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Multi-dimensional Sustainability Evaluation of Indigo Rope Dyeing with a life cycle approach and hesitant fuzzy analytic hierarchy process

Fatma Şener Fidan [a], Emel Kızılkaya Aydoğan [a,*], Nigmet Uzal [b]

[a] Erciyes University, Dept. of Industrial Engineering, Kayseri, Turkey
[b] Abdullah Gul University, Dept. of Civil Engineering, Kayseri, Turkey

A R T I C L E I N F O

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A B S T R A C T

The dyeing process of denim fabric production has the highest potential for significant environmental and human health impacts of denim production, consuming vast amounts of water, chemicals, and dyes. This study aims to assess the sustainability of indigo rope dyeing (IRD) obtained by designing a new recipe with the chemical alternative assessment method. Not only environmental impacts, but also social, economic, and product quality dimensions were included in the multidimensional sustainability assessment. The hesitant fuzzy analytical hierarchy process (HF-AHP) method was used to determine the criteria weights of the determined dimensions. The environmental and social impacts of the existing and newly designed IRD process were evaluated using the gate-to-gate life cycle assessment (LCA) and social life cycle assessment (S-LCA) approach. According to the LCA results, the green IRD process exhibited better performance in terms of all environmental impacts evaluated and the abiotic depletion potential of the conventional indigo IRD process can be reduced by 62.55% by applying the green IRD process. According to the HF-AHP results, the most important criteria were environmental impact with 33%, followed by social impacts with 27%, quality results with 23%, and economic results with 17% in assessing the IRD process's sustainability denim production. These results showed that the sustainability of the IRD process could be improved by substituting the chemicals and dyestuff with green alternatives.

1. Introduction

The denim industry is under tremendous pressure, both with the increased awareness of customers and stringent legislations, due to environmental problems caused by serious chemical consumptions. Therefore, it has become imperative for companies to apply sustainability principles and strategies to compete in the market (Gmelin and Seuring, 2014; Resta et al., 2016). It has been reported that the production of a pair of jeans has a total water consumption of over 10,000 L in the entire supply chain, including cotton cultivation. (Amutha, 2017). Besides, the consumption of chemicals such as fertilizers, pesticides, dyes, and wetting agents for the same unit is approximately 0.5 kg and requires a high amount of energy (Hedman, 2018). The production process of denim starts with the spinning of raw materials such as cotton, lyocell, viscose, etc., followed by rope dyeing, weaving, and finishing, and consumes high amounts of water and chemicals, especially in the dyeing and subsequent washing processes, which makes the life cycles of denim unsustainable (Buscio et al., 2015; Gmelin and Seuring, 2014). Sustainable approaches in this context should mainly be based on pollution prevention and cleaner production measures, which are much more potent than generating and disposing of waste. Hence, process changes that minimize the use of water, chemicals, and dyes are much more preferred and cost-effective (Hussain and Wahab, 2018; Sahinkaya et al., 2008). To minimize the use of natural resources and achieve zero emissions, it is necessary to search for traditional textile dyeing alternatives by focusing on environmental management in the dyeing industry (Shahid and Mohammad, 2013; Yigit et al., 2009).

A guide for the selection of chemical alternatives was published by the National Research Council of the USA (NRC, 2014). GreenScreen® was developed by Clean Production Action, a non-governmental organization defining and implementing the leading edge in safer chemicals and sustainable materials. It is a globally known tool for comparative chemical hazard assessment (CPA, 2012; Heine and Franjevic, 2013; Whittaker and Heine, 2013). The chemical alternative assessment (CAA) was widely applied in IRD literature, especially for reducing agents. Hoque and Faysal (2019) conducted a study for a waterless indigo dyeing chemical to dye rope of denim. The dyeing result was examined for colorfastness and the dyeing cost. Their result showed 60% of

* Corresponding author.
E-mail addresses: ekaydogan@erciyes.edu.tr, emelkizilkaya@gmail.com (E.K. Aydoğan).

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freshwater could be saved in the IRD step (Hoque and Faysal). Hsu et al. (2018) described a sustainable dyeing process that removes toxic reagents' consumption for indigo synthesis and the necessity for a reducing agent in the indigo dyeing process (Hsu et al., 2018). Saikhao et al. (2018) investigated monosaccharides and disaccharides as green alternatives to reduce indigo dyeing agents under alkaline conditions (Saikhao et al., 2018). They reported that all of the tested reduced sugars led to a substantial reduction of almost 50% of the total consumption. When comparing greener alternatives the life cycle approach should be considered an ideal CAA (Heine and Franjevic, 2013). None of these studies applied life cycle assessment (LCA) of IRD. Besides, LCA studies on the dyeing of denim products with alternative sustainable recipes are quite limited in the literature. Pasquet et al. (2012) provided an LCA for six different dyeing methods, including natural indigo vat dyeing, and the results showed that natural indigo vat dyeing has higher impacts on the environment than those of other dyeing processes (Pasquet et al., 2012). Saling et al. (2002) investigated the methodology of eco-efficiency analysis by BASF and showed the specific framework using the eco-efficiency analysis and used indigo dye as an example (Saling et al., 2002). Despite the high consumption of denim in the textile industry, none of the above studies measured the environmental impacts of alternative IRD recipes of denim using LCA. Moreover, the current LCA practices focus on environmental impacts, but social and economic impacts must also be included for sustainability assessment (Hauschild, 2018).

For the comprehensive assessment of the sustainability of products, economic and social impacts need to be integrated (Nygren and Antikainen, 2010). The cost element of the product is still necessary for companies to survive. It is not possible to ignore this dimension in the evaluation of sustainability (Annapoorani, 2017). The use of life cycle costing (LCC) for economic evaluation is frequently used in the literature. However, it is essential to ensure the physical and visual quality characteristics expected from the product, as it guarantees both commercial sustainability and long-term use (Davila, 2000). Therefore, designing commercially acceptable products and providing the desired performance must be a part of this evaluation. For evaluating the social impacts of products, social life cycle assessment (S-LCA) is a valuable tool existing in the literature; however, it is still under development. UNEP/SETAC has published the guidelines and the methodological sheets for the S-LCA of products (UNEP/SETAC, 2009; UNEP/SETAC, 2013). Although those studies in this area gained rapid popularity after the guides' publication, it is not yet at the desired level. The sub-category assessment method (SAM) is the most used in S-LCA (Huarachi et al., 2020). The methods performed even with this method are limited (Ramirez et al., 2014). The only application of the SAM method in the textile industry is the S-LCA study conducted by Lenzo et al. (2017) for a garment produced in Italy (Lenzo et al., 2017). They concluded that S-LCA is an effective approach to assist decisions by evaluating the social impact of the process and product to develop stakeholders' social status, and any effort to encourage S-LCA application was highly recommended.

The life cycle sustainability assessment of alternative processes considers environmental, social, economic, and product quality aspects (Guinée, 2016; Kloepffer, 2008; Muthu, 2017). These dimensions may contain criteria that cannot be defined as deterministic. Also, the weights of the criteria shown vary according to the sector, stakeholder, and decision-maker's priority. Interpretation of LCA results may be difficult due to the uncertainty and weighting of the criteria with different units. Therefore, an LCA-based assessment is a typical multi-criteria decision-making (MCDM) problem and should be integrated with the application of an appropriate MCDM method that takes into account the priorities of the sector and the expectations of the stakeholders for the interpretation of its results (Jolly-Desodt, 2009). As a result, it is essential to propose an integrated method to assess the life cycle sustainability performances of the product or processes.

AHP is a valuable MCDM method developed by Thomas L. Saaty (1980). *The method provides a model for making complex decisions by establishing a hierarchical structure between goals, criteria, and alternatives (*Saaty 1980*).* Fuzzy set theory and its extensions have been developed to be used in uncertain situations that cannot be fully handled with classical decision-making techniques (Beskese et al., 2004). Fuzzy AHP, which is a combination of AHP and fuzzy set theory, is frequently referred to in the literature. Chan et al. (2011) proposed an approach based on LCA and fuzzy AHP to assess the environmental performance of a product design (Chan et al., 2012). Ren et al. (2015) developed an MCDM methodology for sustainability assessment of industrial systems using fuzzy AHP and fuzzy analytical network process methods, taking into account environmental, economic and social dimensions (Ren et al., 2015). Studies on fuzzy AHP regarding the evaluation of sustainability criteria are very limited in the literature and are not available for the textile industry.

