to independently and separately optimizing denim fabric alternatives. When evaluating multiple dimension of sustainability and ranking different manufacturing scenarios, MCDM methods could be the best solution alternative for a systematic and clear framework aiming integrated sustainability assessment (Buyukozkan and Cifci 2012; Chiou et al., 2005; Kaya and Kahraman 2011; Nigim et al., 2004; Streimikiene et al., 2012; Tian et al., 2018; Zolfani et al., 2018).

Most MCDM methods are based on the assumption that decision-makers are rational (Bai et al., 2014). However, the psychological behavior of the decision-maker plays an important role in decision analysis, and should be considered in the decision-making process. TODIM is one of the MCDM methods capable of ranking the alternatives according to the preferences of the decision-makers incorporating prospect theory (Tversky and Kahneman 1992) in its formulation which considers irrational behavioral decision-making under uncertainty (Gomes and Lima 1992; Zhang and Xu 2014). TODIM is a valuable method that generates a complete sequence of all alternatives; investigating the superiority of an alternative not only consider the advantage of the alternative but also takes into account its relative superiority over others; takes into account decision-makers' attitudes towards risk and can be used through a simple spreadsheet without the need for commercial software. For this reason, TODIM is the best option to create an integrated approach together with experts to evaluate the sustainability of denim fabric by considering multiple dimensions. TODIM approach was applied by some researchers as MCDM decision-support tools for sustainability assessment in the literature. The TODIM-based approach was applied for determining the best alternative in terms of environmental aspects of pumped hydro energy storage plant (Lu et al., 2020). Turgut and Tolga (2018) used fuzzy TODIM to select the best sustainable and renewable energy alternative. As stated, MCDM methods can be used as an excellent technique to rank and choose the best alternative based on various attributes and a promising way of integrated sustainability assessments.

Although denim has a large share in the textile industry, current denim LCA studies are limited to the reports of brands, and a few studies only discussing the result for a particular garment product. Also, there is no study examining the contribution of a CHP plant to the environmental impacts of the product from an LCA perspective. This study significantly fills these gaps from the points of examining the environmental impacts of denim fabric with the substitutive use of recycled and virgin cotton raw materials; CHP plant, and grid electricity. Moreover, an important barrier of LCA was that it did not account for other design goals including cost-saving and quality dimensions (Fiksel, 2009; Hendrickson et al., 1997). Although it is high time for the denim industry to implement energy-efficient technologies and designs to reduce costs and environmental impacts (Schrott 2011), when it comes to combined environmental and cost assessments of denim fabric, the number of conducted studies is still scarce and none of them have addressed costs, product quality, and environmental impacts with an integrated approach. The main literature contribution of this study is the addition of economic and product quality dimensions to the integrated sustainability assessment using TODIM of denim fabric while examining the environmental impacts of denim fabric by using recycled raw materials and using CHP plant technology. While LCA is useful for evaluating environmental attributes, it stops short of providing information that business managers routinely utilize for decision-making. Therefore, the decision-making approach is an important tool to provide real-time solutions, especially to sustainable engineering problems, including environmental sustainability problems (Stojčić et al., 2019).

In light of the published literature, this study aimed to provide a comprehensive sustainability assessment of raw materials and energy production options for the denim fabric with the help of the TODIM method. LCA method was used to evaluate environmental impacts for sustainable denim production and product quality tests were conducted for product quality assessment. Finally, TODIM methodology was applied for the integrated assessment of the denim fabric by including the economic evaluation in terms of cost-saving, product quality assessment, and environmental impacts. This work promotes the widespread use of recycled cotton and CHP plants, helping to reduce the overall environmental impact in the denim industry without compromising product quality and cost performance.

2. Materials and methods

In this study, an integrated sustainability approach considering environmental impacts, cost-saving, and product quality was developed by using TODIM method to evaluate the effect of mechanically recycled cotton fiber and CHP plant in denim fabric production. The framework of the proposed methodology for the sustainability assessment of denim fabric was shown in Fig. 1. The steps, in detail, were the following:

- *Setting of the systems:* In the first stage, for simulating sustainable denim fabric production, 8 scenarios were constructed. Different recycled and raw cotton fiber blend ratios were used for the construction of four scenarios to examine the sustainability of denim fabric in terms of raw materials. Moreover, remaining four scenarios were created according to the use of CHP plant instead of grid energy, and a total of eight scenarios were obtained. For the integrated sustainability assessment, the dimensions that were of great significance in denim fabric production were determined and the system settings were completed.
- *Setting of the sustainability dimensions:* In this stage, the methods for evaluating the dimensions to be used in sustainability assessment are determined. LCA, which is a widely used scientific methodology was applied for the assessment of environmental impacts. Quality tests that reveal the physical and visual features of the denim fabric were applied according to international standards for product assessment. Lastly, the product costs of the scenarios were compared with the reference scenario for the evaluation of the economic dimension.

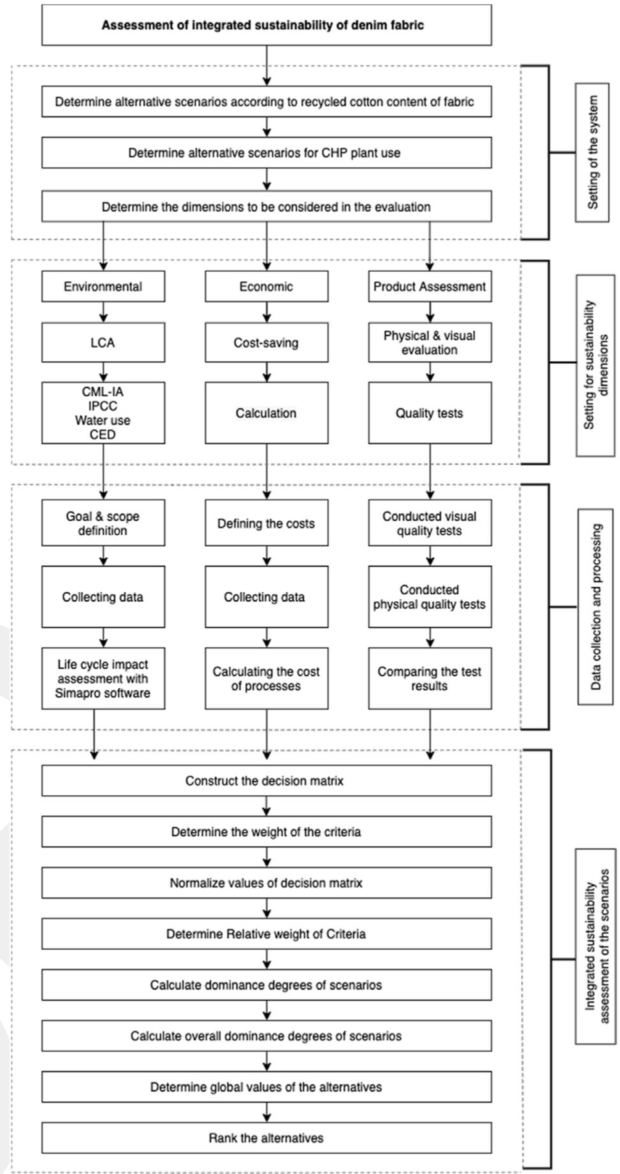

Fig. 1. A framework of the proposed methodology for the sustainability assessment of denim fabric.

- *Data collecting and processing:* The data and information of the scenarios with respect to the LCA were collected according to the system's boundaries. The most relevant environmental impact categories for the denim industry were evaluated by LCA using Simapro Software. Subsequently, the cost units of the production were determined and the required data were collected. After scaling the production costs according to the functional unit, cost-savings were calculated comparing cost values of scenarios with the reference scenario. Product quality tests were conducted for determining the physical and visual features of denim fabric.
- *Integrated sustainability assessment of the scenarios:* Finally, the integrated sustainability approach was applied to evaluate the scenarios. The outputs of all dimensions were considered as the criteria of the TODIM method. The decision matrix was created using the individual evaluation results, and the criteria weights were determined according to the expert opinions. TODIM results were used to compare the sustainability of all scenarios.

Then, the scenarios were ranked with an integrated sustainability perspective.

2.1. Scenarios

The integrated sustainability assessment of denim fabrics produced by using both virgin and recycled cotton fiber and by using both the CHP plant and grid electricity as energy resource was evaluated via 8 scenarios. Within the first part of the scenarios, the effects of mechanically recycled cotton fiber added to the product in different proportions on environmental impacts, product quality results, and the cost-saving was deeply examined. In the second part, the contribution of applying the CHP plant as a source of electricity instead of the grid was taken into account, during fabric production, and all scenarios were analyzed with an integrated sustainability assessment approach.

Textile products are generally produced as blends in order to increase performance and quality properties, to obtain cost-savings to increase durability and hand value (Ibrahim 2011; Radhakrishnan and Kumar 2018). When evaluating textile products, it was decided to consider various blending virgin cotton/recycled cotton ratios such as 100%, 80/20%, 50/50% as it largely affects the cost-saving and product quality as well as the environmental impacts (De Saxce et al., 2012; Esteve-Turrillas and de La Guardia, 2017; Kalliala and Nousiainen 1999; Radhakrishnan and Kumar 2018; Roos et al., 2015; Terinte et al., 2014; Zhang et al., 2015). Therefore, four scenarios were created to analyze the effect of different mechanically recycled cotton fiber ratios contribution to the assessment of the sustainability of denim fabric. The first scenario (S1) was determined in which 100% virgin cotton fiber and used energy from the grid defined as the reference scenario. In scenario 3 (S3), virgin cotton fiber ratio was reduced to 80%, and 20% the recycled cotton fiber was added. This scenario was chosen because of the maximum recycled cotton containing fabric produced by the company, and all the remaining processes were the same as the reference scenario, except for the raw material content. Fiber quality is often related to fiber length, and for recycled fiber, this depends on the purity of the waste stream. It is not always possible to collect cotton waste of the same purity and quality. However, the most of short fibers are discarded during the ring yarn process. To date, two alternative scenarios (S5 and S7) were hypothetically determined to assess the sustainability of denim fabric, as it is technically not possible to produce denim fabrics using 50% and 100% recycled cotton fibers. Scenario 5 (S5) contained 50% recycled cotton fiber and scenario 7(S7) was produced only with 100% recycled cotton fiber. As it is stated above, 50/50% composition was a frequently used ratio in the literature (De Saxce et al., 2012; Esteve-Turrillas and de La Guardia, 2017; Kalliala and Nousiainen 1999; Radhakrishnan and Kumar 2018; Roos et al., 2015; Terinte et al., 2014; Zhang et al., 2015) and 100% recycled cotton denim fabric was used to get the maximum recycling cotton ratio case results.

It was noted that, in the scenarios explained so far, only the raw material contents were changed according to the reference scenario and the energy source was still the grid. After that, four additional scenarios were created to understand the contribution of the use of CHP plant instead of grid electricity during fabric production stages (from spinning to quality control) to assess sustainability of denim fabric (S2, S4, S6, S8). S2 was derived from S1, assuming the use of CHP plant instead of grid electricity as an energy input. Similarly, in S4, S6, and S8, only the energy source was changed in S3, S5, and S7, respectively with aiming to measure how CHP usage contributed to the sustainability of denim fabric. A summary of all scenarios examined in this study for denim fabric production was given in Table 1.

2.2. Environmental impact assessment with LCA

2.2.1. Goal and scope definition

The environmental impacts of using recycled cotton fiber as a raw material in terms of circularity and CHP plant as an energy source in terms of energy minimization were investigated for sustainable denim fabric production using the LCA approach. The results were compared with virgin cotton fiber and grid electricity use (reference scenario) for the denim fabric production. The LCA has been performed in 8.4.1 SimaPro Software using the Ecoinvent V3.0 database according to the guidelines of ISO 14040/44 (ISO 2006a; ISO 2006b; Pré Consultants 2016; Wernet et al., 2016).

When determining the functional unit in textile applications different units such as kg, square meter could be selected depending on the selected product (van der Velden et al., 2014). In

Table 1
Summary of all scenarios (*Reference Scenario; NA: Not Applicable).

Scenario	Composition of fabric	Virgin Cotton Origin	Recycled Cotton Origin	Energy Sources	Data Resources
S1*	100% virgin cotton	25% Turkey 40% USA 15% Greece 20% Brazil	NA	Energy from grid	The local denim production company, Ecoinvent database
S2	100% virgin cotton	25% Turkey 40% USA 15% Greece 20% Brazil	NA	Energy from CHP plant	The local denim production company, Ecoinvent database
S3	80% virgin cotton; 20% recycled cotton	25% Turkey 40% USA 15% Greece 20% Brazil	100% Turkey	Energy from grid	The local denim production, Ecoinvent database
S4	80% virgin cotton; 20% recycled cotton	25% Turkey 40% USA 15% Greece 20% Brazil	100% Turkey	Energy from CHP plant	The local denim production, Ecoinvent database
S5	50% virgin cotton; 50% recycled cotton	40% Turkey 25% USA 15% Greece 20% Brazil	100% Turkey	Energy from grid	The local denim production, Ecoinvent database
S6	50% virgin cotton; 50% recycled cotton	25% Turkey 40% USA 15% Greece 20% Brazil	100% Turkey	Energy from CHP plant	The Local denim production, Ecoinvent database
S7	100% recycled cotton	NA	100% Turkey	Energy from grid	The local denim production, Ecoinvent database
S8	100% recycled cotton	NA	100% Turkey	Energy from CHP plant	The local denim production, Ecoinvent database

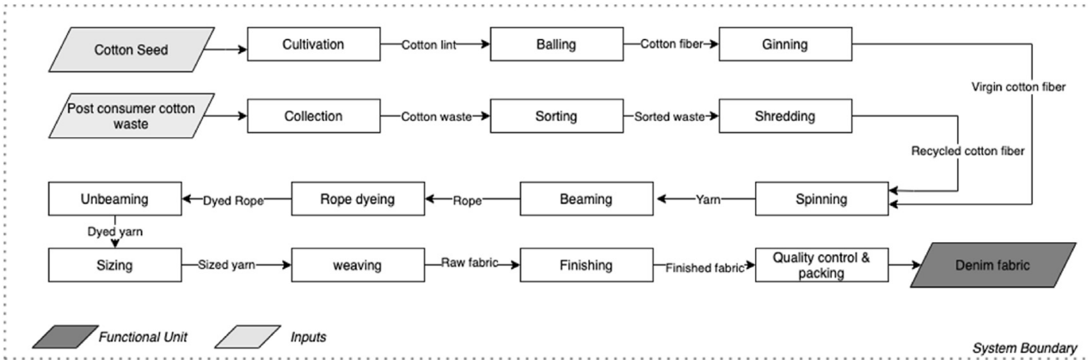

Fig. 2. Denim fabric life cycle flowchart and system boundaries of the LCA.

this study the functional unit was set as "1-m finished denim fabric" with weight 638.2 g and this unit was equal to 1.5 square meters of denim fabric. Virgin and recycled cotton yarn used in the denim fabric within the study was produced of carded ring method and have Z twist and count Ne7. A unit in the meter was a logical choice from the point of view of production and calculations, since the burden of environmental impacts arose from the processes involved in production, and most of the processes such as dyeing, weaving and finishing were tracked in terms of unit in meter. Definitely, the functional unit for this study was defined in meter to facilitate data management and application additionally the values in kg and square meters were also provided for functional unit. The LCA was conducted using 'cradle to factory gate' approach, without considering the production, use, and end of life of the garment, which are the stages after fabric production. The system boundaries of denim production used in this study were given in Fig. 2. Two different "cradle" was defined due to virgin and mechanically recycled cotton fibers have different life cycle stages. While for the virgin cotton fiber production; cultivation, transportation, materials, and fuels, ginning steps were included, for recycled cotton fiber production; the collection, sorting, and shredding processes were included. After the fibers arrived at the factory, they followed through the same production stages for denim fabric manufacturing, regardless of whether they include virgin or recycled cotton. The production stages are spinning, dyeing, sizing, weaving, finishing, quality control (QC), and packaging (Fig. 2).