In light of the literature, the present study aimed to evaluate the environmental, social, and economic impacts of the conventional and redesigned IRD process with a sustainability assessment approach, also considering product quality assessment. When evaluating the sustainability of a product, it can be underestimated by focusing only on specific dimensions. For this purpose, the environmental and social impacts of conventional IRD recipes and a redesigned alternative recipe substituting GreenScreen® certified chemicals were compared using the LCA perspective. The production cost change of the newly developed IRD process compared to the conventional IRD process was calculated through economic analysis. The results obtained for the two dyeing recipes were also examined in terms of physical and visual evaluations to determine whether they had similar shades and properties. Besides, HF-AHP was utilized to determine the weight of environmental, social, economic, and product quality assessment indicators. Although there are studies on fuzzy AHP on sustainability assessment in different products and sectors, there is no study in the textile sector that applied the sustainability assessment using the hesitant form of fuzzy sets which also considers the hesitations of decision-makers. Consequently, this study is unique in the literature as it examines a sustainable evaluation of the IRD process with an innovative perspective for decision-makers implementing the IRD process in denim production.

2. Indigo rope dyeing and chemical alternative assessment

Although there are many techniques used for indigo dyeing in the denim industry, IRD is one of the processes that provide the best performance considering the uniformity of the yarns (Imtiazuddin and Tiki, 2010). IRD process is carried out in four stages: pre-treatment, pre-washing, indigo dipping, and final washing (Meraj and Qayoom, 2016). In the pre-treatment, pre-wetting, bottom dyeing, or washing can be done according to the desired final color appearance. If the sub-dyeing process is applied, the ropes should be washed to remove the excess dye to provide optimum crocking values. After pre-wash, ropes are dyed in indigo dipping boxes. During dyeing, the rope passing through 6–8 pads is first impregnated with a little leuco indigo in each tank, then the dyeing is completed with air oxidation (Uddin, 2014). The dyeing process is based on repeated dyeing and aeration, as the affinity of indigo dye is not sufficient even after reduction. After dyeing the pads, unfixed indigo dye is cleaned by entering the washing pads.

In the IRD process, recipes contain reducing agents, caustic soda, wetting agents, and dyes such as indigo, reactive, Sulphur, etc. Indigo dye is one of the most used textile dyes in the world. However, since indigo is insoluble in water, the dye is converted into its water-soluble form (leuco) using a reducing agent (Hsu et al., 2018). The wetting agents are used to speed up the dye solution penetration and ensure color leveling (Xin et al., 2000). Besides these chemicals and dyes, caustic soda is used to keep the solution of the process alkaline.

A chemical substitution or alternative assessment study is a systematic method of assessing chemicals currently in use and determining whether safer chemical options can reduce potential impacts on people and the environment. Some institutions and organizations have developed guidelines to provide this systematic approach. The well-known program in the textile industry is the GreenScreen certification program of Clean Product Action (CPA, 2012). Products are certified as Bronze, Silver, or Gold for the use of any chemical of high concern listed on globally recognized chemical hazard lists. GreenScreen Certified provides a clear and transparent communication tool on chemical hazards in products and formulations. For this reason, it is well suited for companies to identifying and evaluating viable product design alternatives and gradually eliminating and replacing hazardous chemicals. In this study, the chemical alternatives assessment for the IRD process was made by substituting conventional chemicals with certified GreenScreen® chemicals (hereafter referred to as green). The redesigned IRD process was evaluated in terms of environmental impacts and cost, product quality results, and social impact with sustainability assessment. Content of recipes for conventional and green IRD are given in Table 1.

Liquid and granulate are the different forms of indigo and can be substituted for each other. The desired shade can be obtained easily by adjusting the required volumes according to indigo dye. Liquid indigo was chosen in the green rope dyeing recipe as it is known as an environment-friendly dye due to its high solubility and low water and chemical consumption (Saling et al., 2002). Two wetting auxiliaries in the conventional recipe were changed with green alternative substitutes. Wetting auxiliary I and II in the conventional rope dyeing recipe were substituted by wetting auxiliary IV and V, respectively. According to the Safety Data Sheet data provided by suppliers, wetting auxiliary I contains more chlorosulfonic acid and ethanol in its composition than wetting auxiliary IV. Acrylic acid was replaced with its green substitute, formic acid, in wetting auxiliary V. For the green IRD process, wetting auxiliary III was eliminated and not needed in the dyeing recipe. Substituting chemicals and dye in the recipe with Green alternative chemicals by protecting the fabric's shade and physical properties has been achieved through trials by experts. After the trials, bulk production was carried out with a re-designed recipe.

3. The methodology of the proposed framework

A sustainability assessment considering environmental and social impacts, economic, and product quality was conducted using the HF-AHP method to evaluate a new and more sustainable recipe developed for the IRD process with the CAA method. The framework of the proposed methodology for the sustainability assessment of IRD is shown in Fig. 1. The steps, in detail, were the following:

3.1. Environmental life cycle assessment

To determine environmental impacts of IRD LCA was performed following ISO 14040 and ISO 14044 standards with four phases: 1) goal and scope definition, 2) life cycle inventory analysis (LCI), 3) life cycle impact assessment (LCIA) and 4) interpretation (ISO, 2006a; ISO, 2006b). The selected fabric in this LCA study contained 40% lyocell and 60% cotton used in IRD recipes containing conventional chemicals and green alternative chemicals.

The goal of this LCA was to determine the environmental impacts

Table 1
CAA of IRD process.

	Conventional IRD	Green IRD
Dye	Granulate indigo	Liquid indigo
Reducing agent	Sodium dithionite	Sodium dithionite
Caustic	Sodium hydroxide	Sodium hydroxide
Wetting agents	Wetting agent I	
	Wetting agent II	Wetting agent IV
	Wetting agent III	Wetting agent V

related to the life cycle of the IRD processing with a cleaner and sustainable production perspective using real process data. The system boundary was constructed using the gate-to-gate approach, including chemicals, dye input, energy (electricity, steam, and natural gas), water, and emissions outputs, and is given in Fig. 2.

The functional unit was chosen as indigo dyed rope for 1-m (0.350 kg) denim fabric. Since the scope of this work focuses mainly on the dyeing process, the remaining processes (fiber raw material supply, packaging, transportation, garment production, use and end of life, infrastructure, production of all machines and goods used in processes) were excluded as they were the same for both alternatives.

3.1.1. Life cycle inventory analysis

The life cycle inventory (LCI) used in this study was classified as primary and secondary data. The real IRD process data collected from the denim mill were used as primary data, and secondary LCI were collected from the Ecoinvent V3.0 database (Wernet et al., 2016).

Process-specific primary data, energy, chemical, and water consumption were collected from a denim mill located in Turkey for 2018. Since the mill had a combined heat and power plant, electric and steam production was modeled based on primary and secondary data. The primary data for chemicals and dyes used in the green and conventional IRD processes, in terms of both content and quantity, are given in the supplementary document (SD) 1. For the secondary data, the Ecoinvent Database was used. In the lack of data for chemicals and indigo dyes in the Ecoinvent Database, assumptions were made for the Ecoinvent process. Experts selected the appropriate data set with the Safety Data Sheet of the chemicals and dyes.

3.1.2. Life cycle impact assessment

The LCA was performed using Simapro 8.4.1 software with the gate-to-gate perspective (Pre Consultants, 2008). This study considered the following midpoint impact categories: global warming potential (GWP), ozone layer depletion (ODP), acidification (AP), eutrophication (EP), abiotic depletion (ADP), photochemical oxidant (PCOP) using the CML-IA method (Guinée, 2001). These categories were selected according to the taxonomy (Akı et al., 2020) that was listed as the commonly used environmental impact categories for the textile sector in the literature. Energy, water, chemicals, and dyes were included in the system boundaries. Also, the transportation of dyes and chemicals was neglected.

3.2. Social life cycle assessment

The main purpose of S-LCA is to identify and improve the social impacts of all stakeholders involved in or affected by the entire life cycle of a product or service. These stakeholder groups have been determined by the UNEP/SETAC Directives and the main stakeholder groups are workers, consumers, society, value chain actors, and the local community (UNEP/SETAC, 2013). The first step of the S-LCA is determining which stakeholder is involved in the assessment of the social impact. Sub-categories showing the issues to be considered while evaluating the stakeholders have been also determined with the same directive. After determining the stakeholders and subcategories, the method of evaluation of the impacts on the problem is decided and the evaluation is made. S-LCA follows two main approaches: the reference scale and the impact path approaches (Huertas-Valdivia et al., 2020). Many methods based on performance reference point such as checklist (Franze and Ciroth, 2011), scoring (Dreyer et al., 2006), Social Hotspot Database (SHDB) (Benoît et al., 2010), Subcategories Assessment Method (SAM) (Ramirez et al., 2014) and impact pathways methods (Neugebauer et al., 2014) have been developed for social impacts assessment.