2.2.2. Life-cycle inventory and assumptions

According to the LCA methodology, for each phase of the life cycle, the material and energy flows were quantified and referred to 1-m of denim fabric production (supplementary documents (SD) Table SD1 and Table SD2). Table 2 provided a summary of the data used in the study.

The geographic boundary covered in Turkey for mechanically recycled cotton fiber and fabric production. All the transports of raw materials were considered. The chosen vehicles taking into account the distance between the production site and the place of use were truck and ship. Since the use of dedusting devices, the emission to the air is very low; therefore, environmental impacts caused by dust were ignored at collection, sorting, shredding, spinning, and weaving processes. Primary data were principally collected directly by the engaged denim fabric company on-site for the year 2019. By assuming a 1% cut-off according to the ISO 14040, capital goods (land, buildings, machinery), and packaging, (except those of the finished product) were excluded from the analysis.

The recycled fiber was produced with a mechanical recycling method from garment and sheet wastes made by 100% cotton which were collected from Turkey. Mechanical recycling is more common than semi-mechanical and chemical recycling is the physical conversion of waste into fiber by shredding. After the collection and transportation of cotton fabric wastes, the sorting process is performed manually. The last process, shredding, has approximately 8% of the waste ends up as solid waste which is disposed of in a landfill and consumes a high amount of electricity. The waste collection distance was assumed as 1000 km. Since the collected textile wastes used as raw material will already be garbage, it was assumed that they come with zero environmental impacts, recycled cotton allocation procedures were not performed (Periyasamy and Duraisamy 2018)[fx]. Energy consumption and waste ratio data obtained from the company and the literature for the mechanical recycling process were given in Table 3. The data used in this study were in line with the reported industry averages (Esteve-Turrillas and de La Guardia, 2017; CMG, 2019; Miljögiraff 2016; Schmidt 2016). As a result, the examined mechanical recycling procedure represented the average technical standards of the world. When using recycled cotton fiber, the waste rate in yarn

Table 2
Data sources used in this study.

Data	Sources	Note
Cotton cultivation and ginning	Ecoinvent v3.0	Turkey, Rest of the World
Cotton recycling	Site-Specific	Denim Company based in Turkey (2019
Fabric production	Site-Specific	Denim Company based in Turkey (2019
Grid electricity	Ecoinvent v3.0	Country specific
CHP plant	Site-Specific	Denim Company based in Turkey (2019
Production of chemicals	Ecoinvent v3.0	Dyestuff and chemicals in fabric production
Production of heat and steam	Ecoinvent v3.0	Consumption in fabric production
Road transportation	Ecoinvent v3.0	16–32 ton lorry, Google map for the distance
Ship transportation	Ecoinvent v3.0	Transoceanic ship, Google map for the distance
Cost	Site-Specific	The average cost for 2019
Quality test results	Site-Specific	The average values for the test conducted on-site in 2019

Table 3
Energy consumption and the waste ratio of mechanical recycling of cotton for fiber production from the literature.

Reference	Electricity (MJ)	Waste (%)
This study	0.364	8
Schmidt (2016)	0.36	20
CMG (2019)	0.18	20
Miljögiraff (2016)	0.119	3
Esteve-Turrillas and de La Guardia (2017)	1.31	4

production increased from 12% to 35%. In addition, the energy consumption of the spinning process increased by 10% when recycled cotton fiber was used as an input.

CHP plant is known as a sustainable technology that reduces environmental impacts and costs by using primary fuel more efficiently by generating electricity and heat simultaneously. If the industrial process required constant heat demand, the application of the CHP plant is appropriate for energy and cost-savings. The LCA was conducted on an existing natural gas-fired CHP plant which assumed output of 50% power and %50 heat.

2.2.3. Life cycle impact assessment

The selection of impact categories was done considering the goal and objectives of the study, but also considering the environmental concerns of the textile industry as it stated in the introduction section. The impact categories and applied method within Simapro Software were listed below:

- Global warming potential (GWP 100 years): IPCC 2013 (IPCC 2013)
- Acidification potential (AP): CML-IA (Guinée et al., 2002)
- Eutrophication potential (EP): CML-IA (Guinée et al., 2002)
- Cumulative energy demand (CED): CED (V2.0) (Frischknecht et al., 2007)
- Water use: Net freshwater use is determined by the life cycle inventory of the product (Pfister et al., 2009).

Characterization results at midpoint were calculated with the CML impact assessment method for AP as an atmospheric impact and EP as a water impact considering the fact that CML method is commonly used in previous LCA studies on textile industry (De Saxce et al., 2012). Instead, water use as a water impact results were calculated using the water scarcity method. The calculations were performed by summing all freshwater except rain using the method's raw material inventory. GWP and CED as an atmospheric impact were calculated using the IPCC and CED method respectively. CED, a single issue-based impact assessment method, was used to calculate and compare the energy intensity of involved unit processes. A recent literature review was published by Sandin and Peters (2018) about environmental impacts of textile recycling and reuse had listed the most used impact categories in textile LCA studies. The selected impact categories in this study were in accordance with that literature review (Sandin and Peters 2018).

2.3. Product quality assessment

Since quality is the primary priority of consumers in the purchasing stage, the quality assessment of the product throughout the supply chain should be done through an evaluation (Bell 2008). For this reason, various test methods, standards, and requirements have been developed by international standardization organizations for the appearance and performance specifications of fabrics, fibers, yarns, and garments (Table 4). In the textile industry, tests of the quality of a garment examine the dimensions of performance, durability, serviceability, fit, and aesthetics. (Bell 2008). The performance properties of the fabric are the determining factors in ensuring the durability and serviceability of a clothing product (Annis 2012) and if it is low, it is usually discarded due to an unexpected performance problem such as rupture, tearing, or failure of color durability. For this reason, quality tests are important to respond to customer requests, to ensure the guaranteed properties of the product (Nilsson and Lindstam 2012), and ultimately to ensure long-term use.

When evaluating sustainable denim fabric, the quality of the fabric produced using recycled fiber should be carefully monitored to achieve the required properties and performance. In this study, the performance properties of the recycled cotton fabric were compared with the fabric made from virgin cotton fiber (Necef, 2013) and objectively evaluated whether it meets the specified specifications (Table 4). While performing performance tests, internationally accepted standards were applied. Additionally, color evaluation tests were conducted to examine the effect of using recycled cotton fiber on the outward appearance of the fabric.

Tensile and tear strength was considered one of the most vital elements for characterization of performance as well as woven fabric excellence and is related to the force required to break several threads simultaneously in the warp or weft direction (Hossain et al., 2016). Fastness is the resistance of dye to removal or destruction. Colorimetric difference was used to examine the outward appearance properties of denim fabrics produced with S1–S2 and S3–S4. Color differences were expressed with the L * (Lightness), a * (redness-greenness), and b * (yellowness-blueness) (Maryan et al., 2015). L * a *b * color values of the samples were obtained using the Hunter Lab color meter. Shrinkage, movement, elongation, sation, and weight are other tests whose results are important for the fabric to ensure the desired properties.

The performance and color tests were carried out for fabrics produced by 100% virgin cotton (S1–S2) and 20% virgin cotton replacing with recycled cotton (S3–S4). Performance tests on fabrics were carried out without washing or after 3 home washing, and the color difference test was carried out after the stone wash. Washing was carried out for 1-m of sample fabric with industrial detergent at 60 °C for 1 h and then drying it with tumble dry at 60 °C for 40 min. This process was repeated 3 times for providing 3 home washing. There is no production of 50% and 100% recycled cotton fiber denim fabric due to the limitations of commercial yarn production speed during ring spinning. To overcome this problem blending recycled with virgin fibers to achieve the required fabric performance is needed (Rengel 2017). The product quality test results of 50% and 100% recycled cotton fabrics were determined with quality experts.

Moreover, the most important input for the production of mechanically recycled cotton denim fabric with the desired quality features is recycled yarn and the fiber used in the production of these yarns. For this reason, fiber and yarn properties were also examined for input control purposes. USTER AFIS, which is the most used method in the literature, was used for fiber analysis. AFIS is a valuable tool in predicting yarn performance (Hequet et al., 2007) and measurements were made for Mean Lengths (ML), Short Fiber Contents (SFC), Fiber Neps Mean Size (FNMS), and upper quartile length (UQL). Fiber length (ML) is an important parameter for the quality of the yarns produced, and long yarns have better performance (Bragg and Shofner 1993). It is the weight percentage of wires less than half an inch, which is critical in SFC yarn production. Neps are small fiber entanglements that occur during the cultivation or ginning phase for virgin cotton and during the recycling phase for recycled fiber and have a negative effect on quality. Moreover, in order to examine the properties of yarns used in the production of denim fabrics, standard test methods were applied

Table 4
The international test methods were applied for fabric evaluation.

Evaluation	Unit	Sample situation	Related Process	Test Method
Unwashed Weight	gr/m2	Unwashed	Sizing & Finishing	ASTM-D 3776-96 Standard Test Methods for Mass Per Unit Area (Weight) of Fabric
Washed Weight	gr/m2	Washed	Sizing & Finishing	ASTM-D 3776-96 Standard Test Methods for Mass Per Unit Area (Weight) of Fabric
Elongation	%	Unwashed	Sizing & Finishing	ASTM-D 5278-92 Standard Test Method for Elongation of Narrow Elastic Fabrics
Sation	kg	Unwashed	Sizing & Finishing	ASTM 4032 Standard Test Method for Stiffness Of Fabric By The Circular Bend Procedure
Colorfastness to Crocking Wet	Gray scale	Unwashed	Dyeing & Finishing	AATCC-8-1996 Colorfastness to Crocking
Colorfastness to Crocking Dry	Gray scale	Unwashed	Dyeing & Finishing	AATCC-8-1996 Colorfastness to Crocking
Tear Warp	grF	Washed	Spinning & Finishing	ASTM-D 1424-96 ASTM D1424 - Standard Test Method for Tearing Strength of Fabrics by Falling Pendulum Type
Tear Weft	grF	Washed	Spinning & Finishing	ASTM-D 1424-96 ASTM D1424 - Standard Test Method for Tearing Strength of Fabrics by Falling Pendulum Type
Tensile Warp	kgF	Washed	Spinning & Finishing	ASTM-D 5034-95 Standard Test Method for Breaking Strength and Elongation of Textile Fabrics
Tensile Weft	kgF	Washed	Spinning & Finishing	ASTM-D 5034-95 Standard Test Method for Breaking Strength and Elongation of Textile Fabrics
Warp Shrinkage	%	Washed	Finishing	AATCC-135-1995 Dimensional Changes of Fabrics after Home Laundering
Weft Shrinkage	%	Washed	Finishing	AATCC-135-1995 Dimensional Changes of Fabrics after Home Laundering
Movement	%	Washed	Finishing	AATCC-179 Skewness Change in Fabric and Garment Twist Resulting from Automatic Home Laundering
Color difference	L*a*b*	Washed	Dyeing & Finishing	AATCCC Evaluation Procedure 9—2011 Visual Assessment of Color Difference of Textiles

with ASTM D76 and ASTM D6197 method using the Uster Tensojet and the Uster Tester 5, respectively. Tensile, unevenness and imperfections tests were applied to examine the properties of the yarns produced (Wanassi et al., 2016). Yarn irregularity, strength and elongation test were conducted for examining quality of yarns.

2.4. Economic assessment

Since the consumer is not interested in purchasing high-cost denim products and denim is an aggressive industry, cost is one of the most important financial performance criteria of the product development phase (Hertenstein and Platt 1998). For the cost calculation of denim fabric, there are many items such as raw material, energy, water, labor, auxiliary materials that should be considered. However, in this study, (Siddens 2001), an economic analysis was made using relative costs calculation for cost-saving analyses. Relative cost for the specified scenarios, the change in costs according to the product's raw materials, and electricity costs during yarn and fabric production were included. The calculation was performed by multiplying recycled, virgin cotton fiber and electricity consumption values and unit cost values of each scenario. Recycled cotton fiber is 18% low in cost per kg than virgin cotton fiber in TL currency for 2019 prices. The electricity provided by the CHP plant provides a 40% cost advantage per kWh compared to the grid electricity. These information were gathered from the site experts.

While calculating the cost-savings for 1-m of denim fabric, the varying consumption of raw material and energy supply costs were taken into account in the scenarios. Since our aim was to see how the cost changes according to the scenarios using relative cost values, it was assumed to be zero since the remaining costs do not change. When calculating the cost of the CHP plant, the price change was reflected only in electricity. Steam costs were kept constant as it was same in all scenarios. Information on the raw material and energy cost factors in the production processes used in scenarios was given in Table 5.

2.5. Integrated assessment with TODIM

TODIM is a multi-criteria method offered by Gomes and Lima (1992). Based on the pairwise comparison of alternatives, the TODIM method calculates the superiority of one alternative to another using the value function within the framework of possible theory for each criterion (Tversky and Kahneman 1992). This value function, which displays an S-shaped growth curve, allows the behavior of the decision-maker to be reflected according to gains and losses. Finally, the overall performance of each alternative is determined using an additional function.

Let $M = \{1,2, \ldots, m\}$ and $N = \{1,2, \ldots, n\}$ denote the sets of indices; the set of alternatives are shown as $A = \{A_1, A_2, \ldots, A_m\}$ and the set of criteria is $C = \{C_1, C_2, \ldots, C_n\}$. The performance of all alternatives with respect to all criteria is known and denoted by x_{ij} the performance value of alternative A_i with respect to criterion C_j. ($i \in M$, $j \in N$) We assumed that is $w = (w_1, w_2, \ldots, w_n)^T$ a normalized weight vector; that is $\sum_{j=1}^{n} w_j = 1$and $0 \le w_j \le 1, j \varepsilon N$. w_j criteria shows the weight or importance of C_j. x_{ij} means the value of alternative A_i for the C_j criterion. Algorithmically, the implementation of the TODIM method involves the following steps.

Step 1: Normalized decision matrix is calculated. Normalized decision matrix $G = (g_{ij})_{m \times n}$ is obtained by applying equations (1) and (2) for benefit and cost criteria, respectively, with the linear linearization method $X = (x_{ij})_{m \times n}$to the decision matrix. The normalized values of the decision matrix are determined as shown in Table SD.5.

$$g_{ij} = \frac{x_{ij} - min_i(x_{ij})}{max_i(x_{ij}) - min_i(x_{ij})}, \ (i = 1, 2, \ldots, m \ and \ j = 1, 2, .., \ n) \quad (1)$$

$$g_{ij} = \frac{max_i(x_{ij}) - x_{ij}}{max_i(x_{ij}) - min_i(x_{ij})}, \ (i = 1, 2, \ldots, m \ and \ j = 1, 2, .., \ n) \quad (2)$$

Step 2: The relative weights of the criteria are calculated using the reference criterion value calculated as $w_r = max\{w_j | j \in N\}$ and the formula in equation (3). In this formula, w_{jr} is the relative criterion weight, w_j indicates the criterion weight. The reference level values obtained by considering the maximum relative weight of the attributes were given in Table SD.6.

Table 5
Raw material and energy cost factors in the production processes considered in the scenarios (VC: virgin cotton fiber; RC: recycled cotton fiber).