This part aimed to assess the social impacts of the IRD process using SAM, where all stakeholders and related sub-categories were considered according to UNEP/SETAC (UNEP/SETAC, 2013). The list of all stakeholders and related sub-categories is given in SD 2. Only the company

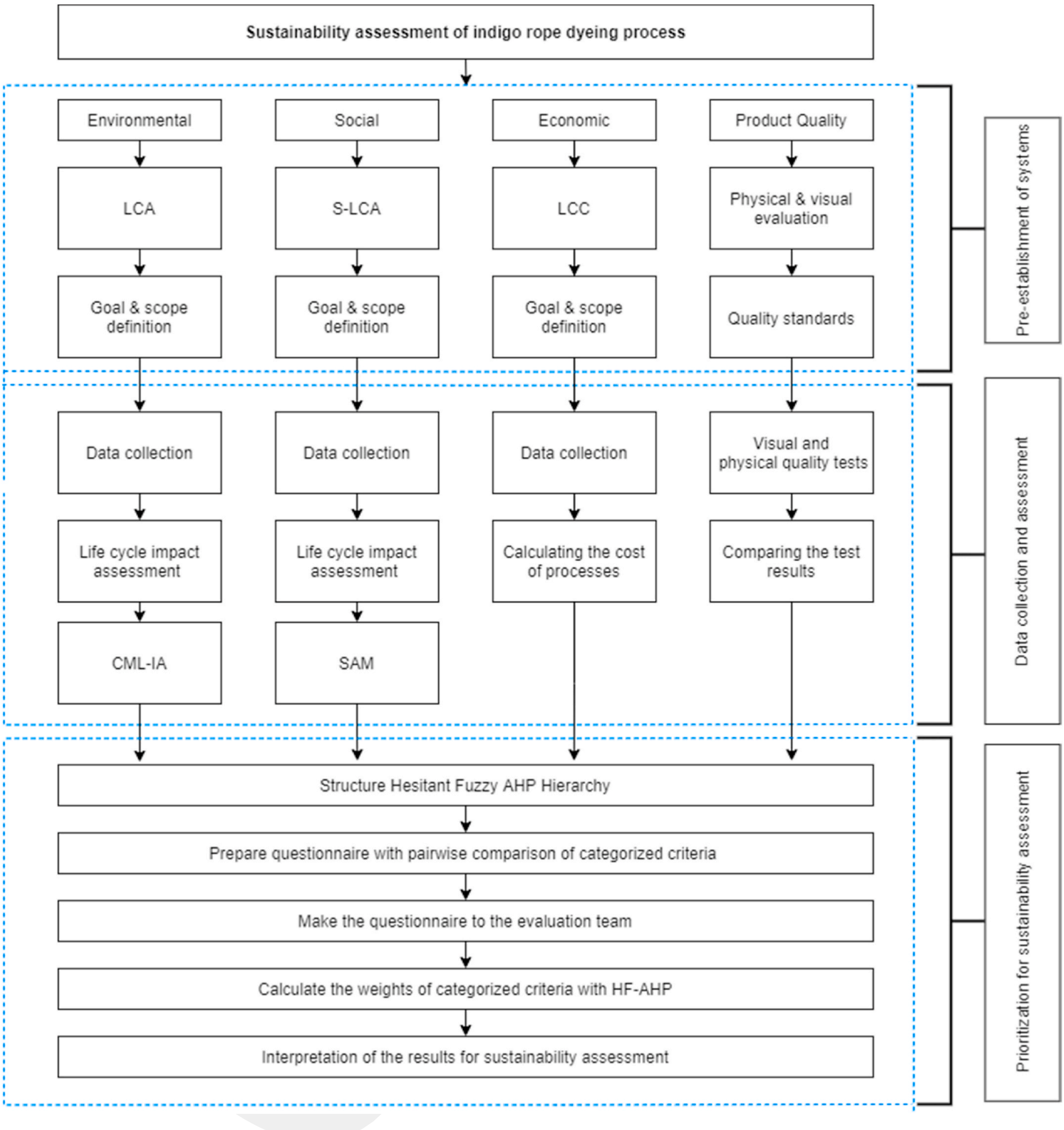

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Fig. 1. The framework of the proposed method for sustainability assessment of IRD processes (LCA: Life cycle assessment, S-LCA: Social life cycle assessment, LCC: Life cycle costing, SAM: Subcategory assessment method, HF-AHP: Hesitant fuzzy analytic hierarchy process).

- *Pre-establishment of the systems:* In the first stage, a new recipe was designed using green alternative chemicals for the sustainable IRD process with the CAA method. For the sustainability assessment, the dimensions of great importance in the IRD process and the methods of evaluating these dimensions were determined. Considering the non-negligible dimensions for the denim industry, environmental, social, economic, and quality dimensions were included in the assessment. The LCA method, which is widely used in literature, was chosen to evaluate the sustainability of products or services. This method is called LCA for environmental, S-LCA for social impacts, and LCC for economic impacts. The product quality added as the fourth dimension, which reveals the denim fabric's physical and visual properties, was applied according to international quality standards for denim products.
- Data collecting and assessment: LCA, S-LCA, and LCC methods require intense data for calculation. Raw material, auxiliary material, and energy consumption, and cost data realized within the system boundary are mandatory for LCA and LCC calculations. For S-LCA, a wide range of information is needed, from the company's employees to the actors in the supply chain. On the axis of the methods used at this stage, IRD process data were collected from the company's site and reports with a life cycle thinking approach. Tests for product quality were carried out in the laboratory. The methods chosen in the impact assessment were made following the literature. The CML-IA method for LCA was chosen according to the published taxonomy of LCA methods used in the textile industry. In evaluating social impacts, SAM, the most commonly used S-LCA method in the literature, was used.
- Prioritization for integrated assessment: Finally, the integrated sustainability assessment was conducted to evaluate the IRD options by the HF-AHP method. In the sustainability assessment, the HF-AHP method was used to consider the sector priorities instead of accepting the weight of the selected dimensions as equal. This method uses expert opinions to calculate the weights of the criteria determined as input. In this study, the outputs of all dimensions were included as the criteria of the HF-AHP method. Expert opinions were collected through a questionnaire from people determined to include all stakeholders. Then, the weights to be followed in the calculation steps of the HF-AHP method were obtained. Results for two IRD processes were obtained by multiplying the weights of the results of the two alternatives. Criteria weights were determined according to the opinions of the expert group, including all stakeholders. Then, the alternatives were interpreted with a integrated sustainability perspective.

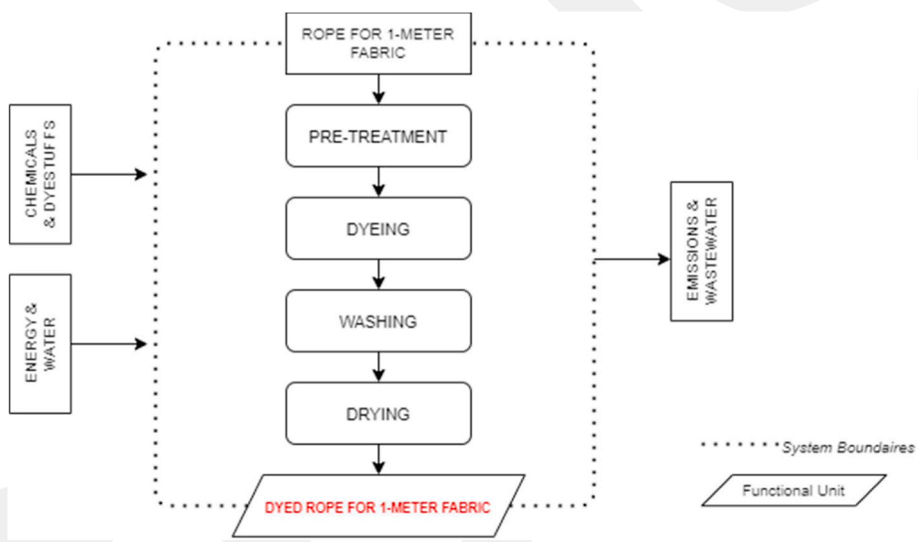

Fig. 2. Flow diagram and systems boundary of Indigo rope dyeing.

that conducted the dyeing process was included in the S-LCA.

While it is quite simple to link the results of both E-LCA and LCC to the functional unit, it can be difficult for S-LCA to do so (Hauschild et al., 2008; Klöpffer, 2008). The S-LCA Guidelines set out different approaches for evaluating social aspects and relating them to the product system (Parent et al., 2010). Since organizational behavior was often common to all unit processes occurring in the same organization, S-LCA values were distributed to functional units using the number of working hours referred to the functional unit (WFU) to compare two dyeing processes in the same organization (Ugaya et al., 2011). The WFU calculation is given in equations (1) and (2) (Ugaya et al., 2011).

$$\mathrm{Wh} = \frac{\mathrm{W} \ \ x \ \ \mathrm{h} \ \ x \ \ \mathrm{n}}{\mathrm{p}} \tag{1}$$

$$\mathrm{WFU} = \mathrm{Wh} \ \ x \ \ \mathrm{c} \tag{2}$$

where W is the number of workers, h is working hour per week, n is the number of working weeks per year, p is the total kg chemicals and dyes consumption in the process, $c_{1,}$ the total kg consumption of the chemicals and dye in the recipe for conventional rope dyeing, and $c_{2,}$ the total kg consumption of chemicals and dye in the recipe for green rope dyeing.

Although SAM provides numerical values for stakeholders' subcategories, it does not provide a suggestion for aggregation, the method suggested by Naghshineh et al. (2020) was used to calculate for obtaining numerical values of each stakeholder category (Naghshineh et al., 2020).

3.2.1. S-LCA life cycle inventory

According to the SAM, the first step is to define a BR (compliance threshold) to assess each sub-category. In this study, the BRs for all stakeholders were taken from Ramirez et al. (2014). The data were collected from the sustainability report of the company and interviews, including stakeholders. Thus, the reliability and accuracy of the data were provided (see SD 2).

3.2.2. S-LCA life cycle impact assessment

SAM is a characterization model that enables the social profile of the scope involved in the product life cycle to be evaluated regarding the fulfillment of the basic requirements (BRs). This method is completed by making a definition of the assessment scale and quantitative assessment using this scale. Organizations are evaluated in terms of fulfillment of essential requirements at four levels for each subcategory. Applied BR's in this study were determined by Ramirez et al. (2014) and given in SD 2. Scala levels of SAM were applied in this study, as shown in Table 2.

This method includes four classification levels, A (proactive), B (consistent), C (non-compliant, negative operation context), and D (non-compliant, positive operation context) to impact assessment for the social dimension. Evaluation is made according to the classification levels for each indicator determined. Evaluating the social impacts of a product using SAM enables obtaining objective results for decision-makers.

SAM allows the company to be evaluated by subcategories, which can then be linked to stakeholders or impacts. In addition to the qualitative evaluation made with the level scale for each subcategory, SAM also enables semi-quantitative evaluation with the score level (1–4; 1 being the worst assessment and 4 the best assessment) it determines. The method can be objective in analyzing social impacts in the life cycle assessment of products by transforming qualitative information into quantitative data (Ramirez et al., 2014).

In this study, collected data were compared with the defined BRs to implement SAM. If the company simply fulfills the BR, it was considered a B. If the organization hits BR along its supply chain, and A was given. The difference between C and D was chosen depending on the country context. A detailed assessment of the selected company was given in SD 2 according to SAM.

3.3. Economic evaluation

Life cycle cost (LCC) is the sum of end-to-end cost estimates of a product or process. The purpose of LCC analysis is to choose the most cost-effective alternative. In this study, the cost change was calculated with LCC based on the change of production costs with the newly designed recipe for the economic analysis dimension by using Simapro 8.4.1 Ph.D. version (Siddens, 2001). The LCC method was conducted by following the guideline published by Ciroth and Franze (2009)(Ciroth et al., 2009). The first step of the method is to create an LCC method by determining characterization, damage assessment, normalization, and weighting properties. In the second step, the reference cost per unit for the IRD process inputs is added under the economic issues section. Life cycle costs are calculated using the created method and the entered economic values. While calculating the cost of the IRD process, the costs of water, energy, dyes, and chemicals were considered. Both IRD alternatives were produced in the same IRD machine with a capacity of 50, 000 m/day. As construction, occupation, and maintenance phases were the same for the alternatives, they were not included in LCC.

3.4. Product quality assessment

Quality, which is among consumers' primary priorities, contributes to the sustainability of the product by providing long-term use (Bell, 2008). With the product providing the expected quality properties, it is prevented from being inferior due to problems such as tearing, rupture, and discoloration (Annis, 2012). For this reason, quality tests performed during production are essential in terms of ensuring the desired properties of the product (Nilsson and Lindstam, 2012). To understand whether the denim fabric surfaces are dyed in a similar color and fabric performances are identical, the effects of different washing processes on the surface properties and various performances of denim fabrics have been examined by international standard test methods and are given in SD 3. Physical and visual quality tests were applied to all fabrics regardless of whether conventional or green-dyed according to the American Society for Testing and Materials (ASTM, 2017), the American Association of Textile Chemists and Colorists (AATCC), and the International Organization for Standardization (ISO).

To compare denim fabrics' performance properties, dimensional weight, tensile strength, tear strength, colorfastness, and elongation were evaluated. The L * a *b * color values of the conventional and green IRD were obtained using the Hunter Lab color meter (Maryan and Montazer, 2013). Performance and appearance tests for fabrics were conducted after no washing or after three home washes according to the related test standard. For washing of denim fabric, 1 m of sample fabric was taken and washed with industrial detergent at 60 °C for 1 h. After washing, it was drum dried at 60 °C for 40 min. This process was repeated three times in a row to obtain three home washes (Bhattacharjee et al., 2019).

3.5. Sustainability assessment with HF-AHP

Decision-making is a very complicated and time-consuming process for people as they are hesitant and indecisive (Xu, 2014). These hesitations may not be taken into account with classical AHP. Fuzzy set theory was defined to deal with uncertain situations in decision-making problems. In the literature, Type-2 fuzzy sets (Zadeh, 1975), interval-valued fuzzy sets (Zadeh, 1965), and interval-valued intuitionistic fuzzy sets (Atanassov, 1999), Pythagorean fuzzy sets (Yager, 2013), Hesitant fuzzy sets (Torra, 2010), and Pythagorean fuzzy sets (Yager, 2013) are used to increase the reliability and flexibility of decision models.

Using the HFS approach, Rodriguez et al. (2011) presented a different approach, called the hesitant fuzzy linguistic term set (HFLTS), to handle the hesitation of decision-makers (Rodriguez et al., 2011). The HF-AHP method used to determine the relative importance of the criteria' weights is an integrated version of the classical Fuzzy AHP approaches with the hesitant fuzzy set (HFS) and Fuzzy Linguistic Expression Sets. The hesitant fuzzy set enables the use of linguistic expressions to manage situations in which the decision-maker hesitates. Because, in real-world problems, decision-makers hesitate to select a precise value. In determining the weight of the sustainability criteria for IRD in denim, this study applied the HF-AHP method in considering the hesitation of decision-makers. Basic definitions of the HFSs approach were given in SD 4. Calculation steps for HF-AHP applied in this study were carried out as follows.

Step 1: The main and sub-criteria that have a direct impact on the subject to be decided are determined. In this study, economic, environmental, social, and product quality assessments were considered the main criteria for implementing HF-AHP for sustainability assessments. While choosing the sub-criteria for the environmental aspect, the most used and meaningful impact categories in the textile industry were selected according to the taxonomy conducted by Akı et al. (2020). In the social dimension, all stakeholders defined by UNEP/SETAC were considered sub-criteria and no category or sub-category was excluded. Quality assessment of the product and process cost change, which is one of the most important issues when developing a new product or process, were also included in the criteria of HF-AHP. The sub-criteria used for the product quality assessment were generally accepted tests for the textile industry and defined by international standards. The list of main and sub-criteria for sustainability assessment is given in Table 3.

Step 2: After determining the main and sub-criteria, the set of linguistic terms $S = \{S_0, S_1, \ldots, S_g\}$ were determined. Hesitant linguistic terms and corresponding triangular fuzzy numbers are applied in this study given in Table 4.

Step 3: Pairwise comparison matrices for criteria by using hesitant linguistic expressions of experts are collected. A questionnaire was prepared to determine the interactions of the criteria for HF-AHP application (SD 5). Unlike classical Fuzzy-AHP, decision-makers are allowed to use more than one fuzzy linguistic expression in HF-AHP. The

Table 2
Scale levels of SAM (Ramirez et al., 2014).

Corporate Behavior	Proactive	Satisfactory and supporting BR	Not satisfactory BR (negative)	Not satisfactory BR (positive)
Level Scale	A	B	C	D
Score Level	4	3	2	1

Table 3
Criteria and sub-criteria list of sustainability assessment with HF-AHP.

Criteria	Environmental	Social	Product Quality	Economic
Sub-Criteria	ADP	Local Community	Fabric Weight	LCC
	GWP	Value Chain Actors	Elongation	
	ODP	Consumer	Colorfastness to dry rubbing	
	PCOP	Worker	Colorfastness to wet rubbing	
	AP	Society	Conditioned weight	
	EP		Tear strength	
			Tensile Strength	
			pH	

Table 4
Hesitant linguistic terms and corresponding triangular fuzzy number.