Scenarios	Fiber Type	Spinning	Beaming	Rope Dyeing	Unbeaming	Sizing	Finishing	QC & Packing
S1	VC	Grid	Grid	Grid	Grid	Grid	Grid	Grid
S2	VC	CHP	CHP	CHP	CHP	CHP	CHP	CHP
S3	RC,VC	Grid	Grid	Grid	Grid	Grid	Grid	Grid
S4	RC,VC	CHP	CHP	CHP	CHP	CHP	CHP	CHP
S5	RC,VC	Grid	Grid	Grid	Grid	Grid	Grid	Grid
S6	RC,VC	CHP	CHP	CHP	CHP	CHP	CHP	CHP
S7	RC	Grid	Grid	Grid	Grid	Grid	Grid	Grid
S8	RC	CHP	CHP	CHP	CHP	CHP	CHP	CHP

$$w_{jr} = \frac{w_j}{w_r}, r, j \in N \tag{3}$$

***Step 3**:* The degree of dominance of each alternative P_i according to each alternative P_k is calculated by equations (4) and (5). The preference index values of all alternatives for all attributes were calculated as given Tables SD.7–SD.14.

$$\delta(P_i, P_k) = \sum_{j=1}^{n} \varnothing_j(P_i, P_k), \forall (i, k) \tag{4}$$

$\varnothing_j(P_i, P_k)$ indicates the contribution of criterion C_j. θ is the factor to reduce losses.

$$\varnothing_j(P_i, P_k) = \begin{cases} \sqrt{\dfrac{w_{jr}\left(g_{ij} - g_{kj}\right)}{\sum_{l=1}^{n} w_{lr}}}, & if\ g_{ij} - g_{kj} > 0 \\ 0, \quad if\ g_{ij} - g_{kj} = 0 \\ -\dfrac{1}{\theta}\sqrt{\dfrac{\left(\sum_{l=1}^{n} w_{lr}\right)\left(g_{kj} - g_{ij}\right)}{w_{jr}}}, & if\ g_{ij} - g_{kj} < 0 \end{cases} \tag{5}$$

Step 4: The normalized global performance value of Alternative P_i is calculated according to all alternatives with the formula below. The overall dominance degree of each alternative was obtained and given the next section of this paper and Table SD.15.

$$\xi_i = \frac{\sum_{k=1}^{m} \delta(P_i, P_k) - min_i\{\sum_{k=1}^{m} \delta(P_i, P_k)\}}{max_i\{\sum_{k=1}^{m} \delta(P_i, P_k)\} - min_i\{\sum_{k=1}^{m} \delta(P_i, P_k)\}}, i \in M \tag{6}$$

Step 5: The alternatives are sorted by normalized global performance value. ξ_i, $(i \in M)$ At this step, the overall dominance degree of each alternative was arranged in descending order.

In this study, scenarios (S1, S2, …, S8) for denim fabric production were evaluated by TODIM method considering environmental impacts, product quality, and cost-saving dimensions. GWP (C1), CED (C2), AP & EP (C3), water use (C4), washed weight (C5), tear (C6), tensile (C7), and cost (C8) were determined as the attributes. Table SD.3 was given in SD demonstrates the decision matrix. The weights used in the method applied by considering 8 alternatives and 12 criteria were realized through one-to-one interviews with experts (Table 11).

3. Results and discussion

3.1. LCA results

In this study, environmental impacts of denim fabric produced using mechanically recycled cotton fiber instead of virgin cotton fiber and using CHP plant instead of grid energy for energy source during fabric production were investigated via 8 scenarios using the LCA approach. Table 6 showed the environmental impact results of the production processes of 1-m virgin cotton denim fabric based on the reference scenario with a cradle-to-factory gate approach. Cotton cultivation was the most important stage in terms of environmental impacts evaluated and can be easily defined as the hot-spot of denim fabric production. According to GWP results, sub-processes could be improved in terms of sustainability for the production of 100% virgin cotton fiber used denim fabric as raw material (53%), spinning (16%), and dyeing (12%). The same trend was observed for the AP and EP, as environmental impact categories evaluated.

The scenarios applied in this study using recycled cotton fiber instead of virgin cotton fibers showed lower environmental impacts than the virgin cotton fiber used scenarios. Fig. 3 showed the improvement of environmental impacts for 1-m denim fabric in percentages and the raw data used in these calculations were given in Tablo SD.16.

In the scenarios applied in this study, recycled cotton fiber denim fabric compared to virgin cotton fabric and the significant improvements of water use (20–98%), CED (12–62%), GWP (10–50%), AP (12–61%), and EP (13–68%) were obtained depending on the recycled ratio content of denim fabric. GWP occurs due to greenhouse gases such as carbon dioxide, nitrogen oxide, and methane in kilograms of carbon dioxide equivalent. As Fig. 3 showed, the recycled cotton fabrics offered significant GWP savings compared to virgin cotton fabrics. The GWP of the recycled cotton fabric decreased by 10% for S3, 25% for S5, and 50% for S7 over the reference scenario. Increasing the ratio of recycled cotton fiber in denim fabric by 1%, provided a 0.5% improvement in GWP. When the recycled cotton ratio increased from 20% to 50%, the improvement in GWP was 15%. It should be noted that for recycled

Table 6
Environmental impact contributions of sub-processes for the production of 1-m denim fabric using virgin cotton fiber as a raw material with a cradle-to-factory gate LCA approach.

	GWP (%)	AP (%)	EP (%)	CED (%)	Water use (%)
Cotton Cultivation	53	60	69	64	98
Spinning	16	12	14	11	0
Dyeing	12	13	4	10	1
Weaving	8	6	8	6	0
Finishing	7	4	3	6	1
QC & Packing	1	1	1	1	0
Transport	4	5	1	3	0

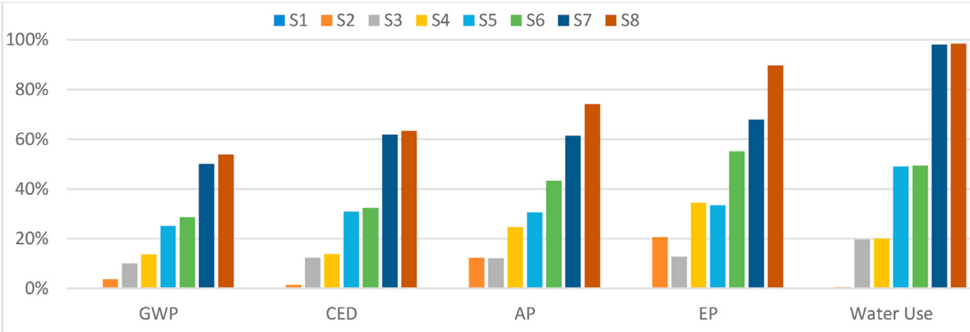

Fig. 3. Percentage improvement of environmental impacts of all tested scenarios for 1-m denim fabric (*S: Scenario, Since S1, was the reference scenario, it does not appear in the figure because it takes the value of zero.).

cotton, the raw material has zero environmental impact. The use of the CHP plant provided a 4% improvement of GWP per product meter regardless of the recycle cotton ratio. According to the production stages evaluated, the main contribution to the GWP value was made by traditional cotton fiber production, yarn production, and fabric production.

As the denim industry is extremely innovative, benchmarking is also important for environmental impacts. An interesting research question within this concept was to compare the results of this study with denim fabrics in the literature. Since the most known and widely used impacts are GWP, comparisons were made according to GWP values. However, LCA studies dealing with sustainable denim production and products are quite limited in the literature. One of them was carried out by Hedman (2018) to compare environmental impacts of three different jeans, the life cycle stages of which take place in different countries (Hedman 2018). The geographical location of the denim fabric production process was Turkey for Tilted Tor Dry Royal Embo jean and GWP was found in 6.21 kg CO_2 eq. in the study. determined the GWP as 11.9 kg CO_2 eq. for the fabric production stage of 1 pair of Levi's® 501® medium stonewash jeans (Levi 2015). Morita et al. (2020) examined actions for improving environmental and energy performances of trouser jeans produced in Brazil and provided the GWP of denim fabric as 3.61 kg CO_2 eq. (Morita et al., 2020). In comparison to other similar studies, denim fabric produced by S1 and S8, which has the best and worst result in this study was located in the sub spectra. S8 comprised of 100% recycled cotton denim fabric GWP value was 1.99 kg CO_2 eq. and the lowest all of them. S1 contained 100% virgin cotton fiber denim fabric and its GWP value was lower than the average of the results in the literature with 4.29 kg CO_2 eq.