Hesitant Linguistic Variable	Triangular Fuzzy Numbers	Inverse Triangular Fuzzy Numbers
Equally Important (EI)	(1/2, 1, 3/2)	(2/3, 1, 2)
Less Important (LI)	(1, 3/2, 2)	(1/2, 2/3, 1)
More Important (MI)	(3/2, 2, 5/2)	(2/5, 1/2, 2/3)
Very Important (VI)	(2, 5/2, 3)	(1/3, 2/5, 1/2)
Absolute Important (AI)	(5/2, 3, 7/2)	(2/7, 1/3, 2/5)

questionnaire was applied to 15 different experts, including academics, stakeholders, consumers, local people, and employees, representing at least one expert from each stakeholder. Five of the experts belong to workers, three to value chain actors and society, and two to the local community and consumer stakeholders.

In this study, the experts selected for filling out the questionnaire were reached by phone and the questionnaire was sent to those who gave their approval via e-mail. Those who did not respond to the survey within ten days received a phone call to remind them that they had not yet answered the questionnaire. The respondents are experts in their field and also related to the denim industry.

Step 4: The fuzzy envelopes, env [d_{ij}], for each i-j pairs of criteria contains linguistic terms. An example of a fuzzy envelope for the social-environmental dimension pair is given in Table 5.

Step 5: Env [d_{ij}] data envelopes are converted to the env [$\tilde{d}_{ij}$] data envelopes containing triangular fuzzy numbers. An example of env [$\tilde{d}_{ij}$] for social-environmental dimension pair is given in Table 6.

Step 6: Arithmetic mean of fuzzy triangular numbers within in env [~dij] data envelopes are calculated. An example of arithmetic mean of fuzzy triangular numbers for social-environmental dimension pair is given in Table 7.

Step 7: Determining the weight of the i_{th} criteria for the k_{th} level by a geometric mean operation. Geometric means of fuzzy comparisons are calculated for the lower, middle, and upper values of each criterion. For example, the first row is calculated as:

$$= [(3/2*9/5)^{1/2}\ (2*11.5/5)^{1/2}\ (5/2*14/5)^{1/2}\ ] = (2.6\ 2.14\ 2.3)$$

Step 8: Calculation of fuzzy weights of each i_{th} criteria is made by using Equation (3).

$$\widetilde{w}_i = \widetilde{r}_i \otimes (\widetilde{r}_i \oplus \widetilde{r}_2 \oplus \ldots \oplus \widetilde{r}_n)^{-1} = (lw_i, mw_i, uw_i) \quad (3)$$

lw_i = lower weight of i_{th} criteria, mw_i = medium weight of i_{th} criteria, uw_i = upper weight of i_{th} criteria.

Step 9: The fuzzy numbers, $\sim w_i$, are converted precise numbers (M_i) using Equation (4) by the area center method developed by Chou and Chang (2008) in the defuzzification step (Chou and Chang, 2008).

$$M_i = \frac{lw_i + mw_i + uw_i}{3} \quad (4)$$

Step 10: Normalization of M_i weights for each i_{th} criteria by using Equation (5).

$$N_i = \frac{M_i}{\sum_{i=1}^{n} M_i} \quad (5)$$

Table 5
The envelope of linguistic terms for each environmental-social criteria.

	Environmental	Social
Environmental	[EI]	[VI,VI,VI,MI,MI]
Social	[LI,AI,MI,MI]	[EI]

Table 6
The envelope of triangular fuzzy numbers for each environmental-social criteria.

	Environmental	Social
Environmental	[(3/2, 2, 5/2)]	[(2, 5/2, 3; 2, 5/2, 3; 2, 5/2, 3; 2, 5/2, 3; 3/2, 2, 5/2; 3/2, 2, 5/2)]
Social	[(1, 3/2, 2; 5/2, 3, 7/2; 3/2, 2, 5/2; 3/2, 2, 5/2)]	[(3/2, 2, 5/2)]

Table 7
Arithmetic averaged fuzzy pairwise comparisons of environmental-social criteria.

	Environmental	Social
Environmental	[(3/2, 2, 5/2)]	[(9/5,11.5/5,14/5)]
Social	[(6.5/4,8.5/4,10.5/4)]	[(3/2, 2, 5/2)]

4. Results and discussion

4.1. LCA results

Conventional and green IRD processes were assessed and compared in terms of their environmental impacts by applying the CAA method as stated above. The results and the improvement percentage of the examined impact categories are given in Table 8.

As a result of the redesign of the recipe for sustainable indigo rope dyeing, the greatest improvement was achieved in the ADP with a

Table 8
Result and improvement ratio of impacts categories for comparing two IRD alternatives with the CML-IA method.

Impact Category (IC)	Unit	Conventional IRD	Green IRD	Improvement (%)
ADP	kg Sb eq.	4.94E-07	1.85E-07	62.55
GWP	kg CO_2 eq.	4.26E-01	3.92E-01	8.11
ODP	kg CFC 11 eq.	6.92E-08	6.08E-08	12.14
PCOP	kg C_2H_4 eq.	7.92E-05	6.70E-05	15.40
AP	kg SO_2 eq.	1.46E-03	1.20E-03	17.44
EP	kg PO_4 eq.	2.62E-04	1.93E-04	26.20

62.55% reduction from 4.94E-07 kg Sb-eq. to 1.85E-07 kg Sb-eq. The majority of this improvement is due to the reduced amount of caustic and indigo reducing agents in the green alternative recipe, and their contribution to recovery was 18% and 79%, respectively (Fig. 3). The change in the form and content of the indigo dye used in the new recipe contributed only 7% negatively. While the use of granulate indigo instead of liquid indigo contributes negatively to environmental impacts dye content, significant improvements were achieved by decreasing the amount of reducing agent and caustic required. With the replacement of wetting agents with green ones, ADP was decreased by 5%.

The GWP of the conventional IRD process decreased from 0.426 kg CO_2 eq. to 0.392 kg CO_2 eq. by applying the green IRD process (Table 8). According to the LCA results, the lowest improvement was achieved in GWP with 8.11%. Decreasing the amount of indigo reducing agent and caustic in the green recipe improved GWP by 71% and 38%, respectively. Of GWP improvement, 1.1% was due to the elimination of wetting auxiliary III; 7.2% improvement was obtained due to the difference in both the content of liquid and granulate indigo and the amount consumed in the recipe. With the substitution of wetting auxiliary I with wetting auxiliary IV and wetting auxiliary II with wetting auxiliary V, there was no GWP improvement. However, the substitution of these wetting auxiliaries with green wetting auxiliaries contributed negatively to this potential (%12.9 and 5.5%). (see SD 4).

ODP was reduced from 6.92E-08 kg CFC-11 eq. to 6.08E-08 kg CFC-11 eq., with a 12.14% improvement. The reduction in the amount of caustic and indigo reducing agent in the recipe similarly provided the biggest contribution to this category (87% and 44%, respectively). Caustic made the highest contribution, resulting in a decrease in the ODP. On the other hand, the change of indigo dye had the highest negative effect with a share of 27% (see SD 4). While the use of granulate indigo instead of liquid indigo contributes negatively to environmental impacts in dye content, significant improvements were achieved by decreasing the amount of reducing agent and caustic required.

Similarly, the 15.4% reduction in PCOP was due to reducing the amount of reducing agent (74%) and caustic (25%) needed for conventional indigo rope dyeing, which contains sodium dithionite and hydrosulfite. With the substitution of wetting agents, environmental impact values increased by 20% in this category, making the highest

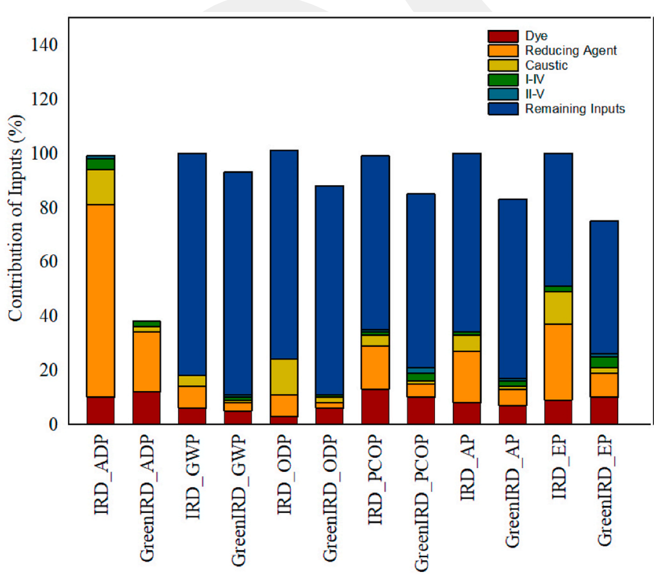

Fig. 3. Percentage improvement results of impact categories including contributions of every input for the two IRD alternatives (ADP: Abiotic depletion potential, GWP: Global warming potential, ODP: Ozone layer depletion, AP: Acidification potential, EP: Eutrophication potential, ADP: Abiotic depletion, PCOP: Photochemical oxidant potential, IRD: Indigo rope dyeing, remaining inputs: energy, and water).

negative contribution (see SD 4). According to the data selected in the Ecoinvent database, replacing wetting agents with green ones increased the environmental impact of the IRD process for the selected functional unit, but the remaining inputs such as dye, caustic minimizes this deterioration. Therefore, the conventional IRD recipe had higher environmental impacts at the end of calculations than the green IRD recipe.