Eutrophication potential is the overgrowth of biomass caused by the release of nutrients, particularly fixed nitrogen and phosphorus. EP was improved by 13% with the addition of 20% recycled cotton (S3). The improvement in EP was increased to 33% with 50% recycled cotton fiber supplement (S5), and was limited to 68% when 100% recycled cotton was added to the fabric (Fig. 3). EP for 1-m denim fabric was reduced by 20% with the use of the CHP plant (S2). When recycled cotton fiber was added to the product, this ratio increased by 1.67%, after 50% cotton addition, the overall improvement remained constant at 22% and was not affected by the addition of recycled cotton fibers. AP was a consequence of acids being emitted to the atmosphere and subsequently deposited in surface soils and waters.

The AP was improved by 12% by substituting virgin cotton with 20% recycled cotton (S3). In addition, a 31% improvement at 50% recycled cotton fiber ratio and a 61% improvement was achieved in 100% recycled product. The AP varied very limitedly according to the percentage of recycled cotton fiber used in the process with the use of CHP. The reduction in the process, which started at 12.4% with the use of CHP, was not affected by the recycle cotton ratio after 50% according to scenarios and remained constant at 13%. It only took place at 12–13% as an improvement in the use of CHP.

In water use evaluations adding 1% recycled cotton fiber to the fabric provided almost 1% improvement in the rate of water use due to the high water consumption of cotton cultivation, the water use potential of the virgin cotton fiber denim fabric (1504 lt/m) decreased significantly (31 lt/m) in 100% recycled cotton fiber used denim fabric. This improvement was significantly important for the protection of freshwater and groundwater. The impacts of the use of the CHP plant in the fabric production in the water use category was limited to 0.42% and was lower than all other impact categories. In addition, the use of CHP didn't affect the water use in all scenarios applied.

CED was the sum of renewable and non-renewable energy consumption. Adding 20% recycled cotton fiber provided a 12% improvement in energy use. Improvement of CED was 31% in 50% and 62% in 100% recycled cotton fiber ratio (Fig. 3). Improvement in energy use was higher compared to the recycled cotton percentage. Although the consumption of electricity in the spinning process increases with recycled content, there were significant improvements in this impact as environmental impacts of virgin cotton fiber were huge. The improvement in the use of CHP in fabric production was 2% when the recycling rate was 20%, while it decreased to 1% when the recycling rate was 50%. This was normal since recycled fiber consumes higher electricity when processed in the spinning process. As the recycled cotton fiber ratio increased, the obtained improvements were limited with excessive electricity consumption in spinning process.

The most important improvement has been achieved in the water use category. This improvement was expected as cotton cultivation is responsible for 98% of the water use category in the denim fabric life cycle and responsible for as much as 2.6% of global water use (Chapagain and Hoekstra, 2008). According to the results, CED and AP categories didn't improve as much as EP. Also, QC & packaging, transport of the raw materals, finishing, and weaving contributed very little to the overall environmental impact. In addition, the use of the CHP plant offered 4% GWP and 0.42% water use saving regardless of the recycled cotton ratio. Also, it provided 1–2% CED, 12–13% AP, and 20–22% EP savings depending on the recycled cotton fiber ratio. Both the use of recycled cotton fiber as raw material and the use of the CHP plant during fabric production stage reduced the impacts for all of the environmental categories examined. Also, it has been observed that virgin cotton fiber was responsible for most of the environmental impacts. According to the results of this study, denim production by using recycled cotton fiber provided significant environmental benefits. According to Kazan et al. (2020) using recovered cotton fibers as the raw material decreased eutrophication, acidification, abiotic depletion potential, and global warming by 96%, 90%, 69%, and 47%, respectively, by eliminating environmental impacts that originate from cotton cultivation stage. Esteve-Turrillas and de La Guardia (2017) emphasized that recovered cotton usage in the textile industry has decreased water, electricity, and chemical consumptions. Our results also in accordance with the published literature.

3.2. Product quality assessment results

Since design is one of the key features of denim fabric (Periyasamy and Militky 2017), considering visuality, quality, and function parameters can be achieved customer satisfaction. Moreover, quality parameters are indispensable parameters for ensuring sustainability in denim fabric for giving long lifetime use and avoid waste. For this reason, the performance and visual evaluations of the fabrics obtained with the scenarios were made via quality test according to the international standards. Applied test results were given in Table 7.

The quality test results of denim fabrics produced with S1−S4 were evaluated, the washed weights of both fabrics were very close to each other. Washed weight was important as it affects many processes to be applied to the fabric for garment making. Tear strength is an important feature for durability and shows its resistance against tearing (Hatch 1993; Mehta 1985). Tear strength tests were performed in the direction of the weft and warp were carried out and the strength values were higher in the fabric containing recycle cotton. Moreover, tensile strength under tensile stress was one of the important and widely measured properties for denim fabric. According to tensile test results, both fabrics have the intended properties and were higher than the desired value. According to the results obtained, the strength values of recycled cotton denim fabric were better than virgin cotton denim fabric. Fabric strength is related to many factors such as yarn count, twist, fiber fineness, hardness, fiber density, fabric structure, cover, yarn density, number of layers, firmness factor, etc. (Bhuiyan 2019). Moreover, Wanassi et al. (2016) conducted a study to compare the physical and mechanical properties of blended yarn with the properties of 100% cotton yarns. According to this study, the quality of the yarns produced with the combination of lower percentages of recycled cotton is almost the same as 100% virgin cotton yarn (Wanassi et al., 2016). Since the rate of recycled cotton fiber used in this study was limited to 20%, having better results for recycled cotton denim fabric support this study. In addition, the sizing process applied to increase the strength of the yarns during the production of denim fabric contributed to these results. As a result, the test results of the two fabrics produced were within the expected values. For the integrated assessment of denim fabric only washed weight, tear, and tensile strength were taken into account since remaining results almost were the same for the scenarios.

Table 7
Quality tests result of 100% virgin cotton (S1−S2) and 80% virgin and 20% recycled cotton (S3−S4) denim fabric.

Evaluation	Unit	S1−S2	S3−S4
Unwashed Weight	gr/m2	505	501
Washed Weight*	gr/m2	493	494
Elongation	%	10.7	10.2
Sation	kg	5.5	5
Colorfastness to Crocking Wet	Gray scale	1	1
Colorfastness to Crocking Dry	Gray scale	3	3
Tear Strength Warp*	grF	7087	7255
Tear Strength Weft*	grF	4705	6570
Tensile Warp*	kgF	108.2	106.4
Tensile Weft*	kgF	74,9	86.4
Warp Shrinkage	%	−2.0%	−2.4%
Weft Shrinkage	%	−3.3%	−3.8%
Movement	%	−0.8%	0

Table 8
Colorimetric difference result of 100% virgin cotton (S1−S2) and 80%virgin & 20% recycled cotton (S3−S4) denim fabric.

Scenarios	Color Coordinates		
	L*	a*	b*
Virgin cotton fiber denim (S1,S2)	16.24	0.8	−9.83
Recycled cotton fiber denim (S2,S3)	16.50	0.9	−10.11

Colorimetric results for scenario 1−4 were given in Table 8. Virgin and recycled cotton denim fabrics were considered the same as there was a small difference between the L *, a *, and b * values obtained for the color difference. As a result, the contribution of recycled cotton fiber selection to the color difference instead of virgin cotton fiber is negligible.

The results according to the tests performed for the blends used in yarn production, which is one of the main inputs of the fabric, were given in Table 9. According to the results, the mean length for recycled cotton fiber was 25.8%−31.6% shorter than mean length for virgin cotton fiber. These results were exactly the same as the results of the study conducted by Utebay et al. (2019). They found this value between 25 and 30% for ML (Utebay et al., 2019). Although recycled cotton fiber has a shorter fiber length, waste rate increases, and short fibers are eliminated in yarn production with a waste of them. There was a significant increase in the SFC ratio for recycled cotton fiber when measured for both weight and number with a 20 mm and 37%. Wanassi et al. (2018) obtained a 21.1% value in SFC for recycled cotton fiber (Wanassi et al., 2018a). This difference fluctuates depending on the waste raw material content for recycled cotton fiber. For FNMS, the difference between recycled cotton and virgin cotton was only 6.3%. The UOL value was 24 mm for recycled cotton fiber, and this value was almost the same as 24.5, which was specified as an optimum value in the literature (Wanassi et al., 2016).

In addition to the fiber quality test results, additional quality tests were conducted for the warp yarns used in the production of the fabrics in the scenario (1−4) and were given in Table 10. The mechanical properties of the obtained yarns were expressed in terms of strength and elongation. It was seen that the strength and fiber elongation rate of the yarn containing 20% recycled fiber were slightly decreased. The yarn strength depends on many properties such as Ne, blend, recycled content, and the results obtained in this study are similar to the literature (Barella et al., 1985; Wanassi et al., 2018b). It was seen that the unevenness and irregularity (U%, CVm) of the yarn increased for recycled cotton fiber (Samanta 2014; Utebay et al., 2019). As a result, the quality test results of the yarns and fibers used in the scenarios were very similar to each other and were supported by the studies in the literature.

Table 9
Quality test results for recycled and virgin cotton fibers (w: weight; n: number).

Measurement	FNMS	ML (w)	ML (n)	UQL (w)	SFC (n)	SFC (w)
Units	um	mm	mm	mm	%	mm
Recycled cotton fibers	610	18	14	24	37	20
Virgin cotton fibers	651	25	20	30	24	9

Table 10
Quality test results for recycled and virgin yarns (U%: Mean linear irregularity of slivers, rovings and yarns; CVm: Coefficient of variation of the yarn mass).

Test	Virgin cotton fiber	Recycled cotton fiber
Tensile strength	19.18	18.15
Elongation (%)	6.77	6.42
U(%)	8.65	9.99
CVm (%)	10.92	12.73

Table 11
The weight of attributes.

Criteria	C1	C2	C3	C4	C5	C6	C7	C8
Weight	0.0875	0.075	0.05	0.0375	0.1	0.2	0.1	0.35

3.3. Economic assessment results

Since many designers needed to define the relative costs of one particular option relative to another in the design process (Siddens 2001), a cost-saving calculation was made in this study. Cost-saving for the applied scenarios were investigated according to the product's raw material and electricity costs change during yarn and fabric production. As the cost-savings analysis plays an important role in recycled product development (Radhakrishnan and Kumar 2018), it was used to calculate the cost of product development with different recycled cotton ratios and CHP plant use. Since recycling should be economically competitive and environmentally beneficial (Wang, 2006), the cost-savings of denim fabrics that emerged in line with the scenarios were examined. The cost of reference scenario was taken zero. The results were given for 1-m denim fabric in Fig. 4.

Apparently, there was a considerable difference in cost-savings calculated for the different scenarios. The S2 was the far most inexpensive scenario, followed by S4 and S6. The most expensive scenario S3 using grid electricity with a minimum recycled cotton ratio. In addition, the least cost-saving scenario (S3) has a very close cost difference to S5 and S7. The cost differences between the scenarios can mainly be explained by the cost-saving in using the CHP plant mainly. By using 100% recycled cotton fiber instead of using 100% virgin cotton fiber, the cost change was only 1%. The reason for this was that recycled fiber is slightly cheaper than virgin fibers, therefore it didn't provide a serious cost advantage due to the use of a high amount of waste. With the use of the CHP plant, a cost reduction of 35–40% was observed for each meter of fabric. However, due to the increase in electricity consumption during the production of yarn using recycled fiber, energy costs increased by 8%. The study showed that harnessing the resource of heat and electricity straight forward CHP plant can be responsible for lower associated cost and carbon impacts than national grids.

As a result, cost-savings were included in the sustainability assessment of denim fabric, and it was aimed to make a useful contribution to designers in designing products taking into account the cost (Bonner et al., 2002; Davila 2000). Because it is not possible to reduce the cost elements that are not considered during the design phase too much during the production phase (Davila and Wouters 2004). Therefore, cost-saving calculations have a priority and is an important performance indicator (Booker et al., 2007) to consider for making better decisions.

3.4. TODIM results

When examining the sustainability of the product, it is necessary but not sufficient to examine the environmental aspects. Other important aspects are the low cost of the product and good quality for long-term use. For this reason, in order to provide an integrated approach to denim fabric, the TODIM method, which is an MCDM method, was used. While the 8 scenarios determined constitute the alternatives, the results of environmental impact, product quality, and cost aspects represented the criteria. Weights for criteria and sub-criteria were determined by experts and are given in Table 11. Sub-criteria for environmental impacts were GWP (C1), CED (C2), AP & EP (C3), Water Use (C4), and for product quality were washed weight (C5), tear (C6), tensile (C7). Cost-saving (C8) was considered as the main criteria. It was clear that product quality criteria were the most important criteria among the three, and there were no big differences in the weigts of all criteria. Cost-saving emerged as the second most important criteria with 0.35 wt and environmental impacts as the third most important criteria with 0.25 weight. Streimikiene et al. (2012) were conducted a study for choosing the most sustainable electricity production technologies using MCDM. According to their holistic approach, all criteria weight was the same with 0.33. Nigim et al. (2004) applied to MCDM for the selection of sustainable renewable energy sources and included 6 criteria in the evaluation. The highest weighted criteria were the ecological impact and the lowest criteria weight was financial viability. Also, energy-saving and recycling criteria were among the top 4 criteria for sustainability assessment conducted by Ecer

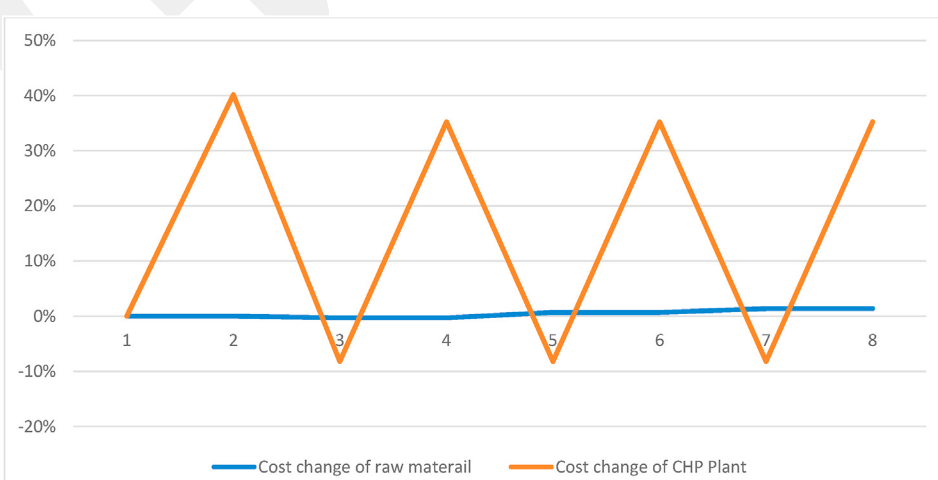

Fig. 4. Cost-saving for recycled cotton and CHP use for 1-m denim fabric for all scenarios.