Besides, it was noted that the substitution of wetting agents with more environmental-friendly ones was not sufficient to make a positive contribution in terms of environmental impacts, and the consumption amounts were significant to provide the desired properties in the fabric.

AP of the conventional IRD process decreased from 1.46E-03 kg SO_2 eq. to 1.20E-03 kg SO_2 eq. by applying the green IRD process, a 17.44% reduction. In this category, the greatest improvement was due to the amount of caustic (28%) and indigo reducing agent (75%) used, while the altering of indigo dyes made a 6% contribution. The EP category improvement occurred at 26.2%, with the contribution of the amounts of caustic and indigo reducing agent used, while the negative contribution was 15% by altering indigo dye and wetting agents (see SD 4). Therefore, indigo dye, reducing agent, and caustic soda are of particular importance for all categories examined. As a result, it was evident that the redesigned green IRD process is environmentally advantageous compared with the conventional process by assessing holistically.

4.2. S-LCA results

In this study, using the SAM method for S-LCA was carried out a comprehensive analysis of the IRD process in Turkey. SAM allows qualitative indicators to be translated into quantitative indicators with a scale definition. The reference BRs was used in this study, have been identified by Ramirez et al. (2014). For a detailed SAM evaluation of the company and results are given in SD 7.

The results of the following eight sub-categories were reported for the worker stakeholder: freedom of association and collective bargaining, child labor, forced labor, fair wages, working hours, equal opportunity and discrimination, health and safety, social benefit, and social security. According to the SAM results, the company had three A and three B grades in worker stakeholder. All workers were associated with a union. Besides this, there was a policy for the elimination of forced and child labor and to eliminate child labor with a declaration from its suppliers. The lowest salary was equal to the minimum wage in the country. The company had ISO 45001 Occupational Safety & Health Management certificate and offered social security, retirement, disability, paid maternity and paternity leave, paid sick leave, and medical insurance.

The following five sub-categories were considered and assessed for the consumer stakeholder: health and safety, feedback mechanism, consumer privacy, transparency, and end-of-life responsibility. The company had four out of five sub-categories are at level A and the remaining 1 at B. As the company had a policy and implemented the Zero Discharge of Hazardous Chemicals program, requirements to ensure the products' health and safety were evaluated at level B (ZDHC, 2019). The company had ISO 10002:2014 Customer Satisfaction and ISO 27001 Information Security Management System certificates. The sustainability report was prepared periodically according to the Global Reporting Initiative Standard (GRI, 2020). The remaining sub-categories were evaluated at level A. According to the S-LCA guidelines (UNEP/-SETAC, 2009), all sub-categories for the local community stakeholder group were assessed – delocalization and migration, community engagement, cultural heritage, respect of indigenous rights, local employment, access to material resources, access to immaterial resources, safe and healthy living condition, and secure living conditions. According to the results, all sub-categories met the BR requirements and were evaluated at A and B. The company has ISO 9001 Quality Management Systems, Global Organic Textile Standard, Global Recycled Standard, Better Cotton, Fairtrade, and ISO 14001 Environmental Management System, and ISO 50001 Energy Management System certificates. The company was generally highly rated within the society and value chain actor's stakeholder group. The determined levels were A and B in the sub-categories, as the procedures following the basic requirements were adopted.

Naghshineh et al. (2020) suggested the method to obtain a single value by gathering the evaluation results of SAM obtained for each sub-category on a stakeholder basis. Since both conventional and green IRD were done in the same company, the S-LCA results were distributed to alternative IRD processes using the WFU calculation (Ugaya et al., 2011). WFU values of green and conventional IRD were 2.03E-04 and 2.66E-04, respectively. To find the result of the SAM method for each dyeing method, the SAM value obtained for the company was divided by the WFU value of the relevant process. The SAM results are given in Fig. 4 and SD 8.

According to the S-LCA assessment of green and conventional indigo rope dyeing, the conventional IRD process had adverse social impacts for all stakeholders considered. It is noted that having a higher score for SAM results indicates a positive aspect. Green IRD can be preferred in terms of both environmental and social impacts.

4.3. Economic evaluation results

Among the sustainability criteria evaluated in this study, the economic dimension was calculated using the LCC method for the conventional and new recipes. For these two alternatives, the energy and water consumed during rope dyeing and the cost of chemicals and dye were included in the calculation. According to the LCC results, the change in the cost of the processes and the conventional IRD as the reference value are given in Fig. 5.

Dye and chemical cost was the main contributor with 78% of the total life cycle cost of the dyeing process. The main reason for this was the high consumption of dyes and chemicals in the IRD process. When examining the change in costs with green IRD compared to conventional indigo rope dyeing, the most important difference occurred in the price of dyes and chemicals. According to the results, the green IRD had a significantly higher LCC (57%). Energy cost had the second-largest share, with 14% of the total life cycle cost of conventional IRD. In the IRD process, there was steam and electricity below the energy cost, and it had the same LCC result for both the conventional and the green IRD process for the functional unit. Finally, water costs account for 8% of the total life cycle cost of conventional IRD. Conventional IRD costs 2.08% more than LCC results in water cost.

As far as the authors know, this is the first time the LCC of an IRD has been performed; therefore, it is not possible to compare these findings with previous findings. As a result, the cost change was also included in the sustainability assessment of the IRD process, thereby providing the framework for a multi-dimensional analysis for decision-makers. The cost factor is one of the top priorities in sustainable decision-making (Booker et al., 2007).

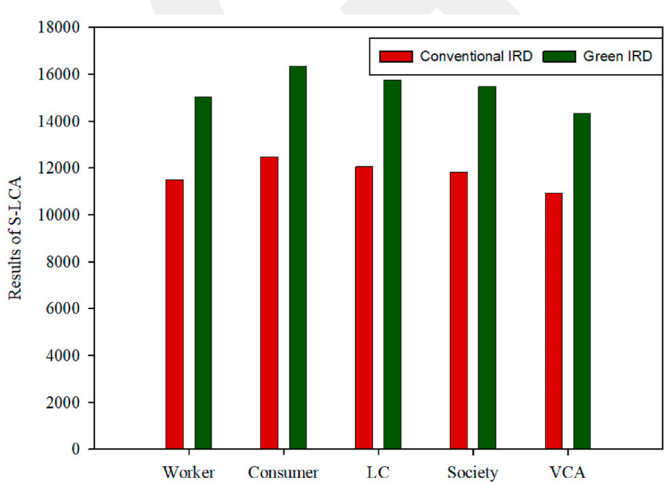

Fig. 4. Results of S-LCA for comparing two IRD options (LC: Local Community; VCA: Value Chain Actors, IRD: Indigo rope dyeing, S-LCA: Social life cycle assessment).

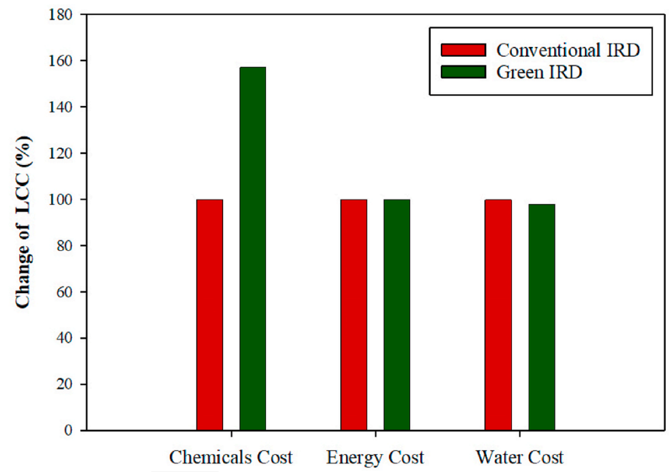

Fig. 5. Comparison of LCC results of two IRD options (IRD: Indigo rope dyeing, LCC: Life cycle costing).

4.4. Product quality assessment results

To check the CAA suitability for the IRD process, it is crucial whether fabric with similar physical and visual properties is obtained. Also, quality tests should be carried out to control the optimum properties expected from the fabric as a sustainability parameter (Fidan et al., 2021). For this reason, the performance and visual evaluations of the fabrics obtained by conventional and green IRD were made with quality tests according to international standards. The test results for physical properties applied are given in Table 9.

According to Table 10, the weight of the green-dyed fabric was 390 gr/m^2 and nearly the same as the conventionally dyed fabric. Conditioned weight for both of the dyed products is satisfactory, with weights of 385 gr/m^2 for the conventionally dyed product and 390 gr/m^2 for the green-dyed product. Since pH is an essential parameter for textiles, and it was expected that the values should be between 5 and 7, the observed pH values of 5.75 for the conventional IRD process and 5.9 for the green IRD process and the results were reasonable (Kan et al., 2011). The elongation criteria were 9.6% for conventional IRD and 11% for the product of green IRD. As a result, the fabric produced with the green IRD process exhibited quite similar physical test results. According to the physical quality test results, the fabrics produced with both the green and conventional IRD processes were acceptable for customer demand. No significant difference was observed between these two fabrics, according to the physical test results.

L *, a *, and b * colorimetric measurements were carried out for the

Table 9
The comparison of conventional and green IRD with physical test results of fabrics.

Physical Tests	Unit	Green IRD	Conventional IRD
Fabric weight	gr/m^2	402	390
Elongation	%	9.6	11
Colorfastness to dry rubbing	Gray scale	4.5	4.5
Colorfastness to wet rubbing	Gray scale	1.5	2
Conditioned weight	gr/m^2	385	390
Tear strength	grF	9083	6700
Tensile strength	kgF	69	88
pH	–	5.75	5.9

Table 10
Colorimetric differences of conventional and green indigo rope dyed denim fabric.

Scenarios	Color Coordinates		
	L*	a*	b*
Conventional dyed denim	−12.00	−25.86	−14.26
Green dyed denim	−11.57	−27.70	−15.28

visual appearances of the fabrics obtained by two alternative dyeings. Colorimetric results of conventional and green IRD were given in Table 10. There was no significant difference between the fabrics obtained due to two dyeings according to L *, a *, and b * values. As a result, denim fabric with desired properties was obtained by applying it as a CAA. The green IRD process showed superior performance in terms of environmental impact, even though the fabric quality of the green IRD process was similar to that of the conventional process.

5. HF-AHP results

To evaluate the sustainability of the IRD process, which was redesigned by replacing conventional chemicals and dyes with green alternatives with a holistic approach, the weights of the selected criteria were determined by using the method of HF-AHP, which is an effective and successful approach to deal with uncertainty and reflects the hesitations of decision-makers. With this approach, we have scientifically reflected the preferences of multiple decision-makers on the selection of criteria. The relative weights of Fuzzy $(\widetilde{w_i})$, De-fuzzified (M_i), and normalized (N_i) for the main and sub-criteria are given in SD 9 and SD.10. Fuzzy $(\widetilde{w_i})$ weights are shown with lw_i, mw_i, uw_i. The sustainability assessment results of the IRD process with HF-AHP are given in Fig. 6.

In the holistic sustainability assessment of the IRD process, the most important criteria according to the decision-maker's preferences were environmental impact at 33%, followed by social impacts at 27%, quality results at 23%, and financial results at 17%. These results were in the textile industry agenda's expected direction due to the high environmental impacts of the dyeing process and the social impacts of the textile (Björklöv and Lindgren, 2017). Considering the importance of environmental and social impacts in the sector, it was clear that green IRD was preferred. However, the physical and visual quality results and economic aspects expected from the product are still important enough not to be ignored. In this study, conventional IRD was preferred according to the cost of the process in terms of economic aspects, while the green IRD process was ahead in terms of quality results.

According to the criteria, weights obtained with HF-AHP, EP with 24%, and GWP with 18% were respectively the most crucial sub-criteria of the environmental dimension. The most important sub-criteria for the social dimension was society (24%) and workers (23%). In terms of quality test results, fabric weight had the highest weight (32%) with a significant difference, and the remaining sub-criteria had approximately equal importance. According to the HF-AHP results, the green IRD process was preferred in environmental, social, and product quality evaluations, while it was high in cost (Fig. 6). However, economically, the values of the two IRD processes were very close to each other, and the conventional process cost slightly less.

6. Uncertainty and sensitivity analysis

The stages of an LCA have various uncertainties resources such as data, models, etc. Decisions taken without taking these uncertainties into account may be flawed. A general incentive for measuring uncertainties is to enhance the transparency of LCA data and results. Typically, a key question in an uncertainty analysis is "To what extent do uncertainties in input values produce uncertainty in model outputs?" (Baker and Lepech, 2009). The sensitivity analysis was conducted with systematically varying input parameters to identify how sensitive the outputs are to each input. Various ratios in literature are applied to measure the variations of the inputs, e.g. ± 5%, ±10%, ±20% (IISBE, 2001; Liu et al., 2020; Igos et al., 2019). In this study, +10% variation was chosen to examine the sensitivity of the results for the selected inputs. Sensitivity analysis for LCA and LCC with quantitative data and Monte Carlo analysis for S-LCA with semi-quantitative data were used for uncertainty analysis. For LCA and LCC analysis, indigo dye and wetting agent 2 were chosen as input parameters because they are the main chemicals considered in this study. Each parameter was examined

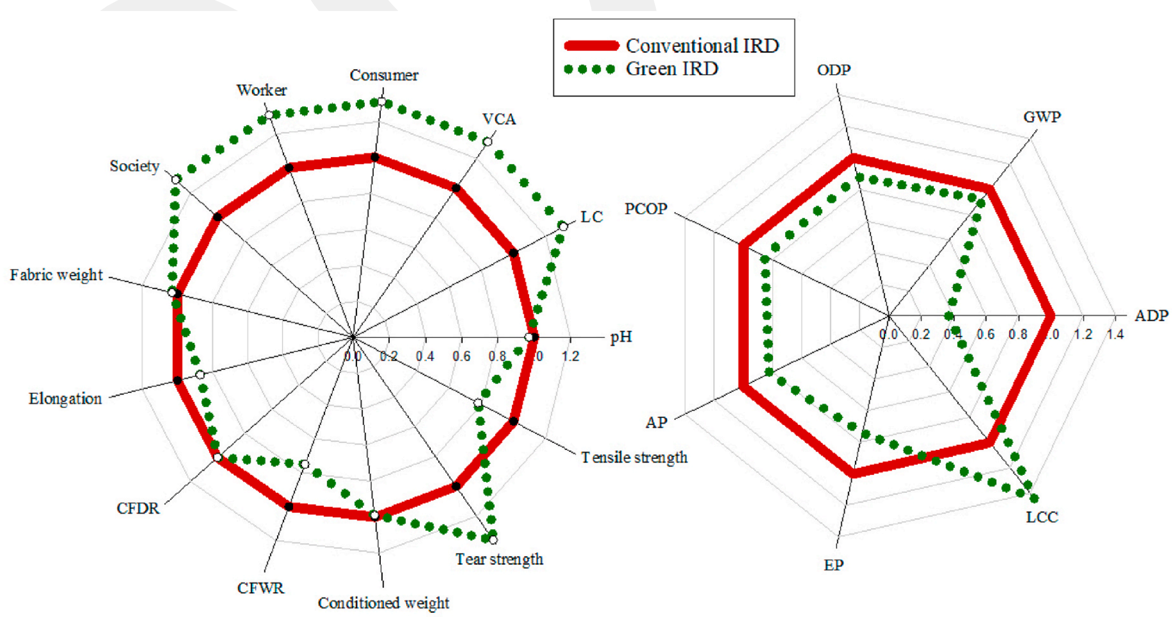

Fig. 6. Normalized HF-AHP Results including all dimension (CFDR: Colorfastness to dry rubbing; CFWR: Colorfastness to wet rubbing; CW: Conditional weight; FW: Fabric weight; LC: Local Community; VCA: Value Chain Actors, ADP: Abiotic depletion potential, GWP: Global warming potential, ODP: Ozone layer depletion, AP: Acidification potential, EP: Eutrophication potential, ADP: Abiotic depletion, PCOP: Photochemical oxidant potential, IRD: Indigo rope dyeing, LCC: Life cycle costing).

independently of the others and was increased +10% from the baseline. The results of the sensitivity analysis are given in Fig. 7 and Fig. 8.

The two IRD processes were not sensitive to the consumption of dye and wetting agent 2 in LCA and LCC, as the changes in results were less than 10%. These outputs showed that the uncertainty of the inputs did not have a significant effect on the results. Besides, environmental impact results were more sensitive to the consumption of indigo dye than the consumption of wetting agent 2. Consequently, the uncertainty in the data does not have a significant effect on the results.

Uncertainty of input data is an issue that needs to be addressed in the S-LCA. The data obtained from the SAM method in this study may show some uncertainties. The scoring uncertainty in the S-LCA has been addressed. Because some social scores may contain subjective analysis and internal biases related to human well-being from the individual's point of view. Concerning the semi-quantitative social indicators, Zheng et al. (2020) work has been followed to address uncertainty (Zheng et al., 2020). Constant scores were transferred to random scores following by uniform distribution. After modeling the uncertainties related to the scoring factors of social indicators, the probabilistic results of the S-LCA were revealed by 1000 iteration Monte Carlo simulations. The results are given in Table Fig. 9.