(2020) for solving supplier selection problem considering green concepts. In the literature, evaluations for integrated sustainability assessment with MCDM were made by considering many criteria such as environmental, financial, technical, etc. and the criteria weights were very diverse as they were determined by studies conducted with experts on the subject.

Since sustainable denim fabric selection included many conflicting criteria, TODIM was used as a multi-criteria decision method for analysis. Using TODIM, the final ranking of denim fabric scenarios was assessed to choose the most suitable scenario. Global values were calculated with equation (6) and Table 12 showed the overall dominance degree of each alternative was arranged in descending order.

According to TODIM results, S8 ranked best among scenarios involving different sustainability approaches such as energy and raw materials. The second-best option was S7 with a global value of 91.3% and very close to S8. The least preferred option was S1 with zero global value. This value was followed by S2 with a global value of 13% and the rank order is 7. The overall rank of scenarios in the integrated approach was S8>S7>S6>S5>S4>S3>S2>S1. As a result, although the use of recycled cotton fiber increased the cost by a very small amount, it provided significant improvement in environmental impacts. As the quality test results didn't vary much for the determined scenarios, it was not as dominant as the environmental impact results. According to these results, the order of the scenarios was the same as the ranking according to their environmental impacts. The analysis showed that sustainable denim fabric, it should focus primarily on environmental impacts, although cost-saving has a slightly higher weight, but lags behind environmental impacts.

3.5. Sensitivity analysis

Although we used real data in this study, considering the differences in production technologies between textile factories, there may be uncertainties in production (Zhang et al., 2015). For this reason, the relationships between input and output variables in the system were analyzed using sensitivity analysis, which is an important uncertainty analysis tool to support the decision-making process. Sensitivity analysis was performed to examine the sensitivity considering electricity consumption in spinning and weaving processes for environmental impacts. These consumptions were chosen as a parameter because they have the highest electricity consumption in the denim fabric production process and examined their effects on contribution changes to environmental impact. Each parameter was examined independently of the others, increasing by + 1% from its base value. The results of sensitivity analysis were given in Figs. 5 and 6.

The results show that selected impact categories were not sensitive to electricity consumption of weaving and spinning process except EP category. The changes in electricity consumption of spinning process mainly affect the EP, especially in the S7, which indicates that CHP plant could reduce this environmental impact. The environmental impact results were more sensitive to the electrical consumption of the spinning process than the consumption of the weaving process. In addition, sensitivity decreases with production using CHP plant and increases when grid electricity is used. While GWP has the highest sensitivity of electricity consumption in scenarios using CHP plant, it was followed by CED, AP, and EP respectively. During the use of grid electricity, the most sensitive impact was GWP, followed by EP, AP, and CED, respectively.

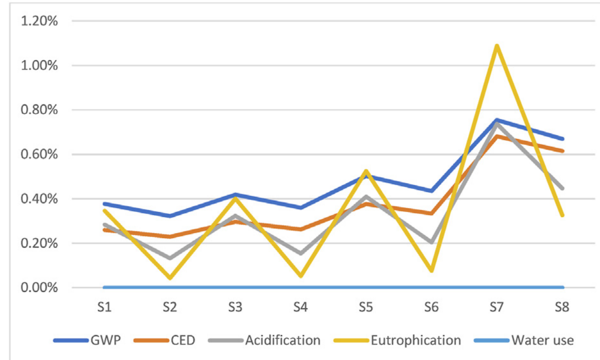

Fig. 5. Sensitivity analysis results for electricity consumption in weaving process.

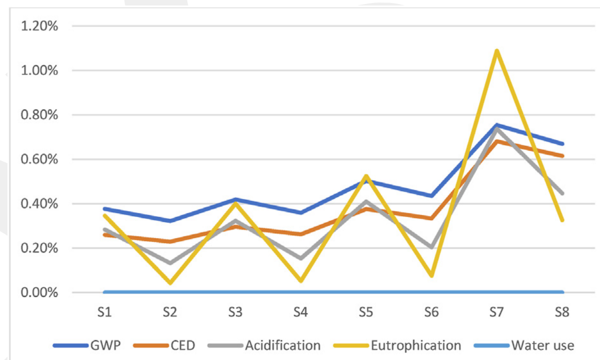

Fig. 6. Sensitivity analysis results for electricity consumption in spinning process.

Table 12
Ranking and global values of the alternatives.

Scenario Options	Global Values (%)	Rank
S8	100	1
S7	91.3	2
S6	79.1	3
S5	68.6	4
S4	56.5	5
S3	43.8	6
S2	13	7
S1	0	8

4. Conclusions

In this study, an integrated sustainability assessment of denim fabric produced using mechanically recycled cotton fiber instead of virgin cotton fiber and applying CHP plant during the fabric production stage was investigated via 8 scenarios. Environmental impact, economic, and product quality assessment studies were conducted with LCA, cost-saving, and quality tests, respectively. In order to integrate these results by considering the selected three dimensions of sustainability, the scenarios were evaluated by applying the TODIM method. Besides, the sensitivity analysis was conducted to evaluate the uncertainties in production data.

According to the environmental impact results obtained for the reference scenario, the most important hot spots of denim fabric were virgin cotton fiber as raw material (53%) and the energy consumed during the spinning stage (16%). From an environmental impact perspective, the S8 has the least environmental impact, using 100% recycled cotton fiber and CHP plants. In this scenario, the highest improvements were obtained in water use (98%) and EP (90%), due to high water consumption in cotton cultivation.

However, the least improvement occurred in GWP (54%) but was still significant. As a result, environmental impacts were decreased in all scenarios and the most important contributor to this decrease was the use of recycled cotton fiber depending on the ratio used in scenarios. For example, adding 1% of recycled cotton fiber to the fabric improved water use by 1% and GWP by 0.5%. Although the use of CHP plant alone contributed to the environmental impacts, this was realized as a maximum of 22% for EP. The cost savings of the scenarios were applied in terms of the economic evaluation were analyzed by taking the value of the reference scenario as 100%. The lowest cost was achieved in S2 with a 40% cost improvement. Cost savings for S4 and S6 were the same with 34%. These improvements mostly depended on the CHP plant and the contribution of recycled cotton fiber to the cost-saving was quite limited. This could be due to the prices of recycled cotton fiber prices that were very close to virgin cotton fiber prices. Besides, the high waste ratio in the spinning process of recycled cotton fiber production also reduced its improvement effect on cost-saving. According to the quality tests applied in the product quality evaluation for denim fabric, there was no significant difference between the use of virgin or recycled cotton fiber (S1−S2 and S3−S4) due to the recycled cotton content was limited to 20%. According to the TODIM analysis results of the scenarios with an integrated sustainability assessment approach, with the support of expert opinions, the best scenario was S8, which is based on 100% recycled cotton fiber and CHP plant used as an energy source. This scenario also was the best scenario in terms of environmental impact. Although the criterion weight of the environmental impact dimension was lower than the other dimensions, it had become the most important dimension in the integrated sustainability assessment with its contribution to the overall results. These results showed that the environmental impacts were the most important dimension in the sustainability assessment of denim fabric and the application of MCDM provides reliable results for the integrated sustainability assessment studies.

The results of the study can encourage textile companies to use recyclable raw materials and the use of more environmentally friendly technologies in energy use. Policy-makers can play a crucial role in sustainable textiles by promoting recycling. To expand this study, garment production, the use phase, and end of life of product could also be included in the integrated sustainable assessment approach using MCDM methods. Moreover, by using the proposed integrated approach the impact of using different kinds of recyclable cotton fibers on product quality may also be investigated. In addition, random or uncertainty conditions may taken into account, stochastic or fuzzy-based MCDM algorithms can also be applied in sustainable denim fabric production assesment.

CRediT authorship contribution statement

F.Ş. Fidan: Formal analysis, Writing - original draft. **E.K. Aydoğan:** Writing - original draft. **N. Uzal:** Writing - original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2020.125439.

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