When the statistical results of S-LCA for both alternatives were examined, it was seen that the green IRD process was higher than the traditional IRD in the case of uncertainty. Green IRD for the local community and value chain actors' subcategories has higher results than conventional IRD. Green IRD's S-LCA is 98% higher than the traditional IRD alternative for the worker subcategory. With 76% probability for the Consumer and 82% for the Society, the green IRD has better results than the conventional IRD process.

7. Conclusions

In this study, a conventional IRD recipe was redesigned with the CAA method to include the GreenScreen® certified chemicals. The options obtained for the IRD recipe were evaluated with a sustainability approach. The environmental and social impacts of the IRD process and the end product's economic and quality assessment were also included in the assessment. To determine the importance of the weights of the sub-criteria of all the dimensions examined, the HF-AHP method was applied for more precise results. For the four dimensions included in the sustainability assessment, two IRD alternatives were evaluated with the weights of the twenty sub-criteria.

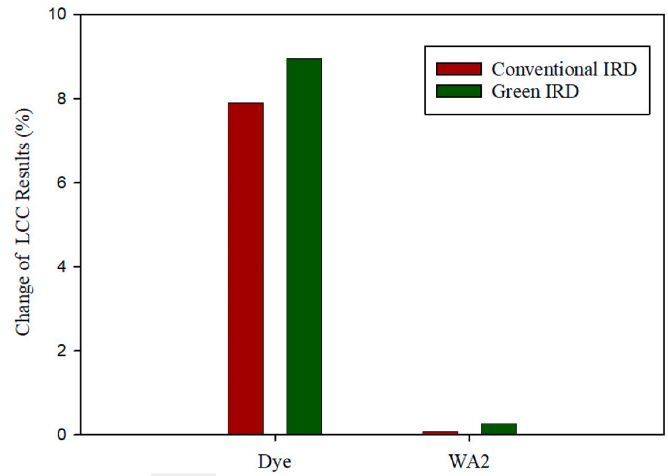

Fig. 8. LCC Sensitivity analysis results for dye and WA2 consumptions (WA2: wetting agent 2, LCC: Life cycle costing, IRD: Indigo rope dyeing.

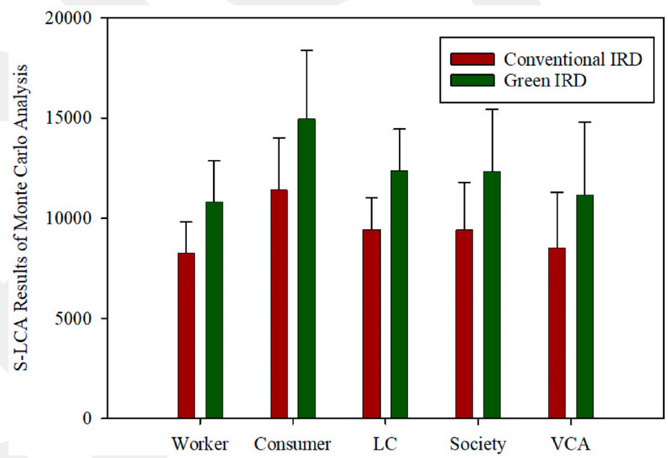

Fig. 9. Monte Carlo Analysis Results (Mean and Standard Deviation) of the two IRD Processes (LC: Local Community; VCA: Value Chain Actors, IRD: Indigo rope dyeing, S-LCA: Social life cycle assessment).

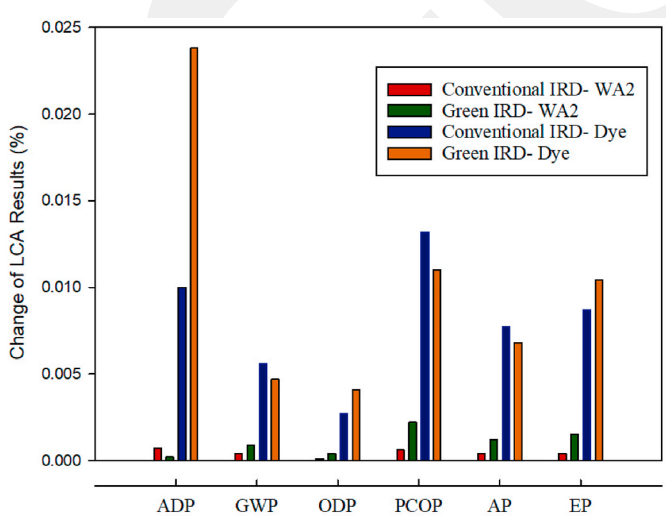

Fig. 7. LCA Sensitivity analysis results for dye and WA2 consumptions (WA2: wetting agent 2, ADP: Abiotic depletion potential, GWP: Global warming potential, ODP: Ozone layer depletion, AP: Acidification potential, EP: Eutrophication potential, ADP: Abiotic depletion, PCOP: Photochemical oxidant potential, IRD: Indigo rope dyeing, LCA: Life cycle assessment).

According to the environmental aspect results, green IRD has a lower environmental impact on all selected categories than the conventional IRD process. The ADP category was remarkable with a 65.55% improvement, while in the GWP category, the improvement was limited to 8.11%, mostly due to its energy-related nature. Also, liquid indigo dye is more environmentally friendly as it requires less reducing agent than granulate indigo dye. Although the substituted wetting agents were green alternatives, they did not provide the desired environmental improvement due to the amount of use. Therefore, even if the selected chemicals have a certificate showing that they are more environmentally friendly, high chemical consumption may not provide the desired environmental and social benefits. For this reason, consumption amounts should be taken into consideration when evaluating chemical alternatives.

From a social perspective, the green IRD process has achieved better results, with an almost "proactive" status compared to the SAM method. In the economic aspect evaluation, the cost of production of green IRD was higher than conventional indigo rope dyeing. According to the product quality test results, two fabrics were acceptable commercially, and no significant difference was observed for either the visual or physical features. HF-AHP was used as a systematic method to overcome the difficulty of evaluating multiple dimensions together. HF-AHP helped decision-makers expressing their opinions with hesitant degrees. According to the HF-AHP results, although the most critical main criteria in sustainability assessment were environment, the least weight criteria were economic aspects. Moreover, the sub-criteria with the highest weight was EP for the environmental aspect, fabric weight for fabric quality assessment, and worker and society for the social aspect. As a result, cleaner production measures such as reducing the consumption amount of chemicals and dyes, reducing water consumption, and using renewable energy resources in the dyeing process should be applied for sustainable production.

Undoubtedly, the proposed framework has some limitations. LCA studies require large amounts of data. Problems such as the availability of these data and the time it takes to collect appear as a limit. The first limitation of this study on data was related to the Ecoinvent database. Although primary data were used for the IRD processes, some assumptions were made from the Ecoinvent database for raw materials such as chemicals, dyes, energy. The selection of the appropriate dataset was made with industry experts based on current data available, and the results were built on these assumptions. The second limitation was the evaluation scale of SAM used for the S-LCA. Conducting the SAM evaluation with precise and limited options may result in the evaluator's lack of sensitivity to fully reflect his thoughts. For this reason, expanding the related method to make a more sensitive evaluation will increase the accuracy of the results. Another limitation was that the scope of the S-LCA was limited to the fabric manufacturing company, as it is a labor-intensive method. There were not yet sufficient databases for an S-LCA to include all supply chains. Also, existing S-LCA methods in the literature cannot evaluate the existing functional unit. Therefore, the results obtained are an evaluation of the relevant company, and an approach based on working hours was used following the literature to relate it to the functional unit. S-LCA is a method that is very limited in the literature and there is no common acceptance of the correct approach. For this reason, while this study makes important contributions to the virgin field of S-LCA, it can provide a fertile ground for conducting comprehensive studies in the future in areas such as methods, databases, linking with functional units."

This study's findings provide insight for scientists, policymakers, and experts to improve the sustainability of denim production an important contribution to the literature. Finally, further studies should be performed on the following: an investigation of the IRD process using chemicals with different sustainability certificates, improving the uncertainty in the LCI data, and integrating MCDM methods for assessing criteria weights on stochastic or fuzzy environments.

CRediT authorship contribution statement

Fatma Şener Fidan: collected to data, analysed the data, and. **Emel Kızılkaya Aydoğan:** and, and. **Nigmet Uzal:** designed the Multi-dimensional Sustainability Evaluation of Indigo Rope Dyeing approach and the computational framework, performed the calculations and wrote the manuscript.

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.2021.127454.

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